Perspective

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Time for a shift in crop production: embracing complexity through diversity at all levels

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Abstract

A radical shift in our approach to crop production is needed to ensure food security and to address the problems of soil degradation, loss of biodiversity, polluted and restricted water supplies, coupled with a future of fossil fuel limitations and increasingly variable climatic conditions. An interdisciplinary network of European scientists put forward visions for future crop production embracing the complexity of our socio-ecological system by applying the principle of diversity at all levels from soil micro-organisms to plant varieties and cropping systems. This approach, integrated with careful deployment of our finite global resources and implementation of appropriate sustainable technology, appears to be the only way to ensure the scale of system resilience needed to cope with many of our concerns. We discuss some of the most important tools such as (i) building soil fertility by recycling of nutrients and sustainable use of other natural and physical resources, (ii) enhancing biological diversity by breeding of crops resilient to climate change and (iii) reconnecting all stakeholders in crop production. Finally, we emphasise some of the changes in agricultural and environmental regulation and policy needed in order to implement the visions.

INTRODUCTION

Global climate change and the current developments within agriculture threaten world food security.[1] The recent report International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) recognises that world agriculture is at a crossroads and that far-reaching changes are required to cope with the global increase in the human population and the consequent increase in demand for food, feed, land and energy.[2] Modern industrial agriculture is based on the availability of cheap fossil energy, which encourages high yields through high inputs in the short term. However, it is likely to fail in the long term because of a lack of consideration for the biological and environmental integrity of food production systems and their connectivity to wider ecosystems.[3] Further, of the services provided by ecosystems, e.g. food, climate regulation, water regulation, soil formation, nutrient cycling, waste treatment, pollination, biological control and genetic resources, many are not appreciated by society even though they all together have an estimated financial value of at least the same magnitude as the global gross national product.[4] We are now seeing the consequences of this practice, e.g. that soil fertility and biodiversity are severely threatened.[5] Decline in soil fertility and biodiversity are likely to increase the dependence of crop yields on high inputs of mineral fertilisers and pesticides. These inputs account for a large proportion of the energy used in modern agriculture. For instance, the European Fertilizer Manufacturers Association calculates that fertiliser production, transportation and application in 2000–2001 accounted for about 50% of the direct and indirect energy consumption in European Union (EU) wheat production.[6]

In many parts of the world, human-induced soil degradation is resulting in a loss of soil physical, chemical and biological structure, including the loss of nutrient value for crops.[7–12] The problems are compounded by the growing impacts of climate change,[13]

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resulting in more volatility in temperature and water supply as well as massive decreases in soil organic matter[14] and thus soil fertility. Biological diversity as the number and abundance of species, as well as genetic diversity within cultivated plants, is decreasing largely owing to the negative impacts of intensive industrial agriculture.[5,15–22] Overall, the ecosystem services delivered by biodiversity, such as plant disease control, soil provision and pollination, are jeopardised by its decline.[23] The damage caused, with its associated environmental and public health costs, has made current industrialised agriculture highly uneconomical from an ecological perspective (see e.g. Ref. 24).

To address the multitude of concerns about current industrialised agriculture, a group of scientists involved in a scientific network dealing with the varietal characteristics and crop diversity required for sustainable low-input cereal production (EU COST Action 860 SUSVAR) formulated visions for the future of crop production (http://www.cost860.dk/publications/doc/DiscussionDocumentsAndParticipants.pdf). The method of 'Appreciative Inquiry' (AI) was used to envision the future and identify strategies and tools to achieve the visions. In short, AI is a way of thinking, seeing and acting on the basis of what works well, and by acknowledging these dynamics it is possible to imagine and shape the future in a more powerful manner.[25] Rather than falling into the trap that 'for every complex problem there is an answer that is clear, simple, and wrong' (HL Mencken 1920, http://thinkexist.com/quotes/henry_louis_mencken/), the resulting visions integrated diversity and all stakeholders as a basis for embracing complexity.

In this paper we present common components of the visions of future crop production developed by the network. Key tools and strategies towards the visions include the building of soil fertility, enhancing biodiversity and connectivity in the crop production system. We also stress some of the policy implications. As a consequence of the AI methodology, we highlight the major factors that we need to concentrate upon for a paradigm shift in agriculture. We are aware that this will generate problems in many areas, but we believe that dealing with such problems is an easier and safer option than the consequences that will arise from not making such a major shift.

COMPONENTS OF THE ENVISAGED FUTURE

The visions are based on the idea that agricultural systems, as part of the complex broader socio-ecological system, must give equal value to economic outputs on the one hand and ecosystem and social services on the other, e.g. reducing pollution, avoiding waste, mitigating and adapting to climate change and enhancing biodiversity. An essential requirement for future crop production is to be environmentally, socially and economically sustainable. This means that the present requirements of society must not reduce the potential for future generations to fulfil their needs. Also, to sustain food security at a global scale, crop production systems must be developed to deliver food, and wider public goods, with greater efficiency. Under these requirements, no system can be considered economical if it fails to be stable in the long term; process chains and recycling must be in the main focus rather than standing as isolated solutions disregarding the complexity of problems. The socio-ecological complexities are embraced by applying the principle of diversity at all levels of the agro-ecosystem from soil micro-organisms to plant varieties and processed agricultural products. In addition, this application of diversity must be coupled with the use of renewable resources, careful deployment of finite resources and the implementation of appropriate sustainable technologies. This is probably the only way to ensure a system resilience that is sufficient to address many of our concerns for the future. Interconnectivity between all stakeholders e.g. breeders, farmers, processors, consumers and scientists, will promote better management and utilisation of soil resources and biological diversity. Agricultural multifunctionality that encompasses food production, ecosystem services and direct societal benefits can then develop, leading to an overall improved quality of life.

A prerequisite for our visions is a fundamental paradigm shift from consumption of resources towards the maintenance or even enhancement of resources. We consider soil fertility and biodiversity to be the most essential biological resources for robust agricultural systems that produce high and stable yields of high-quality crops to feed a growing world population. These resources are influenced by the natural ecosystem, climate and sun; in turn, the agricultural management influences the wider ecosystem. All together, these are the main building blocks for future sustainable crop production which will be considered in more detail below.

Building soil fertility by crop management for minimal environmental impact

Sustainable agricultural systems depend on a dynamic and highly diverse community of soil organisms[26] interacting with diverse crops to recycle nutrients in efficient cropping systems based, wherever possible, on closed cycles.[27–29] For the purposes of this paper, soil fertility is defined as the ability of a soil to provide the conditions required for plant growth.[30] A fertile soil is better able to suppress organisms harmful to plants.[31]

Two of the most important determinants of soil quality and health are the amount of soil organic matter[32] and the level of microbial diversity.[33,34] These determinants improve soil structure and water retention and make the soil more tolerant to abiotic stresses such as drought and compaction. This also helps in sequestering carbon and buffering against the effects of soil salinity and acidity or alkalinity. Heavy and frequent tillage negatively affects a soil's physical and biological properties and is probably the most important reason for decreases in soil structural quality, e.g. rise in bulk density and mean aggregate size.[35] Tillage may also decrease soil organic matter,[36,37] which may be further reduced by rising temperatures.[14]

Crop rotation, nutrient recycling and reduced tillage are the main tools for soil fertility building. By ploughing or applying other invasive cultivations only when necessary, energy use may be reduced. Minimum tillage can improve soil structure and stability, resulting in better drainage and water-holding capacity as well as enhancing microbial activity. The latter helps nutrient recycling and contributes to reducing the impact of soil-borne diseases,[34] the risk of soil erosion[38,39] and leaching of nutrients.[9,40] These practices also reduce losses of soil organic matter[41] and thus carbon losses[42,43] while improving soil structure and water retention and enabling a more permanent soil cover. There is much potential for reduced tillage to mitigate greenhouse gas emissions, though the size of the benefits is uncertain.[42–45] However, reduced tillage does not suit all soil types or climates. Well-structured and stable soils are most suited to reduced tillage, but care must be taken with poorly structured or poorly drained soils,[46] especially where anaerobic conditions result in the direct emission of greenhouse gases such as N_2O.

Currently, there is often a need for tillage to control weeds in organic farming and for the control of some residue-borne pathogens. Many biotic problems could, however, be taken care of by diversification strategies such as cultivar and species mixtures to reduce infection and spread of diseases,[47] by plant traits that confer a high degree of crop competitive ability against weeds[48] and/or by using appropriate crop rotations.[49] Enhancing biological activity and especially earthworm populations by disturbing soils less, combined with appropriate rotations, will speed up the breakdown of infested residues,[50–53] making the burial of residues obsolete.

Crop rotations with diverse crops and green manure cover crops promote these effects, especially by increasing soil organic matter[37] as well as soil microbial biomass and activity,[54] through an increase in biodiversity both above and below ground. If rotations include nitrogen-fixing legumes such as peas, beans and clover, these will help to bring nitrogen from the atmosphere into the soil and thus decrease the need for artificial fertiliser. For example, rotating wheat with red clover reduced foliar diseases as much as the use of fungicides, and yields in the rotation were significantly higher than in the sprayed continuous wheat treatments with conventional fertiliser application.[55] In general, most soil-borne diseases can only be managed with appropriate rotations.

Soil management, as well as crop management, may benefit from technological developments such as robotics,[56] remote sensing[57] and mapping of soil and crop heterogeneity.[58] These technologies help to perform field operations with a high level of precision and thus reduce the requirements for prophylactic use of pesticides and intensive or heavy cultivations.

As the amount of organic matter is a crucial component of soil fertility, it is important to recycle animal manure and plant debris, including straw.[59] Animal manure, plant residues, sewage sludge and municipal waste also contain much nitrogen and phosphorus, which are needed by crops, and are thus valuable resources to be reused by agriculture rather than being considered as waste. In an optimised system, animal and crop production must be closely linked to allow for this efficient recycling and to reduce long-distance transport of feed, food and manure.

Enhancing biodiversity by crop management and breeding to increase ecosystem services

Epidemics may be 'normal agricultural accidents'[60] that are 'largely man-induced'[61] owing to a lack of diversity in space and time, as documented by many catastrophic crop failures in the past due to insects and pathogens.[17,62–65] Spectacular successes in disease control through intercropping at the interspecific level (species mixtures)[66] but also at the intraspecific level (alternating strips, variety mixtures or multilines) have been documented[67–71] (see Ref. 47 for a review). In China, one-third of the total planting area (half of the total grain production) exploits intercropping, often in combination with animal systems (Zhang F, personal communication). The mechanisms reducing disease in mixed crops include distance and barrier effects, induced resistance and a number of compensatory effects.[47]

Besides disease, insect and weed control and consequently reduced pesticide inputs, also nutrient conservation, soil fertility building and enhanced yield stability are some of the ecosystem services that can be achieved by plant diversification.[20,23,47,66,72] Both crop management and breeding need to adapt to climatic changes that increase the risk of crop failures, e.g. more variable or extreme weather and climate.[73–75] Introducing variation over time and space will stabilise the systems. This may include crop rotation (see above) or growing heterogeneous varieties that can adapt to local and changing environments, from the scale of the landscape (different fields with different varieties) to the scale of the field (populations or mixtures of varieties within a field). Perennial energy crops or fruit trees are of great importance here, as they add more structural diversity to the agricultural landscape while further reducing soil tillage needs.

In systems with more variable climate and reduced external inputs, crops will need to be able to cope with spatially and temporally more heterogeneous environmental conditions. Plant breeding will have to provide varieties that are adapted to these new needs in diversified agricultural systems, which will need innovative approaches.[76] The requirements for such varieties are enormous, as they have to combine high yield with high levels of resistance and tolerance to pests and diseases, competitiveness with weeds and an improved stand establishment with effective and efficient use of nutrients, water and light.[77] All these characteristics cannot be included in a single variety, so breeding needs to provide a wide range of different varieties and diverse populations with diverse qualities.[76] Such approaches need to be based on an improved understanding of the interaction between variety and environment.[78]

As new characteristics are needed, breeding will have to rely on the intensive use of genetic resources (landraces, exotic and wild resources) (see e.g. Ref. 79). Many of the required traits are based on a range of genes (polygenic inheritance) rather than single genes (monogenic inheritance) and are thus greatly influenced by the environment,[80] requiring phenotypic selection. It is sometimes possible to identify key component genes, particularly QTLs (quantitative trait loci), and to design molecular markers that can speed up the screening and development of new varieties.[81] This requires research which brings together physiology and ecology at the crop and farming system level and functional genomics.[82]

In the breeding process, common pedigree methods as well as population breeding procedures need to be used, including composite cross-populations[83–86] or modern landraces.[87] Such populations and landraces are propagated on-farm and are therefore able to adapt continuously to changing climate and biotic pressures through changes in gene frequencies and related phenotypes.[88–91] The adoption of participatory breeding approaches within the selection process allows breeders to deal more with traits that are less related to environmental adaptation, such as nutritional quality characters.[87] Farmers, breeders, processors, consumers and scientists can all participate in this integrated approach to plant breeding. However, such a participatory approach requires social skills to set up an effective strategy to incorporate stakeholders in the selection process. Breeding experiments have shown that decentralised, participatory breeding approaches are as cost-efficient as non-participatory, centralised methods, mainly because results are achieved earlier.[92] Therefore we conclude that decentralised and participatory approaches can be an effective and affordable way to breed plants that are better adapted to local requirements, resulting in the availability of a wide array of crop plants that also contribute to biodiversity.[93–95]

Reconnecting all stakeholders in agriculture and food production

The integration of all stakeholders in food and agriculture is needed in future not just in relation to breeding but to all aspects of crop production. All members of society will have to support the changes needed in agricultural production because they are included within the broader socio-ecological system. As an example, wheat grain quality is not defined solely by the industrial baking process but also includes nutritional quality for human (and animal) consumption as well as quality of the production process, taste and health benefits.

Long-term enhancement of soil fertility and biodiversity can only be achieved if planning and decisions are made on a scale appropriate for the system considered and in collaboration with all stakeholders, acknowledging the human resources. For example, experiences in Munich, New York and several cantons in Switzerland[96] show that costs for water purification are reduced when water supply comes from a watershed converted to organic and low-input farming, thus providing overall economic and environmental benefits. Another example is the application of agroforestry, which integrates trees into farming systems to produce a wide array of positive interactions among trees, crops, animals and the farmer.[97] The increased range of products (food, feed, wood products, biodiversity, aesthetics) thus produced can extend income and employment while limiting or eliminating the use of synthetic inputs.

To enable consumers to take part in the way their food is produced and processed, they need to know more about the ecological, cultural and economic aspects of agriculture. Ownership can be achieved across large regions, in part through a restructuring of the marketing system combined with education. Today, farmers and consumers in industrialised countries rarely meet, but they can be reconnected at three different levels. First, consumers can meet producers directly at local farmers' markets or through community-supported agricultural systems.[98] Second, in a regional market system, consumers and farmers are connected by a third party, but information on products and production processes can still be comprehensive. The third level is the global market of products unavailable regionally (e.g. tropical crops). In this system it is important to be able to trace the origin of the products and social issues connected with them. Internet or other discussion forums could be an instrument to involve society in an ongoing process of information exchange to evaluate the production and nutritional value of our food products. Also, information such as rules and availability of seeds, results of research, breeding successes and evaluation of new varieties can be shared. Specialist advice can be made freely available for education of stakeholders such as farmers, agronomists and managers. We can build on current examples of informing consumers not only on the nutritional and sensory quality of the product but also on socially responsible business practices that are applied, such as the Nature & More Trace & Tell system in The Netherlands (www.eosta.com) and other examples.[99]

As most European children grow up in cities, practical work in school gardens and on farms, education in food production and cooking and nutritional health should have a high priority in educational programmes in all types of school starting from kindergarten or preschool. An example of connecting these topics in higher education was the (initially founded by private foundations) establishment of the professorship for Organic Food Quality and Food Culture at the Faculty of Organic Agricultural Sciences of the University of Kassel in Germany.

STRATEGIC POLICIES NEEDED TO ACHIEVE THE ENVISAGED FUTURE

To realise the visions of future cropping systems, integration of government policy, research and development and education is needed. This would allow for implementation of the tools and strategies outlined above to be based on the understanding of their long-term effects. To move towards the envisioned future, national and European agricultural policies have to support improved crop management, particularly diverse crop rotations, incorporation of organic matter and reducing soil tillage where appropriate. The use of appropriate crop varieties, variety mixtures and crop populations which are competitive with weeds and have improved nutrient uptake, water use and photosynthetic efficiency will complement all these practices. Thus appreciation of the complexity of crop management practices may have to become part of an EU agricultural policy that benefits crop production and food supply through connecting research, education and regulation. While animal production has not been explicitly discussed here, its integral role in the system is well recognised and will need to be included in policy decisions. Overall, policy should support involvement of all stakeholders and individual actions.

Regulations should not restrict the diversity of food crops or have negative effects on the environment in terms of reducing biological diversity. A step forward is the possibility of marketing old landraces and varieties under EU Directive 98/95 on conservation varieties. A major concern is the restriction in some countries on farmers' rights to save their own seeds based on the latest (1991) version of the Convention of UPOV (International Union for the Protection of New Varieties of Plants). There are also serious concerns about the increasing number of applications for patents on life.[100,101] Acknowledging breeders' rights already gives the breeder protection without restricting the broad use and exchange of plant genetic resources to keep the genetic base of breeding programmes as broad as possible. As an answer to the concerns over patenting of genetic resources, the concept of 'open source biology' has been recently developed.[102] Open source biology is the analogue in the biological sciences of the 'free and open source software' movement. Genetic materials are distributed under a licence or material transfer agreement which allows free use or distribution but requires any derivative materials to be distributed under the same open source arrangement. This has the effect of a mandate for sharing and also effectively prevents the appropriation of germplasm by those individuals or companies who would use the material for exclusive purposes.

In order to implement the visions, appropriate changes in agricultural and environmental regulation and policy are needed, e.g. non-market valuation techniques for ecosystem services,[103] input/output accounting to change farmers' management practice[104] and greater public and private investments in technologies and human resources.[105] The changes have to be based on internalisation of the external costs of all technologies and practices used (see Ref. 24 for an example) and on evaluating economic outputs and ecosystem and social services equally. Internalisation of costs of production and environmental impact, e.g. through taxes on inputs reflecting the environmental mitigation costs such as clean-up of drinking water, will lead to greater sustainability. In this way, practices with low environmental impact will become more economical even if yields may be somewhat lower.

Technological solutions will be needed more than ever in the future. However, they have to be appropriate and evaluated taking into account the true costs and benefits in their production and application. The challenge is to assemble the tools and technologies in ways based on the principles of diversity and in the context of transdisciplinary collaboration across soil management, plant breeding, land use, food and feed processing, energy production and use and participatory networks. All need to be guided by criteria for sustainable development which we foresee may focus on 'low tech' or 'soft technology' approaches. This differs from the strategy often emphasised addressing mainly single issues and often with a strong dependence on biotechnology.[106,107] In line with this, Pollan[108] pleads for a sun-based agriculture rather than a fossil fuel-based agriculture.

CONCLUSIONS

Although progress through research in specialised disciplines has been huge, there is increasing recognition of the erosion of the links between land management, farming and society. What is required is a more balanced research agenda with emphasis on systems research at higher integration levels. Research for sustainable development needs to be focused much more on a holistic systems approach than is currently the case. The proposed visions embrace complex problems in their complexity and it is imperative that society as a whole participates and ultimately accepts a radical shift in ideas of food and agriculture production and its position within the broader socio-ecological system.

Diversity at all levels, including biodiversity and application of multifunctional approaches, must be at the core of cropping systems research of the future, integrating different disciplines including agronomy, ecology and social sciences. For example, integration of crop management and the appropriate varieties can often be more efficient than genetic or biotechnological solutions alone.

Concerns about how agriculture may support sustainable development are widely shared, though solutions for solving these concerns differ very much. We have presented and discussed some of the most important tools and technologies for conserving or increasing the resources for sustainable crop production: building soil fertility by recycling of nutrients and sustainable use of other natural and physical resources (e.g. equipment, labour, energy and information) and enhancing biological diversity by management or by breeding diversified crops able to deal with increasing variability and allowed to adapt to local conditions. The processes are based on human skills in agriculture, recycling of waste products and greater efficiency in energy use as well as increased connectivity among all stakeholders in crop production, e.g. by local food systems and local education. The future socio-ecological system envisioned here recognises and embraces the inherent complexity and diversity of such systems. As the envisaged future is based on the principles of diversity, it emphasises a range of practical strategies rather than one unifying solution.

Our visions have been driven by 'imagining a desirable future' which released our thoughts from being 'victims of the past'; the future envisioned was not restricted to an extrapolation of the past. Appreciative Inquiry (AI) is an excellent methodology to support this process. Envisioning the future through AI is acknowledged as an organisational development tool in a wide variety of organisations but, as far as the authors are informed, not yet among natural science communities.

The focus of this exercise has been on crop production systems. Clearly, complete integration will include livestock production and fisheries as well as the conversion and use of energy sources. In this context a fully integrative approach leads to a closed production cycle with arable and livestock components providing for each other with feed, bedding, manure and bioenergy in addition to renewable energy from sun, wind and water. This can be considered at different levels such as the farm, region or more globally. Ultimately, this will lead to food becoming a source of joy instead of a source of risks.

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