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

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ABSTRACT

CONTEXT

Planting fruit trees in a market gardening system creates a mixed fruit tree – vegetable system with the potential to address certain environmental issues. However, it results in a complex system where labor has to be allocated between the two activities.

OBJECTIVE

Our objective is to simulate possible trajectories for a perennial transition from market gardening to mixed fruit tree – vegetable systems, in order to study the required trade-offs.

METHODS

We modeled the transition using viability theory, a framework with states, controls and constraints that guarantees sustainability along a transition trajectory. It was used in two iterations, the first step computing a target to be reached during the second step. Trajectory samples were computed from the sets of viable states at each time step.

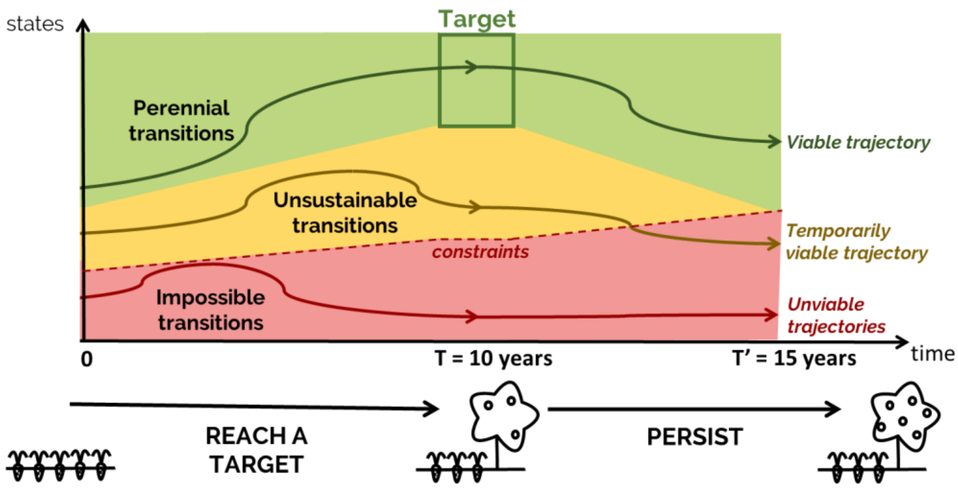
RESULTS AND CONCLUSIONS

In order to guarantee sustainability, at the end of the transition process the farm must not only respect the constraints but belong to a subset of the domain they define. The study of viable trajectories shows a trade-off between capital and working hours, and thus different suitable strategies for the timing of orchard planting and the choice of crop rotations. Some strategies present bottlenecks where the flexibility of the farm is greatly reduced.

SIGNIFICANCE

The variety of resulting viable trajectories means that choosing between them can call upon criteria that are not implemented in the model, such as personal preferences. The establishment of a target through viability computation and the study of trajectory sets avoids the imposition of an *a priori* normativity.

GRAPHICAL ABSTRACT



Keywords: viability theory; crop diversification; perennial transition; mixed horticultural farm; agroforestry

Highlights:

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

1. INTRODUCTION

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

One way to effect a change in these systems while remaining coherent with ecological aspirations is to plant fruit trees in addition to vegetable crops, in order to create a Mixed Fruit tree – Vegetable (MFV) system. Mixing these two types of production results in increased functional diversity. Given their size and their perennial development, trees present morphological characteristics and functional traits very different from annual vegetable crops. They can buffer the microclimate, possibly benefiting lower-growing crops, through a modification of light penetration, air temperature and humidity, soil temperature and moisture, and wind movement. They also provide a wide range of ecosystem services: carbon sequestration, soil structure enhancement, relocation of soil nutrients, erosion control, food and habitat for pest predators and parasitoids, water quality enhancement and reduction in nutrient leaching, etc. (Beillouin et al., 2021; Chittapur and Patil, 2017; Sollen-Norrlin et al., 2020). The resulting system is also very well adapted to direct selling, providing complementary, high-added-value products. Fruit can be considered as an attractive product that will make the consumer more willing to come to the sales point (Léger et al., 2019). Their high efficiency on small areas makes these systems interesting in a context of competition for land use. However, despite all their potential advantages, such systems are also very complex to manage.

Indeed, fruit trees and vegetables have distinct physiological requirements and characteristics that must be considered in their management. They must be spatially arranged in order to minimize competition between crops. Their temporalities differ: most vegetables are annuals whereas fruit trees are perennial crops requiring several years to reach their full potential yield. Fruit tree planting can thus be considered as a long-term investment compared to annual vegetable cropping. When working hours are limited, prioritizing of tasks can favor one type of crop over another. The choices made can provide short-term benefits during the current year (*e.g*. harvesting vegetables) or be long-term investments with benefits over the next few years (*e.g.* pruning trees). Failing to make this investment, by neglecting fruit tree care during the first stages of development, can heavily impact their production for many years. It is therefore crucial for a farmer to pay particular attention to the initial stage of tree development when shifting from MG to MFV. Finding the right balance between long- and short-term objectives is particularly difficult as it requires the ability to project the consequences of short-term decisions onto the system's long-term dynamics.

In this study, we developed a dynamic model of an MFV farm to explore the long-term consequences of crop and workload allocation choices for the dynamics of a farming system during perennial transition from an MG farm to an MFV system. More specifically, we addressed two issues: the paths enabling transition to occur and the conditions under which the targeted MFV system can become perennial. In order to find the set of management options that would make it possible to perform the transition, we used the Viability Theory mathematical framework (Aubin, 1991).

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 C*apsicum 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 throughout the year and, for the fruit trees, growth dynamics. In order to guarantee rotation among the crops on each plot, the same crop cannot be planted on more than 50% of the farm area (Appendix A). Monocultures and their long-term consequences on soils and biodiversity are thus excluded from the model. Crops are considered to be cultivated on distinct plots; no interactions are therefore considered between crops (vegetables or trees).

2.3. Transition description:

The system begins as an MG farm, with no trees. The transition to an MFV system can happen any time between the first year and the time horizon (T = 10 years).

Transition from one system to another is always a long-term projection. The new system must remain viable after the time horizon T at which the transition is considered to be complete. Furthermore, we consider that farmers may be willing to put in a major effort for a few years in order to reach a more convenient situation that will be easier to sustain over the long term. We thus translated an easing of labor conditions after T by an increase in salaries and a decrease in working hours.

Management of such a farm requires the handling of several different tasks beside crop production, such as marketing and administration. Therefore, labor time devoted to crops is lower than the total working hours invested by the farmer. In the current situation and based on farmers' feedback, we consider crop-related labor to account for around 70% of the total. The farm being conceived as being managed by one full-time farmer, and according to what has been observed on highly diversified small farms (Joyeux, 2017), labor time available is around 50h/week. Labor time devoted to crops is thus limited to 140h/month (35h/week), for the first ten years. The farmer's wage is fixed at €1,500/month, which is slightly under the French minimum wage (€1645.58 in 2022). Fixed costs are set at €8,000/year (Declercq and Clerc, 2011). After T, salaries are raised to €2,000/month whereas working hours devoted to crops are reduced to 120h/month (30h/week), reflecting better working conditions after the transition phase.

2.4. States and controls:

Following the viability theory formalism, the model is characterized by states, controls, and constraints. States and controls have been chosen to assess common viability criteria for such farms

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

States are system features that change over time. In our model, the states considered are the farm's economic capital (continuous), three discrete variables describing orchards, once fruit trees have been 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.

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

2.5. Dynamics:

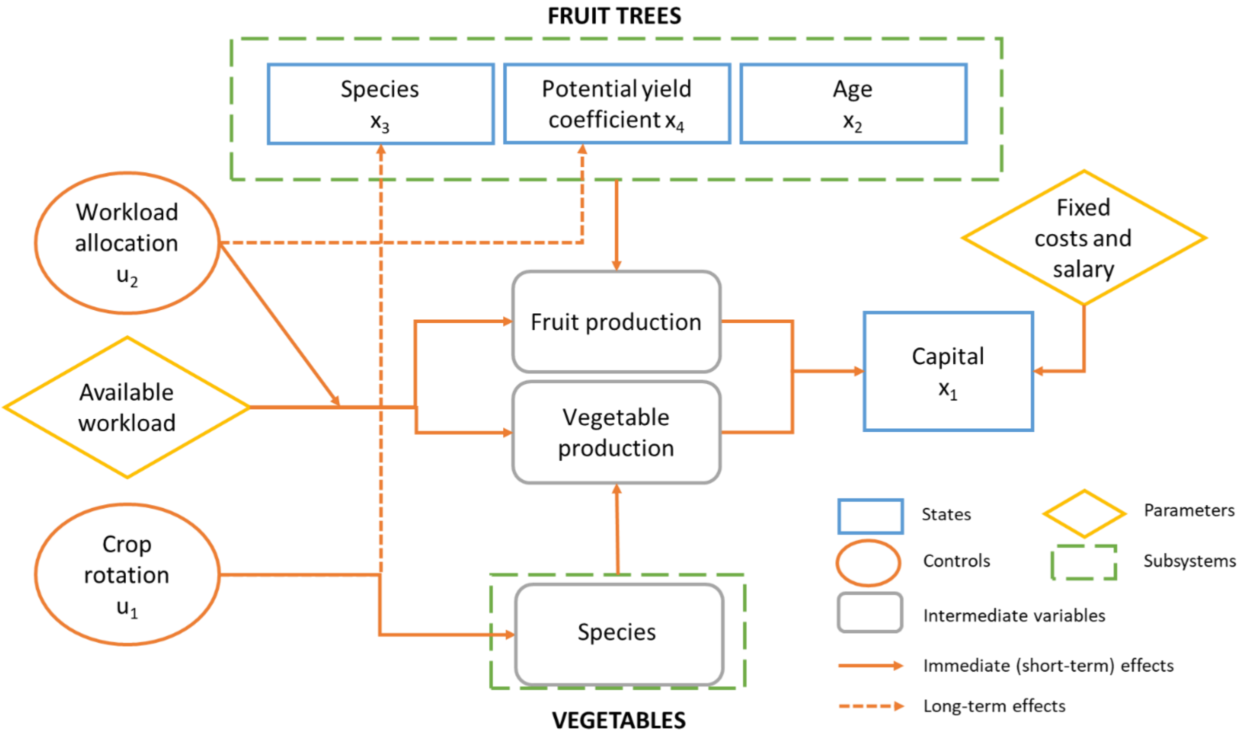


Figure 1: Conceptual representation of the model. Rectangular blue boxes represent states, ellipses are controls. Yellow diamonds are parameters (fixed throughout the simulation). Rounded grey boxes are intermediate variables and dashed green boxes are subsystems. Controls can have immediate effects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

2.5.1 Overall dynamics:

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

Indeed, yearly variation f_1 in capital x_1 increases with annual gross margin for vegetables *GMv* and for fruit trees *GMf*, whereas it decreases with farmer's salary *S* and fixed costs *C*. Costs *C* remain constant throughout the simulation, whereas the salary *S* is revised at *T*, time at which the transition is considered to be over. It therefore depends on time since the start of computation τ.

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 tree composition from rotation choice u_1. If $h(u_1) = none$, the variable x_2 corresponding to tree age is set equal to 0. Otherwise, when $h(u_1) = x_3$, the planted trees remain and their age increases by one each year. Finally, when $h(u_1) \neq x_3$, all old trees are removed, new ones are planted and then all tree ages equal 1 (hence we only need a one-dimensional variable to describe tree age, which is crucial to minimize computation complexity). x_3 takes the value corresponding to u_1's tree composition (f_3). x_4 decreases proportionally to the lack of care of fruit trees (f_4, with δ a function controlling the change in potential yield coefficient). Its value is reset to 1 when trees are newly planted.

2.5.2 Work allocation:

With limited workload available, workload requirements for fruit trees and vegetables can conflict. In this case, management decisions are taken monthly using the workload allocation control u_2. If $u_2 = 1$, working time is first allocated to trees and the remaining time is allocated to vegetables. If $u_2 = 0$, working time is first allocated to vegetables and the remaining time is allocated to trees. If $0 < u_2 < 1$, working time allocation to both crops is proportional to u_2. Formally,

$$\begin{aligned} &W_{v\_month}(x_2, u_1, u_2, \tau) \\ &\qquad = \min\Big((1-u_2)W(\tau) + max\big(u_2 * W(\tau) - W_{n\_f}(x_2, u_1), 0\big), W_{n\_v}(u_1)\Big) \\ &W_{f\_month}(x_2, u_1, u_2, \tau) \\ &\qquad = \min\Big(u_2 * W(\tau) + \max((1-u_2)\,W(\tau) - W_{n\_v}(u_1), 0), W_{n\_f}(x_2, u_1)\Big) \qquad (2) \end{aligned}$$

with $W_{v\_month}(x_2, u_1, u_2, \tau)$ monthly working hours devoted to vegetables, $W_{f\_month}(x_2, u_1, u_2, \tau)$ monthly working hours devoted to fruit trees, $W(\tau)$ available working hours per month when the time since the beginning of computation is τ, $W_{n\_f}(x_2, u_1)$ and $W_{n\_v}(u_1)$ monthly working hours required for an optimal harvest of fruit and vegetables respectively.

The result is then summed over the year and compared to cumulative work requirements, to create relative working hours devoted to vegetables (W_v) and to fruit trees (W_f):

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

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

2.5.3 Change in potential fruit production coefficient:

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

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

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

2.5.4 Potential yield coefficient:

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

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

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

2.5.5 Gross margins:

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

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

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

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

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

where $FGM_a(u_1)$ and $FGM_p(u_1)$ are the theoretical gross margin for apple and peach trees respectively. *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 function that takes the value 1 if an orchard has to be removed, 0 otherwise.

2.6. Constraints:

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

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

In order to model a transition from an MG to an MFV system, at least one plot must be planted with trees from the end of the ten-year transition period. This feature can be represented by x_2 (age of fruit trees), a value of 0 for this state meaning an absence of fruit trees (Eq. (8)).

Furthermore, at any given time, it is not possible to own trees planted before the beginning of the simulation. In other words, tree age x_2 cannot exceed the time elapsed since the beginning of computation τ (Eq. (8)).

Trajectories (combinations of states and controls) respecting all these constraints at any time are called viable trajectories. The subset of state space respecting these constraints is denoted K and can be written as:

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

2.7. Two-step viability algorithm:

The viability kernel is the set of states acting as the start of at least one trajectory that respects the constraints over time. Let *V* be the viability kernel of dynamics (Eq. (1)) facing constraints (Eq. (8)). Denoting as *Q(X)* the set of all trajectories governed by the controlled dynamic system and starting from $X := (x_1, x_2, x_3, x_4, \tau)$, the viability kernel is defined by the equation:

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

To compute *V*, we take advantage of the particular dynamics of state τ. We use an algorithm (De Lara and Doyen, 2008) which employs a backward method to compute V_{τ^*} from V_{τ^*+1} where V_{τ^*} is the section of *V*:

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

In our particular case, *K* is not upper bounded in the τ direction which makes the initialization of the algorithm impossible. However, as constraints and dynamics do not change after time *T*, being permanently viable at any time after *T* requires the same conditions as at *T*: $V_{\tau^*} = V_T \; for \; \tau^* \geq T$. 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 $V'_{T'} = \{(x_1, x_2, x_3, x_4, \tau) \mid (x_1, x_2, x_3, x_4, \tau) \in K' \;\&\; \tau = T'\}$.

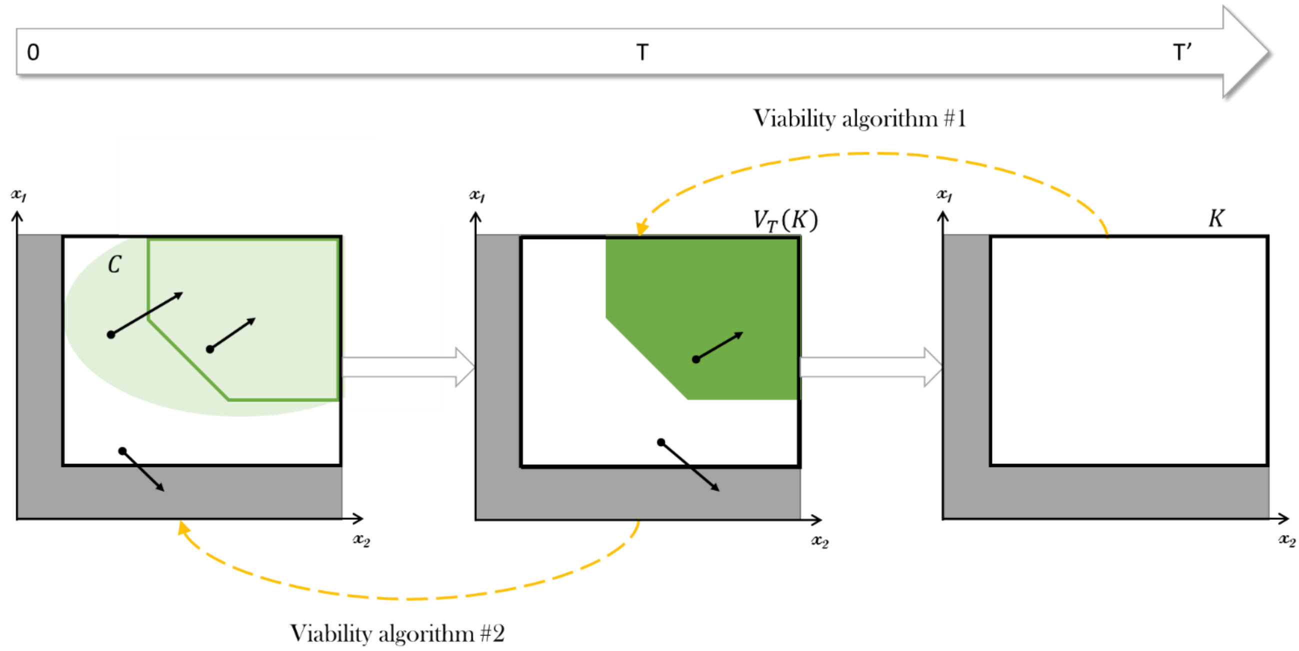


Figure 2: Two-step method to determine viable transition trajectories. Non-viable states are in grey, viable states are within the black frame. The dark green area corresponds to the target: viable states at T from which it is possible to remain viable after the change of parameters. The light green 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 ($\tau \leq T$ and $\tau \geq T$) (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 capture basin is the set of all initial states from which at least one trajectory ending in the target starts. It can be formally defined as:

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

In order to compute viability algorithms, each state and control was discretized on a regular grid. As fruit tree gross margins remain essentially unchanged once maturity is reached, a mature tree category was considered for all trees over 11 years. So x_2 ranges from 0 to 12 with a step of 1. Similarly, the linearity of the dynamics enabled us to ascertain that if a state is viable with $x_1 = x_1^*$, it remains viable with any greater value. We find that x_1 ranging from €8,000 to €50,000 is satisfactory with a step of €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 ranges from 0 to 1 with a step of 0.2.

2.8. Trajectory computation:

As a preliminary step, a static comparison of the potential of the different crop portfolios was realized for the different values of orchard age (x_2) with a maximal production coefficient ($x_4 = 1$). Dynamics 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 capital variation between two successive years ($x_1(t+1) - x_1(t)$). To compute capital, the value of the workload allocation control (u_2) used was that giving the highest capital value. Salaries and fixed costs have been included in the computation.

In a second step, we conducted a dynamic analysis of the system within the Viability framework. Two scenarios were considered: one without any specific constraint about the age of orchards at T (they must simply exist: $x_2(T) \geq 1$) and one imposing an age of 8 ($x_2(T) = 8$). Once viability kernels were found, a random sample of 10,000 viable forward-looking trajectories was computed from each kernel. All trajectories start with the lowest viable capital value, *i.e.* $x_1(0) = x_{1min} =$ €10,000. Controls were drawn randomly at each time step from among the viable ones. These trajectories (*i.e.* viable temporal successions of crop portfolios) were then compared in terms of workload, capital and crop rotations used.

2.9. Computation:

All viability kernels and trajectory computations used Python 3.9.7 (www.python.org/). Statistical analyses used R software 4.1.2 (https://cran.r-project.org). Economic data were obtained from the Provence-Alpes-Côte d'Azur Regional Chamber of Agriculture (Roblin and Bouvard, 2017).

3. RESULTS

3.1. Working hours:

Working hours are mainly occupied by vegetables. This is consistent with previous studies: tree care activity does not demand much time in most months (Boury-Esnault et al., 2018; Léger et al., 2019). Tree-related activity is likely to compete with vegetables only during pruning and harvesting periods, when farmers may have to make a choice over workload allocation.

A static analysis of the workload associated with the different portfolios shows that working hours for portfolios with vegetables only are significantly higher than working hours for portfolios including an orchard, no matter its age (Welch's two sample t-test, $p = 4.6e^{-12}$; Figure 3). Workload marginally increases with tree age but remains much lower than workload with vegetables only.

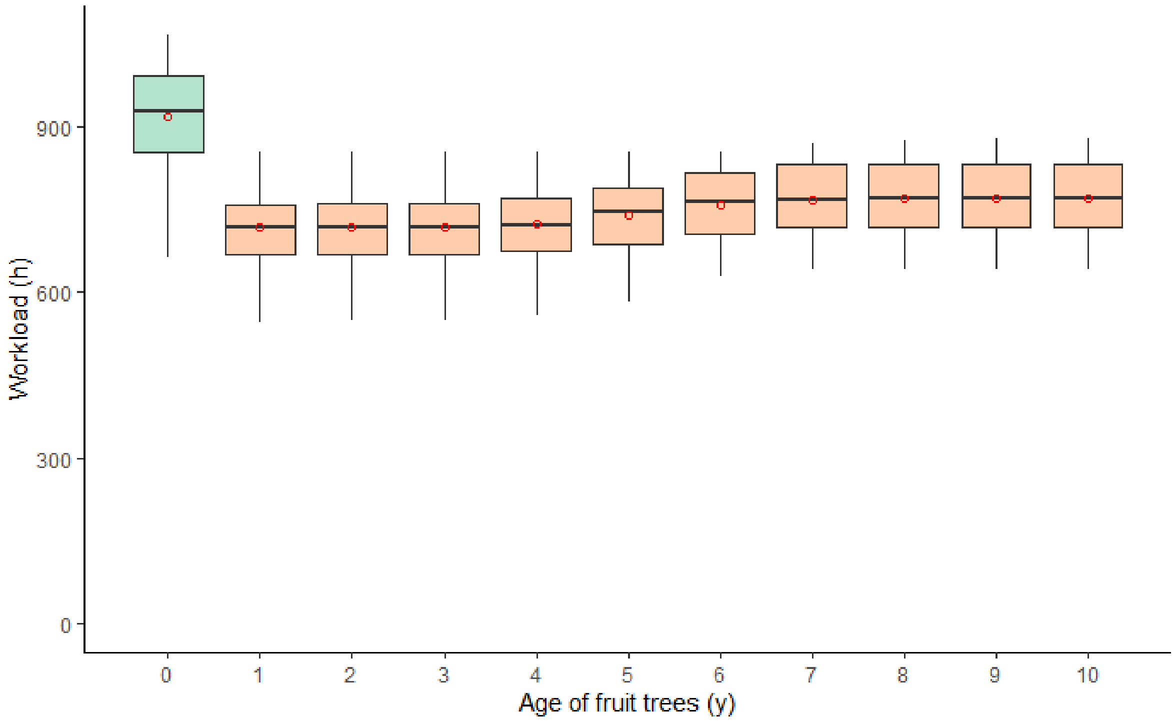


Figure 3: Potential annual working hours for crop portfolios for various ages of fruit trees. The green box (x = 0) corresponds to the set of portfolios with vegetables only. Orange boxes (x > 0) correspond to portfolios with at least one fruit tree species, for different age values of this orchard. 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).

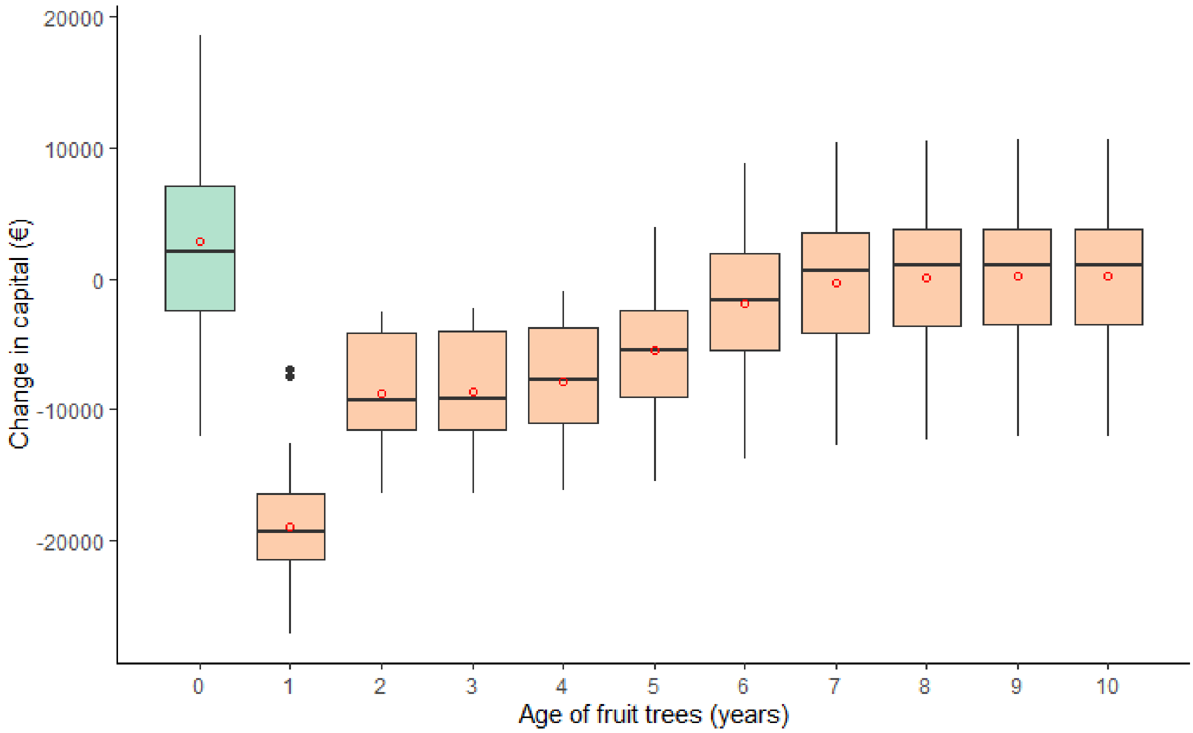


Figure 4: Potential change in capital associated with crop portfolios, for different ages of fruit trees. The green box (x = 0) corresponds to the set of portfolios with vegetables only. Orange boxes (x > 0) correspond to portfolios with at least one fruit tree species, for different age values of this 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.

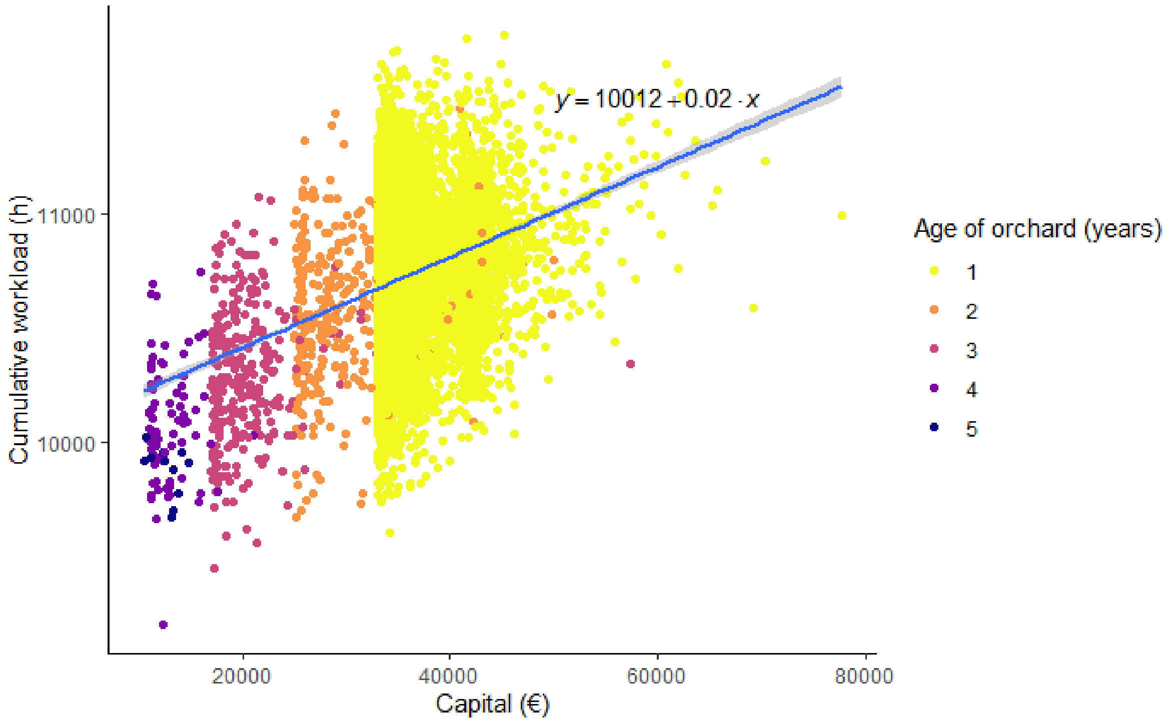


Figure 5: Sum of working hours throughout the simulation depending on final capital, for a sample composed of 10,000 random viable trajectories. Each point is the result of a 10-year trajectory. The blue line corresponds to a linear regression of the whole sample.

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 illustrate what happens in each sample, one trajectory has been randomly drawn from both of them. They are presented on Figure 6.

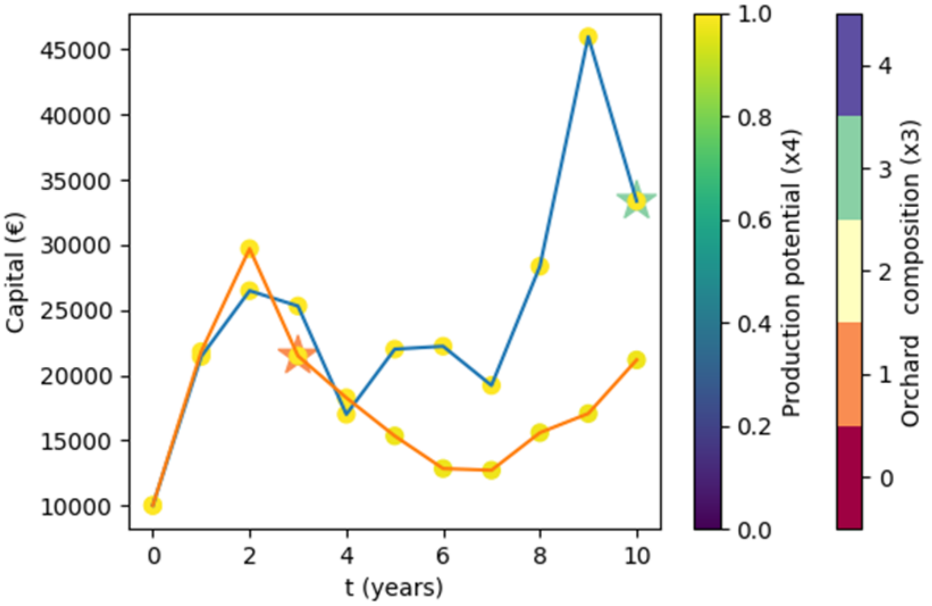


Figure 6: Illustration of trajectories from each of the two samples: random sample in blue and sample aiming at 8-year-old orchards in orange. Stars correspond to fruit tree planting, with a color depending on the type of fruit tree chosen (x_3). Colors of circle dots correspond to the value of the potential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

The cost of tree planting (Figure 4) can be seen on these trajectories. The one with the earliest transition (orange curve) has the opportunity to make profits again five years after planting. This cost has to be anticipated by more or less intense capital accumulation depending on the time provided before tree planting and the amount of money necessary to remain viable with the resulting trees.

3.4. Comparison of two strategies:

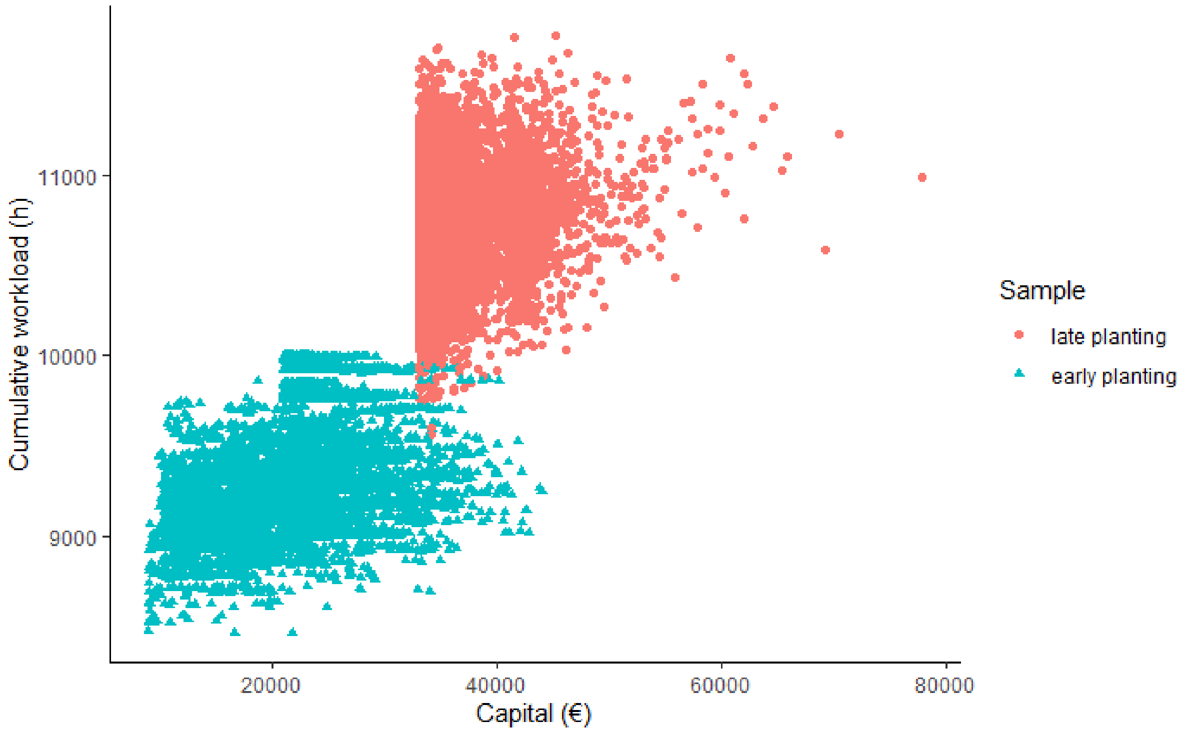


Figure 7: Sum of working hours throughout the simulation depending on final capital, for two samples of random viable trajectories: one requiring 1-year-old orchards (red circles) and the other requiring 8-year-old orchards (blue triangles). Each point is the result of a 10-year trajectory.

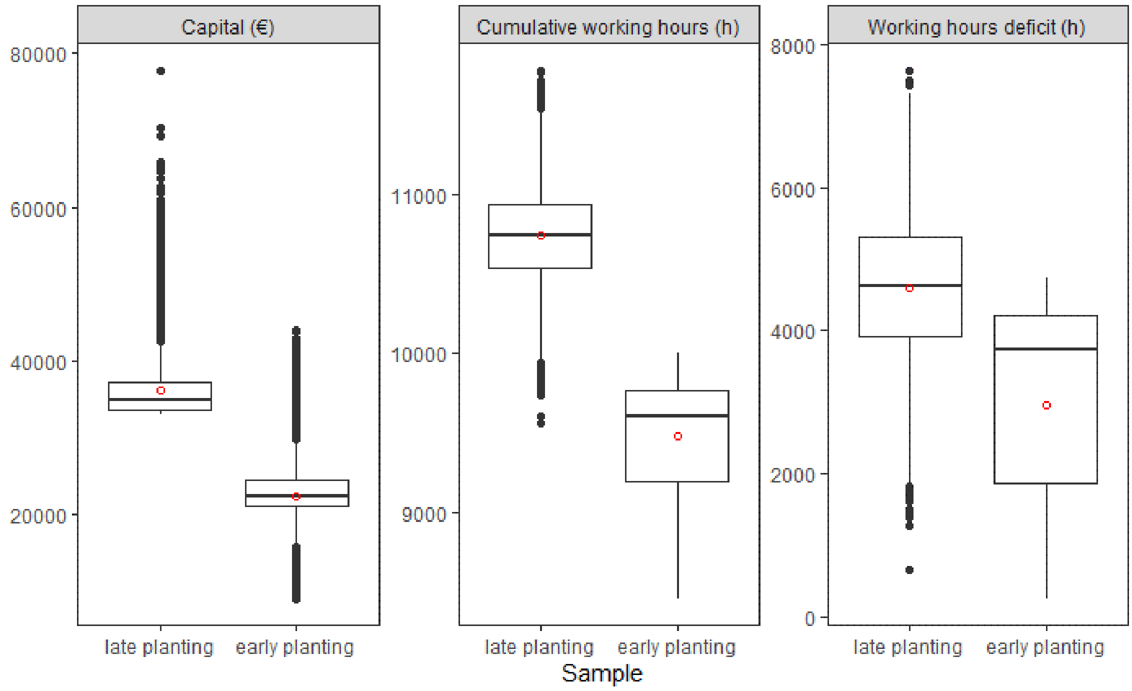


Figure 8: Distribution of capital, cumulative working hours and working hours deficit among the trajectories for the two samples: targeting 1-year-old orchards (late planting) and targeting 8-year-old orchards (early planting). Each sample is composed of 10,000 random trajectories. Red circles correspond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

Aiming at 8-year-old trees results in both lower capital values and lower working hours. It corresponds to a long-term investment made as early as possible. However, there is a limited number of vegetable rotations in the first years that make it possible to accumulate enough money for such an investment (Figure 9). In almost half of the cases (41%), a single plot of peach trees is planted. This choice is a way to cope with less money being available at the time of tree planting, but it is not the most efficient in the long-term. When starting with $x_1(0) = x_{1min}$, no crop rotation is lucrative enough to enable tree planting after less than two years of market gardening.

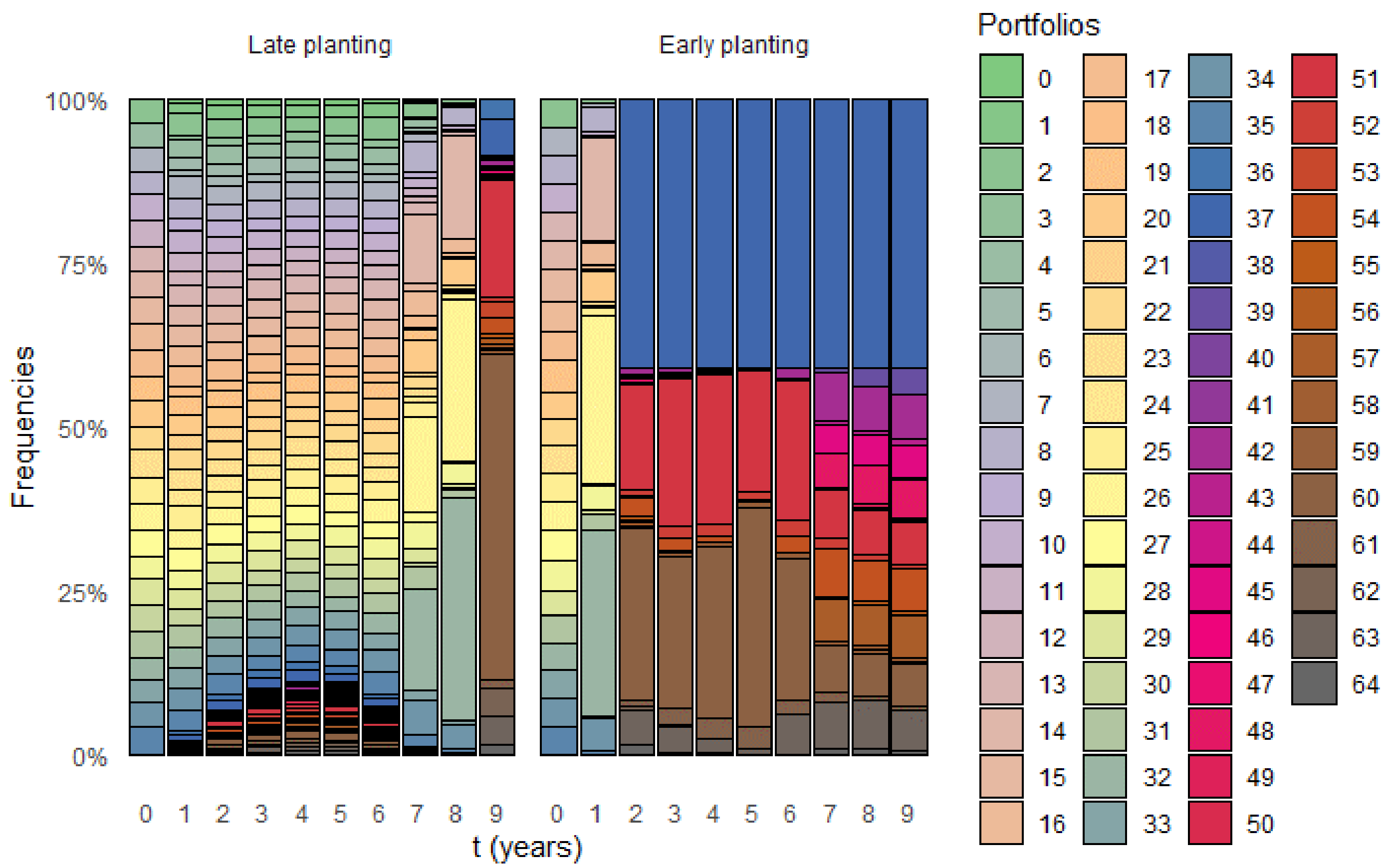


Figure 9: Frequency of use of the different crop rotations through time, for the two samples: aiming at 1-year-old trees (late planting) and aiming at 8-year-old trees (early planting). Portfolios up to 35 are entirely composed of vegetables. Portfolios 36 and 37 include one orchard plot. Portfolios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

3.5. Working hours deficit:

Problematic situations relating to workload appear when not enough working hours are available to meet either vegetable or fruit production requirements. To study these situations, we defined working hours deficit as the accumulated difference between effective workload and required working hours.

Among the random sample, trajectories with a lower working hours deficit seem more interesting in terms of the trade-off between capital and labor (Figure 10). Thus, choosing crops with workload requirements corresponding to available workload can be a means of avoiding the less efficient trajectories.

Furthermore, working hours deficit is significantly lower when trees have been planted early (Figure 8). In other words, crop rotations with fruit trees tend to present work requirements closer to available working hours.

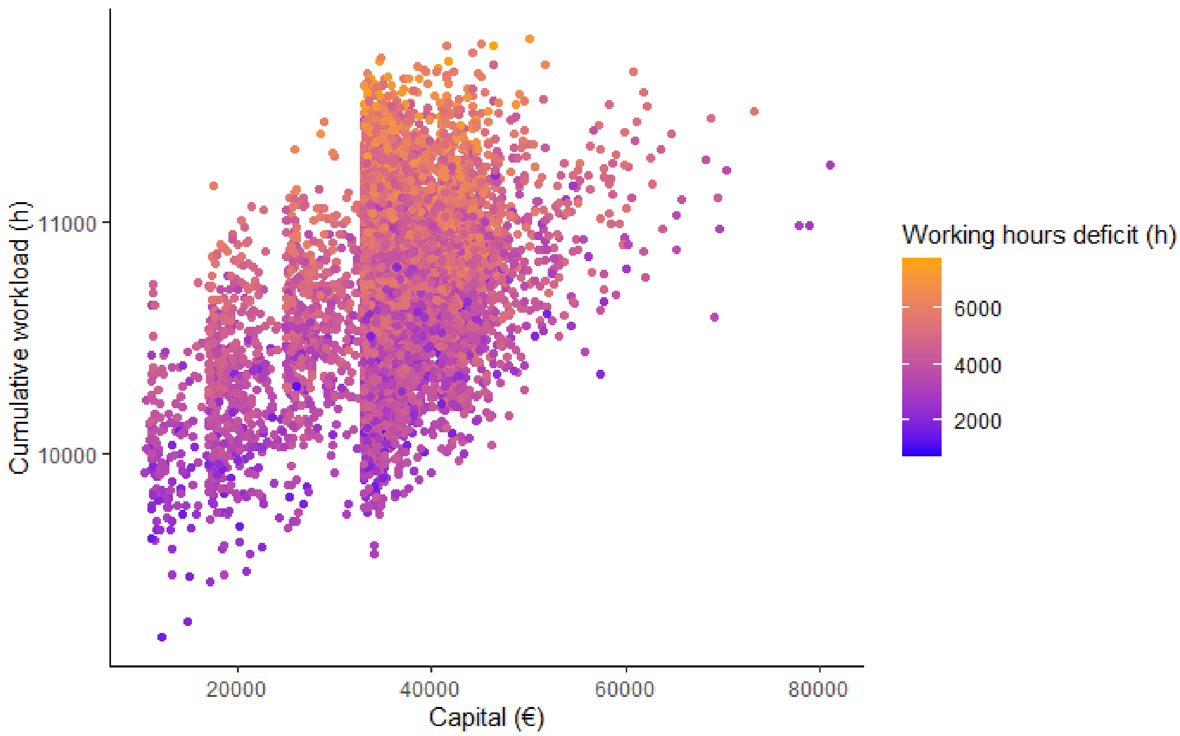


Figure 10: Sum of working hours depending on capital, for a sample of 10,000 random viable trajectories. Colors correspond to working hours deficit values.

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., 2010), that are particularly difficult to include in such a model. For instance, some tree species can be more or less well-adapted to a given soil and climate, or possess specific cultural significance. Some of these decision-making parameters can be included in models, e.g. land heterogeneity in Dogliotti et al. (2005). However, choices have to be made about what to include or not in each model in order to achieve a balance between accurate representation of reality and genericity. Here, a detailed land description would have been inconsistent with the level of abstraction of the model dynamics.

Moreover, such alternative farming systems are often conceived by their author as life projects, and priority is not systematically given to economic performance. Strategies adopted can also address other concerns such as workload, risk (peaches' sensitivity to cold makes them liable to high variations in yield), commercialization (apples are easier than peaches to store and sell), integration into local communities, etc. These considerations can hardly be included in a digital model, as they can refer to values such as beauty, intellectual interest or ecological concerns (Morel and Léger, 2016). They are usually ignored in the modeling process, actors being considered as rational individuals making decisions based on economic criteria.

4.2. Looking for satisfactory solutions

Dynamic models make it possible to study long-term dynamics such as those at stake in transitions, and to explore a wide range of trajectories with uncertain outcomes, whereas proceeding by trial and error with real systems is a time-consuming and risky process (*e.g.* Corbeels et al., 2014; Delbridge and King, 2016; Lescot et al., 2011; Žibert et al., 2022). Thanks to a high enough number of simulated variables and interactions, and to calibration with empirical data, these models can be precise and reliable enough to predict *ex ante* trajectories; for example crop performance in places or climates where the crop of interest has never been grown. In order to discriminate among possible decisions, the best one is generally selected based on a single criterion or a combination thereof, in order to get as close as possible to a predefined target (Bergez et al., 2010). *Ad hoc* modeling tools are used to assess farmers' interest (or lack thereof) in engaging in transition, and thus to explain factors determining the adoption of agroecological practices. In addition to achieving a better understanding of the mechanisms and processes at stake, these models can therefore also be used to provide farming advice. Farmers can thus use the model's optimal trajectory as a benchmark against which to compare their own farm and practices (*e.g.* Rodriguez et al., 2014; Ryschawy et al., 2014). However, with these models, farmers are generally assumed to be rational profit-maximisers with perfect knowledge of the production outputs. This is a crude approximation of farmers' behavior and optimization tools are limited in their ability to include farmers' complex decision-making processes (McCown, 2001; Robert et al., 2016; Sempore et al., 2015).

One main interest of viability theory is to give a set of viable solutions instead of a single 'optimal' solution. The model we developed required very few hypotheses about farmer's behavior and avoided the delicate step of defining decision rules to simulate crop management. It is a means of acknowledging diversity in farmers' motivations, abilities (including knowledge and learning skills) and strategies, as well as the existence of multiple pathways enabling sustainable transitions (Rosenbloom, 2017). It avoids imposing the researcher's normativity, thus increasing the model's legitimacy, defined as the production of fair and unbiased information respecting stakeholders' values and beliefs (Cash et al., 2003; Chang and Morel, 2018). Moreover, decision-making processes can be considered at both strategic (long term) and tactical (short term) scales: the realization of strategic objectives (the transition) depends on yearly choices of crop rotations and workload allocation (Robert et al., 2016). Depending on farmer's individual priorities, one viable trajectory or another can be adopted, offering flexibility in the search for sustainable solutions. When several controls are viable, the choice made for one control or another can correspond to various strategies. Farmers with different objectives can find various ways to create their own viable farm. For instance, an early decision to plant trees can be a way to invest for future income and labor conditions, whereas planting vegetables to increase capital can be another way to face forthcoming adversity. An alternative to computation of every possibility could be to develop several alternative scenarios with farmers, in a participatory modeling approach (Le Gal et al., 2022; Pissonnier et al., 2019).

The framework based upon the satisfaction of certain constraints rather than looking for optimal solutions is also more in accordance with farmers' management. Real-life systems are complex and limited information is available, so farmers often have only a vague idea of the probability distribution of outcomes associated with various control strategies. Therefore, what is sought is the satisfaction of some objectives and operational constraints, rather than the maximization of some utility function (Norton, 1976). The system can then be pushed towards these objectives through a range of available controls, without closely monitoring every dynamic and interaction.

The model does not capture all the complexity of these systems, but the number of computed trajectories makes it possible to select them in hindsight, depending on individual concerns. The predictive power of the model is not necessarily a priority for farmers, who may prefer qualitative discussions (Chang and Morel, 2018). Nevertheless, the accuracy of this model could be increased by including competitive and cooperative interactions between crops. Management of these interactions is often considered to be the main issue of these systems (Wezel et al., 2014), but data is lacking about the exact degree of their effects (Léger et al., 2019; Paut et al., 2020). Another improvement could be to increase the number of available crops to increase the range of possibilities at each time step. This would require computation time limitations to be dealt with. Finally, it could be interesting to include uncertainties, such as climatic events or market instability. This could be achieved by applying stochasticity to yields (see *e.g.* Baumgärtner and Quaas, 2009; Oubraham et al., 2020; Sabatier et al., 2015) and assessing the resilience-related properties of the system (Sabatier et al., 2018). Resilience can also be assessed without assumptions about the probabilities of such catastrophic events, as the inverse of the minimal cost associated with the effort to restore and preserve some properties of the system following disturbances (Martin, 2019). Furthermore, this model could be adapted to the case of a different farm size, or a collective installation on the same farm, by simply changing the parameters. Indeed, collective installation is often a lever for diversification. The combination of each person's specialized skills and knowledge creates a diversified whole-farm system and overcomes the knowledge acquisition issue.

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

Agroecological transition is a wide notion covering a whole range of conceptual frameworks, focusing on different objects at various organizational levels, over medium- to long-term time spans (Duru et al., 2015; Ollivier et al., 2018; Prost et al., 2023). The process of change can be conceived as the transformation of an initial state into a targeted final state, or as a continuous process of successive adjustments between means and goals (Lamine et al., 2021). The transition represented here is farm-centered and quite deterministic: a goal is set from the beginning about what the farm must look like at a given time horizon. This goal is rooted in the way the model has been implemented: the possibility of planting trees is part of the dynamics and determines one of the constraints.

However, even though the objective of obtaining a perennial MFV farm is set from the beginning, the precise target required to meet this goal is not. It is computed through a complementary viability analysis, so every solution consistent with this goal is considered, with as few assumptions as possible. In Joly (2015), viability at final state is defined differently than for other steps, as there are no controls enabling the assessment of usual viability constraints. Therefore, viability at final state was considered as subsequent growth reaching stationary state. This phenomenon was in turn translated into constraints. In our model, fewer hypotheses are required, as conditions at the time horizon for future sustainability are not established at the outset.

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).

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' values. The range of viable trajectories acknowledges the importance of considering the variety of possible means to achieve the same goal in a complex world. Because the conceptual framework is relatively close to the way farmers manage their farms and the plurality of the outputs avoids the imposition of an exclusive solution, it could become a good tool for starting a discussion with stakeholders.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6. REFERENCES

Aubin, J.-P., 1991. Viability Theory. Birkhäuser Boston, Boston. https://doi.org/10.1007/978-0-8176-4910-4

Aubin, J.-P., Bayen, A.M., Saint-Pierre, P., 2011. Viability Theory: New Directions. Springer Science & Business Media.

Baumgärtner, S., Quaas, M.F., 2009. Ecological-economic viability as a criterion of strong sustainability under uncertainty. Ecol. Econ., Methodological Advancements in the Footprint Analysis 68, 2008–2020. https://doi.org/10.1016/j.ecolecon.2009.01.016

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., Makowski, D., 2021. Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob. Change Biol. 27, 4697–4710. https://doi.org/10.1111/gcb.15747

Bergez, J.E., Colbach, N., Crespo, O., Garcia, F., Jeuffroy, M.H., Justes, E., Loyce, C., Munier-Jolain, N., Sadok, W., 2010. Designing crop management systems by simulation. Eur. J. Agron., Cropping Systems Design: new methods for new challenges 32, 3–9. https://doi.org/10.1016/j.eja.2009.06.001

Boury-Esnault, A., Tchamitchian, M., Paut, R., 2018. L'organisation du travail dans un système diversifié : cas des vergers-maraîchers.

Briot, J.-P., de Azevedo Irving, M., Mendes de Melo, G., Vasconcelos, J.E.F., Alvarez, I., Martin, S., Wei, W., 2011. A Serious Game and Artificial Agents to Support Intercultural Participatory Management of Protected Areas for Biodiversity Conservation and Social Inclusion, in: 2011 Second International Conference on Culture and Computing. Presented at the 2011 Second International Conference on Culture and Computing (Culture Computing), IEEE, Kyoto, Japan, pp. 15–20. https://doi.org/10.1109/Culture-Computing.2011.12Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. 100, 8086–8091. https://doi.org/10.1073/pnas.1231332100

Chang, M., Morel, K., 2018. Reconciling economic viability and socio-ecological aspirations in London urban microfarms. Agron. Sustain. Dev. 38, 9. https://doi.org/10.1007/s13593-018-0487-5

Chittapur, B.M., Patil, D.K., 2017. Ecosystem services rendered by tree based land use systems. Indian J. Agric. Sci. 87, 1419–1429.

Corbeels, M., de Graaff, J., Ndah, T.H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat, G., Schuler, J., Nyagumbo, I., Rusinamhodzi, L., Traore, K., Mzoba, H.D., Adolwa, I.S., 2014. Understanding the impact and adoption of conservation agriculture in Africa: A multi-scale analysis. Agric. Ecosyst. Environ. 187, 155–170. https://doi.org/10.1016/j.agee.2013.10.011

Crane, T.A., 2010. Of Models and Meanings: Cultural Resilience in Social-Ecological Systems. Ecol. Soc. 15, art19. https://doi.org/10.5751/ES-03683-150419

Dardonville, M., Urruty, N., Bockstaller, C., Therond, O., 2020. Influence of diversity and intensification level on vulnerability, resilience and robustness of agricultural systems. Agric. Syst. 184, 102913. https://doi.org/10.1016/j.agsy.2020.102913

Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., 2010. Adaptiveness to enhance the sustainability of farming systems. A review. Agron. Sustain. Dev. 30, 545–555. https://doi.org/10.1051/agro/2009053

De Lara, M., Doyen, L., 2008. Sustainable Management of Natural Resources: Mathematical Models and Methods. Springer Science & Business Media.

Delbridge, T.A., King, R.P., 2016. Transitioning to Organic Crop Production: A Dynamic Programming Approach. J. Agric. Resour. Econ. 41, 481–498.

Declercq, Y., Clerc, F., 2011. Référence technico-économique en maraîchage biologique.

Dogliotti, S., van Ittersum, M.K., Rossing, W.A.H., 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agric. Syst. 86, 29–51. https://doi.org/10.1016/j.agsy.2004.08.002

Duru, M., Therond, O., Fares, M., 2015. Designing agroecological transitions; A review. Agron. Sustain. Dev. 35, 1237–1257. https://doi.org/10.1007/s13593-015-0318-x

Joly, F., 2015. Dynamics of a pastoral system of the Mongolian Gobi exposed to climate hazards: a resilience-based case study in a viability framework (PhD Thesis). AgroParisTech, Paris.

Joyeux, C., 2017. Données technico-économiques en maraîchage biologique en France - Etat des lieux de la littérature actuelle et réflexion pour une méthodologie collégiale.

Klapwijk, C., van Wijk, M., Rosenstock, T., van Asten, P., Thornton, P., Giller, K., 2014. Analysis of trade-offs in agricultural systems: current status and way forward. Curr. Opin. Environ. Sustain. 6, 110–115. https://doi.org/10.1016/j.cosust.2013.11.012

Lamine, C., Magda, D., Rivera-Ferre, M., Marsden, T. (Eds.), 2021. Agroecological transitions, between determinist and open-ended visions. Peter Lang International Academic Publishers.

Le Gal, P.-Y., Andrieu, N., Bruelle, G., Dugué, P., Monteil, C., Moulin, C.-H., Penot, E., Ryschawy, J., 2022. Modelling mixed crop-livestock farms for supporting farmers' strategic reflections: The CLIFS approach. Comput. Electron. Agric. 192, 106570. https://doi.org/10.1016/j.compag.2021.106570

Léger, F., Morel, K., Bellec-Gauche, A., Warlop, F., 2019. Agroforesterie maraîchère : un choix stratégique pour garantir une durabilité en transition agroécologique ? Expériences issues du projet SMART. Innov. Agron. 71, 259–273. https://doi.org/10.15454/EK039O

Lescot, J.-M., Rousset, S., Souville, G. (Eds.), 2011. Assessing Investment in Precision Farming for Reducing Pesticide Use in French Viticulture. https://doi.org/10.22004/ag.econ.114387

Martin, S., 2019. Viability analysis as an approach for assessing the resilience of agroecosystems, in: Gardner, S.M., Ramsden, S.J., Hails, R.S. (Eds.), Agricultural Resilience. Cambridge University Press, pp. 273–294. https://doi.org/10.1017/9781107705555.014

McCown, R.L., 2001. Learning to bridge the gap between science-based decision support and the practice of farming: Evolution in paradigms of model-based research and intervention from design to dialogue. Aust. J. Agric. Res. 52, 549–572. https://doi.org/10.1071/ar00119

Menapace, L., Colson, G., Raffaelli, R., 2013. Risk Aversion, Subjective Beliefs, and Farmer Risk Management Strategies. Am. J. Agric. Econ. 95, 384–389. https://doi.org/10.1093/ajae/aas107

Moore, A.D., Holzworth, D.P., Herrmann, N.I., Brown, H.E., de Voil, P.G., Snow, V.O., Zurcher, E.J., Huth, N.I., 2014. Modelling the manager: Representing rule-based management in farming systems simulation models. Environ. Model. Softw. 62, 399–410. https://doi.org/10.1016/j.envsoft.2014.09.001

Morel, K., 2016. Viabilité des microfermes maraîchères biologiques. Une étude inductive combinant méthodes qualitatives et modélisation. (Sciences agricoles). Université Paris-Saclay.

Morel, K., Léger, F., 2016. A conceptual framework for alternative farmers' strategic choices: the case of French organic market gardening microfarms. Agroecol. Sustain. Food Syst. 40, 466–492. https://doi.org/10.1080/21683565.2016.1140695

Norton, G.A., 1976. Analysis of decision making in crop protection. Agro-Ecosyst. 3, 27–44. https://doi.org/10.1016/0304-3746(76)90098-6

Ollivier, G., Magda, D., Mazé, A., Plumecocq, G., Lamine, C., 2018. Agroecological transitions: What can sustainability transition frameworks teach us? An ontological and empirical analysis. Ecol. Soc. 23, art5. https://doi.org/10.5751/ES-09952-230205

Oubraham, A., Saint-Pierre, P., Zaccour, G., 2020. Viability of Agroecological Systems under Climatic Uncertainty. Sustainability 12, 5880. https://doi.org/10.3390/su12155880

Oubraham, A., Zaccour, G., 2018. A Survey of Applications of Viability Theory to the Sustainable Exploitation of Renewable Resources. Ecol. Econ. 145, 346–367. https://doi.org/10.1016/j.ecolecon.2017.11.008

Paut, R., 2020. Analyse des compromis entre diversité cultivée et complexité de gestion à travers le cas d'étude du Verger-Maraîcher. Une approche combinant modélisation et méthodes qualitatives. INRAE.

Paut, R., Sabatier, R., Dufils, A., Tchamitchian, M., 2021. How to reconcile short-term and long-term objectives in mixed farms? A dynamic model application to mixed fruit tree - vegetable systems. Agric. Syst. 187, 103011. https://doi.org/10.1016/j.agsy.2020.103011

Paut, R., Sabatier, R., Tchamitchian, M., 2020. Modelling crop diversification and association effects in agricultural systems. Agric. Ecosyst. Environ. 288, 106711. https://doi.org/10.1016/j.agee.2019.106711

Pépin, A., Morel, K., van der Werf, H.M.G., 2021. Conventionalised vs. agroecological practices on organic vegetable farms: Investigating the influence of farm structure in a bifurcation perspective. Agric. Syst. 190, 103129. https://doi.org/10.1016/j.agsy.2021.103129

Pissonnier, S., Dufils, A., Le Gal, P.-Y., 2019. A methodology for redesigning agroecological radical production systems at the farm level. Agric. Syst. 173, 161–171. https://doi.org/10.1016/j.agsy.2019.02.018

Prost, L., Martin, G., Ballot, R., Benoit, M., Bergez, J.-E., Bockstaller, C., Cerf, M., Deytieux, V., Hossard, L., Jeuffroy, M.-H., Leclère, M., Le Bail, M., Le Gal, P.-Y., Loyce, C., Merot, A., Meynard, J.-M., Mignolet, C., Munier-Jolain, N., Novak, S., Parnaudeau, V., Poux, X., Sabatier, R., Salembier, C., Scopel, E., Simon, S., Tchamitchian, M., Toffolini, Q., van der Werf, H., 2023. Key research challenges to supporting farm transitions to agroecology in advanced economies. A review. Agron. Sustain. Dev. 43, 11. https://doi.org/10.1007/s13593-022-00855-8

Rigolot, C., Martin, G., Dedieu, B., 2019. Renforcer les capacités d'adaptation des systèmes d'élevage de ruminants: Cadres théoriques, leviers d'action et démarche d'accompagnement. INRA Prod. Anim. 32, 1–12. https://doi.org/10.20870/productions-animales.2019.32.1.2414

Robert, M., Thomas, A., Bergez, J.-E., 2016. Processes of adaptation in farm decision-making models. A review. Agron. Sustain. Dev. 36, 64. https://doi.org/10.1007/s13593-016-0402-x

Roblin, C., Bouvard, F., 2017. Références Technico-Économiques 2017 en agriculture biologique. Région Sud Provence Alpes Côte d'Azur.

Rodriguez, D., Cox, H., deVoil, P., Power, B., 2014. A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agric. Syst. 126, 50–61. https://doi.org/10.1016/j.agsy.2013.04.003

Rosenbloom, D., 2017. Pathways: An emerging concept for the theory and governance of low-carbon transitions. Glob. Environ. Change 43, 37–50. https://doi.org/10.1016/j.gloenvcha.2016.12.011

Ryschawy, J., Joannon, A., Choisis, J.P., Gibon, A., Le Gal, P.Y., 2014. Participative assessment of innovative technical scenarios for enhancing sustainability of French mixed crop-livestock farms. Agric. Syst. 129, 1–8. https://doi.org/10.1016/j.agsy.2014.05.004

Sabatier, R., Joly, F., Hubert, B., 2017. Assessing both ecological and engineering resilience of a steppe agroecosystem using the viability theory. Agric. Syst. 157, 146–156. https://doi.org/10.1016/j.agsy.2017.07.009

Sabatier, R., Mouysset, L., 2018. A robustness-based viewpoint on the production-ecology trade-off in agroecosystems. Agric. Syst. 167, 1–9. https://doi.org/10.1016/j.agsy.2018.08.001

Sabatier, R., Oates, L.G., Jackson, R.D., 2015. Management flexibility of a grassland agroecosystem: A modeling approach based on viability theory. Agric. Syst. 139, 76–81. https://doi.org/10.1016/j.agsy.2015.06.008

Sempore, A.W., Andrieu, N., Nacro, H.B., Sedogo, M.P., Le Gal, P.-Y., 2015. Relevancy and role of whole-farm models in supporting smallholder farmers in planning their agricultural season. Environ. Model. Softw. 68, 147–155. https://doi.org/10.1016/j.envsoft.2015.02.015

Sollen-Norrlin, M., Ghaley, B.B., Rintoul, N.L.J., 2020. Agroforestry Benefits and Challenges for Adoption in Europe and Beyond. Sustainability 12, 7001. https://doi.org/10.3390/su12177001

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agron. Sustain. Dev. 34, 1–20. https://doi.org/10.1007/s13593-013-0180-7

Žibert, M., Prevolšek, B., Pažek, K., Rozman, Č., Škraba, A., 2022. Developing a diversification strategy of non-agricultural activities on farms using system dynamics modelling: a case study of Slovenia. Kybernetes 51, 33–56. https://doi.org/10.1108/K-04-2021-0254

APPENDIX (Supplementary data)

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

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

Appendix B. Source code.