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A robustness-based viewpoint on the production-ecology trade-off in agroecosystems

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ABSTRACT

The intrinsic variability of the ecological functions underlying agroecological farming systems calls for a discussion on their robustness, i.e. their ability to maintain their performances in spite of environmental uncertainties. In this study, we apply the mathematical framework of the viability theory to assess three dimensions of robustness in relation with the production and ecological objectives in three contrasted case studies. Our results first show that robustness towards production and ecological constraints follows similar patterns across case-studies. We moreover show that robustness does not conflict with the production-ecological trade-off for the 3 case studies. From the management standpoint, this means that including the robustness criterion in the analysis helps reducing the set of possible options while ensuring the highest probability of success of the management scenarios chosen.

1. Introduction

Over the past decades, agriculture has been deeply transformed and modernized all over the world, including in developed and developing countries. The development of this post-WWII model of agriculture mainly aimed to increase food production so as to reach food security. This model of farming followed a paradigm of control in which the massive use of inputs made it possible to overcome environmental constraints and compensate for environmental variability. However, this model of farming led to many environmental impacts (e.g. Kleijn et al., 2001; Foley et al., 2005; Pe'er et al., 2014). A consensus now exists to look for alternative forms of farming ensuring both high levels of production and low environmental impacts (Bommarco et al., 2013).

In this perspective, many debates about the relationship between agricultural production and ecological conditions have emerged in the literature (Green, 2005; Vandermeer and Perfecto, 2005). These studies generally focus on the synergies or trade-offs between the two objectives and their underlying drivers. Although a synergy between production and the ecological dimension may occur in several ecological forms of agriculture (Altieri, 1995), a consensus seems to emerge towards negative relationships in more conventional systems (e.g. Polasky et al., 2008; Drechsler et al., 2007; Barraquand and Martinet, 2011; Mouysset et al., 2015; Sabatier et al., 2015a). In this context, the question of optimal trading between two objectives, or more technically how to identify the set of pareto-optimal solutions, has become the main question (Groot et al., 2010).

It is interesting to notice that these trade-offs are mainly established with a deterministic point of view on the system considered (e.g. Drechsler et al., 2007; Polasky et al., 2008; Barraquand and Martinet, 2011; Mouysset et al., 2015). Such a deterministic point of view is however not suited to the analysis of new forms of agriculture in which ecological processes are brought back to the heart of the production dynamics. In such systems, uncertainty associated with ecological dynamics cannot be neglected and properties such as resilience, adaptivity and robustness are as important as mean expected productivity (Urruty et al., 2016). In other words, developing an eco-friendly form of agriculture implicitly opens the challenge of its ability to deal with uncertain events.

A key property to assess the ability of a system to deal with uncertainty is its robustness. Robustness has been defined as 'the ability to maintain performance in the face of perturbation and uncertainty' (Stelling et al., 2004). However, robustness is very difficult to measure in real systems since it would require a reproduction of a system's dynamics, all other things being equal, with and without a perturbation. In this context, estimating such a key property of agricultural systems calls for modeling approaches able to simulate the potential evolutions followed by the system considered under different conditions, especially facing a range of perturbations.

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Recent developments of the mathematical framework of the viability theory (Aubin, 1991; Aubin et al., 2011) provide powerful tools to answer this question of robustness of dynamic systems such as agroecosystems (Calabrese et al., 2011; Accatino et al., 2014; Sabatier et al., 2015b; Mouysset et al., 2014). In these approaches, robustness is interpreted as the ability of a system to respect a set of constraints through time. In ecologized agroecosystems, these constraints should account for both agricultural production and ecological performance. On the one hand, these studies that generally highlighted a trade-off between robustness and agricultural production did not look how this production-robustness trade-off interacted with the ecology-production trade-off mentioned above. On the other hand, the few studies that looked for Pareto optimal solutions within the framework of the viability theory, either theoretically (Guigue, 2014) or on application cases (Mesmoudi et al., 2010; Sabatier et al., 2010) did not address the question of the robustness of the system.

In this paper, we investigate the relationship between production and ecological performances in an uncertain context. More specifically, (i) we assess the effects of ecological and agricultural constraints on the robustness of the agroecosystem and (ii) we evaluate how introducing the robustness dimension into the production-ecology analysis modifies the conclusions on the production-ecological trade-off emerging from a deterministic analysis. After presenting the mathematical framework of the viability theory and the way it inspired us to model agroecosystem dynamics and to compute their performances (ecological performance, agricultural performance and robustness), we present three contrasted applications of this framework to the modeling of agroecosystems at different scales and in different environmental contexts.

2. Material and methods

2.1. A viability-based modeling of agroecosystems in a context of uncertainty

Viability theory is a mathematical framework developed by Aubin (1991) that has proved to be particularly relevant for studying the management of natural resources (De Lara and Doyen, 2008). In the past decade and as reviewed by (Oubraham and Zaccour, 2018) it has been widely applied to the modeling of agroecosystems (e.g. Tichit et al., 2004, 2007; Baumgärtner and Quaas, 2010; Barraquand and Martinet, 2011; Accatino et al., 2014; Sabatier et al., 2010, 2013a, 2015a, 2015b; Bates et al., 2018).

This framework aims at identifying the set of so-called viable management strategies, i.e. the management options that make it possible to maintain the system within a set of constraints through time. In other words, the viability approach aims at identifying desirable combinations of states and controls that ensure the 'good health' of the system. The controls are the management strategies implemented within the agrosystems while the states can be interpreted as the ecological and agricultural descriptors of the system. Constraints are the condition that the system should respect over time. There are two main ways of considering uncertainty within the framework of the viability theory: either the system should remain viable whatever the perturbation (tychastic, guaranteed or robust viability, Aubin et al., 2011, or Bates et al., 2018 for an agronomic example) or the constraints have to be satisfied in the probabilistic sense (stochastic viability or strong sustainability Doyen and De Lara, 2010; Baumgärtner and Quaas, 2010). In a stochastic perspective, it is possible to assess a robustness criterion, defined for a given state-control combination as the probability of satisfying the set of constraints in a situation of uncertainty. Notice that following such a stochastic view of uncertainty, we limit our study to situations in which probabilities are computable.

Applied to agroecosystems (Fig. 1 a), the states are the descriptors of the farming system that evolve through time (e.g. grass biomass in a given field) and the controls are descriptors of the management of this system (e.g. cattle density in a given field). Controls interact with the dynamics of the system and define the temporal sequence of states (e.g. evolution of grass biomass through time). These states are generally interpreted in terms of performances through aggregated indicators that reflect specific dimensions of the system (e.g. amount of biomass harvested or habitat quality for patrimonial biodiversity). These indicators are used to define sustainability constraints that characterize the minimal level of performance that the system should reach on the different dimensions of the system. Regarding the temporal aspects of the models, we follow a discrete and finite time approach which is coherent with the modeling of farming activities. Farmers indeed generally conduct a periodic monitoring of their systems resulting in a discrete management.

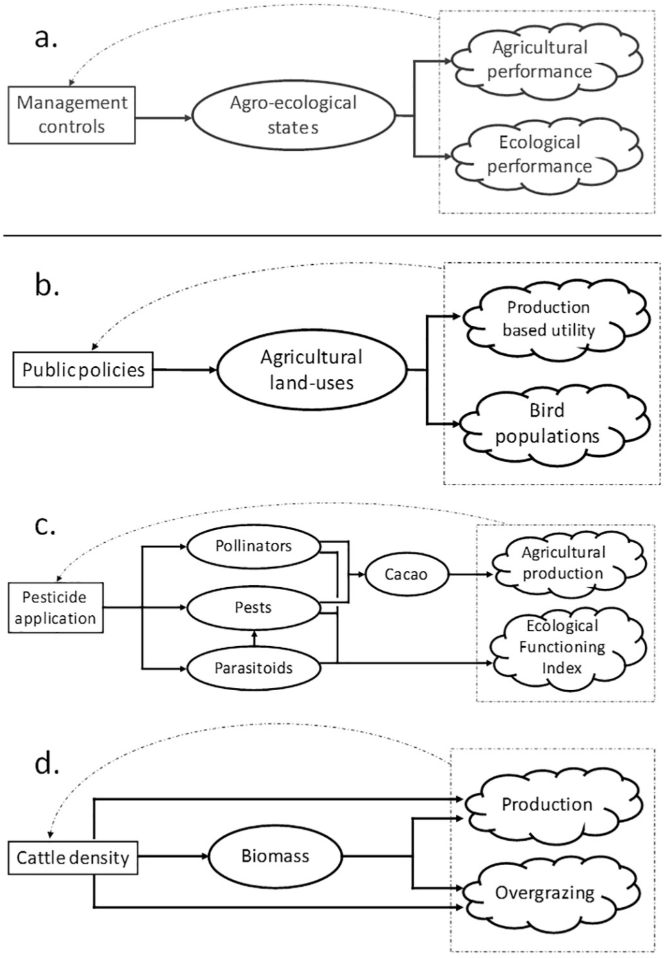

Fig. 1. Conceptuel model of agroecosystem within the viability framework (a) and application to three case studies: (b) public policies in France, (c) Cacao agroecosystem in Sulawesi (Indonesia), (d) Grazed grassland in Wisconsin (USA).

Formally, for a given system characterized by a series of states X, controls U, uncertainty ω and a dynamics f defined as follows:

$$X(t+1) = f(X(.), U(t), \omega(t)) \tag{1}$$

Following (Sabatier et al., 2012; Rougé et al., 2015), we define management scenarios and trajectories as follows. A management scenario $[X(0), U(.)]$ is defined as a temporal sequence of $U(t)$ for $t \in [0,T]$, where T is the time horizon, associated with an initial condition $X(0)$. A trajectory $[X(0), U(.), \omega(.)]$ is defined as a temporal sequence of $X(t)$, $U(t)$, $\omega(t)$ starting from X(0). It corresponds to a stochastic realization of a management strategy, with $\omega(t)$ following a probability distribution.

Once the system and its dynamics are defined, we can assess both its performances (functions of its states and controls that are specific to each case study) and robustness. Robustness of a management scenario is defined as the probability to respect the set of constraints through time.

Following (Rougé et al., 2015; Accatino et al., 2014) who propose an adaptation of the robustness index developed by (Alvarez and Martin, 2011) to the situations where uncertainty occurs as a perturbation of the dynamics rather than a direct perturbation of the state, robustness of a management scenario is defined as the probability to respect the set of constraints through time. Robustness of a management strategy is the percentage of the stochastic environmental conditions for which the system respects the viability constraints. It is defined as follows:

$$R_{XU\omega}([X(.),U(.),\omega(.)]) = \prod_{t\in[0,T]} R_{XU}([X(t),U(t)]) \tag{2}$$

With $R_{XUt}([X(t), U(t)])$ the robustness of a state control combination at time t:

$$R_{XUt}([X(t),U(t)]) = \int_{-\infty}^{+\infty} f_\omega(\omega(t)) V_{XU\omega}(X(t),U(t),\omega(t)) \mathrm{d}\omega(t) \tag{3}$$

with $f_\omega(\omega(t))$ the density function of $\omega(t)$ and $V_{XU\omega}(X(t), U(t), \omega(t))$ the viability metric associated with a given combination of state, control and stochastic realization:

$$V_{XU\omega}(X(t),U(t),\omega(t)) = \mathbb{1}_{\{[X(t),U(t)]\in K(t)\}} \tag{4}$$

where $K(t)$ is the domain of constraints of the system at time t and $\mathbb{1}_{\{[X(t),U(t)]\in K(t)\}}$ is the characteristic function associated with the event $\{[X(t), U(t)] \in K(t)\}$ that takes the value 1 if $[X(t), U(t)] \in K(t)$ and 0 if $[X(t), U(t)] \notin K(t)$. black.

In this sense, our work is strongly inspired by the viability theory approach although it does not require computing Viability Kernels nor other complex viability theory related objects.

2.2. Application to three case studies

This modeling framework is applied to three contrasted case studies (Table 1) illustrating a diversity of scales (from field to national scale), environmental contexts (temperate European agroecosystems, Northern American, and SE Asia tropical ones) as well as a diversity of relationships between the ecological and the production dynamics of the system (synergy, antagonism or a combination of both). In the three following sections, we give a brief presentation of the three models, full details are available in Appendix A, B and C and in the below mentionned publications.

2.2.1. Case 1: Eco-friendly public policies for French agroecosystems

The first case study corresponds to a model of public policies applied to the French agriculture sector at the national scale. Mouysset et al. (2014) have developed a bio-economic spatially-explicit model that articulates bird community dynamics and representative farmers selecting land uses according to public policy incentives in an uncertain context. According to national scenarios based on subsidies or taxes dedicated to different land-uses, the regional farmers optimize their activities taking into account the expected mean income and the associated risk. These land uses generate an income, but also a habitat quality which impact the bird population dynamics in the regions. The bio-economic model thus provides for each region the evolutions of land uses and their consequences in terms of economic and ecological indicators in response to different public policies scenarios (Fig. 1). In other words, the land-uses chosen by the farmers constitute the state variables and are affected by the public incentives which are the control variables (see Table 1). Controls are defined at the national scale and bioeconomic dynamics are defined and calibrated at the regional scale for all regions. The system presents an antagonism between economic and environmental dimensions especially through the trade-off between croplands generating high income for low biodiversity and grasslands generating lower income for high biodiversity (Mouysset et al., 2015).

More formally, the model can be written as follows at the region level:

$$\begin{cases} B_s(t+1) &= f^{(1)}(B_s(t), LU(t), \omega_1(t+1)) \\ LU(t+1) &= f^{(2)}(LU(t), u(t+1), \omega_2(t+1)) \end{cases} \tag{5}$$

where the population B_s of a bird species s at time $t + 1$ depends on the respective population the year before $B_s(t)$ and on the land uses chosen by the farmers $LU(t + 1)$ within an ecologically uncertain context. Farmers determine their land use distribution in order to maximize their profit. Production-based utility function is a function of the land use distribution $LU(t)$, the public subsidies or taxes on the different land uses $u(t + 1)$ and uncertainty of rents $\omega_2(t + 1)$. This bio-economic model is calibrated for each region through national databases. More details are available in Mouysset et al. (2014) and Appendix A.

The viability analysis accounts for constraints on both ecological and economic dimensions reflecting sustainability objectives. The economic constraint corresponds to a minimum threshold on the cumulative profit emerging from the land-use distributions and the ecological constraint corresponds to a minimum threshold on Farmland Bird Indicator computed with the populations of birds. These thresholds were set to 93% of the performances obtained with a Statu Quo scenario which corresponds to the ongoing situation. Uncertainty is integrated in the model through ω_1 and ω_2, multiplicative coefficients of the gross margins and growth rate of ecological populations. ω_1 and ω_2 follow normal distributions calibrated to reflect the variability of data:

$$\omega_1 \sim \mathcal{N}(1, \sigma_1^2). \tag{6}$$

$$\omega_2 \sim \mathcal{N}(1, \sigma_2^2). \tag{7}$$

with σ_1 and σ_2 being calibrated for each region so that sigma reflect the observed variance at the regional scale.

Full details on the equations underlying the model can be found in

Table 1
Summary of the case studies.

Case study	Sulawesi (Indonesia)	Wisconsin (USA)	France
System	Cacao agroforestry	Grazed grassland	National public policy
Climatic context	Tropical	Temperate	Temperate
Scale	Field	Field	Country
Ecology-production relationship	Synergy and antagonism	Synergy	Antagonism
State variables	Insect population sizes Cacao pods	Grass biomass Cumulated production	Land-use areas
Control variables	Pesticide spraying	Cattle density	Public incentives on crops and grasslands
Stochasticity	Insect population growth rates Cacao pod production Effects of pesticides	Grass growth rate	Gross margins Bird populations
Constraints	Yield Ecological functionning index	Cumulated production Overgrazing	Production-based utility Bird functional indicators

(Appendix A, Mouysset et al., 2014, 2015). A sensitivity analysis on the standard deviation of these normal distributions is conducted in Appendix D.

2.2.2. Case 2: Indonesian cacao agroecosystem

The second case study (Sabatier et al., 2013a) develops a model of a Cacao agroecosystem in central Sulawesi (Indonesia). It is a discrete time model with a time step of one month and a time horizon of 20 years ($T = 240$ months). It links the dynamics of cacao production to the main above-ground ecosystem services and disservices associated with cacao production, namely pollination, pest damage and control of the pest population by parasitism (Fig. 1). It therefore represents the Cacao pod dynamics and the population dynamics of a pest species (the Cacao Pod Borer, *Conopomorpha cramerella*) and two characteristic but unspecified beneficial insect populations (a pollinator of Cacao and a parasitoid of the Cacao Pod Borer). The Cacao Pod Borer and parasitoid parts of the model were inspired by both the Cacao model of Day Day (1985) and the more general Nicholson and Bailey host-parasitoid model (Hassel, 1978). Besides ecological dynamics, the model includes the effects of its management through pesticide spraying. At each time step, the farmer may take the decision to spray or not. Pesticide spraying involves mortality on the three insects that differ according to pesticide selectivity and efficiency. The system presents both an antagonism and a synergy between production and the ecological dimension. Production is indeed impacted positively by polination and pest control by parasitoids but negatively impacted by the pest. As a result, a high level of ecosystem functioning has both positive and negative effects on production (Sabatier et al., 2013a).

Formally, the model can be written as follows:

$$\begin{cases} N_{Pods_0}(t+1) &= f^{(1)}(N_{Pol}(t), t, \omega_1(t)) \\ N_{CPB}(t+1) &= f^{(2)}(N_{CPB}(t), N_{Par}(t), N_{Pods}(t-3), \mathbb{1}_{Spray}(t)),\ \omega_2(t)) \\ N_{Par}(t+1) &= f^{(3)}(N_{CPB}(t), N_{Par}(t), \mathbb{1}_{Spray}(t)),\ \omega_3(t)) \\ N_{Pol}(t+1) &= f^{(4)}(N_{Pol}(t), \mathbb{1}_{Spray}(t), \omega_4(t)) \\ Y(t+1) &= f^{(5)}(N_{CPB}(t-1), N_{Pods_0}(t-4)) \end{cases} \tag{8}$$

with $N_{Pods_0}(t)$ the number of pods of age 0 at time t, $N_{CPB}(t)$the size of the Cacao Pod Borer population, $N_{Par}(t)$ the size of the parasitoid population, $N_{Pol}(t)$ the size of the pollinator population, $Y(t)$ the Cacao yield at time t, $\mathbb{1}_{Spray}(t)$ the characteristic function related to the spraying event that takes the value 1 if spraying occurs and 0 if it doesn't and ω_i a parameter reflecting stochasticity of the different parameters. The production performance is assessed through yield and the ecological dimension is assessed through an Ecological Functioning Index. This index is the sum of the pollination rate, the parasitism rate and the cacao infestation rate. It therefore accounts for all ecological processes at stake, regardless of their positive or negative effects on production.

The viability analysis accounts for constraints on both ecological and production dimensions reflecting sustainability objectives. The production constraint corresponds to a threshold on the cumulative yearly yield and the ecological constraint corresponds to a threshold on the Ecological Functioning Index. These thresholds were set to 1.4 on the EFI index (the mean of the possible values of EFI, meaning that the intensity of ecological processes is asked to be better than average Sabatier et al., 2013b) and to 550 $kg.ha^{-1}.year^{-1}$ for cacao production (half way between expected production without pesticide and maximal production Sabatier et al., 2013a). The model reflects uncertainty on ecological dynamics as well as on the effects of pesticide spraying. More precisely, growth rates of the three insects, base production of cacao pods and insect mortalities due to pesticide are multiplied by random coefficients ω_1, ω_2, ω_3, ω_4. These ω_{1-4} follow normal distributions:

$$\omega_{1-4} \sim \mathcal{N}(1, 0.1^2). \tag{9}$$

Due to the lack of sufficient data, these normal distributions were not calibrated on data but a sensitivity analysis on the standard deviation of these distributions is conducted in Appendix D.

Full details on the equations underlying the model as well as on parameter values and sensitivity analyses can be found in (Appendix B, Sabatier et al., 2013a, 2013b).

2.2.3. Case 3: Wisconsin grassland agroecosystem

The third case study develops a model of a grazed grassland agroecosystem in Wisconsin (USA). It is a discrete time model with a time step of one day and a time horizon of one grazing season. It represents the dynamics of a grass cover interacting with cattle grazing (Fig. 1). Grass growth dynamics is modeled with a logistic curve following Voisin (1988). Grazing is characterized by grazing dates and cattle densities.

Formally, the model can be written as follows:

$$\begin{cases} B(t+1) &= f(B(t), t, u(t), \omega(t)) \\ P(t+1) &= P(t) + u(t) \end{cases} \tag{10}$$

with $B(t)$ the grass biomass at time t, $u(t)$ the cattle density at time t, $P(t)$ the cumulative number of grazing days and ω a parameter reflecting stochasticity on grass growth. The production performance is assessed through the cumulative number of grazing days $P(t)$ and the ecological dimension is assessed through the number of days for which the management strategy leads to overgrazing; in other words, the number of days for which the biomass required to feed $u(t)$ livestock units is higher than the available biomass $B(t)$. The system presents a synergy between production and the ecological dimension. Overgrazing indeed has a strong negative effect on production and strategies maximizing production are the ones that avoid overgrazing (Sabatier et al., 2015a).

The viability analysis accounts for constraints on both ecological and production dimensions reflecting sustainability objectives. The production constraint corresponds to a threshold on the cumulative number of grazing days at the end of the year and the ecological constraint corresponds to a maximum threshold on the number of days with overgrazing. These thresholds were set to 5 days of overgrazing (i.e. animals are able to mobilize punctually their body reserve if feed is limited) and to 300 cumulative grazing days (which corresponds to a mean stocking density of 0.8 $LU.ha^{-1}.year^{-1}$, an acceptable level of production in such systems). The model reflects uncertainty on grass dynamics. More precisely, the growth rate of grass biomass is multiplied by a random coefficient ω. ω_1 follows a normal distributions that was calibrated to reflect the variability of data:

$$\omega \sim \mathcal{N}(1, 0.08^2). \tag{11}$$

A sensitivity analysis on the standard deviation of these distribution is conducted in Appendix D. Full details on the equations underlying the model as well as on parameter values and sensitivity analyses can be found in (Appendix C, Sabatier et al., 2015b, 2015c).

2.2.4. Simulations

For each case study, we selected a set of management strategies based on a systematic sampling on the control grids so as to ensure that the whole control space was sampled. Sampling details are given in Appendix A, B and C. For each management strategy, we computed the average production and ecological performance as well as the robustness of the system under different sets of constraints. Robustness of a management strategy (formally defined in Eq. (5)) is the percentage of the stochastic environmental conditions for which the system respects the viability constraints. For a matter of computational power, R is estimated on a sample of 100 stochastic realizations, which constituted a good trade-off between accuracy and computing time. So as to disentangle the effects of the different constraints, robustness was successively computed for three sets of constraints: (i) ecological and production constraints simultaneously to assess the agroecological

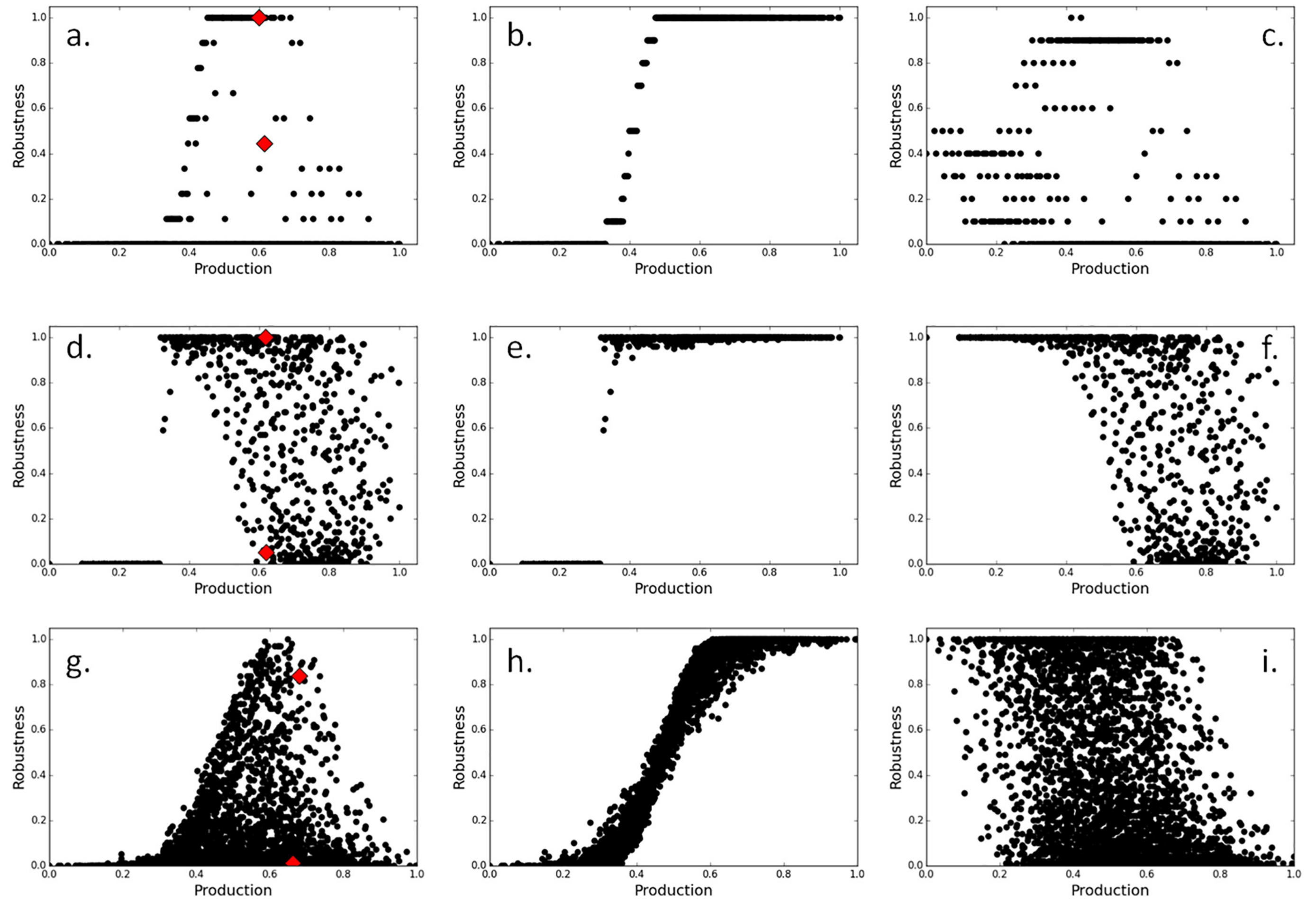

Fig. 2. Agroecological (a,d,g), agronomic (b,e,h) and ecological (c,f,i) robustnesses function of the mean level of production in an uncertain context for the three case studies: agroecosystem in France (a,b,c), agroecosystem in Wisconsin, USA (d,e,f), agroecosystem in Sulawesi, Indonesia (g,h,i). Red diamonds corresponds to strategies illustrated in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

robustness, (ii) production constraint only to analyze the agronomic robustness and (iii) ecological constraint only to evaluate the ecological robustness.

To ease the comparisons between the three case studies, all performance indices were normalized (so as to range from 0 to 1 with 0 the lowest performance and 1 the highest). Computations related to case study 1 were performed with Scilab, computations related to case studies 2 and 3 were performed with Python 2.7.2. Graphical outputs were performed with Python 2.7.2.

3. Results

3.1. The relationship between robustness and agricultural production

The nine graphs in Fig. 2 depict the agroecological, agronomic and ecological robustness as a function of the agricultural performances for the three different case studies. Each dot represents the agregated performances (mean for production and environment, Eq. (2) for robustness) over 100 replicates for one scenario of management. The x-projection stands for its mean production in a context of uncertainty, and the y-projection stands for its agroecological (agronomic, ecological resp.) robustness on the left column (mid column, right column resp.).

A first result is that whatever the type of robustness considered (i.e. for each column), we observe similar patterns for the 3 case studies. This is especially the case for agroecological robustness, i.e. considering both production and ecological constraint (Fig. 2 (a), (d), (g)). For the 3 case studies, we observe that the highest levels of robustness can be reached at intermediate levels of mean production. At this intermediate levels of production it is nevertheless not systematic to reach highest levels of robustness and many management scenarios show intermediate to low levels of robustness. The underlying drivers of these differences are extensiveluy detailled in (Sabatier et al., 2015b, 2015c; Mouysset et al., 2013, 2015; Sabatier et al., 2013a, 2013b) and we do not intend here to present this point in details but in an illustrative purpose Fig. 3 shows dynamics of states or controls illustrating how these different levels of robustness are characterized by contrasted management strategies. In case study 1, the level of subventions and taxes impacts how close the average ecological index can be from the constraint for strategies with good economic performances (Fig. 3a.). In case study 2, similar levels of production may be reached with continuous or rotational grazing for example (Fig. 3b.). Finally, in Case study 2 similar levels of production can be achieved with different pesticide spraying strategies (Fig. 3c.), which impacts the balance between pests and beneficial insects.

At both high and low levels of production it is no longer possible to reach the highest levels of robustness. This suggests that for the lowest levels of production, a synergy occurs between the agroecosystem robustness and the production: it is possible to identify management options that increase both the production level and the robustness. However for the highest levels of production, increasing production level necessarily leads to a decrease in agroecosystem robustness.

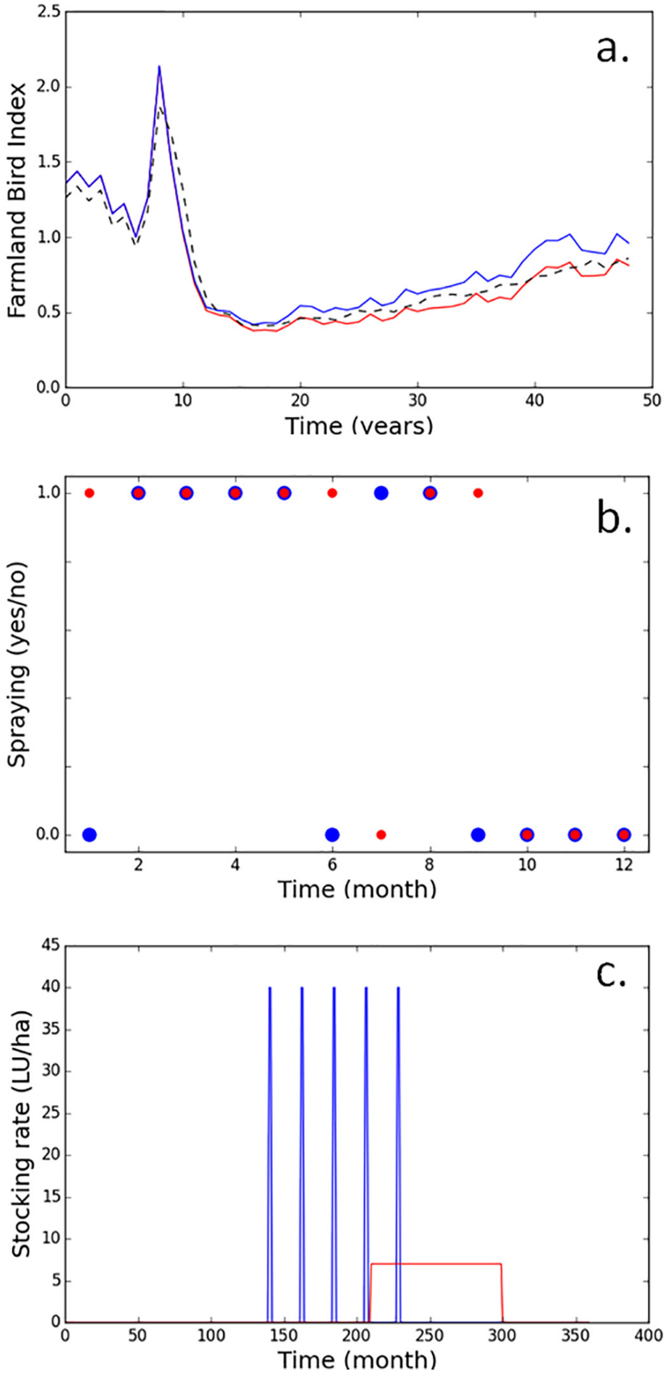

Fig. 3. Examples of dynamics of a robust (blue) and non robust (red) management startegy leading to the same level of average production in the three case studies: ecological dynamics in the France case study (a), Stocking density through time in the Wisconsin, USA, case study (b) and temporal sequence of spraying events in the Sulawesi, Indonesia, case study (c). The dashed line in figure a corresponds to the ecological viability constraint. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Impact of the production constraint

The second column of the Fig. 2 (graphs (b), (e), (h)) focuses on the analyze of the production constraint (and therefore the agronomic robustness). We observe that taking into account the agronomic risk affects mainly and strongly the scenarios leading to low levels of production: in most of the uncertainty situations, they fail to insure the production constraint, leading to small levels of robustness. This effect decreases when considering higher mean production scenarios. The strategies with the highest mean production performances are weakly affected by the agronomic risk: some of them keep a robustness equal to 1 meaning that whatever the uncertainty situations, they are able to satisfy the production goal. Some of them exhibit a robustness a bit smaller than 1, meaning that it exists few uncertainty situations where they are not able to satisfy the production goal. Moreover we observe that the agronomic risk affects similarly the scenarios with the same mean level of production: the difference in robustness within scenarios leading to the same levels of production (i.e. the same abscissa) remains low.

3.3. Impact of the ecological constraint

The third column of Fig. 2 (graphs (c), (f), (i)) focuses on the ecological constraint assessing thus the ecological robustness. The first observation compared to the previous column is that the ecological risk affects the robustness in an opposite way to the agro-economic risk: the impact is strongest for the scenarios with high mean production. A second observation is that the impact of the ecological risk on robustness is overall more heterogeneous than the impact of the production constraint, that is to say that there is more variability in robustness for a given level of production.

The ecological risk strongly affects the scenarios with the highest mean productions. Indeed these scenarios exhibit a sharp decrease in robustness when production level increases, meaning that at highest levels of production it is not possible to fulfill the ecological goal in most of the uncertainty situations. Considering the lowest levels of production, scenarios slightly differ between case studies. For case studies 2 (Wisconsin) and 3 (Sulawesi), the robustness of the scenarios with the lowest levels of production are not (or only slightly) affected. Some of them exhibit a reduced robustness but still close to 1. For case study 1 (France), robustness is always lower than 1 at lowest levels of production. This can be explained by the bioeconomic dynamics at stake in this model in which scenarios with the lowest levels of production lead to overall low ecological performance (see Mouysset et al., 2014, for details). Another difference with the agronomic risk is the fact that the robustness is highly variable among scenarios with the same level of mean production (i.e. the same abscissa), especially for the intermediate levels of production.

3.4. Production-ecology trade-off

To investigate the production-ecology trade-off, we plotted (Fig. 4) the mean production of each scenario against its mean ecological performance. The colour of the dots stands for the agroecosystem robustness (the darker, the higher). Finally the dashed red lines stands for the production-ecology Pareto-frontier with an highlight on solid line when the robustness is close to 1 (dark dots). Fig. 5 provides a 3D point of view of the same dataset that illustrates how the most robust strategies are observed in situations with high levels of production and ecological performances.

The three case-studies show different relationships between production and ecology. In the France case study, it is not possible to maximize both ecological and production dimensions of the system at the same time. In other words, a trade-off characterized by a decreasing Pareto-frontier (Fig. 4 a) occurs between the two dimensions. A similar trade-off is observed in the Sulawesi case-study (Fig. 4 c). A consequence of this decreasing relationship is that many scenarios (the ones on the frontier) are considered as Pareto-equivalent and it is impossible to rank them without any additional criteria. Adding the robustness dimension to the analysis helps shrinking the set of Pareto equivalent solutions. Indeed, not all situations on the frontier show the same level of robustness and we can identify a subset of the Pareto-optimal situations for which robustness is maximal (R = 1, continuous

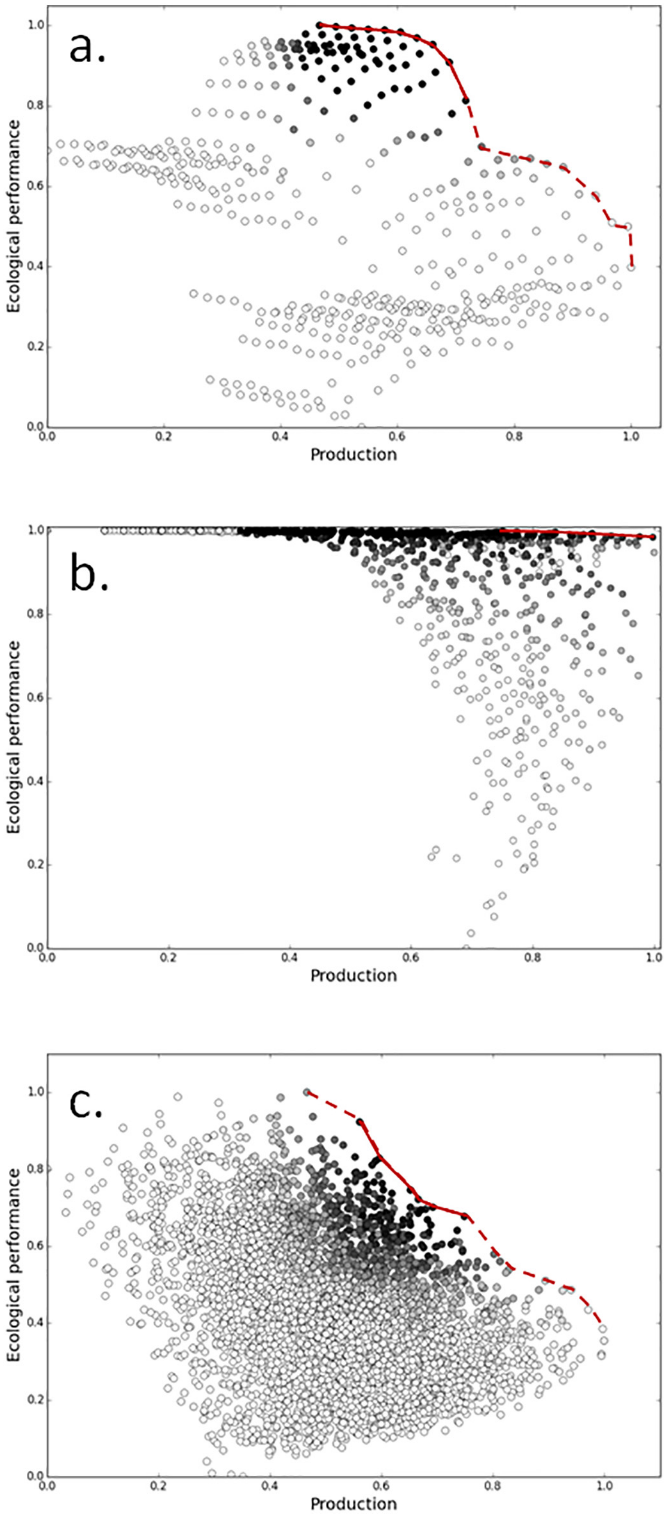

Fig. 4. Relationship between production and ecological performances for the three case studies: (a) agroecosystem in France, (b) agroecosystem in Wisconsin, USA, (c) agroecosystem in Sulawesi, Indonesia. Colour of the dots stand for the agroecosystem robustness (R) of the management strategy (black for $R = 1$, white for $R = 0$). The red lines stand for the Pareto-frontier, the dashed section of the frontier is the section of the frontier for which $R < 1$ and the continuous section is the section for which $R = 1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

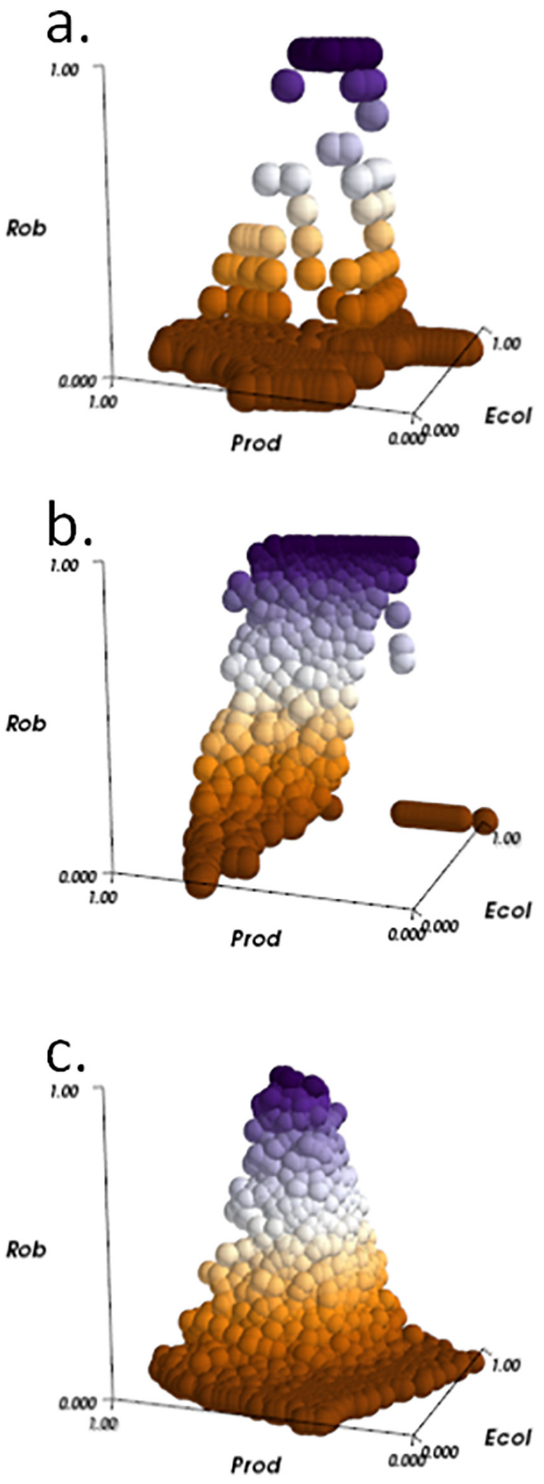

Fig. 5. 3D representation of the relationship between production, ecological performance and agroecological robustness for the three case studies: (a) agroecosystem in France, (b) agroecosystem in Wisconsin, USA, (c) agroecosystem in Sulawesi, Indonesia. Colour of the dots stand for the agroecosystem robustness (R) of the management strategy (blue for R = 1, brown for R = 0). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

red line in Fig. 4). Moving away from this subsection of the frontier, either on the production dimension or on the ecological dimension leads to a decrease in robustness (Fig. 5 a and c). Particularly striking is the case study of the cacao agroecosystem in Sulawesi in which the 3D representation of the relationship shows a sharp peak pointing towards highest levels of production and ecological performance (Fig. 5 c).

The Wisconsin case-study however shows a different production-ecological pattern. In this case study, where the ecological dimension (lack of overgrazing) is closely positively linked to the production dimension, the trade-off between production and ecology is very limited and maximum levels of production lead to almost highest levels of ecological performance (although there is no reciprocity). In this third case-study, although there is a little trade-off between production and ecology, introducing the robustness criterion in the analysis confirms the high interest of the win-win solutions. In this third case study, robustness remains high close to the win-win solutions whatever the production performance but rapidly decreases on the ecological dimension (Fig. 5 b).

4. Discussion

The relationship between production and ecological performances has broadly been investigated in the literature in a deterministic context (Green, 2005; Polasky et al., 2008; Groot et al., 2010; Sabatier et al., 2015a). In this article we aimed at interpreting this relationship in an uncertain context. To do so, we compared several case studies analyzed with the mathematical framework of the viability theory (Aubin, 1991; Aubin et al., 2011). One of the main advantages of this framework is that it makes it possible to extend the concept of equilibrium state to dynamic controlled systems (Saint-Pierre, 1995). This viability approach is particularly suited for the analysis of controlled dynamic systems facing an uncertain environment. With this approach, robustness is interpreted as the ability of a system to stay viable through time despite a stochastic context (Accatino et al., 2014; Sabatier et al., 2015b).

By combining production and ecological constraints, the viability framework moreover fits the multi-criteria perspective required to investigate the production-ecology relationship. Several studies already applied the viability framework to such multi-criteria analyses, generally by jointly assessing production or economic dimension and environmental ones (Barraquand and Martinet, 2011; Mouysset et al., 2015; Sabatier et al., 2010) but only in a deterministic context and our study is, to our knowledge, the first one to study the three dimensional trade-off between production, environment and robustness in agroecosystems.

The main result of this analysis is that high levels of robustness can be achieved by management scenarios that are Pareto optimal regarding production and environment. This conclusion may seem counter-intuitive at first sight since adding a new dimension to a multiperformance analysis of agroecosystems generally involves a new trade-off (e.g. Groot et al., 2010). In other words one may expect that looking for a high level of robustness would lead to be suboptimal regarding the production and ecological performances. However, our 3 case studies (although very contrasted in nature) show that it is possible to be Pareto-optimal while being robust at the same time. This means that shifting from a deterministic representation of the system to a stochastic one does not make the trade-off three-dimensional but rather reduces the set of Pareto-equivalent solutions on the two dimensional production-ecology trade-off.

In a management perspective, our results mean that not all solutions on the production-ecology Pareto frontier are equivalent and that including the robustness criterion helps reducing the set of possible options while ensuring the highest probability of success of the management scenarios chosen. We can also notice that management scenarios leading to the highest levels of robustness are all located on (or close to) the frontier of Pareto-optimal situations. In other words it is necessary (although not sufficient) to be close to the frontier to reach high levels of robustness. But it is not necessary to be on this frontier to show a robustness of $R = 1$. This means that the situations slightly bellow the frontier (that is to say slightly sub-Pareto-optimal) remain robust. This observation is interesting in the perspective of management since it opens room for maneuver for land-planners.

This study focuses the analysis on the robustness of agroecosystems. Doing so, it only accounts for one of the ways agroecosystems may overcome environmental variability. Further developments of this work could consider analyzing other properties related to the ability of agroecosystems to deal with uncertainty such as ecological resilience (sensus Holling, 1996) or its ability to recover from a perturbation such as engineering resilience (sensus Holling, 1996). Recent developments of the viability theory provided methodological advances to assess these properties: flexibility (Sabatier et al., 2015a; Mathias et al., 2015), vulnerability (Rougé et al., 2015), or resilience (Martin, 2004; Martin et al., 2011; Rougé et al., 2013; Sabatier et al., 2017). Extension of our analysis within the same methodological framework would therefore make it possible to test whether all these properties show the same relationship with the production-ecology trade-off.

Finally, the study presented here, although based on three contrasted case studies, does not give a generic proof of the relationship between production, ecological dimension and robustness. It has indeed been showed with different approaches and on non agricultural case studies that optimal solutions of a multi objective environmental problem could significantly differ from the most robust ones (e.g. Kasprzyk et al., 2013, on water supply issues). The development of a simple generic model of interaction between production and ecological dynamics of an agroecosystem and its evaluation through a sensitivity analysis could be an option to evaluate the behavior of the system in a more systematic manner and understand to what extand our conclusion remain valid.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.08.001.

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