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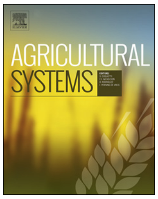

# A robustness-based viewpoint on the production-ecology trade-off in agroecosystems

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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.

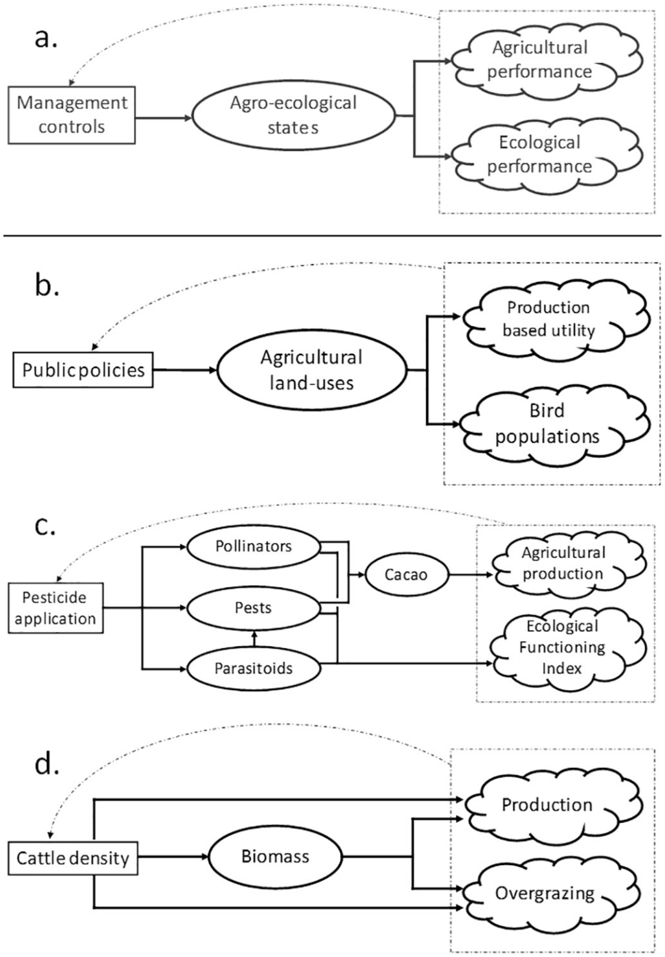

**Fig. 1.** Conceptuel model of agroecosystem within the viability framework (a) and application to three case studies: (b) public policies in France, (c) Cacao agroecosystem in Sulawesi (Indonesia), (d) Grazed grassland in Wisconsin (USA).

Formally, for a given system characterized by a series of states $X$, controls $U$, uncertainty $\omega$ 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