Perennial transitions from market gardening towards mixed fruit tree - vegetable systems

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13   **ABSTRACT**

14   *CONTEXT*

15   Planting fruit trees in a market gardening system creates a mixed fruit tree – vegetable system with

16   the potential to address certain environmental issues. However, it results in a complex system where

17   labor has to be allocated between the two activities.

18

19   *OBJECTIVE*

20   Our objective is to simulate possible trajectories for a perennial transition from market gardening to

21   mixed fruit tree – vegetable systems, in order to study the required trade-offs.

22

23   *METHODS*

24   We modeled the transition using viability theory, a framework with states, controls and constraints

25   that guarantees sustainability along a transition trajectory. It was used in two iterations, the first step

26   computing a target to be reached during the second step. Trajectory samples were computed from the

27   sets of viable states at each time step.

28

29   *RESULTS AND CONCLUSIONS*

30 In order to guarantee sustainability, at the end of the transition process the farm must not only respect

31 the constraints but belong to a subset of the domain they define. The study of viable trajectories shows

32 a trade-off between capital and working hours, and thus different suitable strategies for the timing of

33 orchard planting and the choice of crop rotations. Some strategies present bottlenecks where the

34 flexibility of the farm is greatly reduced.

35

36 *SIGNIFICANCE*

37 The variety of resulting viable trajectories means that choosing between them can call upon criteria

38 that are not implemented in the model, such as personal preferences. The establishment of a target

39 through viability computation and the study of trajectory sets avoids the imposition of an *a priori*

40 normativity.

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43 **GRAPHICAL ABSTRACT**
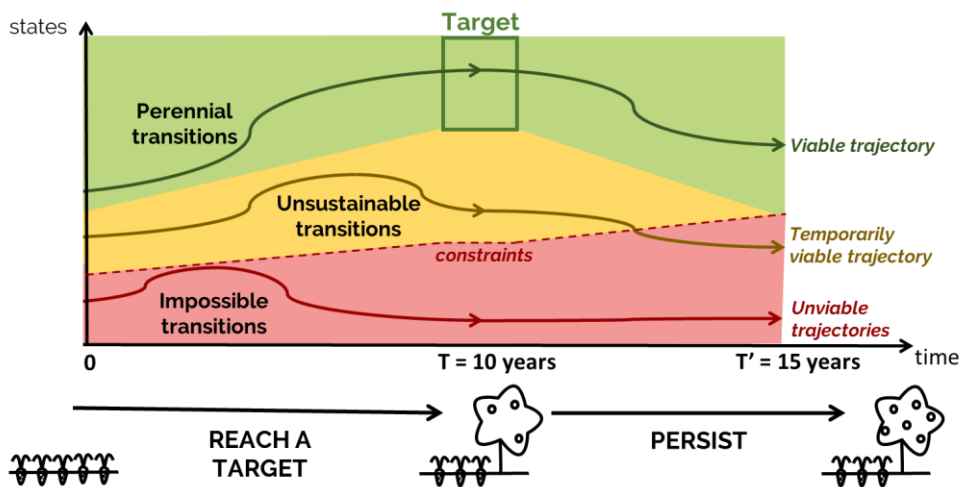
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48 **Keywords:** viability theory; crop diversification; perennial transition; mixed horticultural farm;

49 agroforestry

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Highlights:

53 • The transition from market gardening to a mixed fruit tree – vegetable system increases both
54 the functional diversity and the complexity of a farming system.
55 • Using viability theory, we modeled possible trajectories for a perennial transition from
56 market gardening to mixed fruit tree – vegetable systems.
57 • We show a trade-off between capital and working hours.
58 • This trade-off is driven by the timing of fruit tree planting and the choice of crop rotations.
59 • The sets of viable trajectories give a wide range of possibilities that can be made compatible
60 with individual values and priorities.

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64 **1. INTRODUCTION**

65 In order to meet current environmental and social concerns, new farming systems based on
66 agroecological paradigms are becoming increasingly common in the agricultural landscape (Wezel et
67 al., 2014). In particular, more diversified systems make it possible to improve adaptability and thus to
68 face global changes (Dardonville et al., 2020; Darnhofer et al., 2010; Rigolot et al., 2019). Highly
69 diversified Market Gardening (MG) systems are thus a growing trend in agriculture. They produce a
70 wide range of vegetables (generally over 25 varieties) on small areas, mostly directed towards direct
71 selling (Morel, 2016; Pépin et al., 2021). These farms are generally run by farmers with strong social
72 and environmental aspirations, but who are confronted with pragmatic considerations (Morel and
73 Léger, 2016).

74 One way to effect a change in these systems while remaining coherent with ecological aspirations is to
75 plant fruit trees in addition to vegetable crops, in order to create a Mixed Fruit tree – Vegetable (MFV)
76 system. Mixing these two types of production results in increased functional diversity. Given their size
77 and their perennial development, trees present morphological characteristics and functional traits
78 very different from annual vegetable crops. They can buffer the microclimate, possibly benefiting
79 lower-growing crops, through a modification of light penetration, air temperature and humidity, soil
80 temperature and moisture, and wind movement. They also provide a wide range of ecosystem
81 services: carbon sequestration, soil structure enhancement, relocation of soil nutrients, erosion

82 control, food and habitat for pest predators and parasitoids, water quality enhancement and reduction

83 in nutrient leaching, etc. (Beillouin et al., 2021; Chittapur and Patil, 2017; Sollen-Norrlin et al., 2020).

84 The resulting system is also very well adapted to direct selling, providing complementary, high-added-

85 value products. Fruit can be considered as an attractive product that will make the consumer more

86 willing to come to the sales point (Léger et al., 2019). Their high efficiency on small areas makes these

87 systems interesting in a context of competition for land use. However, despite all their potential

88 advantages, such systems are also very complex to manage.

89 Indeed, fruit trees and vegetables have distinct physiological requirements and characteristics that

90 must be considered in their management. They must be spatially arranged in order to minimize

91 competition between crops. Their temporalities differ: most vegetables are annuals whereas fruit trees

92 are perennial crops requiring several years to reach their full potential yield. Fruit tree planting can

93 thus be considered as a long-term investment compared to annual vegetable cropping. When working

94 hours are limited, prioritizing of tasks can favor one type of crop over another. The choices made can

95 provide short-term benefits during the current year (*e.g.* harvesting vegetables) or be long-term

96 investments with benefits over the next few years (*e.g.* pruning trees). Failing to make this investment,

97 by neglecting fruit tree care during the first stages of development, can heavily impact their production

98 for many years. It is therefore crucial for a farmer to pay particular attention to the initial stage of tree

99 development when shifting from MG to MFV. Finding the right balance between long- and short-term

100 objectives is particularly difficult as it requires the ability to project the consequences of short-term

101 decisions onto the system's long-term dynamics.

102

103 In this study, we developed a dynamic model of an MFV farm to explore the long-term consequences

104 of crop and workload allocation choices for the dynamics of a farming system during perennial

105 transition from an MG farm to an MFV system. More specifically, we addressed two issues: the paths

106 enabling transition to occur and the conditions under which the targeted MFV system can become

107 perennial. In order to find the set of management options that would make it possible to perform the

108 transition, we used the Viability Theory mathematical framework (Aubin, 1991).

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2. METHODS

2.1. Viability theory:

Viability theory is a mathematical framework that applies to the dynamics of state-control systems. It seeks the set of situations and management options that make it possible to maintain the system within a set of constraints over time (Aubin et al., 2011).

A given trajectory is defined by a series of states adopted over time. Changes in state are determined by the choice of controls at each time step. A trajectory is considered as viable if it satisfies the constraints at any time. The set of all initial states from which at least one viable trajectory starts is called the viability kernel.

In the absence of any objective to be optimized, the main objects studied through viability theory are sets of states and sets of trajectories. Therefore, it is particularly well-adapted to studying sustainability issues, as it avoids the contentious issue of weighting different facets of sustainability (environmental, economic and social) in order to provide a single solution. It also avoids trade-offs between short- and long-term considerations through the choice of an intertemporal objective. However, this type of model has rarely been used in relation to agriculture, and where it has, this has mostly been in relation to herd- and grazing-management systems. Few viability studies deal with cropping (Oubraham and Zaccour, 2018).

2.2. Farm description:

The model created is a discrete time (annual time step) dynamic model representing an MG or MFV farming system, enabling simulation of changes over time of the farm's financial capital and the condition of its orchard. It is based on Paut et al. (2021). It considers a one-hectare farm comprising four equivalent plots. On this farm, one or two plots can be planted with trees, either apple (Royal Gala variety) or peach (Big Top variety). Crop rotation can be modified each year. On each vegetable plot, two crops are grown each year (winter and summer crops). They are selected from one of six choices, three winter crops (lamb's lettuce *Valerianella locusta* var. *trophy*, cabbage *Brassica oleracea* var. *capitate* and squash *Cucurbita moschata* var. musquée de Provence) and three summer crops (pepper *Capsicum annuum L.*, zucchini *Cucurbita pepo* var. *cylindrica* and bean *Phaseolus vulgaris L.*). These crops were selected for their contrasting annual gross margin, labor requirements, workload allocation

144 throughout the year and, for the fruit trees, growth dynamics. In order to guarantee rotation among

145 the crops on each plot, the same crop cannot be planted on more than 50% of the farm area (Appendix

146 A). Monocultures and their long-term consequences on soils and biodiversity are thus excluded from

147 the model. Crops are considered to be cultivated on distinct plots; no interactions are therefore

148 considered between crops (vegetables or trees).

149

150

151 **2.3. Transition description:**

152 The system begins as an MG farm, with no trees. The transition to an MFV system can happen any time

153 between the first year and the time horizon (T = 10 years).

154 Transition from one system to another is always a long-term projection. The new system must remain

155 viable after the time horizon T at which the transition is considered to be complete. Furthermore, we

156 consider that farmers may be willing to put in a major effort for a few years in order to reach a more

157 convenient situation that will be easier to sustain over the long term. We thus translated an easing of

158 labor conditions after T by an increase in salaries and a decrease in working hours.

159 Management of such a farm requires the handling of several different tasks beside crop production,

160 such as marketing and administration. Therefore, labor time devoted to crops is lower than the total

161 working hours invested by the farmer. In the current situation and based on farmers' feedback, we

162 consider crop-related labor to account for around 70% of the total. The farm being conceived as being

163 managed by one full-time farmer, and according to what has been observed on highly diversified small

164 farms (Joyeux, 2017), labor time available is around 50h/week. Labor time devoted to crops is thus

165 limited to 140h/month (35h/week), for the first ten years. The farmer's wage is fixed at €1,500/month,

166 which is slightly under the French minimum wage (€1645.58 in 2022). Fixed costs are set at €8,000/year

167 (Declercq and Clerc, 2011). After T, salaries are raised to €2,000/month whereas working hours

168 devoted to crops are reduced to 120h/month (30h/week), reflecting better working conditions after

169 the transition phase.

170

171

172 **2.4. States and controls:**

173 Following the viability theory formalism, the model is characterized by states, controls, and

174 constraints. States and controls have been chosen to assess common viability criteria for such farms

175 (Morel and Léger, 2016), while considering conflicts that can appear between orchard and vegetable

176 management.

177 States are system features that change over time. In our model, the states considered are the farm's

178 economic capital (continuous), three discrete variables describing orchards, once fruit trees have been

179 planted, and one accounting for elapsed time (discrete):

- x_1: Farm's economic capital, in euros (€). Even though money-making is not always a priority for these farmers, we considered that most people have financial constraints, thus making it mandatory to use an economic indicator to assess viability.

- x_2: Tree age in years. A value equal to zero means that no trees are present.

- x_3: Fruit tree composition, *i.e.* fruit tree species already present on each orchard plot. The possibilities are apple once (meaning that only one plot is planted with apple trees), peach once, apple twice, peach twice and an apple-peach combination. In the absence of fruit trees, this state takes the value *none*.

- x_4: Potential fruit production coefficient, which gives the relative production potential of fruit trees given past management. It translates the effects of a lack of labor devoted to fruit trees which can decrease future yields.

- τ: Time since the beginning of the computation, in years.

193 Controls correspond to the ways in which farmers can act on states between *t* and *t*+1. Here, choices

194 can be made about:

- crop rotation (u_1), *i.e.* the list of four vegetables and trees grown during the current year on the four plots (Appendix A). This control makes it possible to simultaneously decide on the vegetable portfolio, fruit tree species, and the proportion of the farm devoted to each. In addition, the planting and/or removal of the orchard can be deduced from a comparison with the previous fruit tree composition, given by x_3.

- workload allocation (u_2), which refers to the farmer's prioritization of labor between orchard and market gardening, when insufficient labor is available to meet the needs of both. It varies between 0 (maximum priority is given to vegetables) and 1 (maximum priority is given to fruit trees).

206 **2.5. Dynamics:**
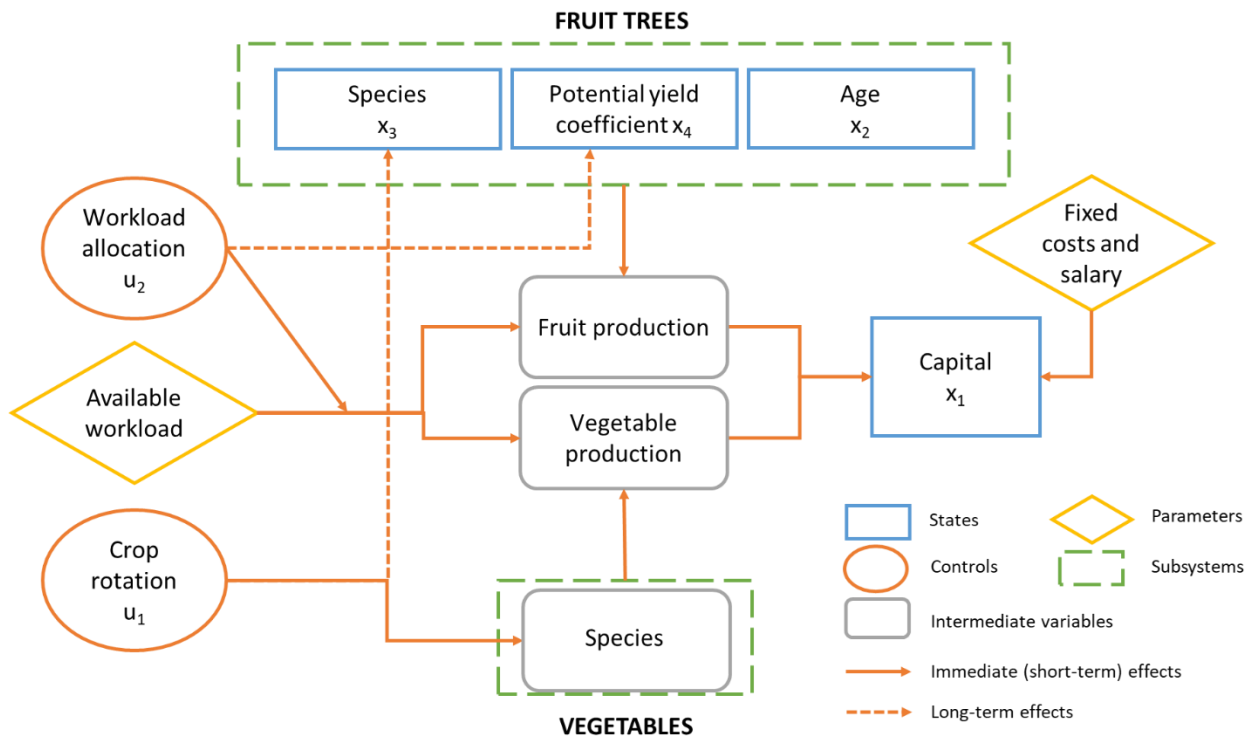
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208 *Figure 1: Conceptual representation of the model. Rectangular blue boxes represent states, ellipses are controls. Yellow*
209 *diamonds are parameters (fixed throughout the simulation). Rounded grey boxes are intermediate variables and dashed*
210 *green boxes are subsystems. Controls can have immediate effects (solid arrows) on dynamics or long-lasting effects (dashed*
211 *arrows) on states.*

212

213 **2.5.1 Overall dynamics:**

214 The overall model dynamics can be formally written as follows:

$$(x_1, x_2, x_3, x_4)(t+1) = f((x_1, x_2, x_3, x_4)(t), u_1(t), u_2(t), \tau)$$

$$\tau(t+1) = \tau(t) + 1$$

with

$$f(x_1, x_2, x_3, x_4, u_1, u_2, \tau) := (f_1(x_1, x_2, x_3, u_1, u_2, \tau), f_2(x_2, x_3, u_1), f_3(u_1), f_4(x_2, x_4, u_1, u_2))$$

and

$$\begin{cases} f_1(x_1, x_2, x_3, u_1, u_2, \tau) = x_1 + GMv(x_2, u_1, u_2, \tau) + GMf(x_2, x_3, u_1, u_2, \tau) - S(\tau) - C \\ \qquad f_2(x_2, x_3, u_1) = \begin{cases} x_2 + 1 \ if \ h(u_1) = x_3 \\ 0 \ if \ h(u_1) = none \\ 1 \ otherwise \end{cases} \\ \qquad\qquad f_3(u_1) = h(u_1) \\ \qquad f_4(x_2, x_4, u_1, u_2) = \begin{cases} x_4 - \delta(x_2, u_1, u_2) \ if \ h(u_1) = x_3 \\ 1 \ if \ h(u_1) = none \\ 1 - \delta(x_2, u_1, u_2) \ otherwise \end{cases} \end{cases}$$

(1)

215

216   Indeed, yearly variation f_1 in capital x_1 increases with annual gross margin for vegetables GMv and for

217   fruit trees GMf, whereas it decreases with farmer's salary S and fixed costs C. Costs C remain constant

218   throughout the simulation, whereas the salary S is revised at T, time at which the transition is

219   considered to be over. It therefore depends on time since the start of computation τ.

220   x_2, x_3 and x_4 vary between t and $t+1$ only if u_1(t) gives a tree present. Let h be the function extracting

221   tree composition from rotation choice u_1. If $h(u_1) = none$, the variable x_2 corresponding to tree age is

222   set equal to 0. Otherwise, when $h(u_1) = x_3$, the planted trees remain and their age increases by one

223   each year. Finally, when $h(u_1) \neq x_3$, all old trees are removed, new ones are planted and then all tree

224   ages equal 1 (hence we only need a one-dimensional variable to describe tree age, which is crucial to

225   minimize computation complexity). x_3 takes the value corresponding to u_1's tree composition (f_3). x_4

226   decreases proportionally to the lack of care of fruit trees (f_4, with δ a function controlling the change

227   in potential yield coefficient). Its value is reset to 1 when trees are newly planted.

228

229

2.5.2   Work allocation:

231   With limited workload available, workload requirements for fruit trees and vegetables can conflict. In

232   this case, management decisions are taken monthly using the workload allocation control u_2. If $u_2 = 1$,

233   working time is first allocated to trees and the remaining time is allocated to vegetables. If $u_2 = 0$,

234   working time is first allocated to vegetables and the remaining time is allocated to trees. If $0 < u_2 < 1$,

235   working time allocation to both crops is proportional to u_2. Formally,

$$W_{v\_month}(x_2, u_1, u_2, \tau)$$
$$= \min\left((1 - u_2)W(\tau) + max\left(u_2 * W(\tau) - W_{n\_f}(x_2, u_1), 0\right), W_{n\_v}(u_1)\right)$$

$$W_{f\_month}(x_2, u_1, u_2, \tau)$$
$$= \min\left(u_2 * W(\tau) + \max((1 - u_2)W(\tau) - W_{n\_v}(u_1), 0), W_{n\_f}(x_2, u_1)\right) \quad (2)$$

236   with $W_{v\_month}(x_2, u_1, u_2, \tau)$ monthly working hours devoted to vegetables, $W_{f\_month}(x_2, u_1, u_2, \tau)$

237   monthly working hours devoted to fruit trees, $W(\tau)$ available working hours per month when the time

238   since the beginning of computation is τ, $W_{n\_f}(x_2, u_1)$ and $W_{n\_v}(u_1)$ monthly working hours required

239   for an optimal harvest of fruit and vegetables respectively.

240   The result is then summed over the year and compared to cumulative work requirements, to create

241   relative working hours devoted to vegetables (W_v) and to fruit trees (W_f):

$$W_v(x_2, u_1, u_2, \tau) = \frac{\sum_{month} W_{v\_month}(x_2, u_1, u_2, \tau)}{\sum_{month} W_{n\_v}(u_1)}$$

$$W_f(x_2, u_1, u_2, \tau) = \frac{\sum_{month} W_{f\_month}(x_2, u_1, u_2, \tau)}{\sum_{month} W_{n\_f}(x_2, u_1)} \tag{3}$$

242

243

2.5.3 Change in potential fruit production coefficient:

245 In accordance with Paut et al. (2021), based on a collective experts' knowledge-sharing workshop, we
246 developed the hypothesis that a lack of work on trees during their growth phase has long-term effects,
247 decreasing future yields, whereas once maturity is reached, this same negligence has only short-term
248 effects. Moreover, we noted that production from both of the chosen tree species (apple and peach)
249 is null if they are completely neglected. In this model we thus used a potential fruit production
250 coefficient (x_4) which can take values between 0 (no production) and 1 (ideal production). The
251 coefficient value is highest when the tree is planted, and it can only decrease, as a consequence of a
252 lack of work on growing fruit trees. We translated these dynamics with the function δ controlling
253 changes in the potential fruit production coefficient x_4 (Eq. (1)) using the equation:

$$\delta: (x_2, u_1, u_2, \tau) \mapsto \begin{cases} \dfrac{1 - W_f(x_2, u_1, u_2, \tau)}{g_{tree}(h(u_1))} & if\ x_2 \in [1, g_{tree}(h(u_1))] \\ 0\ otherwise \end{cases} \tag{4}$$

254

255 where $g_{tree}(h(u_1))$ is a parameter giving the time required for trees of the current species to reach
256 maturity. It takes different values depending on current tree species, which is determined by u_1. If both
257 species are present, a mean value is used.

258

259

2.5.4 Potential yield coefficient:

261 Actual fruit yield is a function of potential yield and working hours devoted to fruit trees. Potential
262 yield can be deducted from the age of the trees (x_2) and previous workload investment (x_4). According
263 to Paut et al. (2021), potential yield trajectories of apple and peach trees as a function of their age (x_2)
264 would follow a sigmoidal dynamic, with fixed parameters k_1 and k_2 for the tree species. The
265 asymptote's value of the sigmoid is governed by x_4, and constant neglect throughout the growth period
266 would lead to zero production. It can therefore be written as:

$$\alpha_{a\ or\ p}(x_2, x_4) = \frac{x_4}{1 + e^{-k_{1a\ or\ p}(x_2 - k_{2a\ or\ p})}}$$ (5)

267

268 The parameter values were taken from Paut et al. (2021).

269

270

2.5.5 Gross margins:

272 For vegetables, gross margin *GMv* depends on the choice of crops in a given year (with no memory)
273 and on the workload W_v devoted to them (Eq.(3)):

$$GMv(x_2, u_1, u_2, \tau) = VGM(u_1). W_v(x_2, u_1, u_2, \tau)$$ (6)

274 where VGM is a function which associates the crop rotation choice u_1 with the theoretical gross margin
275 of vegetables.

276

277 For fruit trees, gross margin *GMf* also depends on the current state of the orchard, reflected by the
278 potential yield coefficient α (Eq. (5)):

$$GMf(x_2, x_3, x_4, u_1, u_2, \tau) = \left[FGM_a(u_1).\alpha_a(x_2, x_4) + FGM_p(u_1).\alpha_p(x_2, x_4)\right].Wf(x_2, u_1, u_2, \tau) -$$
$$\mathbb{1}_{\{h(u_1) \neq x_3\ \&\ x_2 \geq 1\}}(x).rmv$$ (7)

279 where *FGM$_a$(u$_1$)* and *FGM$_p$(u$_1$)* are the theoretical gross margin for apple and peach trees respectively.
280 *rmv* defines the cost of removing previously planted trees, if need be: $\mathbb{1}_{\{h(u_1) \neq x_3\ \&\ x_2 \geq 1\}}$ is the indicator
281 function that takes the value 1 if an orchard has to be removed, 0 otherwise.

282

283

2.6. Constraints:

285 We define a set of constraints to reflect the farmer's set of objectives. They relate to a minimal capital
286 to be maintained through time and temporal objectives related to tree planting.

287 For the farm to be able to perform even in the case of unpredicted events, a minimum amount of
288 money must be kept available. In our viability model, this is translated by a threshold applied to x_1, set
289 at x_{1min} = €10,000 (Eq. (8)).

290   In order to model a transition from an MG to an MFV system, at least one plot must be planted with

291   trees from the end of the ten-year transition period. This feature can be represented by x_2 (age of fruit

292   trees), a value of 0 for this state meaning an absence of fruit trees (Eq. (8)).

293   Furthermore, at any given time, it is not possible to own trees planted before the beginning of the

294   simulation. In other words, tree age x_2 cannot exceed the time elapsed since the beginning of

295   computation τ (Eq. (8)).

296   Trajectories (combinations of states and controls) respecting all these constraints at any time are called

297   viable trajectories. The subset of state space respecting these constraints is denoted K and can be

298   written as:

$$K := \{(x_1, x_2, x_3, x_4, \tau)\} \left| \begin{array}{c} x_1 \geq x_{1\min} \\ x_2 \geq 1 \; when \; \tau \geq T \\ x_2 \leq \tau \end{array} \right. \tag{8}$$

299

300

301

302   **2.7. Two-step viability algorithm:**

303   The viability kernel is the set of states acting as the start of at least one trajectory that respects the

304   constraints over time. Let V be the viability kernel of dynamics (Eq. (1)) facing constraints (Eq. (8)).

305   Denoting as $Q(X)$ the set of all trajectories governed by the controlled dynamic system and starting

306   from $X := (x_1, x_2, x_3, x_4, \tau)$, the viability kernel is defined by the equation:

$$V := \{X \in K \mid \exists x(\cdot) \in Q(X), \forall t \geq 0, x(t) \in K\} \tag{10}$$

307

308   To compute V, we take advantage of the particular dynamics of state τ. We use an algorithm (De Lara

309   and Doyen, 2008) which employs a backward method to compute V_{τ^*} from V_{τ^*+1} where V_{τ^*} is the

310   section of V:

$$V_{\tau^*} := \{(x_1, x_2, x_3, x_4, \tau) \mid (x_1, x_2, x_3, x_4, \tau) \in V \; \& \; \tau = \tau^*\} \tag{11}$$

311

312   In our particular case, K is not upper bounded in the τ direction which makes the initialization of the

313   algorithm impossible. However, as constraints and dynamics do not change after time T, being

314   permanently viable at any time after T requires the same conditions as at T: $V_{\tau^*} = V_T \; for \; \tau^* \geq T$.

315   Moreover, the same target could be computed in finite time, provided that this time would be long

enough: $V_T = V'_T$ where V' is the viability kernel of the same dynamics as Eq. (1) except for τ dynamics: $\tau(t + 1) = \tau(t) + 1 \; if \; \tau < T', \tau(t + 1) = T' \, otherwise$; and facing the bounded constraint set: K' $:= K \cap \{\tau \leq T'\}$ for a value of T' that is large enough. K' is upper bounded in the τ direction so we can use the backward algorithm to compute V' with the initialization $V'_{T'} =$ $\{(x_1, x_2, x_3, x_4, \tau) \mid (x_1, x_2, x_3, x_4, \tau) \in K' \, \& \, \tau = T'\}$.
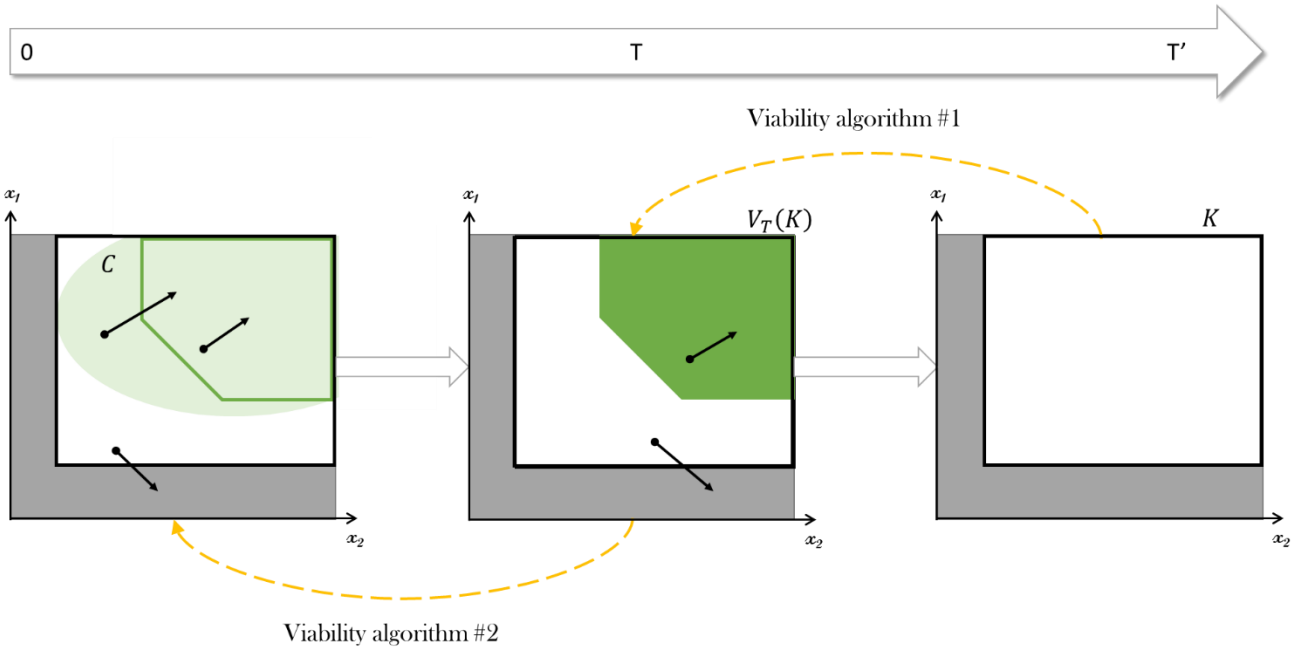
Figure 2: Two-step method to determine viable transition trajectories. Non-viable states are in grey, viable states are within the black frame. The dark green area corresponds to the target: viable states at T from which it is possible to remain viable after the change of parameters. The light green area is the capture basin, i.e. states at t=0 from which it is possible to reach $V_T(K)$ at T. Black arrows correspond to instances of trajectories with different starting points.

The computation of the viability kernel can be divided into two distinct steps, before and after horizon T (τ ≤ T and τ ≥ T) (Figure 2).

The first step of the computation was to apply the viability algorithm between T and T', to compute V'_T. As T' increases, V'_T decreases and then remains constant. Therefore, T' was taken as the minimal value from which there are no more modifications to V'_T. Consequently, any time horizon above T' would result in the same section of the viability kernel at T meaning that $V'_T = V_T$. This situation was reached in 5 years, meaning that T' = 15 years is suitable.

In the second step, the computed V_T was then used as the target to reach during transition. The viability algorithm was thus applied for a second time between 0 and T, to compute viable trajectories reaching this target at T. We thus looked for the capture basin of the horizon viability kernel V_T. The

337   capture basin is the set of all initial states from which at least one trajectory ending in the target starts.

338   It can be formally defined as:

$$C(K, V_T) = \{X \in K \mid \exists x(\cdot) \in Q(X), \exists\, t^* \geq 0, x(t^*) \in V_T \;\&\; \forall t \in [0, t^*], x(t) \in K\} \qquad (12)$$

339

340   In order to compute viability algorithms, each state and control was discretized on a regular grid. As

341   fruit tree gross margins remain essentially unchanged once maturity is reached, a mature tree category

342   was considered for all trees over 11 years. So x_2 ranges from 0 to 12 with a step of 1. Similarly, the

343   linearity of the dynamics enabled us to ascertain that if a state is viable with $x_1 = x_1{}^*$, it remains viable

344   with any greater value. We find that x_1 ranging from €8,000 to €50,000 is satisfactory with a step of

345   €2,000. x_4 ranges from 0 to 1 with a step of 0.1. u_1 belongs to a finite set available in Appendix A. u_2

346   ranges from 0 to 1 with a step of 0.2.

347

348

349   **2.8. Trajectory computation:**

350   As a preliminary step, a static comparison of the potential of the different crop portfolios was realized

351   for the different values of orchard age (x_2) with a maximal production coefficient (x_4 = 1). Dynamics

352   were computed and analyzed in terms of annual workload ($W_v(x_2, u_1, u_2, \tau) + W_f(x_2, u_1, u_2, \tau)$) and

353   capital variation between two successive years ($x_1(t + 1) - x_1(t)$). To compute capital, the value of

354   the workload allocation control (u_2) used was that giving the highest capital value. Salaries and fixed

355   costs have been included in the computation.

356   In a second step, we conducted a dynamic analysis of the system within the Viability framework. Two

357   scenarios were considered: one without any specific constraint about the age of orchards at T (they

358   must simply exist: $x_2(T) \geq 1$) and one imposing an age of 8 ($x_2(T)$ = 8). Once viability kernels were found,

359   a random sample of 10,000 viable forward-looking trajectories was computed from each kernel. All

360   trajectories start with the lowest viable capital value, *i.e.* $x_1(0) = x_{1min}$ = €10,000. Controls were drawn

361   randomly at each time step from among the viable ones. These trajectories (*i.e.* viable temporal

362   successions of crop portfolios) were then compared in terms of workload, capital and crop rotations

363   used.

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365

366   **2.9. Computation:**

367   All viability kernels and trajectory computations used Python 3.9.7 (www.python.org/). Statistical

368   analyses used R software 4.1.2 (https://cran.r-project.org). Economic data were obtained from the

369   Provence-Alpes-Côte d'Azur Regional Chamber of Agriculture (Roblin and Bouvard, 2017).

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373   **3. RESULTS**

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375   **3.1. Working hours:**

376   Working hours are mainly occupied by vegetables. This is consistent with previous studies: tree care

377   activity does not demand much time in most months (Boury-Esnault et al., 2018; Léger et al., 2019).

378   Tree-related activity is likely to compete with vegetables only during pruning and harvesting periods,

379   when farmers may have to make a choice over workload allocation.

380   A static analysis of the workload associated with the different portfolios shows that working hours for

381   portfolios with vegetables only are significantly higher than working hours for portfolios including an

382   orchard, no matter its age (Welch's two sample t-test, $p = 4.6e^{-12}$; Figure 3). Workload marginally

383   increases with tree age but remains much lower than workload with vegetables only.

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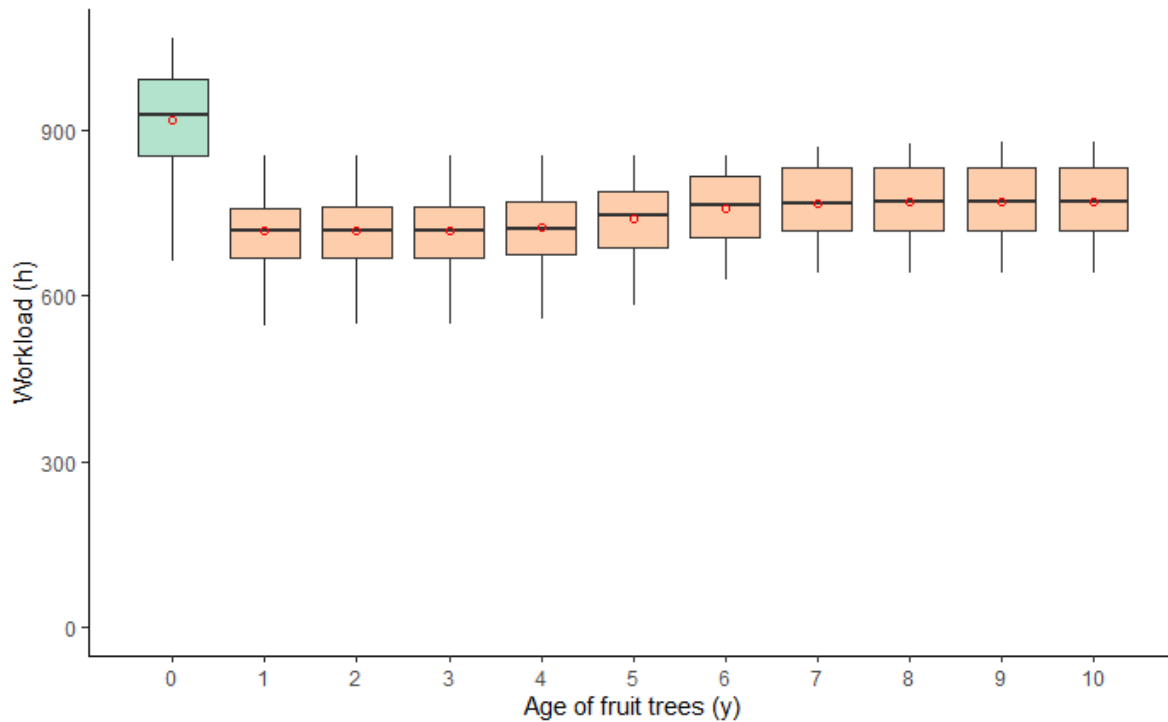
Figure 3: Potential annual working hours for crop portfolios for various ages of fruit trees. The green box (x = 0) corresponds to the set of portfolios with vegetables only. Orange boxes (x > 0) correspond to portfolios with at least one fruit tree species, for different age values of this orchard. For each box, lower and upper limits correspond to the first and third quartiles. Whiskers extend to at most 1.5 times the interquartile range. Red circles correspond to the mean of each dataset.

3.2. Capital:

Static analysis of changes in capital associated with each portfolio shows that high values of income can be reached with vegetables only, in particular when using certain portfolios with high-value crops such as pepper and lamb's lettuce. Tree planting (year 1) is costly and has a strong impact on capital. During the first years of tree growth, trees do not produce anything but occupy land and therefore the farm loses money. Tree planting can thus be viable only if previous capital is high enough to absorb this loss. Revenues exceed costs only after five or six years, with a reduced difference in income compared to portfolios with vegetables only (Welch's two-sample t-test, p = 0.11; Figure 4).

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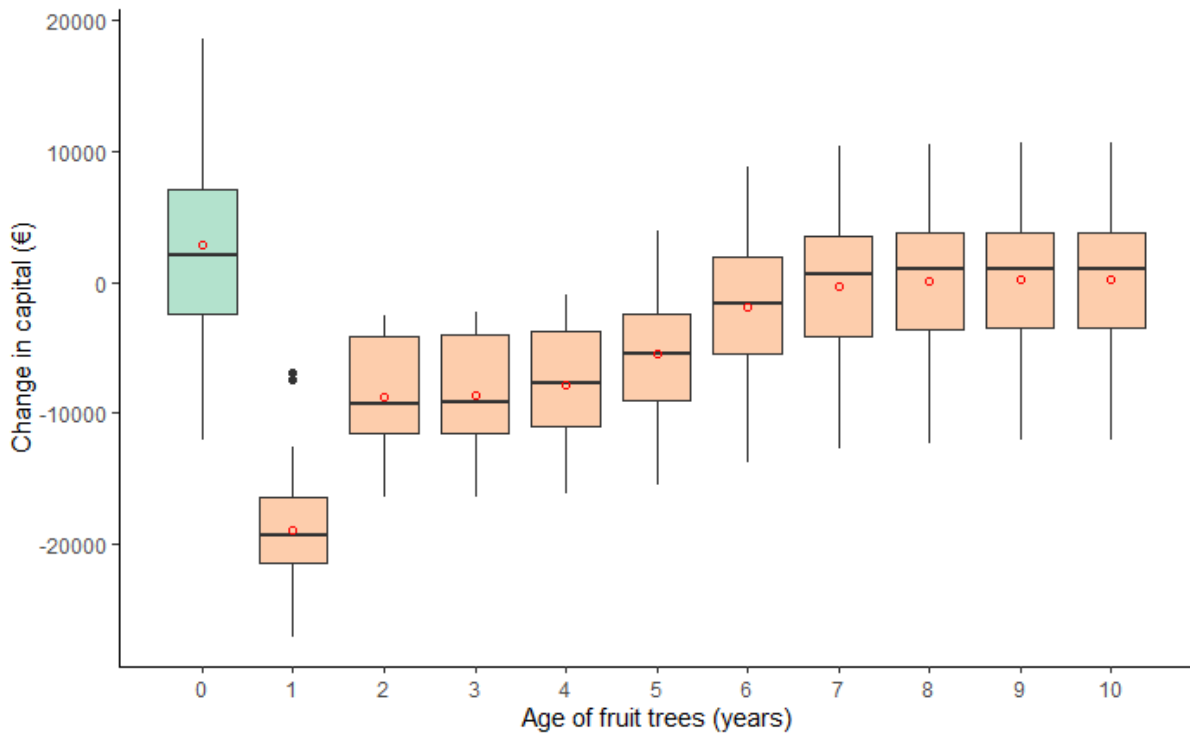
Figure 4: Potential change in capital associated with crop portfolios, for different ages of fruit trees. The green box (x = 0) corresponds to the set of portfolios with vegetables only. Orange boxes (x > 0) correspond to portfolios with at least one fruit tree species, for different age values of this orchard. The best-case scenario was adopted for each point, i.e. the value of workload allocation enabling the highest growth in capital. For each box, lower and upper limits correspond to the first and third quartiles. Whiskers extend to at most 1.5 times interquartile range, outliers are represented as black dots. Red circles correspond to the mean of each dataset.

3.3. Trade-off between capital and working hours:

Since planting fruit trees makes it possible to reduce working hours but affects capital by decreasing income for a few years, different strategies can emerge depending on the way fruit tree plantations are managed. These strategies were examined by studying a sample of random viable trajectories over the 10-year transition period, starting at $x_1(0) = x_{1min}$.

The sum of working hours during the period is positively correlated with final capital (linear regression, correlation coefficient = 0.02, $p < e^{-16}$; Figure 5). In other words, it is hard to improve both capital and labor conditions at the same time, leading to the search for a trade-off between these two variables.
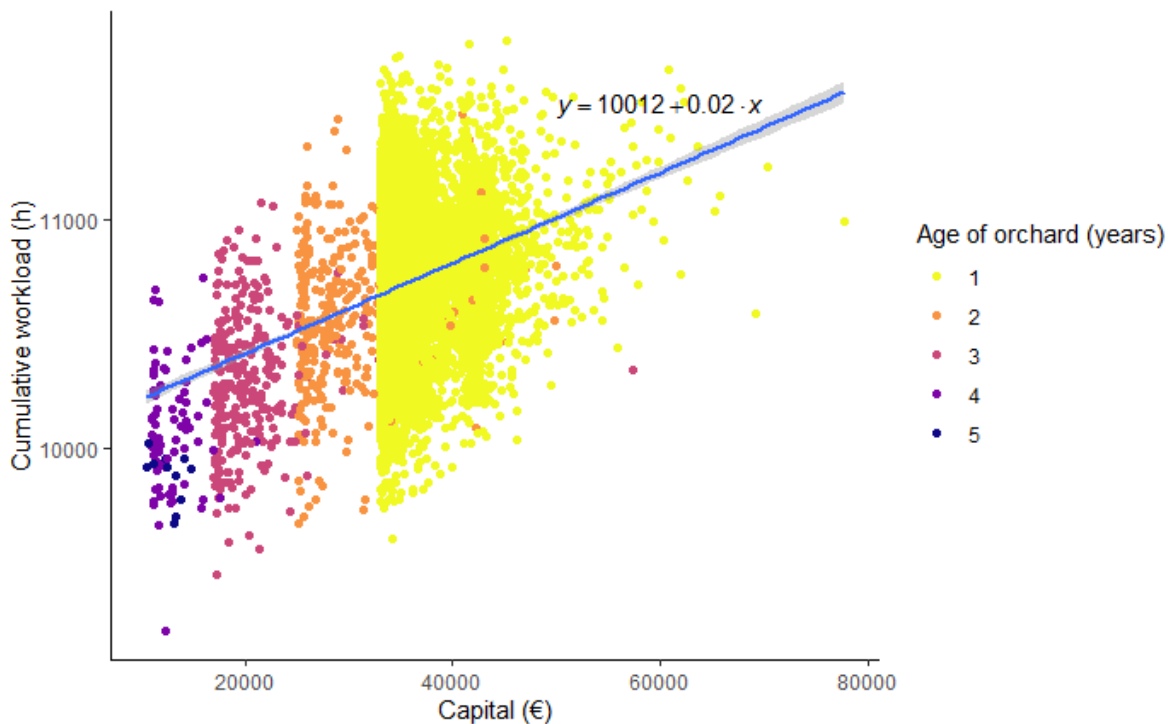
Figure 5: Sum of working hours throughout the simulation depending on final capital, for a sample composed of 10,000 random viable trajectories. Each point is the result of a 10-year trajectory. The blue line corresponds to a linear regression of the whole sample.

In the great majority (93%) of these trajectories, the decision is made to plant trees at t = 9 years, resulting in one-year-old trees at T. Indeed, even if there are almost the same number of rotations with and without trees, the cost of planting fruit trees makes the latter much less frequently viable. Consequently, in most cases, this event happens only when it becomes mandatory. In this case, $x_1(t)$ must be superior to €36,000 to remain viable, which explains the sharp left-side limit of the yellow cloud in Figure 5. Trajectories resulting in older trees can remain viable with a lower capital value.

In this sample, final capital values are very tightly grouped around the mean and median (respectively €39,930 and €39,174), with a standard deviation of σ = €4,918 (12%). However, the range of values it can take is much wider and can go as high as €72,379. Mean cumulative working hours is 10,744h (median: 10,752h), which gives an annual mean of 1,070h/year (Figure 8).

However, these trajectories do not reflect the whole range of possibilities. Therefore, we computed a subset of the viability kernels by modifying the target, requiring 8-year-old orchards to be present at T. Another sample of 10,000 random viable trajectories was drawn out using this kernel (Figure 7). It was compared with the trajectories from the first sample presenting a one-year-old orchard at T. To

439   illustrate what happens in each sample, one trajectory has been randomly drawn from both of them.

440   They are presented on Figure 6.

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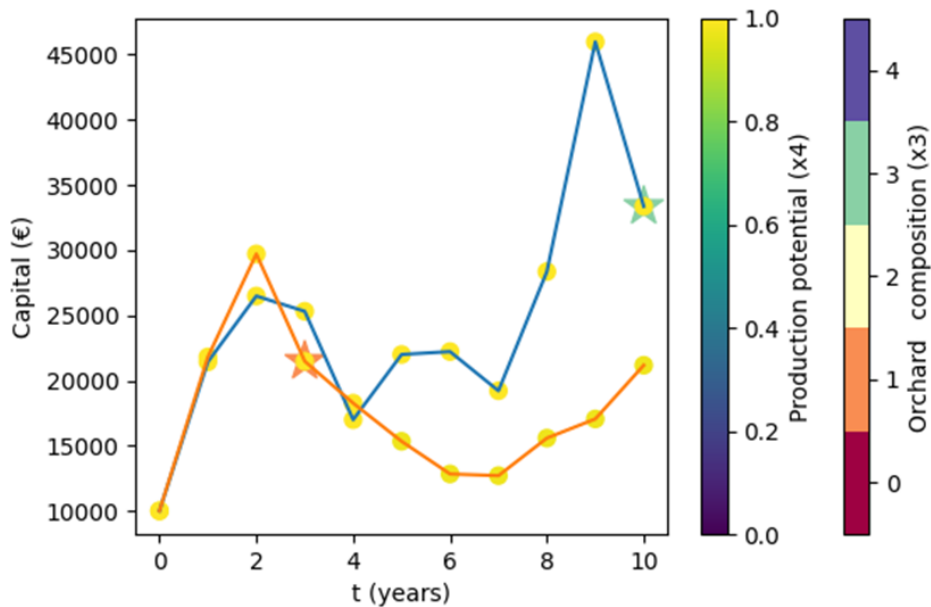
442   *Figure 6: Illustration of trajectories from each of the two samples: random sample in blue and sample aiming at 8-year-old*
443   *orchards in orange. Stars correspond to fruit tree planting, with a color depending on the type of fruit tree chosen (x_3). Colors*
444   *of circle dots correspond to the value of the potential production coefficient (x_4).*

445

446   The cost of tree planting (Figure 4) can be seen on these trajectories. The one with the earliest

447   transition (orange curve) has the opportunity to make profits again five years after planting. This cost

448   has to be anticipated by more or less intense capital accumulation depending on the time provided

449   before tree planting and the amount of money necessary to remain viable with the resulting trees.

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453   **3.4. Comparison of two strategies:**

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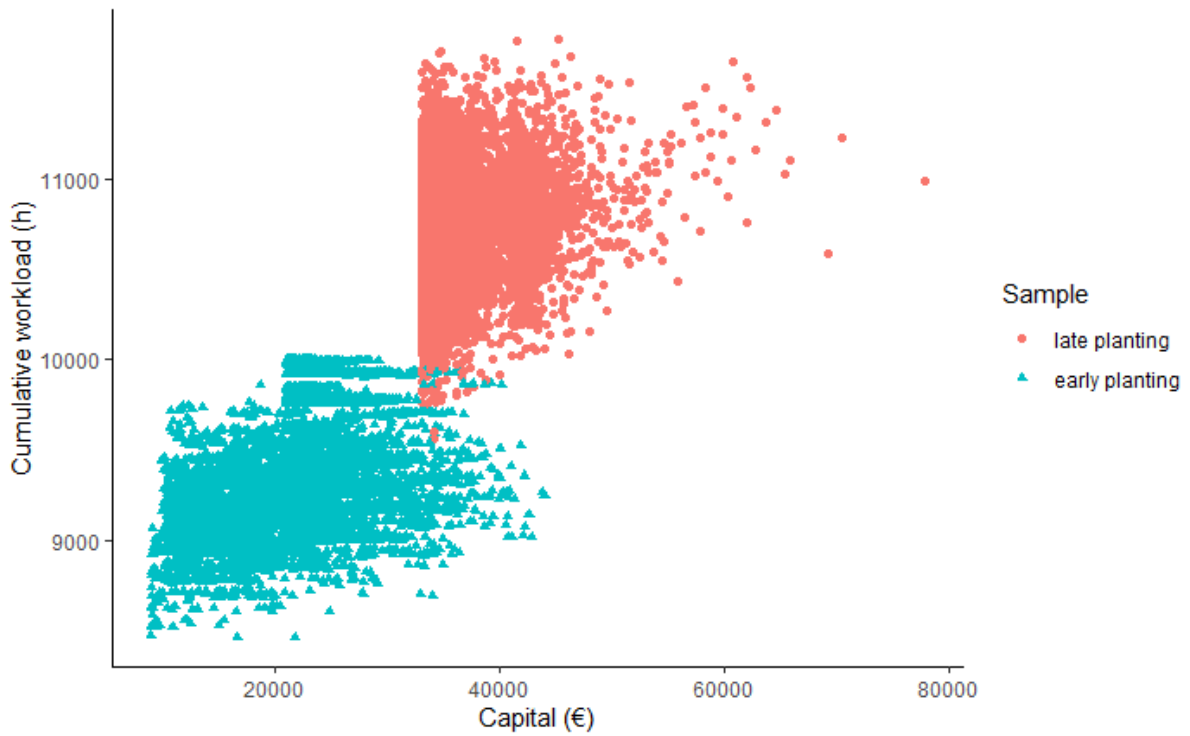
Figure 7: Sum of working hours throughout the simulation depending on final capital, for two samples of random viable trajectories: one requiring 1-year-old orchards (red circles) and the other requiring 8-year-old orchards (blue triangles). Each point is the result of a 10-year trajectory.

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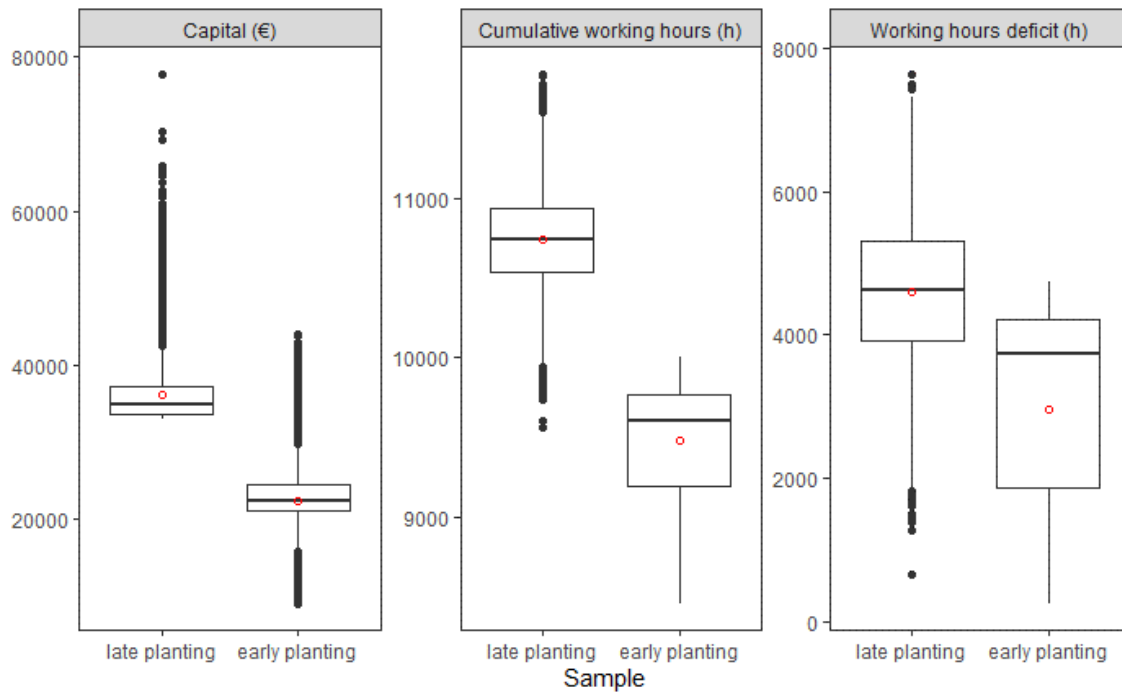
Figure 8: Distribution of capital, cumulative working hours and working hours deficit among the trajectories for the two samples: targeting 1-year-old orchards (late planting) and targeting 8-year-old orchards (early planting). Each sample is composed of 10,000 random trajectories. Red circles correspond to the means of each dataset.

463

464

465   Aiming at 8-year-old trees results in both lower capital values and lower working hours. It corresponds

466   to a long-term investment made as early as possible. However, there is a limited number of vegetable

467   rotations in the first years that make it possible to accumulate enough money for such an investment

468   (Figure 9). In almost half of the cases (41%), a single plot of peach trees is planted. This choice is a way

469   to cope with less money being available at the time of tree planting, but it is not the most efficient in

470   the long-term. When starting with $x_1(0) = x_{1min}$, no crop rotation is lucrative enough to enable tree

471   planting after less than two years of market gardening.

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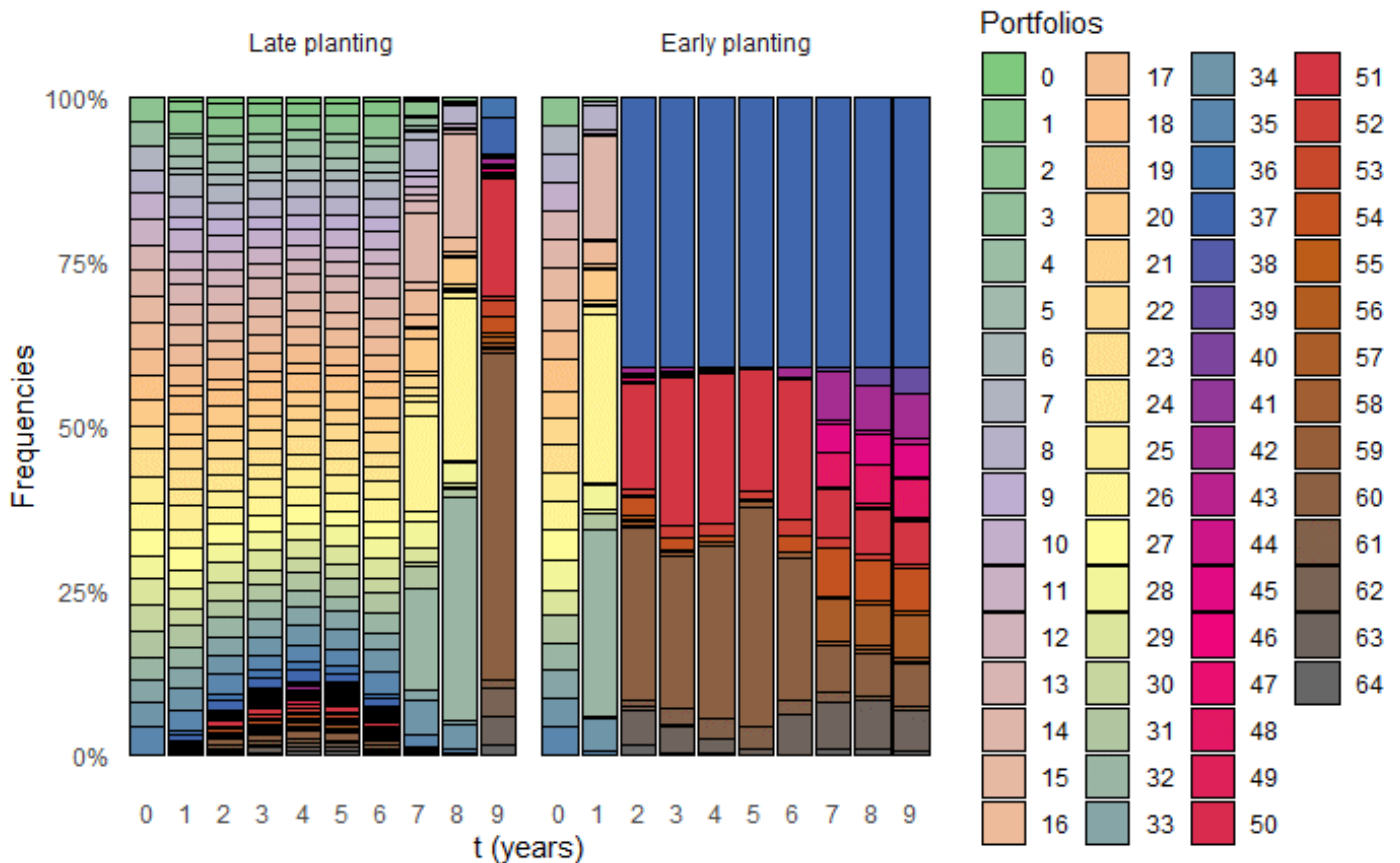
474   *Figure 9: Frequency of use of the different crop rotations through time, for the two samples: aiming at 1-year-old trees (late*
475   *planting) and aiming at 8-year-old trees (early planting). Portfolios up to 35 are entirely composed of vegetables. Portfolios*
476   *36 and 37 include one orchard plot. Portfolios 38 and over include two orchard plots. See Appendix A for the composition of*
477   *each crop portfolio.*

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480   **3.5. Working hours deficit:**

481   Problematic situations relating to workload appear when not enough working hours are available to

482   meet either vegetable or fruit production requirements. To study these situations, we defined working

483   hours deficit as the accumulated difference between effective workload and required working hours.

484   Among the random sample, trajectories with a lower working hours deficit seem more interesting in

485   terms of the trade-off between capital and labor (Figure 10). Thus, choosing crops with workload

486   requirements corresponding to available workload can be a means of avoiding the less efficient

487   trajectories.

488   Furthermore, working hours deficit is significantly lower when trees have been planted early (Figure

489   8). In other words, crop rotations with fruit trees tend to present work requirements closer to available

490   working hours.

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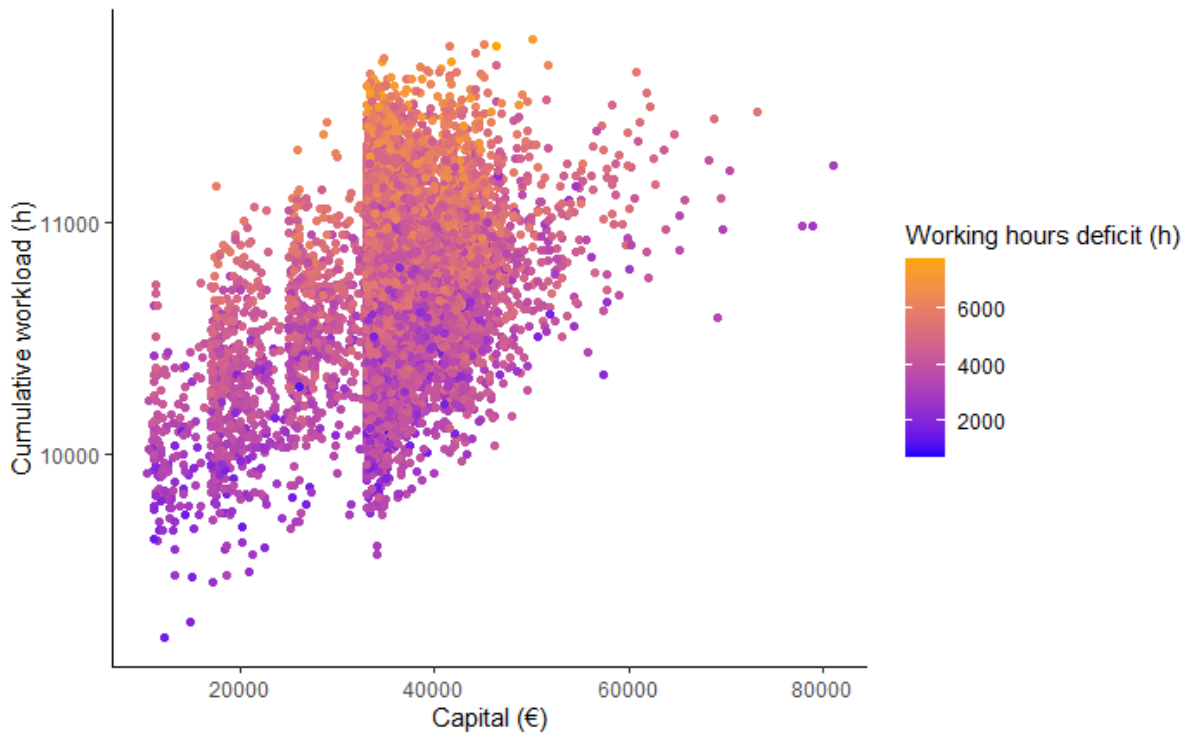
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493   *Figure 10: Sum of working hours depending on capital, for a sample of 10,000 random viable trajectories. Colors correspond*
494   *to working hours deficit values.*

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4. DISCUSSION

4.1. Multiplicity of farmers' decision-making criteria

In this study we focused on the re-design of farming systems to explore the scope for sustainable transitions from MG to MFV farms. Our findings showed that fruit tree planting makes it possible to reach satisfactory income levels while limiting workload, but establishment is costly during the first few years. Therefore, a choice has to be made between different strategies to sustain this cost. We computed a set of viable trajectories based on aspects that can be quantitatively modeled, leaving room for qualitative discussions about the relevance of the different trajectories.

Even though they are all viable, computed trajectories are not all equivalent. Some trajectories seem riskier than others, as they present a reduction in possible choices at certain steps. Being in the viability kernel means that at least one set of controls makes it possible to stay within bounds defined by the constraints and to reach the target, but the number of possible paths can vary a lot. For instance, even though aiming for particularly young or old trees at the time horizon makes it possible to reach higher capital or lower workload values (respectively), it requires a limited set of vegetable rotations to be chosen at some key moments (Figure 9). Risk aversion being an important factor in decisions to change (Menapace et al., 2013; Norton, 1976), an alternative strategy could be to stay far from boundary states in order to maintain a wider range of possibilities at each time step even though that trajectory may be sub-optimal. Indeed, maintaining flexibility in management requires that not all resources be used efficiently at any one point in time, providing trade-offs between efficiency criteria and redundancy in the different resources (Darnhofer et al., 2010; Sabatier and Mouysset, 2018). This is an insurance against uncertainty and surprise and allows for reorganization and renewal.

Market gardening and orchard cultivation are both knowledge-intensive activities, and the choice of a strategy may also depend on knowledge and skills already possessed by the farmer. An effect of diversification is to increase the number of interacting elements and the variety of tasks necessary to manage them (Paut, 2020) and therefore the complexity of the system management. The model shows that various timings of tree planting are viable, making it possible to choose among them according to individual knowledge and learning skills. Delaying fruit tree planting and focusing on well-understood vegetable growing can be a strategy enabling the farmer to devote some time to acquiring knowledge about fruit tree management.

In addition to personal criteria such as risk aversion and learning, farmer's choices are constrained by external structures such as social norms, technologies and the natural environment (Darnhofer et al.,

532 2010), that are particularly difficult to include in such a model. For instance, some tree species can be

533 more or less well-adapted to a given soil and climate, or possess specific cultural significance. Some of

534 these decision-making parameters can be included in models, e.g. land heterogeneity in Dogliotti et al.

535 (2005). However, choices have to be made about what to include or not in each model in order to

536 achieve a balance between accurate representation of reality and genericity. Here, a detailed land

537 description would have been inconsistent with the level of abstraction of the model dynamics.

538 Moreover, such alternative farming systems are often conceived by their author as life projects, and

539 priority is not systematically given to economic performance. Strategies adopted can also address

540 other concerns such as workload, risk (peaches' sensitivity to cold makes them liable to high variations

541 in yield), commercialization (apples are easier than peaches to store and sell), integration into local

542 communities, etc. These considerations can hardly be included in a digital model, as they can refer to

543 values such as beauty, intellectual interest or ecological concerns (Morel and Léger, 2016). They are

544 usually ignored in the modeling process, actors being considered as rational individuals making

545 decisions based on economic criteria.

546

547

548   **4.2. Looking for satisfactory solutions**

549 Dynamic models make it possible to study long-term dynamics such as those at stake in transitions,

550 and to explore a wide range of trajectories with uncertain outcomes, whereas proceeding by trial and

551 error with real systems is a time-consuming and risky process (*e.g.* Corbeels et al., 2014; Delbridge and

552 King, 2016; Lescot et al., 2011; Žibert et al., 2022). Thanks to a high enough number of simulated

553 variables and interactions, and to calibration with empirical data, these models can be precise and

554 reliable enough to predict *ex ante* trajectories; for example crop performance in places or climates

555 where the crop of interest has never been grown. In order to discriminate among possible decisions,

556 the best one is generally selected based on a single criterion or a combination thereof, in order to get

557 as close as possible to a predefined target (Bergez et al., 2010). *Ad hoc* modeling tools are used to

558 assess farmers' interest (or lack thereof) in engaging in transition, and thus to explain factors

559 determining the adoption of agroecological practices. In addition to achieving a better understanding

560 of the mechanisms and processes at stake, these models can therefore also be used to provide farming

561 advice. Farmers can thus use the model's optimal trajectory as a benchmark against which to compare

562 their own farm and practices (*e.g.* Rodriguez et al., 2014; Ryschawy et al., 2014). However, with these

563 models, farmers are generally assumed to be rational profit-maximisers with perfect knowledge of the

564 production outputs. This is a crude approximation of farmers' behavior and optimization tools are

565   limited in their ability to include farmers' complex decision-making processes (McCown, 2001; Robert

566   et al., 2016; Sempore et al., 2015).

567   One main interest of viability theory is to give a set of viable solutions instead of a single 'optimal'

568   solution. The model we developed required very few hypotheses about farmer's behavior and avoided

569   the delicate step of defining decision rules to simulate crop management. It is a means of

570   acknowledging diversity in farmers' motivations, abilities (including knowledge and learning skills) and

571   strategies, as well as the existence of multiple pathways enabling sustainable transitions (Rosenbloom,

572   2017). It avoids imposing the researcher's normativity, thus increasing the model's legitimacy, defined

573   as the production of fair and unbiased information respecting stakeholders' values and beliefs (Cash

574   et al., 2003; Chang and Morel, 2018). Moreover, decision-making processes can be considered at both

575   strategic (long term) and tactical (short term) scales: the realization of strategic objectives (the

576   transition) depends on yearly choices of crop rotations and workload allocation (Robert et al., 2016).

577   Depending on farmer's individual priorities, one viable trajectory or another can be adopted, offering

578   flexibility in the search for sustainable solutions. When several controls are viable, the choice made for

579   one control or another can correspond to various strategies. Farmers with different objectives can find

580   various ways to create their own viable farm. For instance, an early decision to plant trees can be a

581   way to invest for future income and labor conditions, whereas planting vegetables to increase capital

582   can be another way to face forthcoming adversity. An alternative to computation of every possibility

583   could be to develop several alternative scenarios with farmers, in a participatory modeling approach

584   (Le Gal et al., 2022; Pissonnier et al., 2019).

585   The framework based upon the satisfaction of certain constraints rather than looking for optimal

586   solutions is also more in accordance with farmers' management. Real-life systems are complex and

587   limited information is available, so farmers often have only a vague idea of the probability distribution

588   of outcomes associated with various control strategies. Therefore, what is sought is the satisfaction of

589   some objectives and operational constraints, rather than the maximization of some utility function

590   (Norton, 1976). The system can then be pushed towards these objectives through a range of available

591   controls, without closely monitoring every dynamic and interaction.

592   The model does not capture all the complexity of these systems, but the number of computed

593   trajectories makes it possible to select them in hindsight, depending on individual concerns. The

594   predictive power of the model is not necessarily a priority for farmers, who may prefer qualitative

595   discussions (Chang and Morel, 2018). Nevertheless, the accuracy of this model could be increased by

596   including competitive and cooperative interactions between crops. Management of these interactions

597   is often considered to be the main issue of these systems (Wezel et al., 2014), but data is lacking about

598   the exact degree of their effects (Léger et al., 2019; Paut et al., 2020). Another improvement could be

599   to increase the number of available crops to increase the range of possibilities at each time step. This

600   would require computation time limitations to be dealt with. Finally, it could be interesting to include

601   uncertainties, such as climatic events or market instability. This could be achieved by applying

602   stochasticity to yields (see *e.g.* Baumgärtner and Quaas, 2009; Oubraham et al., 2020; Sabatier et al.,

603   2015) and assessing the resilience-related properties of the system (Sabatier et al., 2018). Resilience

604   can also be assessed without assumptions about the probabilities of such catastrophic events, as the

605   inverse of the minimal cost associated with the effort to restore and preserve some properties of the

606   system following disturbances (Martin, 2019). Furthermore, this model could be adapted to the case

607   of a different farm size, or a collective installation on the same farm, by simply changing the

608   parameters. Indeed, collective installation is often a lever for diversification. The combination of each

609   person's specialized skills and knowledge creates a diversified whole-farm system and overcomes the

610   knowledge acquisition issue.

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612

613   4.3. From a deterministic to an open-ended perspective of transition

614   Agroecological transition is a wide notion covering a whole range of conceptual frameworks, focusing

615   on different objects at various organizational levels, over medium- to long-term time spans (Duru et

616   al., 2015; Ollivier et al., 2018; Prost et al., 2023). The process of change can be conceived as the

617   transformation of an initial state into a targeted final state, or as a continuous process of successive

618   adjustments between means and goals (Lamine et al., 2021). The transition represented here is farm-

619   centered and quite deterministic: a goal is set from the beginning about what the farm must look like

620   at a given time horizon. This goal is rooted in the way the model has been implemented: the possibility

621   of planting trees is part of the dynamics and determines one of the constraints.

622   However, even though the objective of obtaining a perennial MFV farm is set from the beginning, the

623   precise target required to meet this goal is not. It is computed through a complementary viability

624   analysis, so every solution consistent with this goal is considered, with as few assumptions as possible.

625   In Joly (2015), viability at final state is defined differently than for other steps, as there are no controls

626   enabling the assessment of usual viability constraints. Therefore, viability at final state was considered

627   as subsequent growth reaching stationary state. This phenomenon was in turn translated into

628   constraints. In our model, fewer hypotheses are required, as conditions at the time horizon for future

629   sustainability are not established at the outset.

630

The large number of trajectories computed, and the consistency of the approach compared to farmers' management, could make this model relevant for discussions with stakeholders at participatory workshops. The use would be different depending on participants' position relative to transition. If they are already engaged in a transition process, it could provide a framework to guide the initial farm diagnosis at the beginning of the support process, by comparing their position in the range of possible to viable trajectories or in the viability kernel (Sabatier et al., 2017). Otherwise, it can help with *ex-ante* assessments of the viability of a range of alternatives (Briot et al., 2011; Chang and Morel, 2018; Sempore et al., 2015). An objective could be, for instance, to compare the feasibility of transition with different amounts of time available (corresponding to their objectives or their possibilities), by comparing viability kernels with imposed orchard planting at the corresponding time point. Given the multiplicity of possible trajectories computed by the model, its use would be closer to that of a heuristic tool, crystallizing reflections during discussions between farmers and mediators, than a prescriptive norm to be respected. It could be coupled with other types of model, such as empirical modeling of social–ecological systems, in order to better understand the values and norms behind management decisions (Crane, 2010; Klapwijk et al., 2014). By redefining the target while the trajectory is ongoing and considering elements that are not explored in the model, it would leave an opportunity for creativity to be expressed in order to find innovative solutions adapted to a very complex and unpredictable reality (Lamine et al., 2021).

649

650

5. CONCLUSION

In this study, we computed a range of viable trajectories leading to a transition towards a more diversified agronomic system. In order to do this, we made an original use of the viability kernel approach by separating our model into two successive parts, using the kernel of the first as an objective for the second. We found that in order for the transition to be long-lasting, the final state must not only be viable, but also belong to a given subset of the constraint domain.

As the installation of an orchard decreases workload but is costly during the early years, computed viable trajectories reflect different trade-offs in the balance between workload and capital. They result from choices about the time of orchard planting and the fruit and vegetable species grown each year. These choices can result from considerations that can be quantified by the model, such as flexibility or working hours deficit, but also qualitative factors outside the scope of this model, such as farmers'

662 values. The range of viable trajectories acknowledges the importance of considering the variety of

663 possible means to achieve the same goal in a complex world. Because the conceptual framework is

664 relatively close to the way farmers manage their farms and the plurality of the outputs avoids the

665 imposition of an exclusive solution, it could become a good tool for starting a discussion with

666 stakeholders.

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830 **APPENDIX (Supplementary data)**

831 Appendix A: List of crop rotations

1	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo
2	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
3	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Zucchini_Zelia	Zucchini_Zelia	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
4	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
5	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
6	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
7	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo
8	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
9	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
10	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
11	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
12	Cabbage _Impala	Cabbage _Impala	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
13	Cabbage _Impala	Cabbage _Impala	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo
14	Cabbage _Impala	Cabbage _Impala	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
15	Cabbage _Impala	Cabbage _Impala	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
16	Cabbage _Impala	Cabbage _Impala	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
17	Cabbage _Impala	Cabbage _Impala	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
18	Cabbage _Impala	Cabbage _Impala	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
19	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo
20	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
21	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
22	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
23	Cabbage _Impala	Squash _Musquee de Provence	Squash _Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden

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24	Cabbage_Impala	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
25	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo
26	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
27	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
28	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
29	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
30	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
31	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo
32	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
33	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Zucchini_Zelia	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
34	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden
35	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
36	Squash_Musquee de Provence	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Beans greenhouse_Pongo	Pepper greenhouse_Almuden	Pepper greenhouse_Almuden
37	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden		Apple_Royal Gala
38	Cabbage_Impala	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo	Pepper greenhouse_Almuden		Peach_Big Top
39	Cabbage_Impala	Squash_Musquee de Provence	Zucchini_Zelia	Beans greenhouse_Pongo			Apple_Royal Gala	Apple_Royal Gala
40	Cabbage_Impala	Squash_Musquee de Provence	Zucchini_Zelia	Beans greenhouse_Pongo			Peach_Big Top	Peach_Big Top
41	Cabbage_Impala	Squash_Musquee de Provence	Zucchini_Zelia	Beans greenhouse_Pongo			Apple_Royal Gala	Peach_Big Top
42	Cabbage_Impala	Squash_Musquee de Provence	Zucchini_Zelia	Pepper greenhouse_Almuden			Apple_Royal Gala	Apple_Royal Gala
43	Cabbage_Impala	Squash_Musquee de Provence	Zucchini_Zelia	Pepper greenhouse_Almuden			Peach_Big Top	Peach_Big Top
44	Cabbage_Impala	Squash_Musquee de Provence	Zucchini_Zelia	Pepper greenhouse_Almuden			Apple_Royal Gala	Peach_Big Top
45	Cabbage_Impala	Squash_Musquee de Provence	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Apple_Royal Gala	Apple_Royal Gala
46	Cabbage_Impala	Squash_Musquee de Provence	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Peach_Big Top	Peach_Big Top
47	Cabbage_Impala	Squash_Musquee de Provence	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Apple_Royal Gala	Peach_Big Top

48	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo			Apple_Royal Gala	Apple_Royal Gala
49	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo			Peach_Big Top	Peach_Big Top
50	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo			Apple_Royal Gala	Peach_Big Top
51	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Pepper greenhouse_Almuden			Apple_Royal Gala	Apple_Royal Gala
52	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Pepper greenhouse_Almuden			Peach_Big Top	Peach_Big Top
53	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Pepper greenhouse_Almuden			Apple_Royal Gala	Peach_Big Top
54	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Apple_Royal Gala	Apple_Royal Gala
55	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Peach_Big Top	Peach_Big Top
56	Cabbage_Impala	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Apple_Royal Gala	Peach_Big Top
57	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo			Apple_Royal Gala	Apple_Royal Gala
58	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo			Peach_Big Top	Peach_Big Top
59	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Beans greenhouse_Pongo			Apple_Royal Gala	Peach_Big Top
60	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Pepper greenhouse_Almuden			Apple_Royal Gala	Apple_Royal Gala
61	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Pepper greenhouse_Almuden			Peach_Big Top	Peach_Big Top
62	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Zucchini_Zelia	Pepper greenhouse_Almuden			Apple_Royal Gala	Peach_Big Top
63	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Apple_Royal Gala	Apple_Royal Gala
64	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Peach_Big Top	Peach_Big Top
65	Squash_Musquee de Provence	Lamb's lettuce greenhouse_Trophy	Beans greenhouse_Pongo	Pepper greenhouse_Almuden			Apple_Royal Gala	Peach_Big Top

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834 Appendix B. Source code.