Review

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Resilience as a universal criterion of health

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Abstract

To promote and maintain health in agricultural and food systems, appropriate criteria are needed for the description and assessment of the health of soils, plants, animals, humans and ecosystems. Here we identify the concept of resilience as a universally applicable and fundamentally important criterion of health in all relevant areas of agriculture. We discuss definitions of resilience for soils, plants, animals, humans and ecosystems, and explore ways in which resilience can be applied as a criterion of health in different agricultural contexts. We show how and why resilience can be seen as a key criterion of health. Based on this, we discuss how resilience can be used as a link between soil, plant, animal, human and ecosystem health. Finally, we highlight four key areas for future research on resilience in agriculture, namely spatial and temporal scaling of resilience; effects of diversity; the role of networks for resilience; and stakeholder involvement.

Keywords: agriculture; concept; health; resilience; stability; stress

INTRODUCTION

Good health is one of the highest human goals,[1] both at an individual and at a societal level. In agricultural contexts, the promotion and maintenance of health are of concern in manifold ways.[2] Agricultural practices, policies and research are directed at the understanding and enhancement of soil health[3] and crop health,[4,5] the health and welfare of livestock,[6] the effects of agriculturally produced food on human health,[7] and at the impact of agricultural management on the health of humans[8,9] and ecosystems.[10] One area in agriculture where the term 'health' plays a particularly central role is organic farming, which, according to its principle of health,[11] 'should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible'.

However, 'health' is also an unwieldy term: it has different meanings in different contexts and its frequent and varied use in colloquial language makes it difficult to devise a concise definition of health that captures its whole richness and complexity.[12] Over the last few decades, there have been comprehensive debates on how health should be defined and measured. Especially with reference to human health, there is a rich literature on meanings and criteria of health.[13–15] Although concepts of health have also been discussed for the domains of soil,[16] plants,[12] animals[6,17] and ecosystems,[18–20] these debates are currently fragmented, separated by disciplinary boundaries, and are also at different stages in their development.[12,21–23]

Bringing the current strands of discussion together has therefore a great potential for advancing the conceptual clarity and understanding of the term 'health' in agriculture.[2] Consistency and clarity are indeed needed if the health of whole agricultural systems is to be assessed, whether at farm level[24] or at a greater scale.[25–27] Apart from helping to achieve consistency and clarity, linking the current debates is also useful in order to explore how far health concepts discussed in one domain (e.g. humans) can be used in another as well (e.g. ecosystems). Can health be understood in ways which diffuse through all levels of agriculture and food production? Can we see the health of soil, plants, animals, humans and the whole planet all through the same lens, possibly using the same or similar criteria to assess it?

One potential lens to look through at health is resilience. In a preliminary way, resilience can be defined as the speed of recovery of a variable entity.[28,29] The term is widely used in a variety of meanings, e.g. as the capacity to resist shocks and regain balance after having been under some kind of pressure or change,[30–32] in psychology as an individual's ability to cope with stressful situations,[33] or in physics, as the ability of materials to absorb energy and release it again.[34] In agricultural contexts, resilience has been understood as some type of 'buffer capacity'.[35]

There is evidence from two scientific databases (Web of Science and Google Scholar, 1991–2010) that health and resilience are becoming increasingly relevant to each other. On one hand, the literature on health is increasingly mentioning the term 'resilience'. On the other hand, the literature on resilience is increasingly making use of the term 'health' (Fig. 1). Also, an international workshop conducted by the authors identified resilience among

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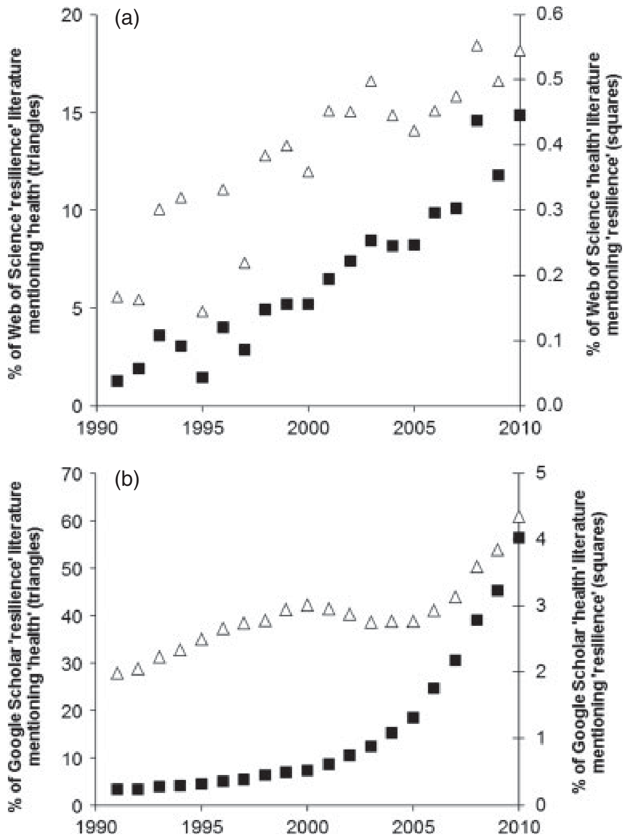

Figure 1. Trend in the use of the term 'resilience' in the literature on health (squares) (obtained by dividing the number of papers retrieved each year searching at the same time for the keywords 'resilience' and 'health' by the number of papers retrieved that year with the keyword 'health'), and trend in the use of the term 'health' in the literature on resilience (triangles) (obtained by dividing the number of papers retrieved each year searching at the same time for the keywords 'resilience' and 'health' by the number of papers retrieved that year with the keyword 'resilience'), for (a) Web of Science and (b) Google Scholar (both 1991–2010, as abstracts are searched in Web of Science starting from 1991 only; some papers published after 2010 may still need to be indexed).

several criteria of health as a potential common denominator among the various domains.[36]

In this paper we explore the relationship between resilience and health and ask if resilience is indeed a useful criterion of health in agricultural contexts. We discuss in what way the term 'resilience' can be applied to the domains of soils, plants, animals, humans and ecosystems, and investigate whether there are any commonalities among these domains. We ask in what way resilience may form biological and ecological links between domains, for example whether there is evidence for soil health and plant health being linked through mechanisms involving resilience. Finally, we look at scale effects of resilience, probing for effects of resilience at smaller scales on resilience at larger scales and vice versa. First, though, we will give a brief overview of what is generally understood by the term 'resilience'.

UNDERSTANDING RESILIENCE

'Resilience' is an increasingly popular term in many scientific disciplines. Ager[37] reported an eightfold increase in the prevalence of the term 'resilience' in the scientific literature accessible from Columbia University over the period 1990–2010. It is therefore no wonder that there is a diversity of definitions for resilience; indeed, many authors reviewing the concept of resilience have bemoaned the multitude of meanings and the lack of lucidity of the term.[31,38–40]

Definitions and dimensions of resilience

The word 'resilience' has Latin roots, with *resilire* meaning 'to jump back'. The concept of resilience has strong traditions in two disciplines: ecology[41–43] and psychology,[39,44] though it has been widely used in several others, including physics, human geography,[31] psychiatry,[45] political science[32] and economics.[46] In ecology, resilience has been defined as 'a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables'.[41] In a psychological context, the term has been described as 'a construct connoting the maintenance of positive adaptation by individuals despite experiences of significant adversity'.[39] A further example of a definition of resilience comes from plant breeding, where the term has been explained as 'the ability of a system to remain functional when under external stress'.[47]

These selected examples can only partly convey the range of meanings of resilience. Although typologies of resilience definitions have already been given,[38,44] we found it useful to analyse a number of resilience definitions from various reviews[31,32,38,39] for commonalities and variations in their constituent elements. According to this analysis, we distinguish three steps that are covered in almost all resilience definitions: disturbance – response – outcome. Resilience is always defined as a capacity or ability of a system or individual to react (*respond*) to an external force (*disturbance*) while fulfilling some further conditions at the end of the response (*outcome*).

Almost all resilience definitions conceive the *disturbance* as external, i.e. the source of the disturbance is outside the system that is assessed for its resilience. The disturbance can be characterized by its frequency and its severity. In the context of resilience, the frequency of the disturbance is generally implied to be low, i.e. the disturbance manifests itself in the form of an event that it is unexpected or unanticipated or is otherwise rare, though some authors focus on recurrent disturbances.[48] At the other extreme, some definitions even speak of unique or singular events. A second characteristic that varies in definitions of resilience is the impact severity or adversity of the disturbance.[44] It ranges from nil (e.g. merely 'new ... operating conditions')[49] to severe (e.g. hazard, damage, shock, disaster) (Fig. 2). In psychological contexts, even positive life events, such as job promotions or marriages, have been seen to fall under the heading of resilience in that they require positive adaptation to novel demands.[44] Thus, while most authors define resilience in the context of low-frequency high-impact events, it is useful to consider both dimensions on a continuum. As one moves from rare high-impact events towards more frequent disturbance events of moderate impact levels, the concept of resilience can be seen gradually to transform into something more akin to general adaptation. This distinction is relevant for determining what factors can contribute to resilience. For example, evolutionary mechanisms at the organism level may lead to the ability to respond to the (more or less) expected disturbances, whereas resilience against the totally unexpected disturbance is likely to be more difficult to evolve.

Referring to the *response* of the system to the event, definitions of resilience differ in three areas. First, there are differences in terms

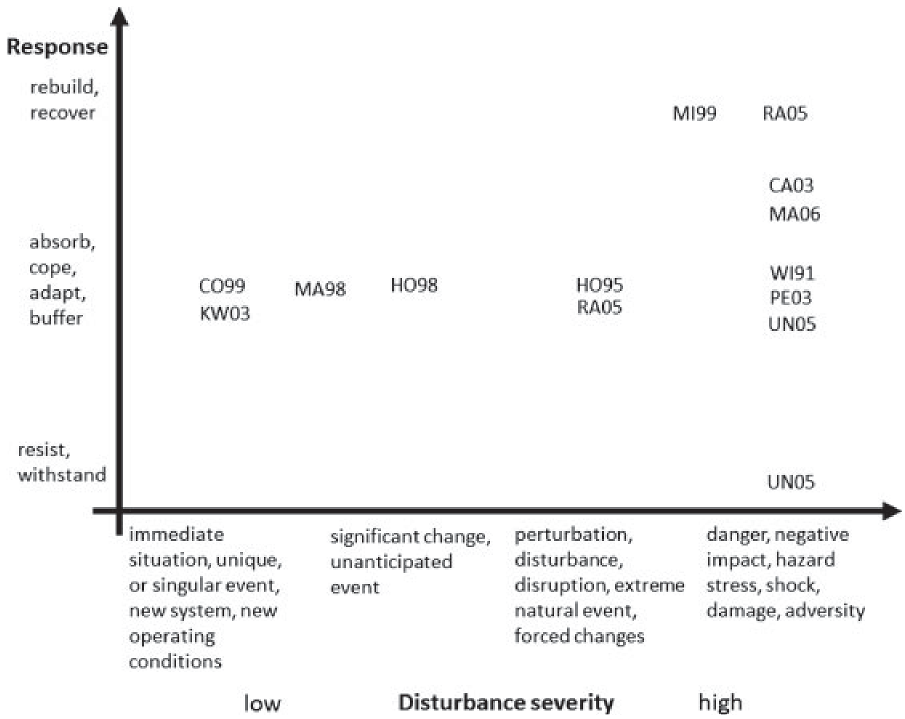

Figure 2. The semantic space of resilience. Classification of resilience definitions according to the severity of the disturbance (*x*-axis) and to the response of the system to the disturbance (*y*-axis); MI99: Miletti;[128] CA03: Cardona;[129] UN05: UNISDR;[130] RA05: Resilience Alliance 2005 (as cited in Manyena);[31] HO95: Holling *et al.*;[131] HO98: Horne and Orr;[132] MA98: Mallak;[133] CO99: Comfort *et al.*;[134] KW03: Kendra and Wachtendorf;[135] PE03: Pelling;[136] WI91: Wildavsky;[137] MA06: Manyena.[31]

of how much temporary impact a resilient system suffers following the disturbance event (Fig. 2). Some definitions imply that there is no impact of the (potential) disturbance factor at all: the resilient system is able to withstand or resist the external force, or may even prevent it from impacting at all. Other definitions imply that resilient systems do experience a temporary negative impact, but are able to recover, or rebuild themselves, or to bounce back following the disturbance event. In a further group of resilience definitions the response lies in between these two extremes: there is an impact of the disturbance on the system but the system is able to buffer, absorb, tolerate, cope or adapt. Again, it is useful to see the strength of the temporary impact of the disturbance as a continuum.

The second area relating to the response of the system is whether external help or support is permitted for resilience: while some concepts of resilience explicitly emphasize that the resilient system responds to the disturbance without assistance from outside,[12] others do not consider this as a criterion for resilience. The third area is the time dimension of the response: Here, definitions range from quick or expeditious response to 'within acceptable time';[32] or no time dimension is given at all, i.e. there is no dynamic response but resilience is seen in a static picture of maintaining functioning under disturbance.[47] Recent research on yeast populations shows that spatial population patterns can be used as an indicator of population resilience, reducing the need to study long time series and providing early warning signs of collapse.[50]

Finally, resilience definitions differ in the way in which the endpoint of the response is specified, i.e. in terms of the *outcome*. The definitions can be grouped by the level of functionality that should stand at the end of the response. At one extreme are the definitions that require as a criterion of resilience that the system responding to the disturbance achieves success or at least maintains functionality.[51] At the other extreme, the only requirement is that the system must not change its structure or does not collapse into a different state; or that it must not suffer devastating loss.

Apart from this typology, there is a further way to distinguish concepts of resilience (Fig. 3). In *static* resilience, there is no time dimension and it is merely observed how well the system can cope with stress. As such, static resilience is very similar to certain concepts of stability (see below). For *dynamic* resilience (which is mostly called 'engineering resilience'),[38] the focus is on the time component of the response to the disturbance, but the performance of the system is measured in one dimension only. We prefer the term 'dynamic' over 'engineering' to characterize this type of resilience because the relevance and application of this concept go far beyond the original area of engineering. For *complex* resilience (closest to the original proposition from ecological science,[41] and often called 'ecological resilience'),[38] the structure of the system in response to the disturbance is studied, rather than any single performance indicator. Again, we prefer the term 'complex' because the application of this concept is possible beyond the science of ecology.

How can resilience be measured?

As has been observed in previous studies on resilience, it is of high importance but not straightforward to operationalize and to measure resilience.[38,39,43,52] For the simplest case, static resilience, it is possible to compare the resilience of systems by measuring their performance (e.g. yield) under a specified disturbance regime (e.g. increased temperature), as well as under undisturbed control conditions (e.g. optimal temperature). Resilience can then be quantified by the absolute or relative difference in performance between the two conditions.

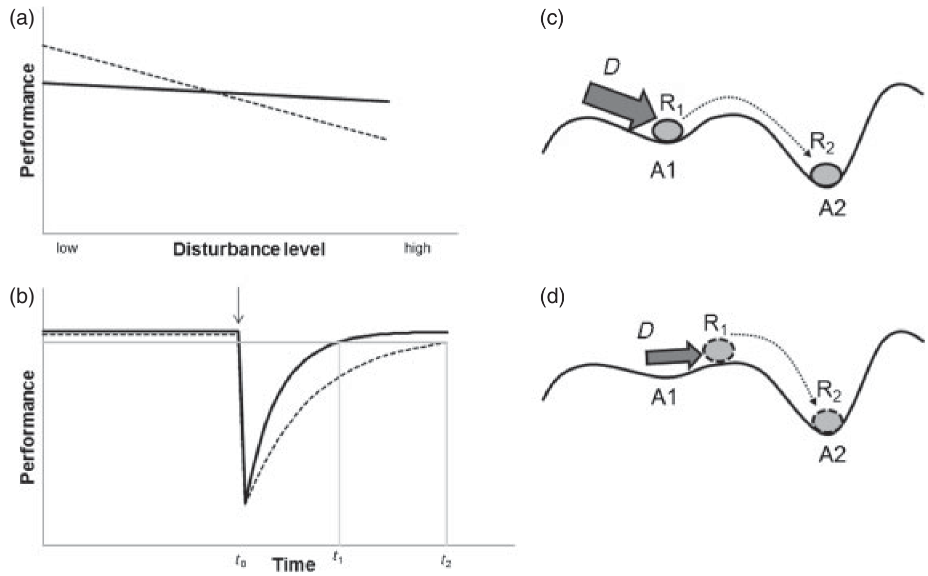

Figure 3. Schematic representation of different concepts of resilience. (a) Static resilience as the ability to perform under high stress (disturbance) levels. The system represented by the dashed line is less resilient than the system shown by the solid line. However, in this case the less resilient system outperforms the other system under conditions of low disturbance. (b) Dynamic resilience (i.e. so-called engineering resilience) as the ability of a system to bounce back after disturbance at time t_0. One system (solid line) is able to recover more quickly, i.e. in this case reach an arbitrary level of 95% of the pre-disturbance performance at t_1, than the other system (dashed line), which reaches the recovery point later (at t_2). (c, d) Complex resilience (i.e. ecological resilience) as the strength of the disturbance that a system can absorb before it changes its structure; in this example, the regime of the system is governed by the attractors A1 and A2. A structural change of the system is represented by moving from the influence of A1 to that of A2. The current regime R_1 of a system is (c) more resilient or (d) less resilient, as the strength *D* of the disturbance required to push the system into the A2 basin is lower in (c) than in (d). Here, this difference in resilience is a consequence of (1) the different topography of the domain and (2) of the precariousness of the system, i.e. its closeness to the A2 attractor prior to the disturbance event.

In relatively simple systems, and with a clear system performance indicator, (dynamic) resilience can be measured by the time needed to bounce back, i.e. the speed with which the system returns to equilibrium after disturbance.[51,53] Expressed differently, resilience can be determined as the rate at which perturbations to an ecological system decay.[54] If the system does not return to the pre-disturbance equilibrium, an alternative measure of resilience is the completeness of functionality reached after disturbance. Various resilience indices used in soil microbiology have recently been reviewed.[55] For more complex dynamic systems, however, the operationalization becomes more and more difficult, in particular as genuine responses to specific disturbances become increasingly hard to separate from fluctuations in functionality of the system; here, approaches need to be system specific and may have to involve a degree of subjectivity.[52]

How does resilience differ from similar concepts?

Resilience, in its multifaceted meanings, shows conceptual similarities with other notions such as adaptation, homoeostasis, allostasis, balance, invulnerability and stability. Depending on the specific definitions, the differences between resilience and these neighbouring concepts are not always clear-cut. Here we give a brief and simplified account of some key differences.

In comparison to *adaptation* (to a specific stress), resilience allows more change and fluctuation in the resilient system. Although some definitions of resilience use the term ‘adapt’ (i.e. a resilient system is able to adapt to new conditions), mere adaptation without resilience would be relatively static, e.g. a plant species may be adapted to low (stressful) nutrient levels, but a resilient species would be able to cope with a (sudden) drop in available nutrients.

Homoeostasis has been defined as the ‘ability or tendency of an organism or a cell to maintain internal equilibrium by adjusting its physiological processes’.[56] While this definition is rooted in medicine and physiology, it can easily be applied to ecosystems and beyond. Homoeostasis is similar to resilience since in both cases the systems stay within certain limits. However, homoeostasis differs from at least some interpretations of resilience in that resilience focuses more on the return of the system to the equilibrium over time (recovery), whereas homoeostasis just maintains a status quo. This implies, or at least includes the case of, constancy over time. Thus resilience allows more dynamic processes, more complexity and more fluctuations than homoeostasis. An example is the response of an agricultural system to a hurricane disaster after which the system rebuilds itself to regain productivity.[57] In this case, the concept of homoeostasis fails to capture the successful response of the resilient system to the catastrophic change. A further difference between the two concepts is that resilience emphasizes the active adaptation to new conditions. *Allostasis* is the ‘maintenance of physiological homoeostasis through changing circumstances’.[58] It is closer to resilience than homoeostasis, but again does not focus on recovery after disturbance as much as resilience.

Balance as a concept to describe systems is often avoided by scholars because it is not well defined.[12] One definition of balance in the context of health is ‘the difference in magnitude between opposing forces or influences, such as for bodily parts or organs’.[56] Other definitions equate balance and equilibrium. Differences between the concepts of balance and resilience are mostly the same as discussed above for homoeostasis. Differences between resilience and *(in)vulnerability* have been discussed elsewhere.[31,39] Resilience focuses more on system dynamics over time and recovery, while invulnerability describes resistance to disturbance.

Finally, it is important to clarify conceptual differences between *stability* and resilience. Holling[41] argued that unstable systems can be resilient and that wide fluctuations of populations can even be a requirement for resilience. Equally, systems may be stable because they lack resilience – if they are unable to deal with a range of disturbances and so maintain a low (but stable) level of performance. According to Holling, stability 'represents the ability of a system to return to an equilibrium state after a temporary disturbance; the more rapidly it returns and the less it fluctuates, the more stable it would be'. While this definition of stability is almost identical to the current core concept of resilience, other definitions of stability (e.g. stability of crop yields) do not refer to temporal disturbances.[59,60]

APPLICATION OF RESILIENCE AS CRITERION OF HEALTH IN AGRICULTURE

In this section we explore the relationship between resilience and health for the five domains: soil, plant, animal, human and ecosystem. Specifically, we ask: (i) Is resilience already used as a criterion of health? (ii) Is the meaning of health and resilience the same or, if not, what is the difference? (iii) Are there cases in which a system or organism is resilient but not healthy? And (iv) how does resilience compare with other criteria of health?

Resilience and soil health

Several definitions of soil health have been given over the last decade. For example, Doran and Zeiss defined soil health as 'the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health'.[61] A similar focus on the functional aspect of soil health, i.e. the capacity of the soil to support productivity and ecosystem services, was chosen by Kibblewhite and co-workers, who further described soil health as 'an integrative property that reflects the capacity of soil to respond to agricultural intervention'.[16] This statement highlights the view that agricultural practices (interventions) represent the main disturbance factor of the soil system; this is in contrast to the situation in crop plants, where the major disturbance forces (pests, pathogens and weather events) are conceptualized as not being (directly) anthropogenic.

Although the terms 'soil health' and 'soil resilience' are sometimes used in parallel,[61] several authors consider resilience as a criterion of soil health,[62–64] as highlighted in a paper stating that resilience 'reflects the "self-healing" capacity of the soil system'.[16] Magdoff lists ten criteria of soil health, one of which is 'resilience following an episode of degradation'.[64] This means that resilience needs to be complemented by other criteria to describe soil health.

A recent review on resistance and resilience of soil systems makes the point that both the diversity of soil microbial communities and soil aggregation are important for soil resilience and, ultimately, soil health.[55] Indeed, soil microbial communities are an excellent way to study resilience since their response to disturbances can be relatively fast (within days or weeks) and protocols to measure their ecologically meaningful functions are well established. The term 'resilience' appears in a relatively high and increasing proportion of papers on soil health (Table 1).

Resilience and plant health

Concepts of plant health have recently been discussed by Döring *et al.*[12] According to this analysis, six dimensions of plant health can be distinguished. These are: (i) naturalism *versus* normativism with regard to the role of values in defining health; (ii) negative *versus* positive definitions of health; (iii) reductionism *versus* holism; (iv) functionality *versus* resilience; (v) materialism *versus* vitalism; and (vi) biocentrism *versus* anthropocentrism.

According to this typology, the functionality–resilience axis concerns the plant's ability to perform under stress conditions with or without *human interference*. A simple example is the treatment of a plant with a fungicide: according to the functionalist view, a symptomless plant would be regarded as healthy even if the absence of disease symptoms is purely a result of the fungicide treatment. In contrast, the resilientist view requires that the plant has the ability to fend for itself, i.e. to maintain or restore functionality in response to stress without human interference. In this case, the capacity to cope with the stress in an autonomous way could be based on genetically inherited disease resistance or tolerance. For example, European ash dieback due to the exotic ascomycete *Hymenoscyphus pseudoalbidus* is causing widespread ash tree mortality throughout Europe, but some ash trees appear to be able to cope with the disease without human intervention, possibly due to their genetic make-up, their leaf flushing or shedding phenology, or their individual endophyte assemblages.

However, there are two problems with this meaning of resilience as a criterion of plant health.[12] The first problem refers to the definition of treatment or interference, because interference might not always be easily distinguishable from non-interference. This is the case, for example, with indirect side effects of agronomic practices such as compost applications or rotation design on the health of plants. Second, when resilience is taken to its extreme, it collapses as a criterion of plant health. In a radical version of resilience, heavily infected, completely dysfunctional plants would be regarded as equally unhealthy as plants that had their functionality restored by curative treatment.

The use of the term 'resilience' in the paper by Döring *et al.*[12] stresses the aspect of *autonomy*. In this respect the concept of resilience provides a useful new perspective to the health of plants. However, other aspects of resilience, as discussed above, are of importance for plant health too. Static resilience as the ability to perform under stress was used to evaluate the effects of genetic diversity in composite cross-populations of winter wheat.[47] While the wheat study did not use resilience as an explicit criterion of health, it is conceivable to do so, especially when more specific stress factors are considered. Also, the commonly used terms, resistance and tolerance, could both be considered as contributors to static resilience and thus plant health. The application of dynamic resilience as a criterion of plant health is perhaps less obvious than in animals, humans or ecosystems, especially in annual crop plants. However, dynamic resilience can be studied in the context of plant health by investigating the recovery of plants from pathogenic infection, insect attack or other stress factors, e.g. through mechanisms of phenotypic plasticity, i.e. compensatory growth.[65] In the plant health literature, the term 'resilience' is used with moderate frequency (Table 1).

Resilience and animal health

A major challenge in conceptualizing animal health is that it is often described in terms of what it is not, i.e. disease or absence of disease.[6,21,66] Sometimes, animal health is measured in terms of high performance, fertility, production and yield. Even when it is acknowledged as being more than the absence of disease, and more than high production, it is frequently just presented in practice as detectable signs of non-health (e.g. veterinary

Table 1. The term resilience in the scientific literature on health for the years 2000–2010, depending on the domain; query on 18 May 2013

	Google Scholar			Web of Science	
Search term	Total number of articles (in thousands)	Proportion mentioning resilience (%)	Trend 2000–2010[a]	Total number of articles (in thousands)	Proportion mentioning resilience (%)
health	11383.0	1.6	+***	568.6	0.3
soil health	12.2	14.9	+(*)	0.4	2.5
plant health	37.2	4.2	+***	0.5	0.4
animal health	153.2	2.7	+***	3.3	0.1
human health	435.5	4.3	+***	16.6	0.2
mental health	1611.8	5.1	+**	47.3	1.4
ecosystem health	36.9	18.7	+**	1.0	3.7

[a] Data from the years 2011 and 2012 were not included because some papers published after 2010 may still need to be indexed. Data analysis including years 2011 and 2012 showed continued upward trends in the use of the term resilience.
Trends of proportions against years were tested with a quasibinomial model using the statistical software R, version 3.0.0; +, positive trend; (*)$P = 0.051$; **$P < 0.01$; ***$P < 0.001$.

costs,[67] which depend much on human choices, treatment criteria and structures of veterinary practices), and aspects of low performance. For example, herd managers in Danish industrialized agriculture update themselves daily with disease and production parameters, often collected automatically and electronically to describe conditions outside the range of what is considered normal with the purpose of catching disease at an early stage, as a part of 'health planning'.[68] Likewise, health is often described only as a part of animal welfare, more or less exclusively linking health to the functions and conditions of the physical body, and ignoring that animal behaviour is an essential part of animal health,[69] as well as the animal's ability to react and interact with its surroundings to maintain health in a constantly changing environment. These views of animal health direct the understanding of health away from a dynamic concept related to the whole animal, and reduce it to a limited part of the individual.

In this context, the term 'resilience' presents a key to a broader understanding of health. Currently however, the term appears in a relatively low proportion of papers on animal health (Table 1), although this proportion has steadily increased over the last few years. Resilience is meaningful in a dynamic understanding where health is not a potential end-goal or target (a state), but an ability to respond and interact with the environment throughout life, involving the physical body, emotions, psychological and behavioural aspects. This emphasizes the importance of our actions as constantly supportive to the animals and their abilities to adapt.[69] A holistic and more dynamic approach to animal health is needed, not least to enable and guide us to create surroundings for animals in which they can react and interact as sentient beings, each with a body, emotions, instincts and a social life. A healthy animal has the ability to react, balance and restore itself to a certain degree, given that the surroundings allow this.

The use of resilience as a criterion for health is highly relevant in this light. It can be described with a focus on functions, as maintenance of physiological, mental and physical functions; or in a teleological view, where the ways in which a healthy organism reacts to influences imposed by its surroundings are regarded as 'wise', contextually specific and determined by the goal of keeping homeostasis. Such an approach can be translated into practice by shifting the focus from disease management to health promotion strategies, moving to a focus where we strive to support the animal in all ways, physically, emotionally and mentally, as individual and as group animals. Clearly, animal health, understood as the ability to respond and react to shocks and disturbances, must necessarily be seen at various levels: at the level of individuals with their genetic background at the group level in terms of social and interdependent living sentient beings; and at the level of the animal population, e.g. by adapting genetically to changing conditions in the environment over time, or being strongly interdependent and each having different roles in the population, such as bees. Resilience as a criterion of health has the strength of being applicable at all three levels.

Resilience and human health

Huber *et al.* reported that an expert conference reviewing the definition of human health found broad support for moving towards a dynamic formulation of health, 'based on resilience or capacity to cope and maintain and restore one's integrity, equilibrium and sense of wellbeing'.[58] Similar ideas, while not using the term 'resilience', were already developed in the 1970s by Aaron Antonovsky, who focused on the ability of humans to cope with stress.[70,71] In the current literature on human health, resilience appears only in a low to moderate proportion of papers, but its use has strongly increased in the last decade (Table 1). Resilience features as a criterion of various facets of human health, including mental health and nutrition. For example, some degree of resilience has recently been demonstrated in the human microbiome, e.g. after disturbance through antibiotic therapy.[72]

There are, however, also cases in which resilience, in a strict sense, is associated with ill-health. Consider the example of a normal-weight person who, following the stress of a prolonged food shortage, has lost considerable weight up to a point where the person's health is affected; after a while, however, food availability increases again and the person recovers, until the original weight and health status have been reached again. Now consider an overweight person in a similar situation: after reducing calorie intake for a while, motivation for dieting wanes and, due the same compensatory mechanisms as in the underweight person, body weight increases to the original level.[73] While this bounce-back effect, in its pattern typical for resilience, provides health in the first person, it may be associated with disease in the overweight person. This example shows that resilience may have some limits as a criterion of health.

Resilience and ecosystem health

As the data from the literature search show, resilience is often used in connection with ecosystem health (Table 1). The connection of resilience with ecosystem health goes back to Aldo Leopold's writings on land health.[74]

In some cases, resilience is equated with ecosystem health: a healthy ecosystem is seen as having the capacity to self-restore after a disturbance that shifts it from a complex to a simple state.[75] This implies that measuring ecosystem resilience is a way to assess ecosystem health in a quantitative way.[76] In other cases, resilience is considered as an indicator of ecosystem health: a healthy ecosystem needs to be resilient to disturbances, but resilience is not a sufficient condition for health.[77] In both cases, ecosystem health is akin to the concept of ecosystem sustainability, i.e. the ability of an ecosystem to maintain its structure and function despite external stresses.[78]

Ecosystem health and resilience have been studied empirically in a number of contexts, e.g. in the marine sciences, from the effects of the BP-Deepwater Horizon oil spill on saltmarshes vegetation in Louisiana[79] to the ability of marine protected areas to protect coral reefs from sedimentation due to upland forest logging in the Solomon Islands.[80] An index of health for the human–ocean system of all coastal countries included resilience in its calculation.[81] In forests and tree plantations, tree genetic diversity is widely recognized as an important way to ensure resilience of forests and thus to maintain forest health.[82] Long-lived organisms such as trees are supposed to be more resilient to disturbances, but this view is increasingly challenged by invasions of exotic pests and pathogens with which trees have not co-evolved.[83] For grassland systems, an independent effect of extreme weather events and of community diversity was observed on the capacity of grasslands to withstand invasion by exotic species.[84] Diverse grasslands have indeed been shown to be likely to be more tolerant to drought stress globally.[85]

Although different health systems are still separated by disciplinary boundaries the integrative importance of ecosystem health is increasingly recognized by 'one health' approaches in higher education, research (e.g. on ecological public health)[86] and health governance institutions.[87]

Bringing the domains together

As we have shown above, resilience is being used as a criterion of health in all its domains, albeit with somewhat different meanings, differences in methodology and varying enthusiasm. Resilience is a 'boundary object',[38] with a relatively flexible meaning and interpretation. This can help interdisciplinary communication, and as a concept resilience still has a core meaning. Differences in meaning can be easily identified in the semantic space (Fig. 2), as resilience definitions form logical continua in the dimensions discussed above.

Resilience offers some advantages over many other terms used to characterize or describe health. First, it has a sensible meaning in all domains, unlike, for example, 'welfare' in the domain of soil health. Second, the concept of resilience is relatively easy to translate into a measuring procedure in all domains, unlike, for example, 'harmony'. Third, and perhaps most importantly, using the concept of resilience to bring the different domains of health together may help to deepen the understanding of mechanisms underlying health.

TOWARDS INTEGRATION: HEALTH, RESILIENCE AND AGRICULTURAL SYSTEMS

In this section we discuss (i) whether resilience can be used as a link between the domains of soil, plant, animal, human and ecosystem health; and (ii) whether it is different between different scales, i.e. whether resilience at low spatial or temporal scales feeds through to higher scales.

Can resilience be used as a link between soil, plant, animal, human and ecosystem health?

In general, the need to work across disciplinary boundaries in health-related research has been shown repeatedly.[88] As we have argued above, resilience has some advantages over other potential health criteria when trying to find and establish links among the domains of health. Here we discuss three more specific examples.

1. *Microbial communities*. Microbes are prime candidates for linking the health of different organisms and systems. Patterns of resilience are well established in microbiology, across an astonishing range of systems from yeasts in the lab, agricultural soils, to the human gut. Joining research efforts across disciplines may therefore help to establish common mechanisms of resilience across systems. Moreover, evidence is accumulating that different domains are physically linked by microbial communities moving from one domain to the other.[89] This means that the microbial community in one domain (such as the soil) is not only likely to affect a downstream domain (such as a plant or a human), but also that differences in resilience are a potential explanation for these effects.
2. *Ageing*. Dynamics of health through ageing organisms can be captured more easily with resilience than with more static criteria of health; ageing as a universal process in all organisms (as well as in ecosystems) is a key for understanding health. For example, the experience of rebalancing is common for all humans as they are getting older and have to adjust to changes in their personal conditions with respect to fitness or emotional well-being. The same will be true for animals, at least for the fitness aspect. Plants also change their fitness with age. Thus, many plants need protection from neighbouring plants when they are young but can cope with them or even benefit from other species as neighbours at older stages. An example is the interaction of lucerne (*Medicago sativa*) with grasses. During the weeks following germination, *M. sativa* is very sensitive to competition. If grasses are established well after *M. sativa*, however, the leguminous plant will compete well as its roots go deep, while the grass will benefit from the N-fixation of the lucerne. Similarly, young trees need protection from competition exerted by other vegetation, while at older age they may profit from that same vegetation.[90]
3. *Diversity*. In numerous cases it has been shown how high diversity and increased resilience are linked. Using resilience as a common criterion of health across all domains in agriculture increases the understanding of underlying mechanisms and thereby enables better management of agro-ecosystems and improved health. Indeed, agro-diversity plays a crucial role in shaping the resilience of various agricultural systems across the world, for example as a buffer and impact-mitigating factor. Crops grown in monoculture and especially monocultures of genetically uniform individuals show a higher vulnerability against diseases, pests and nutrient deficiencies; and increase the pressure on environmental resources like soil or water.[91] This higher vulnerability in turn raises the need for an increased use of external inputs such as pesticides and fertilizers, increasing costs and agroindustry dependency of

farmers.[92] On the other hand, when growing mixtures of different crops or varieties, the system becomes more resistant to fungal diseases and pests, yields are stabilized and the sustainability of the system as a whole increases.[93–96]

There is now evidence that agricultural systems characterized by high diversity are generally more resilient against major environmental changes and climatic extremes than less diverse systems or monocultures. For example, polycultures show greater yield stability and lesser yield declines during droughts than monocultures.[97] A study investigating the effect of hurricane Mitch, which hit Central America in 1998, on the resilience of hillside farms showed significantly less damage and a faster recovery of farms that had adopted methods to support diversity and soil and water conservation like reduced tillage, cover crops, mixed cropping, agroforestry and the use of organic fertilizers and pesticides.[57,98] The positive effect of these more sustainable agricultural management systems on their fast recovery, compared to farms managed conventionally, even increased in areas that were hit more intensively by the hurricane.

Alternative and diverse agricultural strategies achieve medium to high levels of productivity by manipulating and exploiting resources that are mainly internal to the farm, only integrating necessary external inputs such as varieties and seeds that can broaden the diversity and genetic base of the system.[99,100]

Does resilience at a smaller scale feed into resilience at a larger scale?

As the previous sections have shown, resilience can be a useful indicator to describe important aspects of health in a more comprehensive way than many other concepts have done so far within each of the disciplines. However, it is important to be aware of the scale at which the concept is applied, and how it is adopted. Can resilience be used, for example, to describe both the health of an individual organism and a community or ecosystem, or even the entire planet?

Every individual organism (e.g. a plant, an animal, a fungus) can indeed be regarded as an ecosystem, consisting of entire communities and networks of microorganisms and their interactions. For example, take the symbiotic relationship of microbial communities colonizing the digestive system of vertebrates. This remarkable number and diversity of microorganisms provide efficient and highly specific immune responses on a wide range and levels of threats, and support the maintenance of immune homeostasis of the host.[101] Health and particularly resilience is to a large extent determined by these communities of microbes, not by the individual organism – it is the health of the community.[102] Similarly, Berendsen and colleagues state that the complex microorganism communities of the plant, above and particularly below ground, are crucial for plant health.[5]

Furthermore, it needs to be determined if it is possible to draw the concept of resilience further and apply it on larger systems such as the Ural Mountains, the Amazon, the South Pacific or all the way up to a global scale – the Earth, as one global ecosystem. Does it apply similarly, for example, to local communities and economies, political regions, countries and the world? Up to what scope does resilience maintain its importance as indicator and descriptor of health and where are its limits; from what level do indicators of health switch to other properties like productivity, function or performance?

Although first trends of slower growth rates and increased environmental awareness are slowly starting to appear in certain regions,[103] the still growing human population threatens global environmental resources such as soil, water and air; and on the other hand, climate change and the expanding human population increase also the risk of transmission of infectious and non-infectious diseases.[104] This general direction raises doubts regarding the resilience of the Earth and especially of human civilization, and at what cost future growth might come. Although humans have been facing a changing climate and various environmental impacts for thousands of years, it is questionable whether they share the ability to cope with ever wider fluctuating, and more rapidly changing conditions, and where the limits are of the adaptability of humans and the environment.[104]

Kovats and Butler[105] foresee a future where changing environmental conditions threaten some of the scientific, technological and social progress that has led to the large increase in global human life expectancy since the 1950s, stating that environmental changes will pose the largest threat to human health. They argue that through the development of adequate technologies, research, policies and lifestyles (e.g. adapted land-use strategies or changes in human diets), large improvements can be achieved on both human and environmental health. Further, Lal proposes that new restorative land-use strategies and policies on adapted management practices need to be implemented, adding that payments for ecosystem services and the protection of public goods may enhance ecological intensification of agriculture in poorer areas. Also changes in dietary habits, for example the reduction of animal-based ingredients in the human diet (mainly in Western and Westernized countries), are a requirement for the successful adaptation to these future trends.[106]

Kelley concludes that environmental hazard mitigation or planned adaptation is likely to be the main contribution to human and environmental resilience in the future, emphasizing the need to take wider ranges of both natural and anthropogenic changes (e.g. climate change, rising sea levels, food scarcity, soil degradation, terrorism) into account, to support adaptation to these influences.[104]

CONCLUSIONS AND FUTURE PERSPECTIVES

Resilience is a dynamic and relevant criterion of health across all levels and areas of agriculture.

Despite some variations in the understanding of resilience in different disciplines, resilience can be used as a link between the domains of soil, plant, animal, human and ecosystem health.

As a concept, resilience is likely to become more important in the presence of climate changes, both in semi-natural and agricultural ecosystems,[107,108] but also for human health.[109] To comprehend 'resilience' in more depth, we need to understand how organisms and systems can change and move between different phases and in adaptive cycles, and in this way restructure, adapt to change and become robust and interact with their surroundings.[110] To achieve this, we envisage that four points will need to be addressed by future research.

1. *Spatial and temporal scaling*. If resilience is a scale-independent property, ecosystem resilience can be expected to be composed by the resilience of the ecosystem components. If, instead, resilience is an emergent property, the resilience at a certain level may be partly dependent, but not entirely explainable, by the resilience of the sub-components. To make progress in linking the health of different domains and scaling up from the

health of plants to the wellbeing of animals and ecosystems, there is the need for empirical analyses of health and resilience at different spatial scales of observation.[111]

2. *Diversity*. The diversity of study systems is essential in providing variation in the investigated variables so as to discern which factors are relevant for health and resilience. Moreover, diversity (at genetic, species, ecosystem and cultural level) is a key factor for maintaining resilience across domains.[112–116]
3. *Networks*. Network resilience has been rarely explored but could be essential to improve future management strategies in agriculture.[117,118]
4. *Stakeholder involvement*. To overcome the uncertainty inherent in model outcomes and risk assessments, there is a need for enhanced collaboration among stakeholders in developing strategies for resilience.[119] A diversity of approaches (from fieldwork to participatory approaches, from meta-analysis to simulation modelling)[120–123] and a commitment to long-term research is an important component of strategies to make land use and ecosystem management more resilient.[82,124,125]

Research alone, however, cannot improve resilience in agricultural and food systems. Increased pressures on the world's food systems call for a reorganization, but also for moving towards a worldwide 'sustainable intensification' of agriculture and food production. While views on the best ways to implement sustainable intensification diverge,[126,127] such a target will necessarily affect the whole production line from soil fertility to agricultural system development and community involvement, and must turn the potential negative consequences of food production on the environment into resilient agricultural and food systems.

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