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Feeding the world with soil science: embracing sustainability, complexity and uncertainty

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Abstract

Feeding a growing and wealthier population while providing other ecosystem services and meeting social and environmental goals poses serious challenges to soil scientists of the 21st Century. In particular, three dimensions inherent to agricultural systems shape the current paradigm under which science has to contribute knowledge and innovations: sustainability, complexity and uncertainty. The current model of agricultural production, which is also often the source of inspiration to propose solutions for future challenges, fails at internalizing these dimensions. It simply does not provide the necessary means to address sustainability, complexity or uncertainties. Part of the problem is that these are soft concepts, as opposed to hard goals, and so their definition and their translation into concrete actions is always subjective. They have to be sufficiently defined for soil science to embrace them in order to propose viable solutions to (i) produce food where it is most needed, (ii) decouple agricultural production from its dependence on non-renewable resources, (iii) recycle and make efficient use of available resources, (iv) reduce the risks associated with global change, and (v) restore the capacity of degraded soils to provide ecosystem services. This paper examines what the concepts of sustainability, complexity and uncertainty mean and imply for soil science, focusing on the five priorities enunciated above. It also summarizes and proposes new research challenges for soil scientists of the 21st Century.

Keywords: food security; nutrition; global change; soil degradation; agriculture

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1. Introduction

Feeding a growing and increasingly affluent population while providing other ecosystem services, and meeting the social and environmental targets of the UN Sustainable Development Goals (SDG), poses serious challenges to the management of terrestrial ecosystems used for primary production – and hence to soil scientists of the 21st Century (Keesstra et al., 2016). Agroecosystems are complex, dynamic socio-ecological systems in which soils play roles that are central to their functioning (Walker et al., 2010). They exhibit a number of properties that can be characterized as structural and dynamic, and are governed by both biophysical processes and human agency (Conway, 1987). The design of soil management strategies to meet the SDGs requires knowledge and innovation, and embracing three dimensions that define the way we regard agroecosystems nowadays: the notions of sustainability, complexity and uncertainty. These dimensions describe respectively our aspirations, our understanding, and the challenges we face towards the future management of agroecosystems.

The currently hegemonic model of agricultural production issued from the green revolution, and more recently fuelled by advances in genetic engineering and the agrochemical industry, appears often as the primary source of a soil scientist's inspiration to propose solutions for future challenges. This is evident from the report prepared by the Thematic Group on Sustainable Agriculture and Food Systems of the Sustainable Development Solutions Network (SDSN, 2013), which offers new, 'improved' versions of old remedies. In other words, under the optic of this report, the solution to the problems *caused* by current agriculture intensification, or to the problems it *fails* to address, are to come from yet further agricultural intensification. Except that now this is branded as 'sustainable' intensification. Conspicuous examples of this type discourse are such concepts as precision agriculture, good agricultural practices, the development of toxin-producing GM plants supposed to replace pesticides, or more generally the eco-efficiency and sustainable intensification discourses (cf. Tittonell, 2014a). As they fail to internalize the mere notions of sustainability, complexity and

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uncertainty in agroecosystems these solutions have little chance to help us achieve the SDG.

Part of the problem is that sustainability, complexity and uncertainty are soft concepts, as opposed to hard goals. Their definition and their translation into concrete actions are unavoidably subjective (Meynard et al., 2012). Subjectivity governs the way in which we perceive and diagnose a problem, as well as the way in which we come up with solutions. A wrong diagnosis generally leads to proposing the wrong solution. In many cases the solution to a problem is even chosen *a priori*, without properly assessing the problem nor the potential impact of the proposed solution. Blame subjectivity. For example, a well-intentioned soil scientist working on crop nutrition and soil fertility is often inclined to think that the solution to food security, or more generally to achieving the SDGs, will likely come from ample adoption and proper use of fertilisers (e.g. the Fertiliser declaration of the Abuja Summit, 2006). Yet, after 40 years of such policies in places like sub-Saharan Africa, and exactly ten years after this new impetus was installed, we fail to see much progress in terms of agricultural productivity, in per capita income or food availability in rural areas (UNCTAD, 2013; 2014). Most conspicuously, and with the exception of very localised examples, there was weak progress in fertiliser adoption and use in spite of national policies and large international support to achieve that, while soil fertility continues to decline.

It is easy to blame policy makers or the social and economic context for lack of incentives to adoption of technologies, but why not questioning ourselves, soil scientists, whether the solutions we propose are in themselves real solutions to actual problems? This challenges us to revisit our research and its contribution to solving the world's problems from an operational perspective (how do we make sure that our research is sound and solid?), from an epistemological perspective (how do we know that we are addressing the right questions, employing the right methods to approximate the truth?), but also from its ontological grounds (how do we know what the right questions and relevant problems really are?). The concepts of sustainability, complexity and uncertainty

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in the context of agroecosystems can shed some light on this. They have to be adequately defined and operationalized for soil science to contribute viable solutions to five priorities that I deem central to achieving food security:

(i) produce food where it is most needed;
(ii) decouple agricultural production from its dependence on non-renewable resources;
(iii) recycle and make efficient use of available resources;
(iv) reduce the risks associated with global change; and
(v) restore the capacity of degraded soils to support food production and other ecosystem services.

This paper follows from the introductory paper to this special issue by Keestra et al. (2016), to examine specifically what the concepts of sustainability, complexity and uncertainty mean and imply for soil science focusing on the second one of UN Sustainable Development Goals, Food Security and Nutrition, while proposing new challenges for soil scientists of the 21st Century.

2. Definitions

2.1 Sustainability

Much has been said and written about sustainability (e.g., most recently: James et al., 2014; Kahle and Gurel-Atay, 2015). Here, I concentrate on the aspects of sustainability that can help us think through our soils research and its contribution to food security and nutrition. The most widely quoted definition of sustainability is that used by the Brundtland Commission of the United Nations (1987) to define sustainable development as: "[…] *development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" Yet, in ecology, sustainability has a more strict definition and means 'the capacity to endure', the ability of ecosystems to remain productive and diverse indefinitely, bearing a much closer relationship with its etymology. Sustainability derives from the Latin term *sustinere*, formed by the particles *sub-* (up from below) and *tenere* (to hold), which resulted in the terms *sostenir* (old French) and sustain (English). The term sustain appeared in the

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western literature since c. 1300 with the following meanings: give support to, hold up, maintain, endure, bear, undergo, continue, keep up, endure without failing or yielding, etc. Sustainability is thus the ability to sustain. The adjective sustainable has been used to mean 'bearable' since 1610s, 'defensible' since 1845, and 'capable of being continued at a certain level' since 1965, when it was used to describe sustainable growth (cf. Douglas-Harper Etymology Dictionary, 2015).

Well-functioning, resilient soils are those able to hold agroecosystems 'up from below', to sustain their ability to deliver ecosystem services now and in the future, and to endure the stresses and shocks – anthropogenic or from other origins – that agroecosystems may be subject to. Policies, management practices or technological innovations that compromise the ability of soils to sustain current and future agroecosystems functioning and endurance can be thus defined as *un*-sustainable. In line with the approach to agroecosystems as socio-ecological systems, sustainable development *sensu* Brundtland recognizes four interconnected domains: ecology, economics, politics and culture (Kates, 2011). Sustainable development implies tradeoffs between objectives derived from these four domains, and how societies chose between these tradeoffs is central to sustainability (e.g. Anderson et al., 2015). Let us amend the previous statement: Policies, management practices or technological innovations that compromise agroecosystem functioning and endurance, and/or that impact negatively on the wider societal and environmental objectives, can be regarded as unsustainable.

There are a few grey zones associated with this definition of sustainability that deserve further thinking, particularly in the realm of soil science:

1. *Subjectivity*. Sustainability is a soft concept. It is basically a normative assertion about choices among societal values. Every social or interest group will define sustainability and choose its own indicators and thresholds to make it operational. Is preserving a native forest a sustainable activity? Is maintaining a living topsoil a sustainable choice? Is preventing crop residue grazing by livestock in order to restore organic

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carbon to soil a sustainable practice? Societies, or power groups within them, may be ready to trade-off the benefits that can be derived from these management options in order to satisfy other priorities – to everyone or just to a few – at any given moment in time.

2. *Boundaries*. Sometimes the causes and consequences of 'sustainable' decisions are delocalized. This depends on the boundary conditions chosen to define an agroecosystem. A social group may agree on a certain management practice or policy that leads to greater sustainability outcomes within the boundaries of their own ecosystems, but their choices may result in unsustainable outcomes elsewhere. This not uncommon in a globalized economy and the examples are plenty. Such externalities– often overlooked in sustainability assessments – include aquifer pollution through leaching or the siltation of waterways due to soil erosion and sediment transport beyond the boundaries of the agroecosystem.
3. *Thresholds*. As societies trade-off among values to norm on what is considered sustainable or not, the thresholds necessary to operationalize these norms are also the result of negotiations and power balances. One example that relates to soils is the acceptable pollution thresholds defined for glyphosate concentrations in water. Tolerance levels are set at 700 ppb in the USA, at around 300 ppb in countries like Argentina or Canada and at 0.01 ppb in Europe. Such broad discrepancies are not the result of scientists in Europe and the Americas having found different empirical evidence on Glyphosate toxicity in water. They are just the result of the capacity for lobbying, negotiation, or weight throwing of different interest groups in European and American societies.
4. *Objectives.* As the term sustainability is reminiscent of such notions as maintaining, enduring, etc., it somehow falls short of describing other important goals of agroecosystem management. Land degradation assessments based on NDVI trends estimate that about 25% of the agricultural soils in the word are in a severely degraded state (Vlek et al., 2008). Much of this is explained by soil degradation (Bai et al., 2008). Sustainability implies that in many cases it is not enough with

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maintaining the *status quo* or 'conserving' soils. Sustainable soil management may require soil restoration (degraded land) or soil aggradation (inherently unproductive land) as well – i.e., a sort of aggradation-conservation agriculture may be needed, cf. Tittonell et al., 2012).

5. *Predictability*. It is hard to foresee what the next generations will need in terms of resources and ecosystem services. Up until the 19th century salt was an important asset and even wars were fought about its sources (e.g. the Wars of the Pacific, 1879-1883). The efficient use and exploitation of salt would have been a sustainability premise in the past, up until the moment when other technologies replaced the need for salt. Likewise, it is hard to foresee the actual consequences of our current soil use and management for the future generations. How do we know if a current disturbance will lead to a future problem or a future advantage? Think of the high cultural value assigned today to formerly degraded landscapes, such as the dune landscape in north-western Europe that originated after massive peat extraction from the soil surface, or the high economic value of okoumé (*Aucoumea klaineana*) trees in Equatorial west Africa, that grow in places that were cleared through slash and burn agriculture in the past.

One may well imagine that healthy soils and ecosystems will be as necessary for food production in the future as they are today – as they have been for over 7 millennia – but it might well be that the prime functions and services they are expected to provide will be other than those of today. These grey zones pose important ontological questions to soil scientists of the 21ts century. Yet they should not be used as arguments to disturb ecosystems beyond acceptable thresholds, which must be defined using our best available scientific knowledge. It makes sense to be conservative when it comes to choosing thresholds to assess sustainability, particularly in the case of practices or technologies that may have long term impacts on society and the environment that are yet unknown or poorly understood. The goal of sustainable development is to propend towards a form of intergenerational equity, maintaining the ability of global ecosystems to sustain future generations.

2.2 Complexity

We take for granted that agroecosystems are complex yet they are often a simplified version of a natural ecosystem. Through agriculture, we have simplified natural ecosystems so that the flows of solar energy, water and nutrients can be steered in the narrow direction of producing selected forms of plant and animal biomass. Complexity was inevitably lost in the process. When assessed through indicators such as heterogeneity, diversity, dynamics and feedbacks, we can attest dramatic losses in structural, organisational and functional complexity of ecosystems through agriculture. A conspicuous example would be the loss of structural and functional complexity of soil biodiversity when forest soils are put under grazing or cultivation (e.g. Lupatini et al., 2012). The human dimension of agroecosystems, however, introduces new forms of complexity that are hard to unravel using ecological knowledge and principles. The actual complexity inherent to agroecosystems can only be understood when they are perceived as social-ecological systems.

Complexity can be seen as the mere number of components and interrelations in a system, or defined by the nature of such relationships, or by the emerging properties associated with them. Complexity can be associated too with the level of knowledge we have about the functioning of a system: less understood systems tend to be considered more complex. In soil science, complexity has been most often studied in the various fields of soil biology, notably through the study of soil trophic networks, but also in the study of the physicochemical properties, functioning and spatial arrangement of the minerals and particles that define soil composition and structure. More recently, the notion of complexity and ways of assessing it have been applied in the study of the close links between soil management, spatial patterns and collective human decisions or social networks (Rufino et al., 2011; Isaac, 2012; Tittonell, 2014b; Andrieu et al., 2014; Baudron et al., 2014; Speelman et a., 2014). The next examples will focus on these aspects of social-ecological systems, as they bear a close

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relationship with the challenge of achieving the UN Sustainable Development Goals through soil science.

Collective action and decision-making

Introducing a technology or a set of soil management principles in a rural community is often a challenge. Lack of adoption is generally ascribed to the communities' poor understanding of the benefits of the technology, to their lack on interest in or need for it, or to the absence of economic, social or policy incentives to implement it. Often the problem is much more complex than that. In Malawi, soil and water conservation measures have been profusely promoted to halt soil degradation and increase agricultural productivity in the recent past. Some communities were more prone than others to adopt them. In-depth social studies in some of these communities of adopters and non-adopters revealed that the topology of the local social networks that characterised each community was closely associated with the level of adoption of soil and water conservation measures proposed to them (Khonje, 2012; Figure 1).

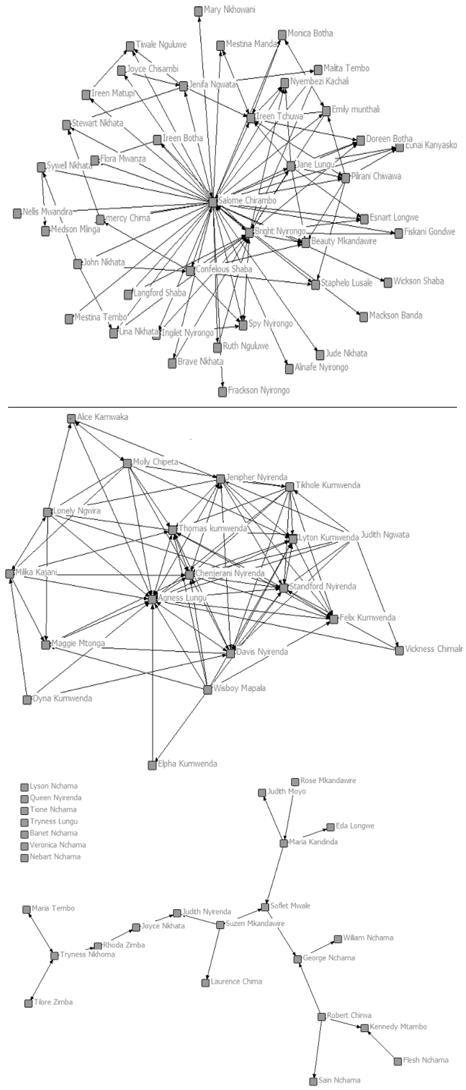

Figure 1: Social network topologies of three villages in Malawi: (A) Ziwambera; (B) Kanyinbwa; (C) Kamkondo (Source: K. Khonje 2012, Wageningen University).

It must be recalled that several soil and water conservation measures, such as building terraces, planting tree lines or digging ditches, require collective effort by members of the community, especially when the landscape is fragmented into very small properties (of often less than half a hectare). The community of Ziwambera village, where the adoption of soil and water conservation measures was successful, exhibited a traditional type of social organisation, in which it is possible to evidence the strong leadership of a local chief, who relates to the rest of the households often through family ties (Fig. 1A). Kanyimbwa village social network reveals a situation in which more than one strong node of relations exists, resulting in a more complex and diverse communal decision-making model (Fig. 1B). Kamkondo village social network points to a loosely connected society (Fig. 1C), composed largely by migrating families with rather weak ties amongst them, with unconnected households, with ties to nearby townships as well, and where community action is hard to coordinate. Non-surprisingly, soil and water conservation measures that required collective effort were least adopted in the latter community. Social network structures can also enhance or hinder the flow of information amongst members of the community and very strongly influence adoption (Khonje, 2012).

Resource flow networks

At farm level, complexity is evident in the way diversity is organised. Diversification of farm activities *per se* brings about greater resilience and adaptability in the face of external shocks, such as low or volatile prices, a drought or a pest outbreak. This is due risk spreading, or the classical egg-in-different-baskets effect. Yet diversity *per se* is not enough to grant efficiency in resource use, as observed for example amongst family dairy farmers in Mexico by Cortez-Arriola et al. (2014) or in rice-based systems of Bangladesh by Arvidashkan et al. (2015). To be functional to a given objective, diversity must be organised in a certain way. In ecology as well as in agriculture, the relationship between biodiversity and efficiency, for example nutrient use efficiency, is generally elusive, and it may become evident only when moving across scales. Processes deemed inefficient at one scale may contribute to greater system efficiency at higher scales (van Noordwijk and Brussaard, 2014). The analysis of individual farms as ecological networks in crop-livestock agroecosystems of East and southern Africa revealed however that resource (nitrogen in this case) use efficiency was closely associated with the complexity and organisation of the internal network of resource flows (Rufino et al., 2009; Alvarez et al., 2012). Across household types and climatic regions, N use efficiency and food self-

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sufficiency at farm level were better explained by the nature of the resource flow network complexity, in the form of path organisation and internal recycling, than by the total amount of externally-sourced N entering and flowing through the farm system annually (Table 1).

Table 1: Indicators of resource endowment, and of the size and organisation of the network of nitrogen flows within eight case study smallholder farms (from: Rufino et al., 2009; Alvarez et al., 2012)

Location/ Farm type	Cropped land (ha)	Livestock owned (TLU)	Farm N network size			Farm N network organisation		Farm N use efficiency (kg kg N^{-1})	Food self sufficiency ratio
			Total system throughput	Dependency on imports (%)	Finn's cycling index (%)	Average mutual information	Diversity of flows		
Ethiopia									
Poorer	0.3	1.2	230	72	2.9	1.1	2.2	23	0.4
Wealthier	2.4	10.0	1340	66	2.6	1.3	2.4	18	1.7
Kenya									
Poorer	1.0	0	45	45	2.2	1.1	2.5	74	0.3
Wealthier	2.9	3.5	190	34	11.0	1.7	3.3	216	1.2
Zimbabwe									
Poorer	0.9	0.3	40	65	0.9	1.0	2.2	44	0.5
Wealthier	2.5	5.4	480	45	5.5	1.5	2.9	86	3.4
Madagascar									
Poorer	2.7	3	110	33	3.5	1.2	2.6	122	1.9
Wealthier	6.9	12	400	31	2.5	1.4	3.4	198	4.7

Total system throughput is the sum of all N flows between all components (activities) of the farming system, expressed here in kg N per family member to allow for comparisons across farms of different size; Dependency on imports is the ratio between N flows into the farm system and total system throughput; Finn's cycling index is calculated as the ratio of the sum of all internal flows to total system throughput; Average mutual information (AMI) is the average number of connexions of each system component and the diversity of flows (HR) or statistical uncertainty is the maximum number of possible connexions between components, or the upper limit to AMI; both AMI and HR are measured in bits (binary decisions); if all the components of a system are connected and the total flow is equally distributed among all components, AMI will approach zero; typical values of AMI in natural ecosystems range between 0 and 6; Farm N use efficiency is the ratio of total biomass productivity to total N flowing into the system; Food self-sufficiency ratio is the ratio of edible calories produced on farm to caloric household needs.

Spatial patterns

At field scale, soil complexity is often reflected in its spatial heterogeneity, which is both inherent to soils and also the result – intentional or not – of human agency. I have worked extensively on the study of spatial soil heterogeneity, its causes and consequences, in smallholder African agriculture (e.g. Tittonell et al., 2005a,b; 2008; 2010; 2013; 2015; etc.). Figure 2 summarises schematically the three most common patterns of soil heterogeneity that can be found across sub-Saharan Africa. Fig. 2A represents the somewhat classical ring effect documented by Prudencio (1993) in Sudano-sahelian zones of West Africa, which describes a gradual decline in soil fertility at increasing distances from the homesteads, organised in villages or *hameaux*. Fig. 2B illustrates discrete patterns of spatial heterogeneity in highly populated and fragmented landscapes, in which homesteads are not centralised in a village but located within individually owned farms, and where soil fertility declines at increasing distances to them (e.g. Tittonell, 2003). One of the most common patterns in less populated regions of East and southern Africa is the discontinuous gradient, which strictly speaking is not really a gradient (Fig. 2 C). In these patterns, described in Zimbabwe by e.g. Carter and Murwira (1995), village fields and outfields are not necessarily contiguous as in the West African case. Due to the rapid increase in population

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densities that can be seen in rural Africa the first and the last pattern are gradually disappearing, tending towards more fragmented, spatially heterogeneous situations as that illustrated in Fig. 2 B.

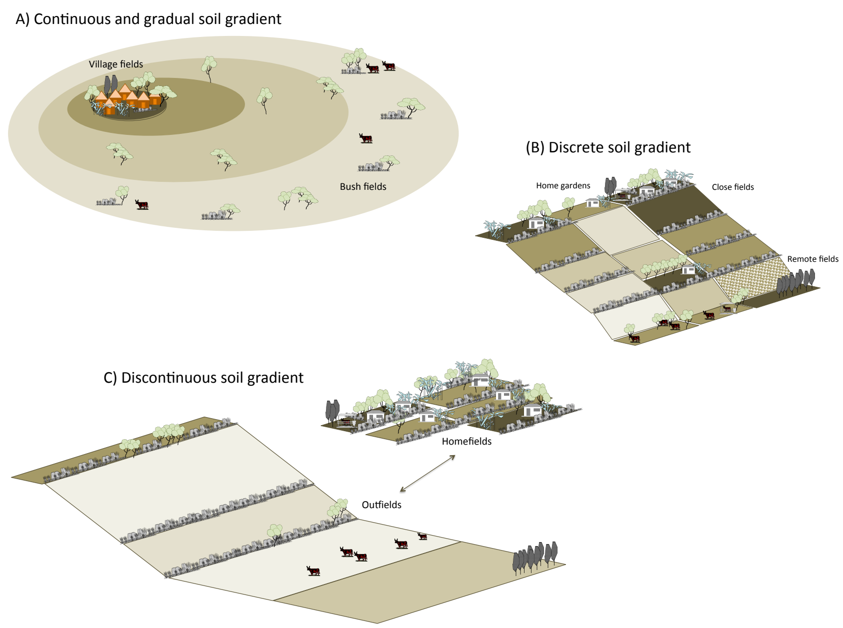

Figure 2: Schematic representation of common spatial patterns of soil heterogeneity in smallholders farming systems of sub-Saharan Africa. Modified from Tittonell et al., 2015.

Spatial soil heterogeneity is important because it is associated to a variable extent with heterogeneity in crop productivity, in their response to nutrient additions, or in the performance of soil improving technologies (Vanlauwe et al, 2006; Wopereis et al., 2006; Zingore et al., 2007; Fermont et al., 2009; Tittonell and Giller, 2013; Bruelle et al., 2015; Diarisso et al., 2015). Fertiliser recommendations tend to fail in sub-Saharan Africa due to this mere reason. The agronomic and economic efficiencies of fertiliser use can vary from benefit to failure within a single, spatially heterogeneous farm. N-fixing legumes may not be able to grow – let alone to fix N – in the poorest or degraded fields of small heterogeneous farms (Giller et al., 2011). But spatial heterogeneity is also important because in some cases it is the result of farmers' intention. Farmers may create 'islands of soil fertility' by concentrating resources in small portions

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of land, where yields are secured through more intense crop husbandry, early planting and nutrient additions from diverse sources (Henry et al., 2009; Castellanos-Navarrete et al., 2014; Diarisso et al., 2015). Such fields tend to exhibit greater soil organic matter, nutrient availability and water holding capacity, and a great diversity of plant species grown in association, which contribute to household nutrition through diverse diets (Figueroa-Gomez et al., 2008). These fields can be also seen as a bank or an insurance asset to secure food production in years of scarcity or erratic rainfall, thereby contributing to whole-system resilience (cf. Tittonell, 2014b).

The above examples indicate that agroecosystem complexity is not scale-agnostic. Understanding complex social relations at village or landscape level, complex networks of resource flows at farm scale, or complex patterns of natural or human-induced soil spatial heterogeneity at field scale are central to the design of soil management strategies towards the achievement of the SDG. The approaches to be used in soil science must therefore embrace scale-dependency. A classical way of dealing with scales and integration levels in soil science, and agricultural science in general has been through the model of hierarchical confinement (e.g. Fresco and Westphal, 1988). Although this model became obsolete after the notion of *panarchy* emerged in ecology (Gunderson and Holling, 2001), it is still widely applied in soil science and must be revised in the light of new insights from complex systems theory (Vandermeer and Perfecto, 2013) – another white glove lying on the ground of soil scientist of the 21st century.

2.3 Uncertainty

Uncertainty in agroecosystems is associated with the probability of occurrence of a certain event and with the sensitivity to and type of response to this event that may be expected. Events are normally associated with the behaviour of external driving variables, such as market or climatic ones, but also with a systems' own structure and function. Uncertainty may arise from stochastic processes and/or unforeseeable futures, but also from our inability to yet understand how things work in nature. There are thus cases in which the type of response to be expected is not known *a priori*, and there are others in which possible responses are known but their patterns, in terms of extent or intensity are not known. These two types of cases define two different domains of research questions relevant to soil science and agriculture. The first one, the uncertainty about the unknown, relates to science's continuous quest to unravel reality and how it works. The second one refers to the probability of occurrence of a known response, which in agriculture often boils down to risk assessments. Climatic risks and price risks are inherent to agriculture, and proper soil management may help curtail them. But the risk of not obtaining the expected response to a given investment is a serious matter for resource-constrained farmers, for whom the consequences of a years' failure may be felt over more than one season. I will explore through a few examples the implications for soil science of uncertainties about the unknown and uncertainties about responses, recognising that there is still a third domain of research questions not addressed here that is concerned with how to reduce uncertainty in agroecosystems.

Uncertainty about the unknown

In the 1940s a group of competent toxicologists led by William B. Deichmann conducted a number of thorough studies using state-of-the-art methods to conclude that the active ingredient dichloro-diphenyl-trichloroethane, or DDT, could be safely released to the environment for its use as insecticide. DDT was one of the first wide spread synthetic pesticides, and its widespread use led to resistance in many insect species. In the early 1970s, a paper authored by Deichmann (1972) himself and other studies provided enough evidence for the US Environmental Protection Agency to finally forbid the use of DDT as it became known to be toxic to humans, persistent in the environment, travel long distances in the upper atmosphere, and accumulate in fatty tissues of living organisms. What did actually happen between the 1940s and the 1970s? Why was DDT first considered innocuous or degradable and 30 years later banned and labelled as poisonous for humans, wildlife and the environment?
There are several possible answers to these questions. In the fist place, the ecotoxicity of certain chemicals when applied in small doses may only appear

through cumulative effects (cf. http://www.efsa.europa.eu/fr/node/872721). Time is needed for problems to arise, or to become evident. Second, and most importantly, the capacity of science to detect the adverse effects of a certain molecule released to the environment can progress substantially in 30 years. Problems that were overlooked or remained undetected in the past could be later on well understood and documented. (And the amount of scientific evidence that needs to be accumulated to be able to bend the arm of the chemical industry in court cases is not a minor detail). Examples such as this one should teach us about the long-term risk (uncertainty) associated with the widespread release of synthetic molecules, either as chemical formulations or produced by genetically modified organisms (cf. Cheeke et al., 2012), into the environment. Alarming ideas such as the commercial release of genetically engineered microorganisms for soil amendment have been underway for a while (e.g. Viebahn et al., 2009), with unknown consequences for soils and the environment.

The adverse effects of certain soil management practices will only arise once a certain sustainability threshold is crossed. This is the case, for example, of turbidity regimes in shallow lakes as affected by the continuous charge of incoming nutrients in regions of intensive crop and animal agriculture (e.g., Scheffer et al., 2001). Such thresholds are often termed 'tipping-points' associated with non-linear, irreversible or hardly reversible dynamics that describe multiple possible equilibriums (e.g., Walker et al., 2010). Evidence of such complex dynamics in agroecosystems is analysed in Tittonell (2014b), where household dynamics and their livelihood strategies are portrayed as complex systems that follow non-linear trajectories, with impacts on soil productivity and spatial heterogeneity. Lower equilibrium situations, in which farms are caught within vicious cycles of soil fertility depletion, low productivity, meagre incomes and poor investment capacity to restore soils are often termed poverty traps (Tittonell and Giller, 2013). Further evidence on the dynamics of smallholder African households and their impact on soils was presented by Valbuena et al. (2015), who suggested that they often behave as 'moving targets' for soil research for development.

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Uncertainty about response patterns

Why would farmers invest in actions to restore degraded soils if they do not know the possible outcomes of such actions? The dynamics of soil responsiveness to restorative measures can be characterised by two attributes: hysteresis and time lags (Tittonell et al., 2012). Hysteretic responses are desirable, so that the trajectory of soil recovery diverges as much as possible from the one of degradation, and soils may in time recover properties that are as close as possible to those exhibited by non-degraded soils (Figure 3). In a long-term study in Benin diverse soil management practices, from a control without soil amendments and crop residue removal, to a full treatment with application of mineral and organic fertilisers and crop residue incorporation to soil, were compared for 20 consecutive years. After 10 years, however, soil in the control treatment degraded to such an extent that maize yields became virtually nil (red markers in Fig. 3B). During the next 10 years, in which these soils received amendments of organic and mineral fertilisers and of crop residues at the same level as the full treatment (blue markers in Fig. 3B) their productivity recovered, but never reached the level recorded in soils that received such inputs throughout the 20 years of the experiment (green markets in Fig. 3B); the relative yield was about 60%. In some cases, although hysteretic responses are achievable and soils can potentially be restored, the fist signs of response to restorative measures only show up after a number of years of farmers' investment (e.g. Corral et al., 2015). Such time lags often deter farmers' investments in soil restoration measures. Note now in Fig. 3B that when the degraded soil started receiving organic matter and nutrient inputs it immediately produced a yield that was comparable with the initial yield without inputs, and it took four years before a substantial response was obtained.

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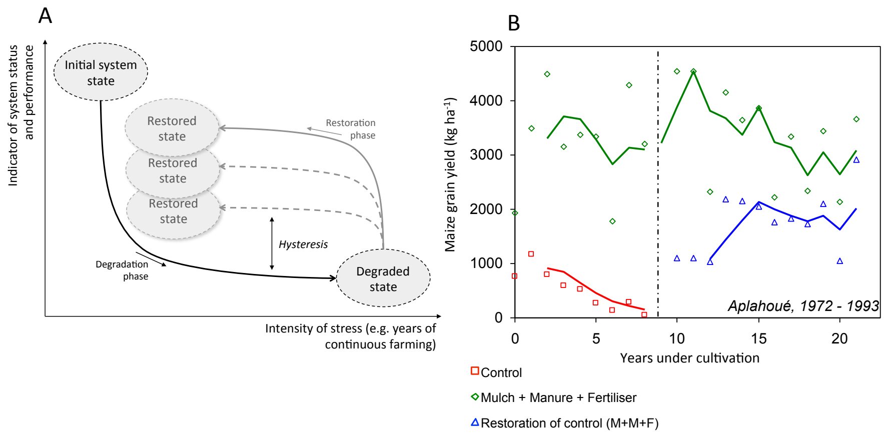

Figure 3: (A) Schematic representation of hysteretic responses to sol rehabilitation in which three alternative 'restored states' are represented; (B) Maize yields without nutrient inputs and crop residue removal (control) and with additions of manure, fertiliser and crop residues from the beginning or after year 10 (restoration of control) in a long term experiment in Aplahoué, Benin. Source: *Institut National de Recherches Agronomiques du Benin* (INRAB).

Farmers perceive uncertainty in responses mostly in the short term. Farmers engaged in a 4-year development project supporting sustainable agricultural intensification practices in 3600 upland rice fields in Madagascar were trained and encouraged to adapt conservation agriculture and nutrient management practices as they saw fit (Bruelle et al., 2015). As initial responses to synthetic fertiliser applications were highly variable, with yields ranging from 0.4 to 4.2 t ha^{-1} on the most risky hillside fields, farmers adopted conservative fertiliser rates, intuitively targeting the highest efficiency zone of a fertiliser response curve. Farmers' fertiliser N rates on hillside fields (n = 857) were in the order of 20 to 35 kg ha^{-1} on average. The variability in crop responses observed was large and multivariate, which is a common phenomenon observed on smallholder farms (e.g. Vanlauwe et al, 2006; Wopereis et al., 2006; Zingore et al., 2007; Tittonell et al., 2008; Fermont et al., 2009; Diarisso et al., 2015). The analysis of yield variability using classification and regression trees revealed that significant yield responses to N fertilisers (>15%) were only observed in in 55% of the fields and only in two out of four years, with a cut-off threshold of 28 kg ha^{-1} N applied (cf. Bruelle et al., 2015). Amongst the fields that received less than 28 kg

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ha^{-1}, 13% of them exhibited higher yields than the average of fields receiving greater fertiliser rates. It is not surprising that such uncertainty in crop responses to synthetic fertilisers deters resource-constrained farmers from investments in supposedly 'quick fixes' for soil fertility management.

3. Soil science priorities for food security and nutrition (SDG 2)

In the introduction to this paper I proposed five priority areas that soil science needs to address in order to contribute to food security and nutrition (SDG 2):

(i) Produce food where food is most needed;
(ii) Decouple agricultural production from its dependence on non-renewable resources;
(iii) Recycle and make efficient use of available resources;
(iv) Reduce the risks associated with global change; and
(v) Restore the capacity of degraded soils to provide food and ecosystem services.

It takes much more than just good soil management to achieve food and nutritional security and addressing these priorities will often exceed the realm of soil science and call for trans-disciplinary research. Non-exhaustively, Table 2 provides some examples of pathways that could be followed and possible research approaches to address these priorities from the perspectives of sustainability, complexity and uncertainty.

Table 2: Soil research priorities to achieve UN Sustainable Development Goal 2 Food Security and Nutrition, and examples of approaches from the perspectives of sustainability (what needs to happen), complexity (what do we know/ should consider) and uncertainty (foresee and minimise what could go wrong)

Priority	Sustainability	Complexity	Uncertainty
Produce food where food is most needed	Design food production systems and soil management technologies adapted to the context of resource-poor, less favourable, or less developed regions; Think beyond major staple foods to design	Transdisciplinary understanding of institutional, societal (cultural) and ecological interactions in resource-poor, less favourable or less developed regions; Understanding and exploiting the role of	Make food production systems more resilient and adaptable to shocks and stresses through diversification, and credit and insurance policies to assist in case of natural and human-made disasters;

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	diverse, nutrition-sensitive landscapes; Promote local autonomy and belligerence in food systems governance;	man-made 'fertility islands' in agroecosystems and other forms of indigenous precision agriculture;	
Decouple agriculture from non-renewable resources	Intensification of food production systems through diversification and ecological replacement; Foster the provision of soil-mediated ecosystem services (e.g. nutrient regulation, biological N fixation)	Understanding of soil trophic networks and biodiversity, and their contribution to nutrient capture and cycling; Understanding to what extent N fixation by organisms other than legume plants contribute to ecosystem's N budget (e.g. in grasslands);	Foster the provision of ecosystem services to reduce pest impacts (e.g., pest regulation, soil suppressiveness); Minimize agriculture's dependence on fossil fuels and volatile oil markets;
Recycle and make efficient use of available resources	Look beyond partial efficiencies at plot/crop scale to embrace whole-system efficiency at farm and landscape levels; Improve the recycling of energy and matter within and between agroecosystems, and between rural and urban areas;	Efficiency is not scale-agnostic: new theory is needed, perhaps ascendency (cf. Ulanowicz, 2001), to measure systems' efficiencies at farm and landscape level; Understanding the links between biodiversity and efficiency at different scales;	Introduce the notion of risks in the calculation of efficiencies; Can risks of leakages be minimized through recycling? What are the tradeoffs associated with pursuing efficiency at one single scale/component?
Reduce risks from global change	Foster the provision of soil-mediated ecosystem services (e.g. water regulation); Ecological intensification of food production systems through diversification and exploitation of niche-complementarities (e.g. crop-livestock-tree systems);	Understanding the relationship between functional soil biodiversity and its adaptive capacity in the face of climate change; Analysis of nature's structure-function relations and adaptability mechanisms to inform agroecosystems design (e.g. ligneous components in grasslands);	How can soil act as a reactor to detoxify the environment? What are meaningful indicators and tipping points to monitor soil functioning and service provision? How can soil information best contribute to insurance policies and mechanisms?
Restore degraded soils	Reduce time lags and initial investments; Whenever possible, restore soils while producing; Make use of locally available resources and knowledge for soil restoration; Promote local autonomy and ownership in soil restoration initiatives;	Understanding of mechanisms behind hysteretic and non-hysteretic responses to soil restoration; Understanding of sequential processes in soil and associated functions during a restoration phase.	What are the costs and benefits associated with restoring soils? How can smallholder farmers overcome time lags? What are the institutional and governance mechanisms necessary to ensure long-term engagement in soil restoration?

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In the light of sustainability, complexity and uncertainties, let us think critically about the model of agricultural intensification that several international organisations – with good intentions – are pushing in developing countries: what is the reasoning behind the idea that a mono-culture of a uniform maize hybrid receiving large inputs of synthetic fertilisers and other agrochemicals is the most appropriate cropping system for a subsistence, sometimes illiterate household in a remote, food- and land-insecure, and inaccessible rural village exposed to climatic risks and demographic pressure, and located in a fragile ecosystem in the tropics, where input prices are ten times higher than those paid by farmers in e.g. Europe? (On input prices cf. Tittonell et al., 2007). Can such simplified and risk-prone cropping system really contribute to food security, namely availability, access, stability and utilization of food, and nutritional diversity in smallholder contexts? Beyond any ecological consideration about the consequences of simplifying tropical ecosystems in this way, and just from a mere economic perspective, what would happen with rural food security and its sustainability under the uniform hybrid scenario if for example oil prices (and fertilisers) sky rocket, or if multinational seed companies manage to enforce payments for intellectual property upon farmers as is happening in other parts of the world?

Sustainability, complexity and uncertainty represent respectively our aspirations, our understanding, and the challenges we face towards the future management of agroecosystems to achieve the UN Sustainable Development Goals. Although several epistemological questions remain unanswered around these notions, particularly around sustainability as a guiding concept, they represent three complementary perspectives from where we can analyse the potential of our contributions from soil science. On the basis of this, here are three lines of action that may help us soil scientists of the 21st Century make our research more impact-oriented towards the achievement of food security and nutrition:

1. Let us invest effort and creativity in 'translating' the new insights and understandings coming from soil science into knowledge-intensive

innovations that can contribute to food security. Exciting research results on formerly unknown soil interactions in the root zone are a sure ticket to a high impact publication. Yet the path from understanding processes in soil to implementing this knowledge in the design of sustainable agroecosystems is a long and tortuous one. We can contribute to make it shorter. But doing research on applied science, moving from questions such as '*how does this work*' (analysis) towards '*how to make it work*' (design) penalises soil scientists, as design-oriented research is hard to publish in high impact journals. This requires also to rethink the scientific reward systems in research and the academia;

2. Let us dare to challenge the establishment. Many of us in soil science are under the influence of those who were our mentors, who provided guidance and/or trained us as researchers. They are the ones who nowadays act as consultants for international organisations, who direct research institutes, participate in boards, act as journal editors, evaluate projects, etc. Most soil scientists of that generation were educated and developed their careers within the paradigm of the green revolution: improved germplasm, fertilisers and agrochemicals can fix anything. Some scientist of that generation knew how to adapt and change their views and discourses as new evidence and methods came along. For others, a change of view at this point is felt in a way as being equivalent to accepting that what they did in the past was wrong. Let us engage in persuasive actions to break such inertia, and let us not be shy when it comes to defending our new insights – provided that they are supported by sound scientific evidence;
3. Let us contribute to creating credible narratives that bring important messages to society and/or install useful ideas among agroecosystem managers, policy and decision-makers. Narratives are well-packed pieces of information that convey simple, common sense messages. A popular one is this: "*it will be impossible to feed the world without GM crops*". Although this assertion does not resist any serious scientific scrutiny, the industry managed to install this message successfully amongst some policy makers, the public opinion in general and, most disquietingly,

among certain members of the scientific community. I propose to liaise with communication experts to develop simple narratives to convey meaningful messages from soil science to society, with the ultimate intention of influencing policy and research agendas;

The complexity of the social-ecological systems where food is produced and consumed requires trans-disciplinary research, knowledge brokerage, and a permanent dialogue with policy makers. The relationship between scientific evidence and policy development and implementation is not rectilinear, but a rocky path (Caceres et al., 2016; Keesstra et al., 2016). It would be naïve to think that we can feed the world just with soil science, as the title of this paper ironically claims. Hunger is not the result of insufficient agricultural production. Hunger is the result of poverty and inequality. Feeding the world, or achieving the second of the UN Sustainable Development Goals, requires much more than soil science and it certainly exceeds agricultural research. Yet it helps to be aware of the role we can play in this puzzle, a role that is not minor.

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