Review

Received: 7 August 2013 Revised: 16 April 2014 Accepted article published: 28 April 2014 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.6708

Assessing health in agriculture – towards a common research framework for soils, plants, animals, humans and ecosystems

Anja Vieweger[a*] and Thomas F Döring[a,b]

Abstract

In agriculture and food systems, health-related research includes a vast diversity of topics. Nutritional, toxicological, pharmacological, epidemiological, behavioural, sociological, economic and political methods are used to study health in the five domains of soils, plants, livestock, humans and ecosystems. An idea developed in the early founding days of organic agriculture stated that the health of all domains is one and indivisible. Here we show that recent research reveals the existence and complex nature of such health links among domains. However, studies of health aspects in agriculture are often separated by disciplinary boundaries. This restrains the understanding of health in agricultural systems. Therefore we explore the opportunities and limitations of bringing perspectives together from the different domains. We review current approaches to define and assess health in agricultural contexts, comparing the state of the art of commonly used approaches and bringing together the presently disconnected debates in soil science, plant science, veterinary science and human medicine. Based on a qualitative literature analysis, we suggest that many health criteria fall into two paradigms: (1) the Growth Paradigm, where terms are primarily oriented towards continued growth; (2) the Boundary Paradigm, where terms focus on maintaining or coming back to a status quo, recognising system boundaries. Scientific health assessments in agricultural and food systems need to be explicit in terms of their position on the continuum between Growth Paradigm and Boundary Paradigm. Finally, we identify areas and concepts for a future direction of health assessment and research in agricultural and food systems.

Supporting information may be found in the online version of this article.

Keywords: agriculture; criterion; food; health; operationalisation

INTRODUCTION

More than seven decades ago, the British farmer and campaigner Lady Eve Balfour published what became one of the founding documents of the organic agriculture movement.[1] Her book, entitled *The Living Soil*, was written following the publication of several studies that had shown the effects of diet and nutrition on human health.[2,3] In this context, one of Balfour's key statements was that 'the health of soil, plant, animal and man is one and indivisible'. According to this statement, the promotion and maintenance of human health, as one of the highest goals of humankind, critically depends on the health in the other agricultural domains, namely soils, plants and animals.

Balfour's indivisibility statement, i.e. that the various domains of health cannot be separated from each other, can be understood in two ways. First, it can be interpreted as a *non-separation imperative*: there can be no overall health in the agricultural system if there is ill health in any one domain. Studying health, therefore, always requires referring to the whole system. Whenever health is considered in one domain, the other domains should not be disregarded.

The second interpretation of Balfour's statement could be called the *connectivity hypothesis*. According to this reading, there is a mechanism that links the health of various domains together, transmitting health from one domain to another.[4] Indeed, Eve Balfour was involved in a long-term experiment that attempted to test this hypothesis of health transmission, the Haughly Experiment.[1] Started in 1939 in Haughley Green, Suffolk, UK, this comparative study of organic and conventional food systems assessed the links between health and nutrition, comparing nutritional values, vitality and health-promoting attributes of the produced food, in particular relation to soil fertility and its biological aspects. While the experiment remained ultimately inconclusive in terms of the tested hypothesis, both interpretations of the indivisibility statement call for a joint consideration of health in agriculture, bringing the different domains together.

Traditionally, however, the issues of health have been debated separately for each domain.[4] In this paper we examine the possibilities and consequences of weaving strands from the different domains together. While some efforts have been made in the recent past to bring animal and human medicine closer together

* Correspondence to: Anja Vieweger, Organic Research Centre, Elm Farm, Hamstead Marshall, Newbury, Berkshire, RG20 0HR, UK. E-mail: anja.v@organicresearchcentre.com

a Organic Research Centre, Elm Farm, Hamstead Marshall, Newbury, Berkshire RG20 0HR, UK

b Faculty of Agriculture and Horticulture, Humboldt University Berlin, Albrecht Thaer-Weg 5, D-14195 Berlin, Germany

through the 'One Health' paradigm,[5,6] further links among the domains have been left largely underexplored.

In this task of linking up the different domains of health in agriculture, a central question is how these domains describe health, i.e. what criteria and descriptors of health they use. This question is so essential because the promotion and improvement of health critically depends on the way in which health is defined, measured, assessed or monitored.

Looking at the five agricultural domains of humans, animals, plants, soils and ecosystems, we begin the paper by comparing the ways in which these domains motivate and justify the promotion of health in their respective subject. We then give an overview of current and emerging research questions on health in agricultural contexts. In the following part we consider the operationalisation of health, investigating criteria used to assess and describe health in the five domains with a quantitative survey in the current scientific literature. Based on the results of this survey, we ask whether the operationalisation of health should be harmonised among the five domains. Finally we discuss ways in which data on health in agricultural systems can be aggregated across these domains to ultimately arrive at a joint and more comprehensive assessment of health.

MOTIVATIONS FOR PROMOTING HEALTH IN AGRICULTURAL CONTEXTS

The issue of justifying health

All activities that refer to health in agriculture, including research activities and actions for research implementation, have their own specific motivation. In other words, the goal to maintain, improve or promote health always follows a rationale. However, in communications on health research, such rationales are not always made explicit. As we show here, though, it is important to do so, i.e. to openly give reasons for the promotion of health, especially when different domains of health are brought together. This is mainly because the issue of justification, i.e. the question why health should be promoted at all, is solved in different ways by the different domains.

Motivations for promoting health differ among domains

Health, as we are saying, is among the highest goals of humanity. Many people might read this as referring to human health only. In fact, human health is subordinate to few other goals, for some not even to survival. In the other domains, however, the promotion of health is less absolute, and rationales for promoting health differ. While the philosophical concepts and arguments in this context are manifold and complex,[7] two broad approaches to justify the promotion of health can be distinguished in a simplified way.[4] In an *anthropocentric* view the value of soils, plants and animals is seen in the services they provide to humankind, and their health is to be promoted only because of these beneficial services. A contrasting *biocentric* perspective recognises values inherent in the animal, plant, soil or ecosystem, apart from any functions that may be useful for humanity.

The debates on soil health, plant health, animal health and ecosystem health gravitate towards different positions on the anthropocentric–biocentric continuum because of the different nature of their subjects. For example, less inherent value is often ascribed to soils than to animals, since animals, but not soils, are seen as organisms with self-interest. Therefore the predominant, if not the only, justification for protecting soil health is anthropocentric: it refers to the services to humankind that the soil provides. These services build on various functions of the soil (such as supporting agricultural productivity or, interestingly, supporting plant health). In contrast, the justification for promoting animal health, though often resting on a productivist view, often has biocentric elements, in arguing with the need to avoid unnecessary suffering in animals.[8]

Not only for animal health but also for plant health, the biocentric view constitutes a potential alternative to anthropocentrism. Plants and animals can be seen to have interests; actions to promote health in plants and animals would therefore be justified as being for the sake of the living organism. However, this biocentric view is problematic, partly because one has to justify why the interests of a plant or livestock animal are preferred over the interests of a pathogen or pest that is attacking the plant or animal and damaging its health. This issue is difficult to solve without resorting to anthropocentric reasoning. Therefore, and because the promotion of health in agriculture is often mainly based on a perspective focused on productivity, the mainstream literature justifies plant and animal health in an anthropocentric way.

Biocentrists cannot explain why pests are less valuable than the plants and animals they attack. Yet, this argument would not be valid for the two domains of soils and ecosystems (in the following considerations we refer to soil, but similar arguments can be made for ecosystems). First, there are no direct antagonists to soils, attacking their health. Second, soils, though containing organisms, *are not* organisms. Nevertheless, there are several weak points of a biocentric (or, more precisely, non-anthropocentric) view for justifying soil health. As soils are not individuals, where do they begin and end? How and to which unit would interests then be assigned? The soil is difficult to be seen as an entity with interests in the way of defending its own life.[9]

On the other hand, a purely anthropocentric view has its drawbacks too. It may be seen to be too 'cold-hearted' and therefore may fail to be inspirational, so that it actually does not result in effective protection of soil health in practice. When soil health is solely justified with the services that soil provides to humans, there is indeed the risk that functions associated with soil health are traded against each other, because the subject soil has no absolute value in this view. Ironically and paradoxically, a quasi-non-anthropocentric view may thus lead to a better protection (in the long term) of human interests. Soil health would be promoted for the sake of the soil, knowingly accepting the philosophical inconsistency that the soil, although no self-interest can be attributed to it, has an absolute value. This non-anthropocentric perspective would introduce an element of caution, care and restraint in soil management.

So, even in the absence of visible or measurable or yet-to-be-determined changes to functionality of soil for human uses, the view that soil health should be promoted for its own sake can be made valid. With an absolute value assigned to soil and soil health, independent of functions that are relevant to humans, there would be less soil loss or destruction.

Joining up the domains

As we have shown, there are different possibilities of justifying health in the different domains. When health is viewed across all domains together, i.e. when there is a more holistic view of health within an agricultural system such as a farm, the justifications of health need to be brought together. An example that highlights this need is provided by the case of plant growth-promoting microorganisms; some species, e.g. *Pantoea agglomerans*, promote plant health but negatively affect human health.[10]

Such conflicts can only be dealt with in an open dialogue among different disciplines, clarifying the hierarchies of aims. Also, these conflicts cannot be solved in a theoretical way, once and for all, but need to be negotiated on a case-by-case basis. It is important for agents from all domains to understand why the health of other domains is promoted; here the understanding of other domains' health problems does not so much refer to mechanisms but to ultimate goals. Only then is it possible to find solutions for a whole agricultural and food system.

RESEARCH QUESTIONS IN THE INTERSECTION BETWEEN HEALTH AND AGRICULTURE

The relevance of health in agriculture in the five domains of health

Health research in agricultural contexts comprises a tremendous diversity of topics. According to methodology and discipline, these can be grouped into eight approaches, namely (1) nutritional, (2) toxicological, (3) pharmacological, (4) epidemiological, (5) cognitive and behavioural, (6) cultural, (7) economic and (8) political (Table 1). In each of the domains of soil, plant, animal, human and ecosystem health, all of these methodological approaches are represented, with the exception of cognitive approaches to soil and ecosystem health. Not all of these research topics receive the same level of attention, and the focus of research has shifted substantially over the past few years.

In this very dynamic research area, current research trends include (1) the relationships between human diet, food systems and obesity[11–13] (following the recognition that humanity faces a global epidemic of obesity and overweight in both developed and developing countries and in both adults and children), (2) the relationship between aging and diet[14,15] (following the analysis of current and predicted future demographic developments of increasingly aging populations), (3) the relationship between global climate change and health of soils,[16] plants,[17] animals[18] and humans[19] and (4) health aspects of urban and peri-urban farming[20,21] in the wake of the global trend of ever-increasing urbanisation. While these research topics are responding to external drivers, there are further emerging research areas that are driven by current advances in research methods. These include (5) nutrigenomics and individualised interactions between genome and diet[22] and (6) the epigenetics of health.[23,24]

Although these dynamic topics are certain to receive increasing interest over the coming years, and some of them need to be addressed with the utmost urgency, it should not be forgotten that there is a multitude of additional important health-related problems in agriculture that are still unresolved, including health effects of agrichemicals,[25,26] appropriate housing systems for promoting livestock health,[27–29] contamination of agricultural soils and other causes of deteriorating soil health, and optimisation of ecosystem services for the regulation of plant or livestock pests and diseases.

Thus there is still some hard research work to do to deliver solutions for agricultural practice, comparing different agricultural management options and different agricultural systems for their health effects in soils, plants, animals, humans and ecosystems. These tasks will not go away with the emergence of novel research topics; in research prioritisation it is therefore important not to exclusively judge research questions on the basis of their novelty.

Linking health research across the domains

There are several ways in which the domains of soil, plant, animal, human and ecosystem health can be linked up. The most obvious way of linking the domains is by following one disciplinary topic, e.g. nutrition, along the production chain, working through all domains. This can be done by tracking the fate of nutrients (e.g. nitrogen) and assessing their effects on health in the different domains.

Another relatively straightforward example of the possibility to link research across the domains is to focus on specific toxins. Many toxins, including heavy metals and certain organic chemicals such as dioxins, have negative health effects in all five domains.[30] Ozone is another toxin with health effects across domains.[31]

The benefits of studying the effects of toxins or nutrients in more than one domain of health are threefold, referring to basic research, agricultural practice and risk monitoring. First, comparing the response to specific chemicals between microbes, plants, animals and humans will deepen the understanding of the physiology of health in all domains. For example, it was recently found that the physiological pathways of detecting cadmium are similar in animals and plants.[32] Also, new insights into toxicities of chemicals in livestock will help to assess risks for humans; for example, knowledge about toxicokinetics in animals is expected to reduce uncertainties about toxin levels in food.[33] Second, managing nutrients and toxins in agricultural and food systems will inevitably affect all domains; for a comprehensive assessment of agricultural management options it is therefore necessary to study effects across domains. It is also possible that there are interactions among the domains, i.e. the response of one domain to the nutrient or toxin affecting the next. Third, the information from feed quality monitoring can be included in controls of food quality, thereby facilitating the application of a risk-based approach through the targeted analysis of animal products.[33]

As Table 1 shows, the health links between the domains are more diverse than the material flows of nutrients and toxins through the food chain, and possibly messier than Eve Balfour may have anticipated in the 1940s. Here we highlight three additional types of links.

First, *microbial organisms* are an important component for determining health in all domains, in terms of both health promotion and causing ill health. e.g. for diet and human health.[14] Well-known cases of linkage between the domains include the fact that some pathogens are shared by livestock and humans[5] and that soil microbes can affect plant health by interfering with plant resistance against pathogens or nutrient uptake.[34] However, recent research shows that microbial links of the domains go much further than previously thought. For example, microbial species such as *Salmonella enterica* that are pathogenic for humans are also found on fresh food plants.[35] Further, the survival of human pathogenic bacteria in the soil was found to be affected by soil properties, by manure management[36] and by the composition of the diet fed to the cattle that produced the manure.[37] Remarkably, *S. enterica* is not only able to ingress and colonise tomato plants,[38] but organic soil management was also found to reduce this internal colonisation.[39]

Second, the management of *biodiversity* as a general approach to solve health problems in agricultural contexts provides a link of the domains.[40] Greater biological diversity has been found to promote soil health,[41,42] plant health,[43,44] animal health[45] and human health[46] and has been used as an indicator of ecosystem health.[47] Linking research across the domains therefore offers

Table 1. Intersections of health and agriculture: research topics grouped by domain and methodological approach

	Domain					
Approach	Human health	Animal health	Plant health	Soil health	Ecosystem health	Elements linking domains
Nutritional	Quality and quantity of agricultural produce[40,57] (e.g. vitamins, minerals, secondary plant metabolites, trace elements)	Quality and quantity of feed[58]	Effects of macro- and micronutrients on plant health; nutrient deficiencies in plants	Feeding the soil; carbon cycles and microbial communities	Nutrient cycles and balances	• Nutrients,[59] toxins,[33,60–62] drugs;[63,64] • physiological mechanisms common to subjects of different domains;[32] • microbial communities inhabiting subjects of different domains;[38] • antibiotic resistance in zoonotic pathogens
Toxicological	Toxins in food[65] (e.g. pesticide residues, mycotoxins, antinutritional factors); direct exposure to toxins[66] (e.g. pesticides); tobacco and other drugs[67]	Toxins in feed;[62] direct exposure of livestock to toxins (for examples, see human health)	Herbicide damage to crops;[68] toxic levels of elements in the soil (e.g. Al)	Soil contamination[30] (e.g. heavy metals); acidification	Contamination of ecosystems (e.g. persistent organic chemicals, eutrophication)	
Pharmacological	Pharming of plants and animals;[69] agricultural production of medicinal plants for human health[70]	Drugs for treating livestock; self-medication of livestock[71]	Plant extracts for protecting plants against pests and diseases	Effects of medicinal plants or drugs on soil health	Effects of pharming or production of medicinal plants on ecosystem health[72]	
Epidemiological	Epidemiology of diet-related illnesses;[73] epidemiology of illnesses related to agricultural toxins[74]	Epidemiology of livestock diseases and parasites[75]	Epidemiology of plant diseases and pests[76,77]		Regulation of plant or livestock pests and diseases as an ecosystem service	• Epidemiological modelling;[76,78] • transmittable diseases shared by farm animals and humans[5,6,50,79]
Cognitive and behavioural	Care farms: agricultural and horticultural work for treating mental illnesses;[80] neurobehavioural toxicity of agrichemicals[26]	Welfare and behaviour; housing conditions of livestock[81] (e.g. free-range)	Plant behaviour[82] as part of plant health			• Concepts of behaviour; • health effects of relationship between livestock and humans[81]
Cultural	Food as part of lifestyle and food culture;[83,84] recreation in agricultural landscapes; cultural differences in health concepts[85]	Cultural differences in perception of livestock health;[81] religious aspects of treating livestock	Cultural differences in perception of plant health[4]	Cultural differences in perception of soil health	Cultural differences in perception of ecosystem health; recreation in agricultural landscapes as an ecosystem service	• Cultural paradigms[86]
Political (legislation and policies)	Occupational health of farm workers;[87,88] food safety regulations;[89] food taxes and policies;[83,90] global value chains[91]	Animal health regulations	Plant health regulations[92] (e.g. quarantine and trade restrictions)	Policies on soil protection	Regulations on ecosystem contamination	• Common policies and regulations;[93] • approaches to risk assessment
Economic	Economic costs and benefits associated with food system management affecting human, animal, plant, soil and ecosystem health					• Econometric methods

opportunities to elucidate general mechanisms of how biodiversity affects various components of health. At the same time, synergies and trade-offs of managing biodiversity in agricultural practice can be established in more integrated and more meaningful ways.

Third, there are structural links associated with the *food system*. For example, increased consumption of meat products has well-established negative effects on human health;[48,49] at the same time, increased demand for these products has led to more intensive livestock production, with (indirect) negative effects on both human and animal health.[50] Even plant health and soil health have been affected by these developments, again indirectly, through the simplification of crop rotations[51] as the demand for grain as animal feed has increased, and short-term grass-based leys used as pastures have largely disappeared from intensive rotations.

ASSESSING HEALTH: DEFINITIONS AND CRITERIA

Thus far we have dealt with the question of what the research focus should be when investigating health in agriculture and food systems, and how health-related research questions can be enriched by integrating perspectives from the different domains. Once the research questions and the problem to be tackled are defined, however, the crucial next step is the operationalisation of health. How should health be assessed and measured? What are appropriate criteria of health when dealing with multiple disciplines? As we show below, the disciplines of soil science, plant pathology, veterinary science, human medicine and ecology have answered these questions in different ways. First, though, we briefly explain what we mean by a criterion of health.

The relationship between definitions and criteria of health

In any deeper discussion about the topic of health in agriculture, there is and will always be the question 'What is health?'. Once this question is raised, the way the discussion often goes is to look for a *definition* of health, short and succinct; in other words, a definition apt for a dictionary. However, because the concept of health is so complex, it is impossible to give a satisfying dictionary definition that is not too concise (restrictive) and not too vague (difficult to operationalise).[4]

However, to test the connectivity hypothesis (see above) and also to optimise and improve agricultural and food systems towards increased health, it is crucial to measure health or, if it is not measurable, to find an alternative way of assessing health. We could start with a definition of health and then ask how it is operationalised, i.e. translated into criteria and then into procedures for measurement. This would be a top-down approach. Given the problems of finding a definition of health, however, the process could also follow a bottom-up approach, i.e. the 'definition' of health is at the end of the process, trying to capture the essentials of the measurement programme. In this case, any particular health concept can be described meaningfully through its operationalisation and measuring procedure.

Thus criteria of health are half-way between concrete measuring or assessment procedures and an abstract definition of health. Criteria of health are sub-concepts of health that together form the concept of health. Useful criteria of health should be translatable into an operable procedure that allows the comparison of different subjects (e.g. different plants or animals).

Criteria of health in the five domains of health

To study what criteria of health are currently used in the five domains of soils, plants, animals, humans and ecosystems, we conducted a content analysis of 50 recently published scientific texts, ten from each domain. The analysis of these texts was used to gain a first insight into the concepts and ideas used most frequently to describe and define health in the various domains.

Using the content analysis programme QSR NVivo10, we coded 50 texts of the scientific health literature published mainly between 2000 and 2013. Sections within the papers were selected for coding when they defined or described health in their specific domain. References of all coded papers are given in 'Supporting information'. The coding system was developed using 48 terms, examples being 'balance', 'coping', 'immunity', 'regeneration' and 'tolerance'; for the full list, see 'Supporting information'. The list of terms was based on views expressed during an interdisciplinary and international expert workshop on health concepts conducted by the authors.[52] After NVivo identified and highlighted the predefined terms used in the selected texts, the terms were coded (scored) on a five-point scale by one of the authors (AV) to rate how strongly the authors of the selected text describe the term as a suitable criterion of health (for definitions of scores, see 'Supporting information'). The coding system was found to be robust against change of the coding person, following a test of inter-coder agreement; this was based on the coding of ten papers by both authors of this paper (AV and TFD). Here we present the frequency of terms coded with the highest score, i.e. the terms most clearly used as criteria of health.

According to our analysis, terms used most frequently to describe health in the 50 papers are partly shared among the different domains; however, there are also considerable differences (Table 2). The terms 'function', 'maintenance' and 'resilience' are used in all five domains. Other terms are frequently used in one domain ('resistance' in plant health, 'sustainability' in soil health) but much less frequently or not at all used in the other domains. Still others were found to be used very infrequently as criteria of health (such as 'normality', 'coping', 'wholeness') despite there being a considerable amount of literature on the respective topics. This indicates that the number of papers analysed here is likely to be too small to cover the entire diversity of health definitions. However, this very diversity is also reflected in the analysis, since we found that overall 40 different terms are used in one way or another as criteria of health. In each domain the authors of the selected texts used 20 or more different criteria to describe health, with the exception of animal health, where we found only ten different terms.

As our results show, many of the criteria are not used across all domains. We interpret this as a sign of domain-specific concepts of health being used and different 'languages' being spoken. Therefore, setting up a common concept of health for agricultural and food systems faces difficulties of communication and terminology. However, the trends identified in this analysis also show that there are some similarities of concepts and shared criteria to describe health in the different domains. Our results further indicate and confirm that one of the most promising might be the concept of resilience,[53] which is among the most frequently used criteria when considering all domains together.

We can go one step further by classifying the terms used as criteria of health into three paradigms: (1) the Growth Paradigm, where terms are included that are, at least potentially, oriented towards continued growth and increase ('efficiency', 'fitness', 'output', 'performance', 'productivity'); (2) the Boundary Paradigm,

Table 2. Criteria of health according to a content analysis of 50 papers (ten in each domain: soil health, plant health, animal health, human health and ecosystem health)[a]

	Number of papers (out of 10)					
Term	Soil	Plant	Animal	Human	Ecosystem	Count overall domains
Function	6	3	1	4	3	17
Maintenance	6	3	3	2	2	16
Resilience	2	1	2	3	5	13
Productivity	7	1	2	2	0	12
Capacity	6	1	0	2	3	12
Resistance	3	7	2	0	0	12
Sustainability	7	0	1	2	0	10
Wellbeing	0	0	2	4	3	9
Diversity	3	2	0	1	0	6
Dynamic	3	0	0	1	2	6
Adaptation	1	1	0	3	1	6
Integrity	1	1	0	1	2	5
Complexity	1	2	0	0	1	4
Equilibrium	0	1	0	1	2	4
Survival	2	2	0	0	0	4
Stability	3	0	0	0	1	4
Tolerance	1	1	1	0	1	4
Vitality	3	1	0	0	0	4
Naturalness	0	0	0	1	2	3
Balance	0	1	0	1	1	3
Performance	0	2	0	1	0	3
Recovery	1	0	1	1	0	3
Provision	1	1	0	0	0	2
Efficiency	1	1	0	0	0	2
Immunity	0	1	0	1	0	2
Coping	0	0	0	2	0	2
Normality	0	1	0	0	1	2
Welfare	0	1	1	0	0	2
Homeostasis	0	0	0	1	1	2
Sum over all terms	60	36	16	38	35	185
Count over all terms	21	22	10	23	20	40

[a] The table gives the number of papers in each domain using the term as a criterion of health; terms listed are mentioned in at least two papers. In addition, there were terms that are mentioned in only one paper (ecosystem health: wholeness, regeneration, self-maintenance, self-regulation; human health: resource, restoration, allostasis, self-management; plant health: vigour; soil health: fitness, output) or not mentioned at all (freedom, harmony, quality of life, self-healing, self-organisation). Overall sums and counts include terms that appeared in only one paper. For references, see 'Supporting information'.

where terms focus on maintaining or coming back to a status quo, recognising, at least implicitly, some boundaries of the system ('equilibrium', 'homoeostasis', 'maintenance', 'recovery', 'regeneration', 'resilience', 'sustainability'); (3) all other terms that cannot be assigned to either of the two previous paradigms (e.g. 'function', 'wellbeing', 'welfare').

While this classification is certainly still of a preliminary nature and needs to be validated for semantic robustness, it may already help to suggest some differences in the general approaches used to describe health in the five domains. For example, in soil health and plant health, criteria appear to be more strongly oriented towards the Growth Paradigm than in human or ecosystem health, whereas animal health takes an intermediate position. The main point here is that the Growth Paradigm and the Boundary Paradigm have dramatically different consequences for the way health is assessed and therefore also for the ways in which departures from health will be treated. Therefore we suggest that scientific health assessments in agricultural and food systems would benefit from being explicit in terms of their position on the continuum between Growth Paradigm and Boundary Paradigm.

Harmonising the assessment of health across the domains?

Above we have shown that bringing the domains of health together in interdisciplinary research projects offers the production of new insights and solutions to health-related problems in agriculture and food systems. Is it also useful to harmonise the assessment and operationalisation of health across the different domains? For several reasons, this appears to be difficult. First, the same words may be used (as criteria of health) but these words may have different meanings in the different domains (and, on another level, in different languages). Second, criteria in the different domains are necessarily somewhat independent from each other, because they need to take into account the particularities of each domain. A good example is welfare in animal health: this concept cannot be adopted in the domains of soils or ecosystems.

Despite these difficulties, one benefit of bringing the domains together by analysing the way they describe health is that it reveals and may change common thinking about food system output and underlying paradigms. For example, it may indeed be useful for soil scientists to know what the criteria are for plant health or animal health, because it helps them to question their own criteria in terms of completeness, appropriateness and underlying paradigms; it adds flexibility and shows that criteria of health are not fixed in stone; it inspires the use of novel approaches; and it is necessary in a food system study because clear terminology is needed, i.e. the differences in the use of words need to be made explicit to avoid confusion.

Thus criteria of health need to be chosen in accordance with the domain's particular requirements. An attempt to use the same or similar sets of criteria in all domains (in a cross-domain study) would be pointless or impossible. However, there is the chance to achieve more clarity and common ground among the domains by explicitly stating and justifying the paradigms underlying the chosen criteria. The choice and explicit statement of the paradigm is important already in single-domain studies, but it is even more critical in cross-domain research because the choice can have an effect on the study design, e.g. the experimental set-up.

Synthesis: aggregating and evaluating data from different domains

The multitude of definitions and criteria of health in each domain raises the question of how the operationalisation of health in cross-domain research can avoid arbitrariness and ensure robustness and objectivity. Stakeholder involvement and open dialogue will be key in achieving these aims. Also, when bringing the different domains together, a suitable methodology to aggregate data is needed. In fact, one of the most important considerations when collecting and aggregating data from multiple sources and disciplines is to ensure that comparable and reliable data are aggregated, that assessments are conducted using the same or comparable units, sample sizes, scales or frequencies, etc. This can pose immense difficulties when the specific framework is not agreed upon beforehand, for example when health assessments in different domains are undertaken on different levels, in isolation from other disciplines and without consideration of a potential joint analysis.

In addition, agreed evaluation strategies of systems or management options need to be identified before the research is undertaken. In the case of interdisciplinary health-related cross-domain research this is particularly difficult, since multiple criteria are used and multiple stakeholders may have different views about the evaluation of results. One possible approach for aggregating data and arriving at a joint assessment is the use of outranking methods,[54] though other tools are available too.[55,56]

CONCLUSIONS

One of the main conclusions we draw from our review is that an intensified interdisciplinary *dialogue* of relevant disciplines, including soil science, plant pathology, veterinary science and human medicine, is a necessary and overdue step towards a more integrated and more comprehensive understanding of health in agriculture. In fact, if we take the goal to promote health seriously, then research in agricultural and food systems will need to completely refocus. The multitude of health links between soils, plants, animals and humans calls into question all monodisciplinary research on health in agricultural and food systems. In interdisciplinary health research the role of biodiversity, the promotion of beneficial microbial communities and the integrated consideration of the living soil will be key to the success of this approach. An interdisciplinary dialogue will not only be needed to clarify the hierarchy of underlying research aims so that agricultural and food systems can be designed and redesigned for the health of all, it will also reveal new promising research avenues to explore the fascinating ways in which the 'healths' of soils, plants, animals, humans and ecosystems are connected. These new insights are urgently needed to design agricultural systems that use health synergisms between the different domains.

Finally, a practical rather than purely research-based approach to a dialogue among domains could further strengthen the communication of health connections and improve health assessment in agricultural systems and food chains. Here a clear identification and demonstration of health effects, links and connectivity among the different domains is needed. Ultimately, a better understanding of health gained through research approaches needs to be translated and implemented into explicit working methods for health promotion. This could for example take the form of adapted rules and regulations for agriculture. If formulated in an applied and clear form, standards and guidelines can ensure the comprehensive integration of health promotion and maintenance into agricultural practices.

ACKNOWLEDGEMENTS

We thank the Ekhaga Foundation (Sweden) for funding this research. We also thank participants of two international workshops on health in agriculture for insights and discussions, namely Chris Aukland, Kirsten Brandt, Maria Finckh, Machteld Huber, Marthe Kiley-Worthington, Elselijn Kingma, Paul Mäder, Marco Pautasso, Angelika Ploeger, Michael Shaw, Elisabeth Stockdale, Christopher Stopes, Bruno Taupier-Letage, Mette Vaarst, Ariena van Bruggen, Andrew Whitley, Martin Wolfe and Lawrence Woodward.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 Balfour EB, *The Living Soil*. Faber and Faber, London (1943).
2 McCarrison R, The relation of manure to the nutritive and vitamin value of certain grain. *Br Med J* **1**:567–569 (1924).
3 McCarrison R, Nutrition in health and disease. *Br Med J* **2**:611–615 (1936).
4 Döring TF, Pautasso M, Finckh MR and Wolfe MS, Concepts of plant health – reviewing and challenging the foundations of plant protection. *Plant Pathol* **61**:1–15 (2012).
5 Kahn LH, Kaplan B and Monath TP, 'One Health' in Action Series: Nos 1–8. *Vet Ital* **45**:195–208 (2009).
6 Fisman DN and Laupland KB, The 'One Health' paradigm: time for infectious diseases clinicians to take note? *Can J Infect Dis Med Microbiol* **21**:111–114 (2010).
7 Nordenfelt L, *Animal and Human Health and Welfare: a Comparative Philosophical Analysis*. CABI, Wallingford (2006).
8 Rollin BE, Annual Meeting Keynote Address: Animal agriculture and emerging social ethics for animals. *J Anim Sci* **82**:955–964 (2004).
9 Schweitzer A, *Kultur und Ethik – Kulturphilosophie Zweiter Teil*. C.H. Beck'sche Verlagsbuchhandlung, Munich (1923).
10 Dias T, Dukes A, Caldwell E and Antunes PM, Accounting for soil biotic effects on soil health and crop productivity in designing crop rotations. *J Sci Food Agric* (2014). DOI: 10.1002/jsfa.6565.

11 Popkin BM, Adair LS and Ng SW, Global nutrition transition and the pandemic of obesity in developing countries. *Nutr Rev* **70**:3–21 (2012).
12 Clark SE, Hawkes C, Murphy SM, Hansen-Kuhn KA and Wallinga D, Exporting obesity: US farm and trade policy and the transformation of the Mexican consumer food environment. *Int J Occup Environ Health* **18**:53–64 (2012).
13 McPhail D, Chapman GE and Beagan BL, The rural and the rotund? A critical interpretation of food deserts and rural adolescent obesity in the Canadian context. *Health Place* **22**:132–139 (2013).
14 Claesson MJ, Jeffery IB, Conde S, Power SE, O'Connor EM, Cusack S, *et al*, Gut microbiota composition correlates with diet and health in the elderly. *Nature* **488**:178–184 (2012).
15 Akbaraly T, Sabia S, Hagger-Johnson G, Tabak AG, Shipley MJ, Jokela M, *et al*, Does overall diet in midlife predict future aging phenotypes? A cohort study. *Am J Med* **126**:411–419 (2013).
16 Singh BP, Cowie AL and Chan KY, *Soil Health and Climate Change*. Springer, New York, NY (2011).
17 Pautasso M, Döring TF, Garbelotto M, Pellis L and Jeger MJ, Impacts of climate change on plant diseases – opinions and trends. *Eur J Plant Pathol* **133**:295–313 (2012).
18 Skuce PJ, Morgan ER, van Dijk J and Mitchell M, Animal health aspects of adaptation to climate change: beating the heat and parasites in a warming Europe. *Animal* **7**:333–345 (2013).
19 Balbus JMB, Boxall ABA, Fenske RA, McKone TE and Zeise L, Implications of global climate change for the assessment and management of human health risks of chemicals in the natural environment. *Environ Toxicol Chem* **32**:62–78 (2013).
20 Lente I, Keraita B, Drechsel P, Ofosu-Anim J and Brimah AK, Risk assessment of heavy-metal contamination on vegetables grown in long-term wastewater irrigated urban farming sites in Accra, *Ghana. Water Qual Expos Health* **4**:179–186 (2012).
21 Marsden T and Sonnino R, Human health and wellbeing and the sustainability of urban–regional food systems. *Curr Opin Environ Sustain* **4**:427–430 (2012).
22 Afman LA and Müller M, Human nutrigenomics of gene regulation by dietary fatty acids. *Prog Lipid Res* **51**:63–70 (2012).
23 Petronis A, Epigenetics as a unifying principle in the aetiology of complex traits and diseases. *Nature* **465**:721–727 (2010).
24 Collotta M, Bertazzi PA and Bollati V, Epigenetics and pesticides. *Toxicology* **307**:35–41 (2013).
25 Marin-Morales MA, de Campos Ventura-Camargo B and Hoshina MM, Toxicity of herbicides: impact on aquatic and soil biota and human health, in *Herbicides – Current Research and Case Studies in Use*, ed. by Price AJ and Kelton JA. InTech, Rijeka, Croatia, pp. 399–443 (2013). DOI: 10.5772/55851.
26 Ross SM, McManus IC, Harrison V and Mason O, Neurobehavioral problems following low-level exposure to organophosphate pesticides: a systematic and meta-analytic review. *Crit Rev Toxicol* **43**:21–44 (2013).
27 Vaarst M and Alrøe HF, Concepts of animal health and welfare in organic livestock systems. *J Agric Environ Ethics* **25**:333–347 (2012).
28 Aland A and Banhazi T, *Livestock Housing: Modern Management to Ensure Optimal Health and Welfare of Farm Animals*. Wageningen Academic Publishers, Wageningen (2013).
29 Simoneit C, Bender S and Koopmann R, Quantitative and qualitative overview and assessment of literature on animal health in organic farming between 1991 and 2011 – Part I: General and cattle. *vTI Agric Forest Res* **62**:97–104 (2012).
30 Alloway BJ, *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability*. Springer, New York, NY (2013).
31 Iriti M and Faoro F, Oxidative stress, the paradigm of ozone toxicity in plants and animals. *Water Air Soil Pollut* **187**:285–301 (2008).
32 Chmielowska-Bąk J and Deckert J, A common response to common danger? Comparison of animal and plant signaling pathways involved in cadmium sensing. *J Cell Commun Signal* **6**:191–204 (2012).
33 Dorne JLCM and Fink-Gremmels J, Human and animal health risk assessments of chemicals in the food chain: comparative aspects and future perspectives. *Toxicol Appl Pharmacol* **270**:187–195 (2013).
34 Workneh F and van Bruggen AHC, Microbial density, composition, and diversity in organically and conventionally managed rhizosphere soil in relation to suppression of corky root of tomatoes. *Appl Soil Ecol* **1**:219–230 (1994).
35 Franz E and Van Bruggen AHC, Ecology of *E. coli* O157:H7 and *Salmonella enterica* in the primary vegetable production chain. *Crit Rev Microbiol* **34**:143–161 (2008).
36 Franz E, Semenov AV, Termorshuizen AJ, de Vos OJ, Bokhorst JG and van Bruggen AHC, Manure-amended soil characteristics affecting the survival of *E. coli* O157:H7 in 36 Dutch soils. *Environ Microbiol* **10**:313–327 (2008).
37 Franz E, van Diepeningen AD, de Vos OJ and van Bruggen AHC, Effects of cattle feeding regimen and soil management type on the fate of *Escherichia coli* O157:H7 and *Salmonella enterica* serovar Typhimurium in manure, manure-amended soil, and lettuce. *Appl Environ Microbiol* **71**:6165–6174 (2005).
38 Gu G, Cevallos-Cevallos JM and van Bruggen AHC, Ingress of *Salmonella enterica* Typhimurium into tomato leaves through hydathodes. *PLoS ONE* **8**:e53470 (2013).
39 Gu G, Cevallos-Cevallos JM, Vallad GE and van Bruggen AHC, Organically managed soils reduce internal colonization of tomato plants by *Salmonella enterica* serovar Typhimurium. *Phytopathology* **103**:381–388 (2013).
40 Fanzo J, Hunter D, Borelli T and Mattei F, *Diversifying Food and Diets: Using Agricultural Biodiversity to Improve Nutrition and Health*. Routledge, Abingdon, UK (2013).
41 Zak DR, Holmes WE, White DC, Peacock AD and Tilman D, Plant diversity, soil microbial communities, and ecosystem function: are there any links? *Ecology* **84**:2042–2050 (2003).
42 Stefanowicz AM, Kapusta P, Szarek-Łukaszewska G, Grodzińska K, Niklińska M and Vogt RD, Soil fertility and plant diversity enhance microbial performance in metal-polluted soils. *Sci Total Environ* **439**:211–219 (2012).
43 Wolfe MS, Crop strength through diversity. *Nature* **406**:681–682 (2000).
44 Döring TF, Pautasso M, Finckh MR and Wolfe MS, Pest and disease management in organic farming: implications and inspirations for plant breeding, in *Organic Crop Breeding*, ed. by Lammerts van Bueren ET and Myers JR. Wiley-Blackwell, Hoboken, NY, pp. 39–59 (2012).
45 Yoshihara Y, Mizuno H, Yasue H, Purevdorj NO and Ito TY, Nomadic grazing improves the mineral balance of livestock through the intake of diverse plant species. *Anim Feed Sci Technol* **184**:80–85 (2013).
46 Dobson A, Cattadori I, Holt RD, Ostfeld RS, Keesing F, Krichbaum K, *et al*, Sacred cows and sympathetic squirrels: the importance of biological diversity to human health. *PLoS Med* **3**:e231 (2006).
47 Shea J, Kersten GJ, Puccia CM, Stanton AT, Stiso SN, Helgeson ES, *et al*, The use of parasites as indicators of ecosystem health as compared to insects in freshwater lakes of the Inland Northwest. *Ecol Indicat* **13**:184–188 (2012).
48 Willett WC and Stampfer MJ, Current evidence on healthy eating. *Annu Rev Publ Health* **34**:77–95 (2013).
49 Yip CSC, Crane G and Karnon J, Systematic review of reducing population meat consumption to reduce greenhouse gas emissions and obtain health benefits: effectiveness and models assessments. *Int J Publ Health* **58**:683–693 (2013).
50 Rabinowitz P and Conti L, Links among human health, animal health, and ecosystem health. *Annu Rev Publ Health* **34**:189–204 (2013).
51 Bennett AJ, Bending GD, Chandler D, Hilton S and Mills P, Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. *Biol Rev* **87**:52–71 (2012).
52 Vieweger A and Döring TF, Resilience: linking health in soils, plants, animals and people. *Org Res Cent Bull* **111**:11 (2012).
53 Döring TF, Vieweger A, Pautasso M, Vaarst M, Finckh MR and Wolfe MS, Resilience as a universal criterion of health. *J Sci Food Agric* **00**:000–000 (2014). DOI: 10.1002/jsfa.6565.
54 Kangas A, Kangas J and Pykäläinen J, Outranking methods as tools in strategic natural resources planning. *Silva Fennica* **35**:215–227 (2001).
55 Van der Werf HM and Zimmer C, An indicator of pesticide environmental impact based on a fuzzy expert system. *Chemosphere* **36**:2225–2249 (1998).
56 Marks LA and Dunn EG, Fuzzy multiple attribute evaluation of agricultural systems, in *Using Multi-criteria Decision Analysis in Natural Resource Management*, ed. by Herath G and Prato T. Ashgate Publishing, Aldershot, UK, pp. 119–137 (2006).
57 Martin C, Zhang Y, Tonelli C and Petroni K, Plants, diet, and health. *Annu Rev Plant Biol* **64**:19–46 (2013).

58 Ingvartsen KL and Moyes K, Nutrition, immune function and health of dairy cattle. *Animal* **7**(Suppl. 1):112–122 (2012).
59 Simpson SJ and Raubenheimer D, The nature of nutrition: a unifying framework. *Aust J Zool* **59**:350–368 (2011).
60 Mebs D, Occurrence and sequestration of toxins in food chains. *Toxicon* **36**:1519–1522 (1998).
61 Colborn T, vom Saal FS and Soto AM, Developmental effects of endocrine-disrupting chemicals in wildlife and humans. *Environ Health Perspect* **101**:378–384 (1993).
62 Streit E, Schatzmayr G, Tassis P, Tzika E, Marin D, Taranu I, *et al*, Current situation of mycotoxin contamination and co-occurrence in animal feed – focus on Europe. *Toxins* **4**:788–809 (2012).
63 Lecours N, Almeida GE, Abdallah JM and Novotny TE, Environmental health impacts of tobacco farming: a review of the literature. *Tobacco Control* **21**:191–196 (2012).
64 Wallinga D and Burch DGS, Does adding routine antibiotics to animal feed pose a serious risk to human health? *Br Med J* **347**:f4214 (2013).
65 Dabrowski WM and Sikorski ZE, *Toxins in Food*. CRC Press, Boca Raton, FL (2005).
66 Cherry N, Burstyn I, Beach J and Senthilselvan A, Mental health in Alberta grain farmers using pesticides over many years. *Occup Med* **62**:400–406 (2012).
67 Haustein KO and Groneberg D, *Tobacco or Health?* Springer, Heidelberg (2010).
68 Huang Y, Thomson SJ, Molin WT, Reddy KN and Yao H, Early detection of soybean plant injury from glyphosate by measuring chlorophyll reflectance and fluorescence. *J Agric Sci* **4**:117–124 (2012).
69 Lössl AG and Clarke JL, Conference Scene: Molecular pharming: manufacturing medicines in plants. *Immunotherapy* **5**:9–12 (2013).
70 Briskin DP, Medicinal plants and phytomedicines. Linking plant biochemistry and physiology to human health. *Plant Physiol* **124**:507–514 (2000).
71 Villalba JJ and Landau SY, Host behavior, environment and ability to self-medicate. *Small Ruminant Res* **103**:50–59 (2012).
72 Goven J, Campbell H, Cram F, Heinemann JA, Mackenzie A, Morris C, *et al*, Biopharming in New Zealand: risk and governance implications. *Constructive Conversations/Kōrero Whakaaetanga Research Report No. 19* (2009).
73 Reynolds K, Epidemiology of obesity and metabolic syndrome in China. *Curr Cardiovasc Risk Rep* **6**:109–111 (2012).
74 Koutros S, Freeman LEB, Lubin JH, Heltshe SL, Andreotti G, Barry KH, *et al*, Risk of total and aggressive prostate cancer and pesticide use in the Agricultural Health Study. *Am J Epidemiol* **177**:59–74 (2013).
75 Thrusfield M, *Veterinary Epidemiology* (3rd edn). Blackwell Science, Oxford, UK (2007).
76 Hughes G, *Application of Information Theory to Epidemiology*. American Phytopathological Society, St Paul, MN (2012).
77 Jeger M, Chen Z, Cunningham E, Martin G and Powell G, Population biology and epidemiology of plant virus epidemics: from tripartite to tritrophic interactions. *Eur J Plant Pathol* **133**:3–23 (2012).
78 Fisher MC, Henk DA, Briggs CJ, Brownstein JS, Madoff LC, McCraw SL, *et al*, Emerging fungal threats to animal, plant and ecosystem health. *Nature* **484**:186–194 (2012).
79 Hoorebeke SV, Dewulf J, Immerseel FV, Jorgensen F, Sandilands V and Hocking P, Production systems for laying hens and broilers and risk of human pathogens, in *Proceedings of the 30th Poultry Science Symposium, University of Strathclyde, Glasgow, Scotland, 2011*, ed. by Sandilands V and Hocking P. CABI, Wallingford, pp. 77–96 (2011).
80 Iancu SC, Zweekhorst MB, Veltman DJ, van Balkom AJ and Bunders JF, Mental health recovery on care farms and day centres: a qualitative comparative study of users' perspectives. *Disabil Rehabil* **36**:573–583 (2014).
81 Kiley-Worthington M and Rendle-Worthington J, *Exploding the Myths: Large Mammal Welfare, Handling and Teaching*. Xlibris, London (2012).
82 Karban R, Plant behaviour and communication. *Ecol Lett* **11**:727–739 (2008).
83 Nestle M, *Food Politics: How the Food Industry Influences Nutrition and Health* (10th edn). University of California Press, Berkeley, CA (2013).
84 Rothgerber H, Real men don't eat (vegetable) quiche: masculinity and the justification of meat consumption. *Psychol Men Mascul* **14**:363–375 (2013).
85 Amoguis DMK, Bontilao SMR, Galarido CD, Lumamba JAW, Paelmo JNA and Rosal RMB, Experiences in pesticide used among farm workers and its effect to their health. *Adv Nurs Res* **2**(1):127–139 (2010).
86 Renzaho A, Fat, rich and beautiful: changing socio-cultural paradigms associated with obesity risk, nutritional status and refugee children from sub-Saharan Africa. *Health Place* **10**:105–113 (2004).
87 Rautiainen RH, Heiberg AM, Mattila T, Kaustell K and Danielson A, *Factors Affecting Occupational Health of Foreign Farm Workers in Nordic Countries*. Nordic Council of Ministers, Copenhagen (2012).
88 Xiao H, McCurdy SA, Stoecklin-Marois MT, Li CS and Schenker MB, Agricultural work and chronic musculoskeletal pain among Latino farm workers: the MICASA study. *Am J Ind Med* **56**:216–225 (2013).
89 Assmann S, Reassessing food safety, risk and globalization in China and Japan: an overview of emerging research trends. *Food Cult Soc* **16**:7–19 (2013).
90 Mytton OT, Clarke D and Rayner M, Taxing unhealthy food and drinks to improve health. *Br Med J* **344**:e2931 (2012).
91 Hattersley L, Agri-food system transformations and diet-related chronic disease in Australia: a nutrition-oriented value chain approach. *Agric Hum Val* **30**:299–309 (2013).
92 Liebhold AM, Brockerhoff EG, Garrett LJ, Parke JL and Britton KO, Live plant imports: the major pathway for forest insect and pathogen invasions of the US. *Front Ecol Environ* **10**:135–143 (2012).
93 IFOAM, The principles of organic agriculture. [Online]. (2005). Available: http://www.ifoam.org/en/organic-landmarks/principles-organic-agriculture [12 May 2014].

