Farm resilience for sustainable food production: A conceptual framework[1]

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ABSTRACT. So far resilience work has mostly focused on regional-scale, extensively managed ecosystems. We argue that, as over 40% of the earth's surface is used for agriculture, it would be fruitful to apply resilience thinking to agro-ecosystems. Resilience thinking could contribute to shifting farming systems from equilibrium-based command-and-control management approaches towards sustainable food production through a better understanding of the factors and processes that contribute to farm resilience. We focus on farms, understood as intensively managed local-level social-ecological systems. Focusing on the local level could allow new insights for resilience thinking, especially on the influences of human perceptions and the dynamics of decision-making processes. To enable a farm to persist both in times of predictable growth and in times of turbulent change, a farmer needs to implement strategies that exploit current strengths, while simultaneously building adaptability and transformability. The challenge is that these strategies compete for scarce resources. The appropriate mix of strategies will thus depend on the farmer's preferences, the state of the farm along its adaptive cycle and the co-evolutionary processes between the farm and its environment, taking into account various spatial and temporal scales. To assess the resilience of farms, resilience thinking will need to be operationalized, but there are temporal and spatial hurdles involved in identifying suitable surrogates, as well as the challenge to capture the 'human dimension' through surrogates.

Key Words: *sustainability; agriculture; social-ecological system; farm management; adaptive capacity; adaptive management*

INTRODUCTION

Producing food while maintaining biodiversity and ecosystem services is one of the greatest challenges facing the Earth's population (Millenium Ecosystem Assessment 2005, Ehrlich 2008). With more than 40% of the Earth's surface being used for agriculture (FAO 2007), farmers and herders manage vast tracts of land and the natural resources found on them, shaping ecosystems, habitats and landscapes (OECD 2008). Farms are vital in securing the survival of humans, both directly by producing food and fiber, and indirectly by producing amenities. Furthermore, many farming practices not only affect the ecosystems on-farm but also those off-farm, sometimes over large distances, through importing ecological subsidies (Moller et al. 2008) and exporting pollution (Gordon et al. 2008).

With this publication we would like to draw attention to the potential of applying resilience thinking to agriculture, especially at the farm level. Given the shortcomings of conventional farm management approaches (Norgaard 1987, Holling and Meffe 1996, IAASTD 2008), and a dearth of models integrating ecological, social and economic sustainability over various temporal and spatial scales, resilience thinking holds great promise to better understand the interlinkages and the challenges involved in moving towards sustainable food production.

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The concepts of social-ecological resilience and panarchy (Gunderson and Holling 2002) provide one way to address the environmental, economic and social concerns linked to change in agriculture and the persistence of farms. Resilience thinking shows that persistence is born out of resistance to change, adaptive renewal and system transformation (Walker et al. 2004). Understanding and guiding the maintenance of the current state or its change and reorganization into a new state requires an integrated, transdisciplinary approach that can complement conventional farm management. Indeed, whereas conventional farm management seems well suited to guiding operational management during times of gradual, predictable change, resilience thinking could contribute to a better understanding of how farms can persist over the long term and during times of rapid and often unpredictable change.

However, despite the importance of intensively used agro-ecosystems within the larger management of natural resources, resilience thinking has so far rarely been applied to agriculture. This may be linked to the fact that agriculture, and especially farm level studies differs in a number of ways from the social-ecological systems (SES) to which most resilience thinking has been applied so far. Firstly, the spatial scale considered is much smaller, limiting the ability to comprehensively manage a whole ecosystem. Secondly, agro-ecosystems tend to be managed much more intensively, i.e., are subject to on-going human-induced ecological disturbance (Moller et al. 2008). Thirdly, farms are usually privately owned, not a common property resource. Thus decisions hinge more on personal decision making than on governance involving deliberation between a range of stakeholders. Finally, economics tend to play a more important role in farm management than in subsistence-oriented land uses or the management of landscape-scale ecosystems for conservation.

The bias within resilience studies towards the study of large-scale ecosystems over the long term, and the lack of attention given so far to agro-ecosystems, is reflected in the proceedings of the "Resilience 2008" conference. An analysis shows that nearly 40% of the abstracts refer to studies of regional-scale SES over the long term (Fig. 1). Of the 82 abstracts that were related to the local level, 23 address farming (including extensive rangeland management) and only 10 abstracts (i.e., approx 5% of contributions) were about farming in a western country. However, this is where agricultural practices are, arguably, the most problematic.

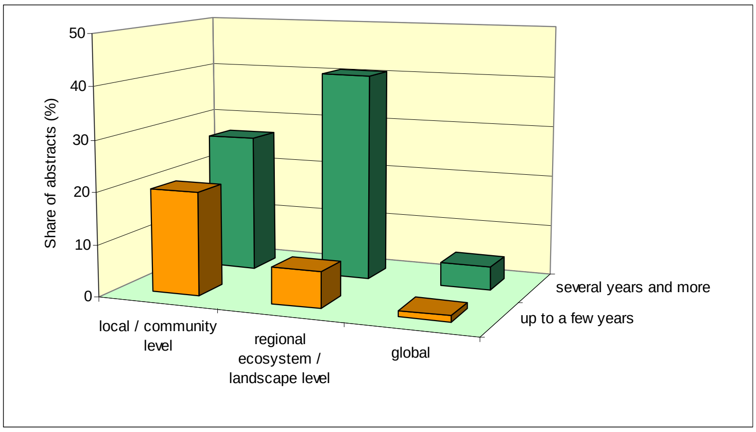

Figure 1: Tentative categorization of 175 abstracts included in the proceedings of the "Resilience 2008" conference according to the spatial and temporal scale that are at the dominant focus of the study

Note: The proceedings of the Resilience 2008 conference were selected as the work presented at the conference can be seen as representative of current research in resilience thinking. The proceedings include 195 abstracts. Of these 20 could not be categorized, mostly as they were theoretical in nature and thus did not focus on any specific spatial or temporal scale. The categorization of the remaining 175 abstracts was necessarily rough, as – true to resilience thinking – studies usually address various scales and their interlinkages. However, most studies do have one focal level from which they discuss the interlinkages to other spatial and temporal scales.

Regarding the time scale, there was a rough differentiation between those studies that focused on the short- to medium-term (i.e. up to 3-5 years), and those focusing on longer time periods.
Source of data: "Abstracts and panels of Resilience 2008" from the conference held 14-17 April 2008 in Stockholm (available on-line: http://resilience2008.org)

In agriculture and food production, the local scale is the primary site of action. It is at the farm-level that information from the ecological, social and economic environment is processed and that decisions are made and implemented. It is the interaction between the farmer (his or her perception and goals), the physical environment (land, animals, technology, climate) and the social environment (norms, markets, policy) that result in the managed configuration of a specific farming system.

Given their pivotal role for human welfare, many governments invest substantial efforts to maintain farms while steering them towards sustainable production methods. To support this drive towards sustainable farming systems, the ultimate goal of our research is to identify key factors that affect farm resilience. In other words we are interested in the mechanisms, processes and attributes that allow a farm to successfully navigate panarchy. This covers on the one hand the factors that help build the resilience of those farms that pursue ecologically, socially and economically sustainable practices, and on the other hand the factors that help reduce the resilience of those farms that are 'locked-in', i.e., trapped in practices that are not sustainable so as to allow them to redirect their development paths.

In this paper we follow a broad-brush approach showing how resilience thinking can be applied at the farm level, thereby identifying new research questions. We begin the paper by reframing the farm as a SES and review the possibilities to ensure stability or induce change. We then concretize our understanding of the identity of a farm ("resilience of what?") and the perturbations of interest ("resilience to what?"). Finally, we discuss the need to operationalize resilience at the farm level to allow for a transition from resilience theory to practice, and thus explore the hurdles involved in identifying suitable surrogates.

CONCEPTUALIZING FARM RESILIENCE

The farm as a social-ecological system within panarchy

A farm is understood as a SES, i.e., a unit made up of the farmer (with his or her mental models, preferences, goals, abilities, etc. making up its social and cultural capital) and the physical farm (with its land, animals, crops, building, finances, etc. making up its natural and economic capital). A farm can be organised in a variety of social forms, e.g., a family farm or a corporate farm.

Managing the resilience of a farm means taking into account that its various subsystems are semi-autonomous, but interact (Fig. 2). Indeed, the subsystems are situated at different spatial scales (e.g., plot, farm, local networks, regional partners, national regulations, international trade agreements) and belong to different domains: ecological (balance between pests and beneficial insects, water cycle), social (norms, expectations of urban population) and economic (market pressures, quality standards). These subsystems interact across spatial and temporal scales and across domains. Global warming might serve as an example of interactions across spatial scales: it is a global phenomenon that results from local economic activities and affects farms at the local level, e.g., through longer growing periods, thus influencing the crops planted and the pest incidence (Battisti et al. 2005), thus the regional agro-ecosystem and landscape. Interactions across time scales can be exemplified by the dependence of western agriculture from crude oil, a form of intertemporal subvention, or the cumulative effect of soil management techniques on soil biota and structure. Interactions across domains can be exemplified by the influence of agricultural policies (e.g., quotas or direct payments) on the economic framework and thus on the relative profitability of crops and of production methods, thereby influencing the choices of arable farmers and thus the agro-ecosystem (Roschewitz et al. 2005).

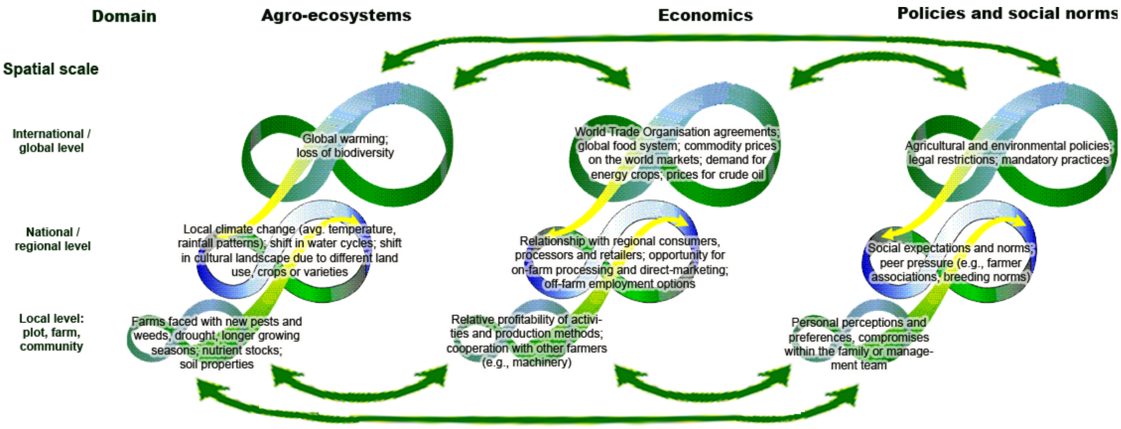

Figure 2: Interactions between hierarchies of nested set of adaptive systems within the ecological, economic and social domains. The adaptive systems are semi-autonomous but they influence each other, both within and between domains. The arrows are schematic, as there are obviously also interactions at the regional/national level between the three domains. These arrows were not inserted to avoid over-crowding the graphic.
Source: Panarchy graphic modified from Holling, 2001

The subsystems also evolve at different speed: there are sudden and rapid changes such as consumer preferences following a food-safety crisis (e.g. pesticide residues or avian flu), and slow changes such as the erosion of the genetic material of rare breeds of domestic animals. Moreover, the spatial and temporal scales do not necessarily match (Table 1): there are rapid changes at the global scale (e.g., the rapid rise of the world market price for wheat, rice and milk in 2007/08) and there are slow changes at the farm-level (e.g., farmers' mental models).

Although agricultural scientists are aware of these various factors, there is so far a dearth of models that would allow to integrate them and allow to understand their interactions across spatial and temporal scales as well as across the three domains.

Table 1: Examples of social, economic and ecological drivers of on-going change and sources of perturbations for farms, operating at various spatial and temporal scales.

Temporal scale	Spatial scale Farm level, local	Regional, national	International, global
Short (weeks to months)	• Choice of feed source (e.g., on-farm/regional/imported) • Impact of temperature and rainfall on of growth of crops and animal feed • Choice of crops and inputs (e.g., fertilizer, pesticide, integrated pest management) • Shift in the combination of activities (on-farm and off-farm) • Management of social disputes (e.g., due to pesticide drift or GMO crops)	• Effect of drought, existence of drought relief • Local, regional, national market opportunities or export markets • Competition in food and fiber markets affecting prices • Ability to buy ecological subsidies and stock feed from off the farm	• Food safety crises (e.g., BSE, avian flu) • Short-term fluctuation in commodity prices due to international political crises
Mid term (several months to a few years)	• Change in production method (e.g., conversion to organic farming) • Change in ownership (e.g., scale increase, succession on family farms) • Changes along the farm family	• Changes in trader and retailer relationships (e.g., loss of local retailer, increasing power of supermarkets) • Changes in values (e.g., acceptance of organic	• Shifts in commodity prices (e.g., for wheat, rice, milk in 2007/08, linked e.g., to demand for energy crops, increasing food imports to China and peak oil) • Increase in fuel costs, with

	life cycle (e.g., children, marriage, divorce) and effect on labor availability • Change in mental models and interpretation framework; learning • Involvement in the local community, farmer groups or associations (social capital)	farming among regional farming community) • Citizen's expectations of farming (e.g., multifunctionality, provision of amenities, environmental protection) • Changes in agricultural policies (e.g., willingness to subsidize to ensure ecological services vs. liberalization) • Changes in ecosystems and landscapes (e.g., clearing hedges and felling windbreaks) • Changes to nearby farms (e.g., the increase in dairy farms around sheep farms in NZ)	it the threat to increase transportation cost for inputs (e.g., soja from Brazil as feed for European cattle and poultry) as well as prices of fuel and fertilizer • Shifts in diets (e.g., 'Europeanization' of diets in many Asian countries: shift from rice to wheat) • Global degradation of critical ecosystem services (e.g., provision of drinkable water)
Long term (several years to decades)	• Build-up or reduction of soil organic matter • Degradation of soil biotic communities • Soil erosion • Degradation or building of soil structure • Increase or reduction of on-farm biodiversity • Reduced room for manoeuvre due to large investments (animal shed, irrigation) or specialization, debts, etc.	• New, invasive species (e.g., due to global warming) • Demographic change (e.g., ageing population, rural depopulation) • Change in consumer preferences and values (e.g., demands for animal welfare, rejection of GMOs) • Desertification of farm landscapes	• Adjustments in the world food systems (e.g. linked to the economic development in China and India) • Climate change and its effects • International agreements (e.g., WTO) • Demographic growth, ageing population, migration • Global degradation of critical ecosystem services

The nature of change

A core insight of the research on the resilience of social-ecological systems is that many SES seem to cycle through qualitatively different types of changes, i.e., changes that are different in speed and predictability (Gunderson and Holling 2002). This insight has been formalized in the adaptive cycle metaphor (Holling 2001). Typically a SES will spend by far the majority of its time in the forward loop, interrupted by short, episodic phases of back loop dynamics. For example, the historical analysis of a regional system (Goulburn-Broken Valley in Australia) has shown that in a 150 year time span, it has spent four periods, totaling 20 to 25 years (i.e., about 15% of the time) in back loop dynamics (Walker et al. 2002). Thus it is likely that prolonged periods of relative stability and gradual changes will suddenly be interrupted by a shock as was for example the case of the beef sector following the bovine spongiform encephalopathy (BSE) crisis.

This understanding of the nature of change is radically different from the assumption of a system-near-equilibrium on which conventional farm management is based, leading to a one-sided emphasis on predictability and stability. However, the alternation between long periods of somewhat predictable change and short periods of chaotic change illustrates how a farm is forced to cope with different challenges over time. Different and complementary management strategies are needed. While the farm is in the forward loop, i.e. during the growth phase, which is characterized by stability and the slow accumulation and transformation of resources, an exploitation-led strategy is likely to be successful. However, when the farm travels through the backward loop, characterized by opportunities for reorganization and innovation, an exploration-led strategy might be required. To persist over the long term a dynamic balance of the various strategies (see Tab. 2) may be most promising.

Resilience theory may be helpful to understand why certain configurations are stable over long periods – despite disruptions – and why they suddenly flip. This would allow to better understand what enables farms to resist disruptions while at the same time organizing and influencing transitions, i.e. simultaneously fostering the attributes necessary for stability, adaptability and transformability.

Options and challenges to manage farm resilience

Resilience thinking offers a vision of sustainability, which is not reduced to stability. Indeed, persistence is born out of both resistance to change and maintenance of current states as well as adaptive renewal leading to new states when episodic shocks redirect the system (Walker et al. 2004). We thus need to understand both which management strategies allow farms to persevere and those that allow them to adapt when it is needed and seems opportune.

Table 2: Overview of the strategies that farms may need to be able to persist over the long-term. The strategies should not be understood as alternatives as they usually must be implemented simultaneously. The question is what combination of strategies is most appropriate for a specific farm at a specific time. As a farm moves along its adaptive cycle the relative emphasis of various strategies will likely shift. How a specific strategy is implemented on a farm depends on its natural, economic and social capital. Whether a change is 'predictable' or 'sudden' will also depend on the perception of the farmer. Changes can be either external (e.g., policies, norms) or internal (e.g., life cycle of the farm family).

Nature of change	Response at farm level Approach	Strategy	Description, examples
Predictable, slow change	Perseverance; no or marginal change	Exploit	The farm takes advantages of successful activities (i.e., those that are well adapted to the current environment). Farms might shift more resources to these activities (specialization) and exploiting economies of scale
Sudden, major disturbance	Perseverance; no or marginal change	Absorb	The stress is absorbed without changes being required. The farm has sufficient buffer capacity to be able to cope with the crisis. For example a drop in price of a key produce can be absorbed due to a healthy financial basis.
Sudden, major disturbance	Exploration of new options; change in activities, in the use of resources or of the system	Adapt	The disturbance requires some adaptation at the farm level, but these remain within the traditional realm of farming (i.e., production of food and fiber). These can include new production methods, new crops, introduction or removal of animal husbandry, on-farm processing, direct marketing, etc.
Sudden, major disturbance	Exploration of new options; change in activities, in the use of resources or of the system	Transform	The perturbation requires a major realignment of the resources and involves the introduction of activities from outside the traditional realm of farming. These can include agri-tourism, care farming, energy production (e.g., electricity from biogas, windmills or photovoltaic panels), etc.

Following the amount of change in the environment and the response by the farm, four constellations can be distinguished (see Tab. 2). In an environment characterized by predictable change and a farm that is well adapted to this environment, exploiting current strengths and focusing on efficiency seem promising strategies. In an environment characterized by surprises, a farm might choose to absorb the shock without initiating change, i.e. to weather the crisis and wait for things to calm down again. A farm might also adapt by reconfiguring its resources, shifting the emphasis between activities or starting new, related activities (Ingrand et al. 2007). If these adaptations are not sufficient i.e., when ecological, economic, or social conditions make the existing system untenable, or if it is a suitable time for the farm, it might be transformed into a fundamentally new system, e.g., by diversifying into activities that were not previously considered the realm of farming (van der Ploeg and Renting 2004, Darnhofer 2005).

Whether or not a farm is able to maintain its functions despite changes in its environment will depend on its attributes (Milestad and Darnhofer 2003). Fundamentally, changes can be either implemented on the farm itself, or the farm can influence its surrounding evolutionary landscape. Indeed, the farmer can not only influence the adaptability and resistance of his own farm by selecting production processes and combining activities, he can also engage with his social, economic and political environment to ensure support and try to pre-empt unwanted transitions at other spatial levels of the panarchy. For this, pertinent networks, trust, leadership, information flows, knowledge of appropriate temporal and spatial scales, etc. are required. Here again, it is the linkages between the farm and its environment, between different scales and domains (Knickel and Renting 2000) that are decisive, rather than the individual elements in and of themselves.

Whereas it is likely that there is an overlap in the attributes that promote resilience, adaptability and transformability (Walker et al. 2004), there are also trade-offs, especially between the attributes ensuring success during periods of stability and those that require adaptation. There are tensions if a farm needs to be able to maintain a desired current configuration in the face of shocks and, simultaneously, build the capacity for transformability. Managing for efficiency through exploiting current strengths and opportunities is different from managing for adaptability through exploring new options. Maximizing short-term cash flows (while necessary to some extent) does not ensure long-term financial viability. How farmers perceive these impacts, how desirable the alternatives are to them and how they actively manage the trade-offs is unclear. Where the ‘right’ mix is will also depend on the resources available on the farm, on the stage the farm is in its adaptive cycle, and where the other levels of the panarchy are along their adaptive cycles.

The decisive human component

Overall farms are a SES that is under more direct influence from humans than the landscape-level SES that have been the focus of resilience work so far. Applying resilience thinking at farm-level thus requires putting more emphasis on the role of the social component in organizing processes that strengthen or weaken the resilience of the system.

Private ownership mean that it is the farmers’ right to manage their property as they see fit (while taking into account the more or less numerous legal regulations). Thus it is ultimately the farmer who decides whether or not to cut down a windbreak, how much agrichemicals to use on her field, whether to plant a woodlot or to drain a swamp. This practical, day-to-day farm management, while dependent on the economic and social framework, the local agro-ecosystem, and the structure of the farm (size, buildings, herd), is thus decisively influenced by human perceptions, preferences and choices (Fairweather and Campbell 2003, Schmitzberger et al. 2005, Burton and Wilson 2006, Slee et al. 2006).

Individual-level decisions do have (intended and unintended) consequences which are born by the larger community. As these landscape-level effects, which result from the self-organization of the system, usually cannot be influenced directly, the point of entry for change processes is the farm-level. The challenge is thus to anchor the decision-making processes at the local level, while taking into consideration and understanding the reach of the global factors influencing the food systems. Both threats and opportunities may originate in faraway places and may not be influenceable, much less controllable locally (Campbell et al. 2006). Yet the readiness for adaptation and the responses to threats and opportunities must be managed and understood at the local farm level.

For this, it is necessary to understand real-life farmer decision-making. These decisions are usually not so much based on rational choice, scientific information and objective assessment of facts, than based on information filtered through selective perception and the farmer's mental models. How a farm is managed thus hinges on the farmer's goals and values, the potentials as perceived by the farmer and the obstacles expected by him or her (Dedieu et al. 2008). Given this dominant role of the farmer, it is important to understand the key characteristics of social systems, typical human biases and processes of social self-organization (Dörner 1989, Westley et al. 2002, Beratan 2007, Elster 2007, Scheffer and Westley 2007).

To achieve a robust conceptualization of key processes affecting farm resilience, we need a nuanced understanding of how farmers influence and respond to change, how they make sense and work with uncertainty in future system trajectories. Studying farms could thus also advance resilience thinking, allowing to better understand the human dimension and individual decision-making for the resilience of SES.

Farm resilience: of what to what?

As Carpenter et al. (2001, 2005) have pointed out, the transition from resilience theory to practice requires the resilience of a SES to be assessed or estimated. However, before the resilience can be assessed, it is crucial to specify what system state is being considered (resilience of what) and what perturbations are of interest (resilience to what).

Resilience of what?

The goal is for a farm to be sustainable and to persist, i.e., to maintain its identity in the face of both internal change as well as external shocks and disturbances (Cumming et al. 2005, Loring 2007). Focusing on the ability of a farm to maintain its identity as a cohesive unit through space and time implies that its functions must be maintained, but not necessarily its components. In other words a farm is expected to change its activities over time, e.g., shift from dairy production to pig fattening, stop animal husbandry, grow different crops, or convert to organic farming. Such a change in components or a reconfiguration of resources is a system innovation that entails a degree of reorganization, but not a loss of identity.

Indeed, resilience is not driven by the identity of the elements of a system, but rather by the functions those elements provide (Allen et al. 2005). Which functions define the identity of a farm will depend on the ecological framework and on the social context (e.g., society's expectations of the functions that a farm should fulfill, for example the 'multifunctional' model of European agriculture or the export-oriented neo-liberal economic model in Australasia). Thus, we consider a farm to be resilient, if it maintains its essential attributes as well as functions within and across scales despite the turnover of specific components or activities.

Resilience to what?

When studying farm resilience, we must also clearly state the (external and internal) drivers of change, i.e., the kind(s) of change that we would like the system to be resilient to, as well as the time scale we consider. Table 1 provides examples of the wide range of stressors and drivers from the ecological, economic and social domain that a farm must be able to tackle. Farm resilience also needs to cover several spatial scales, i.e. from the ecological processes at the field-level to the social processes at the farm level (e.g., farm family cycle) and at the local and regional level (e.g., knowledge networks, social and cultural capital).

As the resilience in one time period or at a particular scale should not achieved at the expense of resilience in a later period or at another scale (Carpenter et al. 2001), farm resilience needs to be considered over at least one generation (i.e., 30 years), but a longer time period (i.e., 50 years) would be desirable, so as to include crucial phases such as the handing-over of a farm to the next owner.

Challenges in assessing the resilience of individual farms

To be able to apply resilience thinking to farms, we need to operationalize the concept, so that it is empirically measurable. However, the abstract, multidimensional nature of the concept of resilience makes it difficult to operationalize. It is by no means obvious what leads to resilience in a complex adaptive system, or which variables should be measured in a given study of resilience (Cumming et al. 2005). Although we cannot yet propose concrete 'measures' of farm resilience we would like to raise a number of issues that will need to be taken into account.

As the direct measurement of resilience is difficult or impossible, Carpenter et al. (2005:941) have proposed to use the word "surrogates" (instead of indicators) to acknowledge that important aspects of resilience in SES may not be directly observable, but must be inferred indirectly. The term also acknowledges that resilience and its relationship to the surrogates may be dynamic, complex and multidimensional. The goal is thus to develop a set of surrogates that address multiple aspects of resilience of farms.

The challenge when identifying surrogates is to ensure their validity and their reliability. There are three major hurdles to overcome: a temporal hurdle, i.e., the likelihood that surrogates will change as the SES evolves, a spatial hurdle, i.e., the likely context-dependence of surrogates, and the hurdle to incorporate the 'human dimension' into the assessment.

The temporal hurdle is linked to the fact that, if we want to derive recommendations for farmers, ideally we would like to measure surrogates in the present that will explain resilience at some point in the future. We thus face the fundamental challenge of trying to capture the essence of a moving target through a snapshot-approach. But the future of a complex adaptive system and its shocks are unknown and unknowable. Indeed, the policy demands, market opportunities and farmer perceptions are subject to on-going change (both in degree and in direction, see Tab. 1). The issue of farm resilience is thus not so much a question of whether a farm is fit at a specific moment in time, nor if they are able to change *per se* (because change it must, to remain fit in a changing fitness landscape). The question is rather if a farm fits at every point along its development path, i.e., whether its development path remains compatible with the changing fitness landscape. In other words, whether a farm is able to change in one of several 'right' ways, where what is right cannot be defined before hand, and can only be assessed retrospectively. Thus surrogates of resilience that are appropriate for the current farming system may become useless as ecological structures, markets or social expectations shift.

The spatial hurdle is closely linked to the temporal hurdle: the aspects of a system that confer resilience are context-dependent (Holling 2001). Indeed, the aspects that confer resilience to a farm in a country where the agricultural policy emphasises the multifunctionality of farming and is thus willing to subsidise farms that provide public goods (e.g., in the European Union) are not necessarily the aspects that confer resilience to a farm in a liberalized context (e.g., in Australasia). In other words, a farm is unlikely to be resilient *per se*, but can be resilient given its current ecological, economic, and political context. Just as the fitness of a farm can change over time, so the fitness of a farm is dependent on the fitness landscape it is currently in. As Walker et al. (2002) have pointed out, the rules that govern SES dynamics are not fixed. They evolve over time in response to both biophysical and social changes. Understanding how they evolve is crucial if we are to achieve policies that enable SES to self-organize along acceptable trajectories. It also implies that any surrogate of resilience needs to be able to capture adaptability, responsiveness to feedback and learning.

The third hurdle is linked to the 'human component' of a farm. The interaction between the farmer and her farm is crucial in building resilience. Indeed, it is less the structure of the farm that is decisive, but what the farmer makes of it (Giddens 1979). In other words, resilience can be understood as an emergent property of the system, it is strengthened or weakened through the interaction between farmer and farm. Thus, the structure of the farm itself (the activities currently engaged in, the organisation of production, its assets) is only of limited use as a surrogate. Indeed, the farm reflects the farmer's goals and preferences only to some extent: the farm is also the product of its past history (path dependence); reflects time-lags due to learning processes or to the time between implementation of a measure and it having the desired effect; shows unintended consequences of past choices; and is limited by the current (economic and social) environment. All of these limit the farmer's ability to shape the farm according to her preferences. The structure of the farm may thus be used as a surrogate only when taking into account the farmer's perceptions and intentions as well as the history of a particular physical aspect. This implies a participatory approach to establishing and assessing resilience surrogates and precludes a 'remote assessment' by scientists (Ingrand et al. 2007).

CONCLUSION

Resilience thinking offers a framework to emphasize dynamics and interdependencies across time, space and domains. The resulting complex dynamics require a shift from developing more sophisticated forecasting and risk assessment methods, to enabling a system to cope with on-going change and surprise. A farm with a one-sided focus on efficiency is unlikely to be resilient. The goal is thus to take advantage of current opportunities, while managing the conditions that expand future possibilities, i.e., ensure adaptability and transformability. Understanding a farm as a SES that moves through the adaptive cycle and co-evolves with its environment could allow to shed new light on theses dynamics and how to manage them.

Applying resilience thinking to agro-ecosystems and farm management offers a range of challenges linked to the specificity of this type of SES, and may thus present an opportunity to further develop the concepts underlying resilience thinking. Especially the ability to capture and integrate social and economic self-organization into the conceptual models will allow to further deepening the understanding of the social component, that to date has received less attention than the ecological component of SES. Whenever the social component has been addressed it was mostly at the institutional level, while individual resilience has so far been neglected. However, within the panarchy, each component and spatial level deserves the same attention.

Applying resilience thinking to farms also offers a welcome opportunity to push for the operationalization, for the development of adequate surrogates to assess the resilience of a SES. Only once the hurdles involved in designing an assessment tool for resilience have been overcome, and the surrogates have been empirically tested, will it be possible for resilience thinking to develop its full potential in shedding new light on the nature of farm resilience as well as the pathways to sustainability in agriculture.

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