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REVIEW ARTICLE

Stability, robustness, vulnerability and resilience of agricultural systems. A review

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Abstract Global warming and price volatility are increasing uncertainty for the future of agriculture. Therefore, agricultural systems must be sustainable not only under average conditions, but also under extreme changes of productivity, economy, environment and social context. Here, we review four concepts: stability, robustness, vulnerability and resilience. Those concepts are commonly used but are sometimes difficult to distinguish due to the lack of clear boundaries. Here, we clarify the role of these concepts in addressing agronomic issues. Our main findings are as follows: (1) agricultural systems face different types of perturbations, from small and usual perturbations to extreme and unpredictable changes; (2) stability, robustness, vulnerability and resilience have been increasingly applied to analyze the agricultural context in order to predict the system response under changing conditions; (3) the four concepts are distinguished by the nature of the system components and by the type of perturbation studied; (4) assessment methods must be tested under contrasted situations; and (5) the major options allowing system adaptation under extreme and unpredictable changes are the increase of diversity and the increase of the adaptive capacity.

Keywords Perturbation · Agriculture · Stability · Robustness · Vulnerability · Resilience

Contents

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1 Introduction

Farming activities are regularly exposed to unpredictable perturbations, i.e. changes in environmental or socio-economic constraints which cannot be anticipated. Facing uncertainties, farmers have to deal not only with urgent and short-term tactical issues (e.g. protecting a crop from pests or taking advantage of sowing opportunities) but also with more strategic decisions driven by their medium- to long-term objectives (Rodriguez et al. 2011). In general, the predominant approach to mitigate the impacts of exogenous changes on cropping and livestock systems is based on controlling environmental conditions (ten Napel et al. 2006). Modern intensive farming, which relies heavily on pesticides, antibiotics, mineral fertilizers and irrigation in order to control system conditions, has proven to be a successful approach to maximize productivity per production unit and increase agricultural production in the world. The most illustrative example of this approach is greenhouse production where fruits and vegetables are grown in a highly standardized and controlled environment. Nevertheless, evidence of drawbacks of this approach is accumulating: despite a strong artificialization of agricultural landscapes and intensive use of chemical inputs, crops and livestock around the world are still exposed to various types of exogenous perturbations, such as outbreaks of infectious diseases in animal production and development of pest and pathogen resistances to pesticides in crop production. Moreover, negative environmental impacts of intensive farming systems are evident, such as air and water pollution and loss of biodiversity (Millennium Ecosystem Assessment 2005).

In recent years, social and political pressure for more sustainable agricultural systems showed up the need for implementing more sustainable production systems and led to the emergence of various methods and indicators to quantify the sustainability of farming activities. These methods generally include economic, environmental and societal pillars and are usually based on multicriteria approaches addressing these different issues (Bockstaller et al. 2009). However, these methods are generally focused on the assessment of average agricultural outputs (i.e. under conditions that are considered as "normal") and do not consider performance changes in time and space, particularly when exogenous perturbations occur. Thus, scientists and stakeholders are currently reconsidering agricultural system design in order to better take into account the variability of environmental conditions (Naylor 2008). As part of this new vision, changes and adaptations are recognized as essential elements: the ability to continue to achieve goals despite the occurrence of perturbations is becoming a central issue in the assessment of agricultural sustainability (Tendall et al. 2015). This concern is generally expressed through a paradigm shift, from maximizing average productivity in a stable environment towards reducing performance changes in an environment subject to greater variation (Milestad et al. 2012). However, this transition requires new knowledge and expertise to characterize and assess the ability of agricultural systems to maintain high levels of agricultural outputs in a non-stable environment (Fig. 1).

In the face of this challenge, different concepts such as stability, robustness, vulnerability and resilience have been developed in recent decades. Despite conceptualization from different discipline backgrounds, these four concepts all focus on the ability of diverse systems to maintain or recover their functionalities in a challenging environment. An increasing number of review articles illustrate the growing interest of scientists from different disciplines in these concepts (see, for example, Mumby et al. (2014) for a review of resilience, robustness and vulnerability applied to marine ecosystems; Gallopín (2006) for a review of vulnerability and resilience applied to socio-ecological systems; and Mens et al. (2011) for a review of robustness, resilience and vulnerability applied to flood risk management). These concepts have also been used in agricultural sciences, either as equivalent terms (National Research Council 2010) or as concepts to be combined for a more comprehensive and integrative approach (Callo-Concha and Ewert 2014). Due to fuzzy boundaries between these four concepts, we have noticed the difficulty for some scientists in agricultural sciences in defining them correctly and understanding their differences and potential uses. Furthermore, a clear analytical framework associated with each concept is still lacking and hence limits their usefulness to assess the ability of agricultural systems to cope with perturbations.

In the present paper, we aim to clarify the potential of stability, robustness, vulnerability and resilience as operational concepts to assess the ability of agricultural systems to deal with a context of increasing uncertainty. In the following sections, the paper will first introduce agricultural systems and their exposure to exogenous changes (Sect. 2). Then, we will review different strands of literature to define more clearly each concept and assess their differences and respective uses in agricultural sciences (Sect. 3). Based on recent papers, we will discuss operational methods available to characterize and quantify the ability of agricultural systems to cope with various types of perturbation (Sect. 4). Finally, the paper will outline some key levers to improve the ability of agricultural systems to deal with a more changeable environment (Sect. 5).

2 Agricultural systems facing a more changeable environment

In order to explore the position of each concept regarding the assessment of agricultural performance in a variable environment, we start by clarifying what agricultural systems are and what are their interactions with external drivers.

Fig. 1 Agricultural systems are facing multiple and unpredictable perturbations. The impact on a sunflower field of salted sea water flooding induced by Xynthia storm in 2010, in Rochefort area (France). Photo credit: INRA

2.1 Agricultural systems

Agricultural systems are socio-ecological systems, comprising biotechnical and social factors, and dedicated to the production of productive, economic, environmental and social outputs (Renting et al. 2009). On the one hand, biotechnical factors consist of biological and technical components linked through feedback mechanisms (ten Napel et al. 2011). Biological components comprise not only domesticated plant and animal species but also non-domesticated species like pests and pollinators of crops. Technical components consist of engineering elements designed to optimize agricultural outputs (e.g. irrigation system and decision support tools). On the other hand, social factors refer to farmers' actions and attitudes and in which may be considered separately the psychological make-up of the farmer and the characteristics of the farm household (Edwards-Jones 2006).

According to this basic conceptual scheme, the agricultural outputs of a farm are highly influenced by the interaction between the different components that constitute biotechnical and social factors. However, agricultural systems are also embedded in larger systems such as food, institutional or social systems. Hence, they are also influenced by external drivers which can be a source of unpredictable changes for farmers.

2.2 A more changeable environment

External drivers of agricultural systems encompass bio-geophysical, social, economic and political environments that determine how agricultural activities are performed. These drivers can vary significantly in time and space and therefore can affect agricultural systems positively or negatively. Depending on the frequency, duration and predictability of these changes, Maxwell (1986) distinguished four different types of perturbations that affect agricultural systems: noise when perturbations occur on a regular basis and are usually expected by farmers, shocks when perturbations are unusual and difficult to anticipate, cycles when the variation is due to cyclical changes, and trends when the change is gradual over time.

In terms of trends, global warming is expected to impact agricultural activities gradually in the future: by the end of the twenty-first century, temperature is projected to rise by 1.4 to 5.8 °C while atmospheric CO_2 concentration could reach three to four times the pre-industrial levels (IPCC 2014). In Europe, simulations of future climate have suggested an increase of average temperature and a slight decrease in rainfall (Trnka et al. 2011). Livestock systems may also be impacted by global warming, directly by the effects of heat on animal health, growth and reproduction and, indirectly, for herbivores, through impacts on the productivity of pastures and forage crops (Maracchi et al. 2005). Climate change is also expected to increase the risk of potential pest pressure in agriculture by providing more suitable environmental conditions for exotic pests to adapt across areas which were previously detrimental for their survival (Lamichhane et al. 2014). In this context of gradual changes, farmers and researchers can partly anticipate the impacts on agricultural activities through mitigation and adaptation programs (Olesen et al. 2011; Reidsma et al. 2010). For example, many research and implementation projects are currently dealing with adaptation strategies using local knowledge and low inputs for soil protection and water management in the context of climate change (Meynard et al. 2012).

Beyond average trends, agricultural systems are also exposed to less predictable perturbations, such as climatic or economic shocks. These perturbations, exhibiting various intensities and durations, can also heavily impact agricultural activities. For example, climate variability is considered to explain part of wheat yield stagnation in Europe since the middle of the 1990s (Brisson et al. 2010; Moore and Lobell 2014), while food price volatility has negatively impacted farmers' income stability in recent years (Huchet-Bourdon 2011). In addition to these individual perturbations, local issues may also interact with global economic issues and further increase overall perturbations. For example, due to the specificities of the world agricultural market (inelastic demand for agricultural products, high seasonality and relatively long production period coupled with a short shelf-life for many agricultural products), a severe climatic shock, such as drought on grain production in an exporting country, may have significant repercussions on international, national and local markets and, therefore, on food security and political stability on local and global scales (Sternberg 2012).

Furthermore, the relationship between agricultural systems and their external drivers requires that the intrinsic sensitivity of agricultural systems to exogenous perturbations be taken into account. For example, the impact of market volatility during the period 2007 to 2009 was particularly severe in Europe as the progressive change of CAP policies more directly exposed farmers to commodity price volatility (Enjolras et al. 2014). Moreover, there is also increasing evidence that the trend towards specialization and homogenization of genetic diversity across agricultural landscapes (Hoisington et al. 1999) is increasing the sensitivity of many agricultural systems around the world to various types of perturbation. In cropping systems, for example, genetic and crop uniformity over large areas tends to amplify pest invasions and outbreaks (Altieri and Nicholls 2004), while in animal husbandry, regional specialization of agricultural activities can increase sanitary risks by facilitating the spread of animal diseases Fèvre et al. (2006).

In this context and in order to get a better understanding of the overall context in which agricultural systems are implemented, researchers have developed and used several concepts that deal with the response of agricultural systems when facing perturbations. In the next section, we introduce these different concepts, their historical backgrounds and their main differences according to how the relationship between agricultural systems and perturbations is expounded.

3 Conceptual frameworks

We focus on four different concepts: stability, robustness, vulnerability and resilience. These four concepts are characterized by having a highly multidimensional nature and have been used in various papers related to agricultural systems. At first glance, they may appear to be linked by fuzzy boundaries and to be suitable in various contexts. Depending on authors, there is a call for more *stable* (Mishra and Sandretto 2002), more *robust* (ten Napel et al. 2006), less *vulnerable* (Schröter et al. 2005) or more *resilient* (Naylor 2008) agricultural systems and sometimes a combination of all of these (de Goede et al. 2013; Tendall et al. 2015).

In order to clarify the specificities of each concept and based upon the existing literature, we will present in this section their historical backgrounds and their main differences according to how they are used in papers related to agricultural systems. More precisely, each concept is discussed separately in order to highlight in which context it proved to be the most useful. As already pointed by Carpenter et al. (2001) concerning resilience, these multidimensional concepts acquire significance only if the studied object (the system and its boundaries), the type of output to be maintained and the nature of the perturbations are precisely defined. Thus, we will answer simple but essential questions when assessing each concept: *what kind of system is studied*, *what kind of output is targeted* and *against what kind of perturbation*?

Table 1 summarizes the main elements for each concept and includes some examples from agricultural sciences. It may help readers to choose the most suitable concept according to the nature of their research questions.

3.1 The concept of stability

The word stability originates from the Latin *stabilis*, meaning to stand firm or steady. It has been widely used in several scientific disciplines (mathematics, engineering, economic, social and natural sciences) to express the ability of an object to maintain equilibrium. In natural sciences, the concept of ecological stability was first defined as the constancy of a given attribute, regardless of the presence of disturbing factors (Justus 2008). For example, stable ecological communities were those with relatively constant population sizes and compositions (MacArthur 1955). Later, the definition of ecological stability has been expanded to describe other properties of ecosystems, such as the ability to maintain ecological functions despite disturbances (Turner et al. 1993) or the ability to return to the initial equilibrium state (Ives and Carpenter 2007). This led to multiple definitions and interpretations of stability (Grimm and Wissel 1997) and sometimes to the feeling that it is defined in many ways depending on how scientists wish to look at the problem (Lin et al. 1986).

In agricultural sciences, the concept of stability has been mainly used with the original meaning of ecological stability, i.e. as a criterion to measure the spatial or temporal constancy of specific features of agricultural systems (Fig. 2a). For example, the stability of genotypes has been widely used in plant breeding programs in order to identify genotypes that maintain specific features (e.g. yield or protein content in the grain) over a wide range of environments (Brancourt-Hulmel 1999; Sabaghnia et al. 2012). Based on genotype × environment interactions, two types of stability are sometimes distinguished: (i) static stability which refers to a genotype for which variance is small between different environments and (ii) dynamic stability which refers to a genotype for which the response to various environments is correlated to the mean response of all genotypes in the trial (Annicchiarico 2002). In other terms, the first type of stability focuses on constancy regardless of the variability in system environments whereas the second type of stability includes these environmental differences.

Even though analysis of yield stability has been largely confined to multienvironment trials for comparing spatial stability of crop cultivars, stability analysis has also been applied to compare the temporal stability of different agronomic treatments in long-term experiments. For example, Berzsenyi et al. (2000) and Govaerts et al. (2005) implemented stability analysis to evaluate the effect of diverse crop rotations, fertilization treatments or tillage management techniques on crop yield stability.

Table 1 Summary of the main differences between the concepts of stability, robustness, vulnerability and resilience

Concepts	Definition in agricultural context	Nature of the system studied What part of the system is studied?	Agricultural output To maintain what?	Perturbations Against what kind of perturbations?
Stability	Constancy of agricultural outputs over long periods of time or across various spatial environments	Biological components of agricultural systems	Individual features of biological components	Not explicitly defined
Examples	Brancourt-Hulmel (1999)	Wheat genotypes	Wheat yield	–
	Tilman et al. (2002)	Cereal crops	Agricultural production	–
	Govaerts et al. (2005)	Maize-wheat rotation (Mexico)	Maize and wheat yields	–
	Devictor and Jiguet (2007)	Farmland bird communities (France)	Farm biodiversity	–
Robustness	Ability to maintain desired levels of agricultural outputs despite the occurrence of perturbations	Biological and technical components of agricultural systems	Individual features of biological and technical components	Short-term and specified perturbations
Examples	Mosnier et al. (2009)	Livestock systems (France)	Farmers' income	Weather and price fluctuation
	Dourmad et al. (2010)	Pigs	Sow productivity	Multifactorial diseases
	ten Napel et al. (2011)	Pig production unit	Various features (pig mortality, quality of meat,…)	Short-term variation in costs of feed, water, medication and bedding material
	Sabatier et al. (2013)	Cacao agroecosystem (Indonesia)	Cacao productivity	Pest outbreak
Vulnerability	Degree to which agricultural systems are likely to be harmed due to perturbations	Biotechnical and social components of agricultural systems	Individual and integrated features of agricultural systems	Specified perturbations
Examples	Jalan and Ravallion (1999)	Households (China)	Household income	Risk-market failures
	Luers et al. (2003)	Farms in Yaqui Valley (Mexico)	Wheat yield	Drought
	Reidsma and Ewert (2008)	European farms	Regional wheat productivity	Climate variability
	Simelton et al. (2009)	Rice, wheat and corn production (China)	Provincial harvest production	Drought
Resilience	Ability to absorb change and to anticipate future perturbations through adaptive capacity	Biotechnical and social components of agricultural systems	Integrated features of agricultural systems	Specific perturbations to unpredictable changes
Examples	Darnhofer (2010)	Family farms (Austria)	Adaptability and transformability of the farms	Changes in the economic and political framework
	David et al. (2010)	Organic farms (France)	Flexibility of organic farms	Market fluctuations and regulatory changes
	Astigarraga and Ingrand (2011)	Limousin beef systems (France)	Flexibility to match different factors of uncertainty	Market variations and climatic fluctuations
	Rodriguez et al. (2011)	Farms in Australia	Farm profit	Climate change scenarios

Considering these first elements, it appears that the concept of concept has been applied in agricultural studies with a meaning relatively close to ecological constancy, i.e. as the stability of agricultural outputs in time or space but without explicitly referring to the external drivers of change and to the occurrence of perturbations. Moreover, the concept of stability has been mainly applied to individual components (e.g. genotypes) or outputs (e.g. yield or income) of agricultural systems rather than through a more integrated approach. Hence, it may show a low potential for describing and explaining the behaviour of complex agricultural systems in a context of unpredictable changes.

3.2 The concept of robustness

The word robustness comes from the Latin *robustus*, meaning strong. Widely used in statistics to refer to methods that are not affected by small deviations from model assumptions (Maronna et al. 2006), robustness also emerged in recent years as a major concept for analyzing the response of diverse objects facing perturbations. Industrialists and engineers first mobilized this concept in the early 1950s in order to optimize the manufacturing design of various devices and reduce their sensitivity to variation over which makers have little or no control (Taguchi and Clausing 1990). Subsequently, robustness theory was applied to various engineering processes, such as information networks, electronic circuits or flight control systems, in airplanes in order to make them capable of operating under a wide range of constraints (Fowlkes et al. 1995).

More recently, the concept of robustness has also been used by biologists to describe the ability of living systems to maintain specific functionalities despite unpredictable environmental or genetic perturbations (Kitano 2004). For example, biological robustness can be illustrated by the ability of genomes to compensate for the loss of function in one gene by means of other copies of this gene (Gu et al. 2003). Based on these observations from engineering and biological sciences, robustness has been described as an intrinsic property of complex adaptive systems (Carlson and Doyle 2002) and as an important trait for the species' capacity to evolve through natural selection (Wagner 2008).

Comprising both technical and biological domains, agricultural systems can also be defined as complex and adaptive systems. Hence, the robustness concept was recently introduced into agricultural sciences and has been used in an increasing number of scientific papers to represent the complex interactions between the biotechnical factors of agricultural systems and external drivers of change (de Goede et al. 2013; ten Napel et al. 2006; Verhagen et al. 2010). In these papers, robustness has been mainly defined as the ability to minimize the variability of specific agricultural outputs despite the occurrence of explicitly defined perturbations (Fig. 2b).

A large part of the literature recently devoted to this subject deals with robustness as a key breeding goal for animal farms (Knap 2005; Sauvant and Martin 2010; Star et al. 2008). The aim is to select animals that achieve a high production level in a wide diversity of environmental conditions, including stressful conditions. These stressors can be disease challenges, extreme temperatures, low-quality feed or challenges due to changes in housing or management (Merks et al. 2012). However, robustness has also been discussed in the context of cropping systems exposed to climatic or biotic perturbations. For example, Sabatier et al. (2013) compared the robustness of two contrasting types of management strategies for a cacao agroecosystem in Indonesia facing pest outbreaks and pesticide changes.

Applied to agricultural systems facing an environment subject to perturbations, two forms of robustness are frequently distinguished and sometimes called, respectively, passive and active robustness: (i) resistance, i.e. the withstanding or tolerance of perturbations, and (ii) flexibility, i.e. the ability to adapt the configuration of the system in order to limit damage (ten Napel et al. 2006). For example, robustness on a pig farm level can include genetic components of heat stress tolerance in pigs (passive robustness) and temperature control systems to adjust indoor conditions in real time (active robustness).

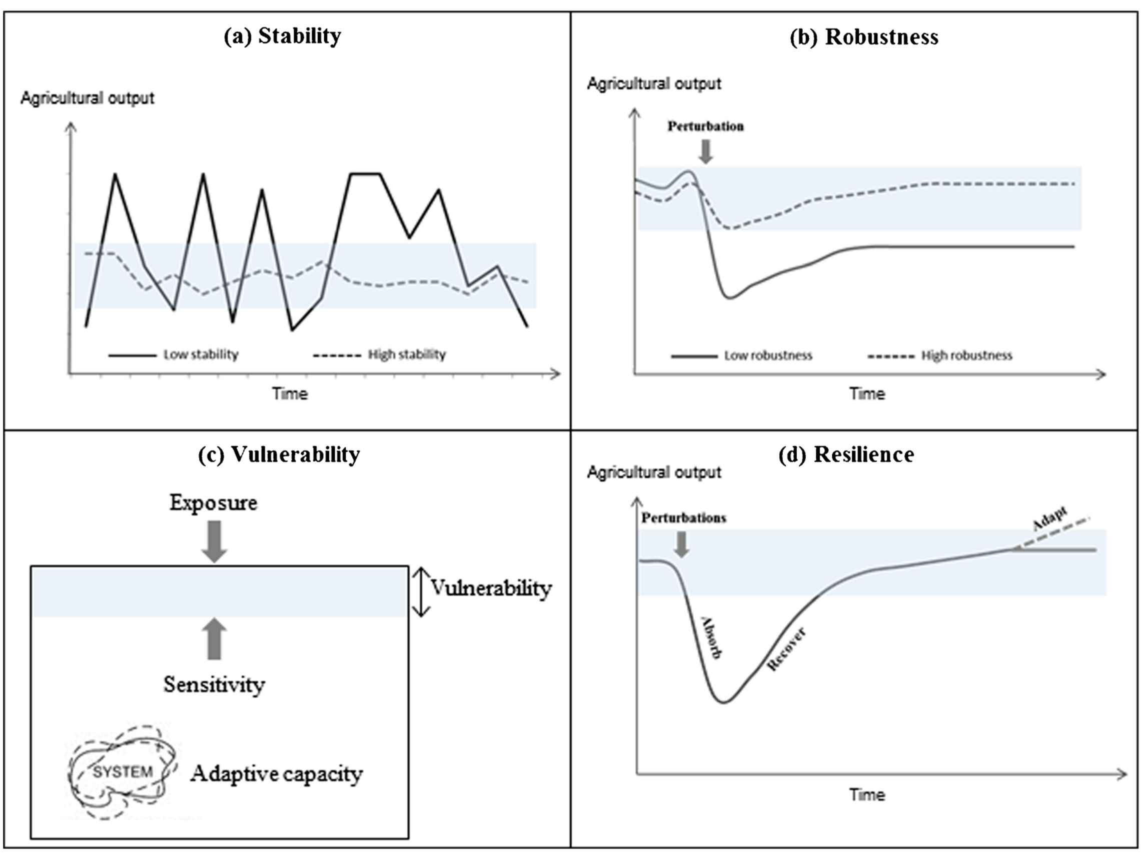

Fig. 2 Illustration of stability, robustness, vulnerability and resilience concepts (adapted from Mumby et al. (2014) and de Goede et al. (2013))

To conclude, we might say that robustness is a concept that goes further than stability through a more precise description of the interactions between agricultural systems (and their different components) and changes in environmental conditions. Due to its history, robustness appears to be a concept that better integrates biological and technical aspects of agricultural systems than stability. However, it rarely takes into consideration the social aspects of agricultural systems.

3.3 The concept of vulnerability

The term vulnerability originates from the Latin word *vulnus*, meaning injury. Vulnerability thus refers to a state of fragility, a disposition to be hurt. This concept started to be used in the 1970s by geographers and social scientists in risk management issues to describe the fragility of certain communities or countries facing severe environmental or socio-economic risks, such as earthquakes (Blaikie et al. 1994) or food exchange crises (Watts and Bohle 1993). In the decade after 2000, the use of the vulnerability concept increased sharply with its adoption by the Intergovernmental Panel on Climate Change (IPCC) to assess the potential impacts of global warming at regional and global levels (Mc Carthy et al. 2001). As a result, vulnerability recently became a very central focus of the global change science research community for discussing and defining adaptation and mitigation plans (Downing et al. 2005).

Based on the seminal work by IPCC, the vulnerability concept benefits from a highly operational framework to describe the relationship between the studied system and its environment (Adger 2006; Luers et al. 2003; Paavola 2008; Turner et al. 2003). This framework usually distinguishes between three distinct elements (Fig. 2c): (i) the level of exposure (i.e. the frequency, intensity and duration of perturbations affecting the studied system), (ii) the level of sensitivity (i.e. the degree to which the studied system is affected by exposure to perturbations) and (iii) the adaptive capacity (i.e. the ability of the studied system to deal with perturbations and increase the extent of variability that it can cope with).

This operational framework of vulnerability has allowed its use in several fields, including agriculture for which it has been applied at various spatial scales (from farms to countries) but with an emphasis on the regional level (Reidsma and Ewert 2008; Simelton et al. 2009). The vulnerability of agricultural systems has mainly been studied with regard to the exposure to climatic perturbations, such as temperature changes (Luers et al. 2003), drought (Simelton et al. 2009) or floods (McLeman and Smit 2006; Silva and Lucio 2014). It has also been used to describe the response of agricultural systems exposed to diverse socio-economic changes, such as market fluctuations (Luers et al. 2003) or land use changes (Metzger et al. 2006). Sensitivity level generally refers to biotechnical or socio-economic factors that are intrinsic to agricultural systems and interact with external perturbations to amplify or reduce their impacts. For example, the level of sensitivity of a crop to drought depends to a high degree on soil characteristics and access to irrigation (Wilhelmi and Wilhite 2002). At regional level, the level of sensitivity of Indian farmers to international trade has been evaluated as a function of crop productivity and distance to major ports (O'Brien et al. 2004).

The third factor of vulnerability, the adaptive capacity of agricultural systems, is usually described as the system's ability to design and implement effective changes so as to reduce the impacts of harmful perturbations. In practice, adaptive capacity represents the set of natural, financial, institutional or human resources that agricultural systems can mobilize for coping with constraints and overcoming them (Brooks and Adger 2005). Hence, the adaptive capacity of agricultural systems encompasses both internal and external factors that can be used to deal with a changeable environment. For example, Tengö and Hammer (2003) analyzed the role of both management practices and the institutional framework for promoting the adaptive capacity of northern Tanzanian agro-pastoralists.

Thus, vulnerability can be seen as a concept mainly focused on the assessment of the potential impacts of perturbations and on the target measures needed to reduce them. Compared to the concepts of stability and robustness, vulnerability appears to be a broader concept that encompasses the biotechnical and social factors of agricultural systems. It benefits from an operational framework that simplifies its use in various agricultural contexts, including institutional, social and financial determinants.

3.4 The concept of resilience

The word resilience comes from the Latin *resilio*, meaning to rebound. Resilience was originally used in material and psychology sciences to describe the resistance of materials to physical shocks (Winson 1932) and the ability of individuals to cope with adversity, trauma or other significant sources of stress (Murphy 1974), respectively. In ecology, Holling (1973) popularized this term by defining the resilience of ecological systems as a measure of their persistence when confronted by unpredictable perturbations and of their ability to absorb change. Subsequently, the concept of resilience has been increasingly adopted as a generic approach to describe social-ecological systems as complex entities which are continually transforming themselves through cycles of change (Carpenter et al. 2001; Folke et al. 2010; Holling 2005).

Based on extensive literature from various scientific backgrounds, resilience has been variously characterized as a loosely organized cluster of concepts (Carpenter and Brock 2008), a collection of ideas (Anderies et al. 2006) or a way of enabling exchanges across disciplines (Brand and Jax 2007). A first part of this literature mainly focuses on the "specific" meaning of resilience and is relatively close to the concepts of robustness and vulnerability. In such cases, resistance to perturbations and rate of recovery after their occurrence are considered as key aspects of resilience (Holling 1996). Specific resilience has been used, for example, on vegetative systems to study the rate of recovery after a fire (Lavorel 1999) or other natural hazards (MacGillivray and Grime 1995). Accordingly, it has been discussed for particular aspect of socio-ecological systems and for well-characterized perturbations, such as storms, earthquakes, floods and fires, for which existing knowledge provides a basis for building specified resilience (Carpenter et al. 2012). Another part of recent literature was more oriented towards the "general" meaning of resilience, i.e. the capacity of socio-ecological systems to adapt and transform in response to unfamiliar, unexpected and extreme shocks (Holling 2005). In such papers, general resilience is studied through the way that socio-ecological systems persist and innovate when facing unknown perturbations (Walker and Salt 2006). This second aspect of resilience is more difficult to apprehend because it refers to potential changes outside the scope of experience. For example, it has been used to study how socio-ecological systems are transforming themselves in order to continue to achieve specific goals, to better anticipate critical transitions in the future (Scheffer et al. 2012) and improve conservation plans (Standish et al. 2014).

Resilience thinking, referring both to specific and general aspects of resilience, has been applied to a wide variety of social-ecological systems, such as everglades (Gunderson et al. 2002), marine ecosystems (Mumby et al. 2014) and forests (Parrott and Meyer 2012) but less frequently to agricultural systems. This might be explained by marked differences between agricultural and other socio-ecological systems, such as a smaller spatial scale, a high controllability of the ecological structure and processes on the farm by human activities, and the strong influence of economic drivers to ensure both the short-term and long-term economic survival of agricultural systems (Darnhofer 2010). Moreover, despite some extreme examples such as the Dust Bowl period in the 1930s in North America, after which farmers fundamentally changed their practices and adopted planting and plowing methods that ensured a better conservation of the soil, critical transformations of agricultural systems are not easy to analyze, particularly over short time periods.

Nevertheless, despite these differences, the resilience concept has recently been applied to several studies dealing with the behaviour of agricultural systems facing various kinds of perturbation. Reflecting the contrasting understandings of this concept, the resilience of agricultural systems has been used in several ways: sometimes to measure the degree of resistance to shock in the face of economic (Abson et al. 2013) or climatic perturbations (Keil et al. 2008), but more frequently as the ability of agricultural systems to preserve their intrinsic functions through flexibility (Astigarraga and Ingrand 2011; Carlisle 2014) and plasticity (Rodriguez et al. 2011). In these cases, resilience is mainly used to discuss the factors that build the ability of agricultural systems to respond to changes, to reorganize their structure, to anticipate future changes and to take advantage of new opportunities (Folke et al. 2002).

Resilience is probably the broadest concept among the four discussed in this paper. Applied to agricultural systems, it appears to be a heuristic framework that is most relevant on a long-term basis in order to describe and understand farm transformations over periods of time marked by significant economic, environmental or sanitary crises (van der Leeuw and Aschan-Leygonie 2000). It embeds both a timescale approach and a recovery process (Fig. 2d). Hence, contrary to the concept of vulnerability which focuses on the direct impacts of specific perturbations on a given feature of the system, the resilience concept mostly focuses on the consequences of one to several perturbations, including unpredictable ones, on the overall trajectory of the system (Mathevet and Bousquet 2014).

4 From concepts to assessment in agricultural systems

Based on review literature concerning stability, robustness, vulnerability and resilience, it appears that the research community has produced an insightful and extensive literature in recent years to describe and understand better the behaviour of various systems, including agricultural systems, in a context of unpredictable change. However, operationalization of these concepts into empirical assessments remains limited due to their multidimensional nature and because they are not directly observable phenomena (Callo-Concha and Ewert 2014). The situation is even more complicated when assessments are extended from time-limited events, such as drought, to gradual perturbations such as climate change. Hence, there is an urgent need to have a better knowledge of the models and metrics available to quantify the ability of agricultural systems to cope with various types of perturbation.

In this section, we review existing approaches that have been used in empirical studies to quantify the stability, robustness, vulnerability and resilience of agricultural systems. These approaches are classified in three categories according to the system level at which they were used: (i) approaches focusing on the variability of agricultural outputs regardless of the context of perturbations, (ii) approaches focusing on the relationship between agricultural outputs and perturbations and (iii) approaches including a broader scale and taking into consideration the adaptive capacity of agricultural systems. We illustrate and discuss these different approaches through the description of some case studies.

4.1 Variability of agricultural outputs

The first approach, and probably the simplest one, quantifies the ability of agricultural systems to cope with a changeable environment by characterizing agricultural outputs and their variability across large environmental (time, space, management practices) series. This approach has been used in various studies and can be carried out using different statistical methods. A first method is to quantify the statistical deviation of agricultural outputs from the average or median and can be undertaken using common indices of statistical dispersal (e.g. standard deviation, coefficient of variation, interquartile range). For example, Abson et al. (2013) used the coefficient of variation of economic returns to study the impact of landscape diversity on economic “resilience” in the UK between 1996 and 2010.

Other methods focus more on the behaviour of agricultural systems facing rare but extreme perturbations. These methods are mainly used in risk assessment studies (Iglesias and Quiroga 2007; Luo et al. 2009) and are usually based on the analysis of output anomaly distribution. For example, Cernay et al. (2015) analyzed the yield anomaly distribution of diverse grain legumes over the period 1961–2013 in order to compare variability in legume yields across Europe and the Americas. More precisely, they used value at 10th percentile risk as a measure to assess in which countries legume yield losses have been the largest over this period. Lastly, other methods focus on the probability of achieving farmers’ goals and can be measured as the probability that agricultural outputs remain above a certain threshold. For example, Sabatier et al. (2015) used a stochastic model of grassland dynamics to measure, for various grazing strategies, the likelihood of fulfilling the feeding requirements of grazing animals. They quantified it as the percentage of weather sequences for which the grass resource was sufficient to feed the herd present on the grasslands every day.

Finally, this first approach is relatively close to the stability concept because it does not explicitly characterize and take into account the intensity and variability of perturbations that affect agricultural systems. It only describes a part of the ability to cope with an environment subject to perturbations, and it does not deal satisfactorily with the ability of agricultural systems to resist and adapt to specific perturbations.

4.2 Relationship between agricultural outputs and perturbations

This second approach focuses on the response of agricultural systems to specific perturbations and has been used in various studies, referring both to robustness (Mosnier et al. 2009) and vulnerability frameworks (Simelton et al. 2009). More precisely, this approach is associated with the notion of resistance that is frequently used in those two frameworks to refer to a low sensitivity of agricultural outputs to environmental system conditions. As a result, resistance is measured with respect to specific perturbations affecting agricultural systems. Indeed, this approach requires the characterization and quantification of the intensity of perturbations that affect agricultural systems (Li et al. 2009; Wu and Wilhite 2004). For example, Simelton et al. (2009) measured a drought index to assess the resistance of agricultural production in China to water deficit. The drought index was quantified as a negative rainfall anomaly, i.e. by the ratio between average amount of rainfall between 1960 and 2011 and the actual amount of rainfall for each year. In livestock systems, perturbations can refer to changes in environmental conditions. For example, the variation in the herd environment of dairy cows (Windig et al. 2006) and breeding sows (Herrero-Medrano et al. 2015) has also been studied to measure the resistance of these livestock systems to changes in environmental conditions.

Once perturbations have been characterized and quantified, the resistance of agricultural outputs to changes in environmental conditions is usually assessed through regression methods. This method has been used by various authors to study the relationship between agricultural outputs and perturbations which are highly correlated, such as yield and drought (Luers et al. 2003) or farmers’ income and price volatility. For example, Mosnier et al. (2009) studied the sensitivity of farmers’ incomes to climatic and economic perturbations in France on a panel of 55 farms. Using multiple linear regressions, they identified the influence of stocking rates and length of production cycles on the sensitivity of livestock systems to weather and beef price variation. In Nicaragua, Holt-Giménez (2002) has studied the resistance of more than 800 farmers after Hurricane Mitch. He discriminated “conventional” and “agroecological” farms in order to study, under different levels of storm intensity, the differences of response on several indicators (e.g. erosion or economic returns). He showed that patterns of resistance are not easy to describe and include complex interactions and thresholds. However, the differences in favour of agroecological plots tended to increase with increasing levels of storm intensity, increasing slope and increasing years under agroecological practices.

Despite its potential to assess quantitatively the response of agricultural outputs to specific changes in the system environment, this approach remains limited to biotechnical components of agricultural systems. In particular, social components, including adaptive capacity, of agricultural systems are difficult to consider in this approach.

4.3 Multiscale and adaptive capacity assessment of agricultural systems

In order to integrate the different components of agricultural systems, a third approach is frequently used. Contrary to the two previous ones, this approach focuses on the description of internal system features through a set of proxy indicators more than on the variability or resistance of agricultural outputs. This indicator-based approach is applicable to multiple scales and can include the adaptive capacity of agricultural systems (Darnhofer et al. 2010). Consequently, this approach has mostly been used for assessing and measuring vulnerability (Gbetibouo et al. 2010) and resilience (Quinlan et al. 2015) of agricultural systems rather than their stability or robustness.

In this approach, indicators are generally chosen to describe key aspects of biotechnical and social components that are supposed to increase or decrease the ability of agricultural systems to cope with various perturbations. For example, Cabell and Oelofse (2012) compiled 13 behaviour-based indicators which cover different properties of agricultural systems, such as spatial and temporal heterogeneity across landscapes and the human resources available on farms. Systems in which these 13 indicators are positively evaluated are supposed to better resist and adapt to perturbations, while a negative evaluation of these indicators points to a need for intervention. Based on the vulnerability framework, Wiréhn et al. (2015) reviewed indicators of exposure, sensitivity and adaptive capacity. The latter ones describe socio-economic factors that can assist agricultural systems to adapt and rebound better after perturbations (e.g. farm income, farm size, crop diversification). Altieri et al. (2015) used indicators of soil conservation practices, crop diversity and food self-sufficiency to describe the adaptive capacity of various agroecological farms in Latin America. These indicators are frequently aggregated and their results displayed in geographic representations to improve the identification of the most vulnerable, or less resilient, areas within a territory (O'Brien et al. 2004; Wilhelmi and Wilhite 2002). This indicator based-approach has proven to be valuable for monitoring trends but, as reported by Wiréhn et al. (2015), is limited in its applicability by considerable subjectivity in the selection of variables and their relative weights and by the difficulty of testing and validating the different metrics.

To conclude this section, it appears that various approaches are available to study the behaviour of agricultural systems in a more changeable environment. Despite their differences, these approaches can provide additional details and improve visibility of what improves the ability of agricultural systems to cope with unpredictable changes. In particular, they can provide complementary findings at different scales. In the next section, we review the main elements that emerge from researches completed to date.

5 Key levers for improving the ability of agricultural systems to cope with perturbations

Based on previous sections, it appears that various concepts and methods have been mobilized in recent years to characterize and quantify the ability of agricultural systems to cope with a changeable environment. Despite fuzzy boundaries, these concepts have specific historical backgrounds and have been applied to describe different features and behaviours of agricultural systems.

Based on literature focusing on conceptual definitions and empirical assessments in agricultural studies, some key levers are emerging as important properties for a transition towards more stable, more robust, less vulnerable or more resilient agricultural systems. These generic elements are summarized in two categories: first, increasing the intrinsic diversity of agricultural systems and, second, increasing their adaptive capacity.

5.1 Increasing diversity at different levels

Based on recent literature, many authors have emphasized the potential of increasing diversity in its various forms to improve the behaviour of agricultural systems when facing various perturbations (Altieri et al. 2015; Lin 2011; Naylor 2008; Østergård et al. 2009). This assumption relies on the hypothesis that implementing more diversity at different levels provides greater functional redundancy, i.e. system components and organization with overlapping functions to buffer year-to-year changes. However, diversification can be implemented in a variety of forms and at a variety of scales, allowing farmers to choose a strategy that both increases their ability to cope with perturbations and provides economic benefits Lin (2011).

Among biological components, increasing genetic diversity through cultivars and animal breeds characterized by different agronomic features (e.g. diversity in earliness for cultivars; diversity in disease resistance for animal breeds) is supposed to spread the risks of failure by reducing the overall exposure to perturbations (Di Falco and Perrings 2003; Tooker and Frank 2012). Increasing breeding of cultivars and animals with distinctive traits is therefore becoming a research priority to allow farmers to choose biological components adapted to various contexts and perturbations (Casadebaig et al. 2014; Knap 2005). Similarly, increasing diversity at the species level by using crops characterized by different exposure periods and sensitivity features allows the spreading of risks through the entire cropping rotation (Lin 2011). Following seminal work by Hector et al. (1999), Tilman et al. (2006) showed that greater complementary and functional diversity among grassland species were able to stabilize annual plant production. As reported by Huyghe et al. (2014), the use of mixtures of grasses and legumes has been largely implemented in grasslands worldwide.

Increasing diversity is also feasible by changing the nature of crop rotations and introducing perennial tree crops into annual cropping systems. Based on complementarities between annual crops and trees, agroforestry systems are characterized by a strong structural complexity (Jose 2009). These systems have demonstrated their capacity to provide a better protection for annual crops not only from habitual climatic perturbations (changes in temperature and precipitation), but also from extreme perturbations such as hurricanes (Lin 2011). At a larger scale, increasing diversity through regional landscape diversity is also a strategy for minimizing the impacts of perturbations on agricultural systems: Reidsma and Ewert (2008) showed that diversity in farm size and intensity (e.g. cultivar choice, fertilizer and pesticide use) reduces the regional vulnerability of wheat production to climate change. Abson et al. (2013) also found that land use diversification in the UK was positively correlated with the resilience of agricultural returns in the face of uncertain market and environmental conditions. Furthermore, preserving or increasing the diversity of agricultural systems can also maintain or stimulate various resources (technology, information and knowledge) at the territorial level that can be used by farmers in order to cope with current or future challenges (Nelson et al. 2007). In that sense, increasing diversity of agricultural systems can also improve their adaptive capacity.

5.2 Increasing the adaptive capacity of agricultural systems

Cited mainly in robustness, vulnerability and resilience literature, adaptive capacity refers to the ability of agricultural systems to transform their nature or structure to cope with an ever-changing environment (Milestad et al. 2012). It focuses on ensuring sufficient room for manoeuvre, identifying transition capabilities and extending the degrees of freedom of agricultural systems. More often emphasized in livestock than in cropping systems (Blanc et al. 2010), adaptive capacity can be improved at different levels and in biological, technical and organizational components.

Applied to biological components, adaptive capacity has been widely discussed in robustness literature as a key breeding goal for animal breeding (Knap 2005). It refers to the ability of animals to adjust their behaviour to exogenous constraints. For example, the adaptive capacity of dairy cows may refer to their ability to mobilize body reserves during specific periods in order to support milk production. Blanc et al. (2010) showed that animals in extensive livestock systems are frequently adjusting their behaviour and physiological responses to cope with low-feed-intake periods. Such ability to adjust their behaviour varies between breeds and highlights their ability to produce and maintain their reproduction in an unstable environment. Various research programs have focused on increasing these properties in various plants and animals (Knap 2005; ten Napel et al. 2006), but some authors have underlined a potential trade-off between intrinsic adaptive capacity and the productivity of livestock systems (Sabatier et al. 2015).

On a larger scale, improving the adaptive capacity of agricultural systems can be based on improvements in the design of agricultural systems and the implementation of technical components designed to help farmers to adjust day-to-day operations. For example, design can rely on the choice of renewable materials, such as bedding material, feeder type for livestock and new fertilizers and decision support tools in crops to prevent abiotic or biotic risks. Several tools are already available to inform farmers about pest outbreaks, soil water availability or nitrogen nutrition index, and farmers can opportunistically respond to variability by adjusting pesticide, irrigation or fertilizer uses (Mulla 2013). In livestock systems, increasing adaptive capacity can also refer to organizational management and to the adaptation in time and space of feed management to secure feed supply, especially in grassland systems that can be highly sensitive to drought periods (Mosnier et al. 2009; Tichit et al. 2004). By introducing more flexibility in agricultural systems, these technical and decision making components emerge as important characteristics of agricultural systems which consciously or automatically adjust options to reliable clues from the environment in which they operate (Rodriguez et al. 2011).

Beyond farm scale, adaptive capacity can also be improved through collective actions between stakeholders that voluntarily share their goals and production tools. Ireland and Thomalla (2011) showed that collective action between farms can promote the establishment of social networks and enhance the ability of local stakeholders to cope with a changeable environment. It may also increase their financial resources which can be used during times of hardship. These new forms of cooperation between farms are also helping them to establish new relationships with downstream industries and to adapt better to changes in market context.

6 Conclusion

The context of increasing uncertainty induces major challenges for agricultural systems. The need for more sustainable agricultural systems in an increasingly changeable environment implies a shift from the aim of maximizing agricultural outputs in a non-disturbed environment to the aim of maintaining desired levels of outputs in a context of unpredictable perturbations. For agronomists, it entails the need for a better characterization and quantification of the ability of agricultural systems to cope with unpredictable changes. A literature review of stability, robustness, vulnerability and resilience highlighted several differences and complementarities between these four concepts. Depending on the system's scale, the type of agricultural output studied and the kind of perturbation, each concept can be meaningful and provide insights to better characterize agricultural system behaviour in the face of perturbations. This literature review also provided insights into the various methods available to quantify these properties in agricultural systems, from the analysis of the variability and resistance of agricultural outputs to multiscale and indicator-based assessments. Based on this literature, increasing diversity and adaptive capacity of agricultural systems emerge as key drivers for increasing the ability of agricultural systems to cope with different types of perturbation. However, further empirical studies are still needed to test and validate these methods and results in various contexts and across various spatial and temporal scales. Further research is needed to work out to what extent and based on which value judgements the urge for more stable, more robust, less vulnerable or more resilient agricultural production systems is moving research towards a course of breeding stable cultivars, towards breeding robust cows, towards protection and exposure avoidance or towards resilience and adaptation. Of particular interest are the trade-offs involved.

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