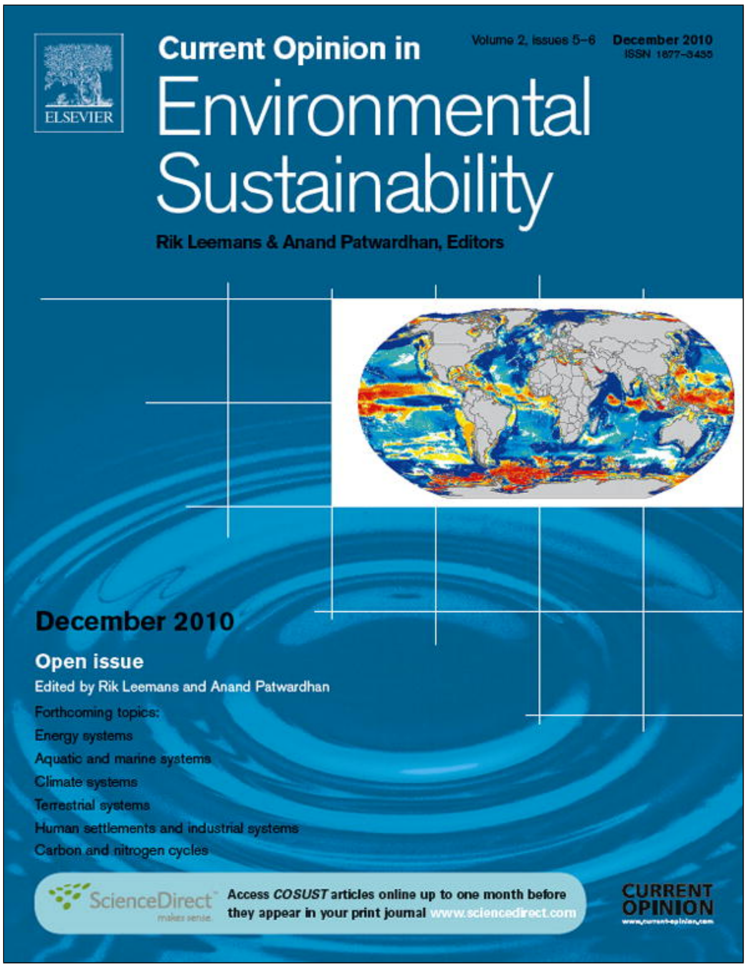
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Food production, crops and sustainability: restoring confidence in science and technology

Huub Spiertz

By 2050, the global food requirement will increase significantly, driven by a population increase to more than nine billion and by a richer diet. There is a need for agricultural and food systems that are not only more productive, but also sustainable. Currently, progress is hampered by a lack of understanding how to close the yield and sustainability gap. The consequence is stagnation in implementing policies and regulations that meet future needs. The challenge of meeting global food security in a sustainable way requires a knowledge-intensive approach and the use of advanced technologies. The confidence in modern agrotechnologies and biotechnologies should be restored by sound science, transparency and regulatory institutions.

Address
Centre for Crop Systems Analysis, Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands

Corresponding author: Spiertz, Huub (huub.spiertz@wur.nl)

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Introduction

Agriculture currently appropriates a substantial portion of the Earth's natural resources. Land used for crop production, pasture and livestock grazing systems amounts to 38% of total land area [1]. Population growth and expanding demand for agricultural commodities constantly increase the pressure on scarce land and natural resources [2]. The drop in cropland in relation to population is very evident. Until the middle of the 20th century, available cropland was in the order of 0.45 ha per person; by 1997 it had been reduced by almost a factor 2 resulting in 0.25 and the projection for 2050 is 0.15 ha per person [3]. The question is if we can produce enough food, feed, fibre and fuel to meet the needs of a 50% larger global population in 2050 in a sustainable manner. Cassman *et al.* [4••] concluded that '*avoiding expansion of cultivation into natural ecosystems, increased N-use efficiency, and improved soil quality are pivotal components of a sustainable agriculture that meets human needs and protects natural resources*'. More resources are required for meeting the demands of the growing human population. Recent studies [5••] indicate that significant systems improvements and efficiency gains in agriculture are needed worldwide in the next decades, to be able to feed the increasing global population and at the same time to circumvent large-scale degradation of natural ecosystems and deterioration of ecosystem services through agricultural activities. The sustainability framework, comprising the balance between short-term and long-term objectives with respect to profitability, ecological health and social-ethical acceptance gives guidance to research directions and policy measures. The conceptual framework of a sustainable gap was presented by Fischer *et al.* [6•]. They suggest a hierarchy of considerations with the biophysical limits of the Earth setting ultimate boundaries. The question is, if this concept with the 'economies' embedded in 'human societies' does fit for major food production systems with free trade as drivers at a global scale.

Transitions in agriculture are a response to external and/or internal 'events' that provide the incentive for structural change [7••]. Possible events or '*driving forces*' for transitions in agriculture include gradual and sudden processes, like population pressure, changes in natural conditions (climate, diseases, and flooding), changes in markets and market prices, innovations and applications of new technology. Transitions in agriculture involve large-scale structural changes, which have a distinct impact on society. The difficulties in understanding the causes and effects of changes in agriculture arise from the diversity and complexity of agriculture, and the multitude of factors that affect agriculture [7••]. Demands by society, economy and environment determine the direction of change in agriculture. Decision making requires intensive mutual interaction and discussion to identify the challenges, trade-offs, discrepancies, and possibilities for synergy. A more effective strategy for the transition towards sustainable agriculture is setting suitable goals with clear targets and indicators to measure progress, when the gap between (socio-)economic and ecological targets is too big. To meet the challenges of a global food security in a sustainable way requires the intensification of knowledge-intensive approaches and the use of modern agrotechnologies and biotechnologies.

In this paper the following topics are addressed: first, transitions in food production systems; second, to what extent are emerging technologies and sustainable agriculture compatible? third, prospects to integrate technology and sustainability.

Causes and consequences of a lack of trust in science and technology as well as the prospects for restoring trust are presented.

Transitions in food production systems

The focus on food security and the establishment of a free trade world market triggered a strong intensification and specialization of agricultural production technological innovations contributed to a rise in production and labor productivity. Intensification and specialization of agriculture in most industrialized countries took place from the 1950s onwards to raise the profits. Environmental side-effects were neglected in the beginning. Nitrogen fertilizers comprise almost 60% of the global reactive N load attributable to human activities. This resource use has a major impact on the functioning of the ecosystems and human well-being. From 1985 onwards, a series of environmental policies and measures have been implemented in EU-countries, especially constraining the use of nitrogen (N) and phosphorus (P), insecticides, fungicides, heavy metals, and the use of land near nature conservation areas [8].

A major point of concern for many intensively managed agricultural systems with high external inputs is the low resource-use efficiency on the plot and field level, especially for water and nitrogen [9,10•]. These efficiencies are even lower when nutrient flows of the whole food chain are taken into account. Ma *et al.* reported that average N use efficiencies in China for crop production, animal production and the whole food chain amounted to 26, 11 and 9%, respectively [11•]. A high input combined with a low efficiency ultimately results in environmental problems such as degradation of resources (reduced stocks of fresh water and phosphorus), eutrophication and emissions of greenhouse gases [12,13•].

Cultivated land should also provide ecosystem services to society, such as biodiversity, water conservation, wildlife and mitigating climate change [14,15•]. A framework for the assessment of ecosystem goods and services was presented by Posthumus *et al.* [16•]; they explored six alternative floodplain management scenarios and found that there are both synergies and conflicts between ecosystem services. For example, there is a conflict between agricultural production and environmental outcomes [17•] such as water quality, GHG, habitat and species. Johnson [18] analysed the policies of two competing visions on food and agricultural sustainability; one to promote organic and local food and another to continue the productionist hegemony, emphasizing biotechnology and technological panaceas. He contends that the political will to promulgate radical agricultural policies that break the productionist hegemony are lacking. The dichotomy between 'intensive agriculture' and 'eco-agriculture' was denied by others. Brussaard *et al.* [19•] suggest that biodiversity loss undermines the provision of ecosystem services on which agriculture itself depends on. However, this hypothesis is not underpinned by a quantitative analysis of intensive and eco-based farming systems. In their paper they present a figure based on the work of Swift *et al.* [20••] that nicely shows the trade-offs between agricultural production and biodiversity. I agree with their conclusions that there are prospects for synergy (symbiosis, facilitation, etc.), but these should be present not only in low-productive systems but also in systems that are able to produce high yields per unit of land. Hard evidence for synergy in high-yielding systems was not shown. In the recent past, increased productivity of the major cereal crops has been derived from genetic improvement by conventional breeding and greater use of external inputs (fossil energy, fertilizers, feed, pesticides, and irrigation water). Now, the focus should be on enabling technologies and transitions in cropping systems to increase overall resource-use efficiencies under biotic and abiotic stress conditions [10•], including climate change, in order to prevent environmental degradation.

Are emerging technologies and sustainable agriculture compatible?

A sense of urgency to apply emerging technologies in solving some of the most severe problems (drought, salinity, diseases, pests, weeds, nutrient acquisition, etc.) in food production is lacking. The issue of genetically modified crops — GM crops — has been highly controversial since the introduction of the recombinant DNA technology in the 1970s [21]. It was shown that the debate on genetically modified organisms (GMOs) extended in terms of actors involved and concerns reflected. A GMO is '*an organism in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural recombination*' (EU Directive 2001/18). The concerns on developing and commercializing GMOs have been worldwide [22••], but are most prominent in the European Union and many African countries. European countries have been very defensive to adopt GMO crops based on the precautionary principle. In a reconstruction to analyze the complexity of concerns and actors involved Devos *et al.* [21] distinguished four phases:

a. how recombinant-DNA technology evolved in a dynamically changing context from laboratory science to societal concerns on ethics, ecological risks and socio-economic conflicts;
b. the impact of these concerns for the growing involvement of actors in the debate;
c. the change and dynamics in the content of the concerns;
d. how scientific objectives became intertwined with extra-scientific objectives.

Depending on underlying values and ideals the appreciation of new technologies will differ between stakeholders. Scientists and end-users (e.g. modern farmers) tend to be more positive about the benefits of GM-crops. However, the growing awareness of educated citizens about food safety, sustainability and equity has led to an increasing distrust in multinationals, but even in private funded research by scientific institutions [22••,23,24]. By scaling up scientific and technological developments into commercial activities, techno-scientific developments are entering society more directly, exposing it at large to potential risks and benefits. Science and technology have become public goods.

Recently, the academic institutions take part in the public discussions by publishing reports on the prospects and challenges of plant genomics in the 21st-century [25]. The essential claim is that '*plants form the basis of the food web that sustains all other forms of life*'. They focus on the following themes: improving food crops (food quality and plant-pathogen arms race), biofuels and bioenergy goals, environmental stewardship (saving on water and fertilizer use, biocontrol of pests, and plant defense) and biomedical (drug discovery and immune systems). The plea is to maximize the potential of the plant genome sciences in contributing significantly to human health, energy security and environmental stewardship. Strikingly, food production is not listed as one of the major challenges; however, climate change and the world food crisis bring a '*sense of urgency*' in the debate on meeting the demands of a growing global and wealthier population.

In Europe the rejection of GM crops is more categorically than it is the case for the application of biotechnology in producing medicines for human health. The opposition is complex and rooted in ethical-religious, environmental and social-economic objections [24]. It seems that this opposition is not generic for all modern technology (e.g. IT and nanotechnology) because the latter technologies do not affect the integrity and composition of food directly.

Prospects to integrate technology and sustainability

The compatibility of modern biotechnology and sustainability was recently addressed by Ervin *et al.* [22••]. They presented a comprehensive analysis based on a sustainability framework that includes the full spectrum of environmental, economic and social impacts. A review on each impact revealed that '*crop biotechnology cannot fully be assessed with respect to fostering a more sustainable agriculture due to key gaps in evidence, especially for socio-economic distributive effects*'. First generation GM crops generally showed progress in reducing agriculture's environmental footprint and improving farmers profits; however, these crops fall short of the technology's capacity to develop a more sustainable agriculture. The latter was based on the presupposition that all stakeholders should be engaged and salient equity issues should be addressed. For realization of the potential of biotechnology, fundamental changes are required in the way public and private research and technology development and commercialization are structured [26]. More public/private partnerships in advanced research using enabling technologies are needed during the pre-competitive phase. Furthermore, transparency in objectives and methodologies should be realized through an open dialogue with all stakeholders. A good example is the concerted action taken by CGIAR research institutes (CIMMYT and ICARDA), advanced research institutes and national institutes in Ethiopia and Kenia to deal with the outbreak of the race Ug99 of the stem rust *Puccinia graminis tritici* causing severe epidemics in wheat. A major threat to wheat production not only regionally but also globally, because of the susceptibility of the existing plant material and the rapid spread by air of spores over large distances in North Africa, Middle East and West-South Asia [27]. Within 10 years new seed material could be released as a result of rigorous screening in labs and the field on resistance for the race. Combining genetics, molecular assisted selection and modern breeding made it possible to control a disease that potentially could destroy half of the global wheat production.

A plea for radically rethinking agriculture for the 21st century was presented by advocating systems that close the loop of nutrient flows from microorganisms and plants to animals and back [28]. By making better use of sunlight and seawater it would become possible to decrease the land, fossil energy, and fresh water demands of agriculture, while at the same time ameliorating the pollution currently associated with agricultural chemicals and animal waste. A combination of scenario development and back-casting will be required to identify ways where science and technology can contribute effectively. The study of solar-powered drip irrigation of vegetables in the rural food-insecure Sudano-Sahel region of West Africa [29•] nicely shows the potential of modern technologies to augment both household income and nutritional intake in a cost-effective manner compared to conventional technologies.

The prospects to integrate enabling technologies and sustainability while securing the needs for food, feed, fibre and fuel should be explored at various scales: molecular, cell, plant, field, agroecosystem and landscape. Integration of crop modeling into genetic and genomic research facilitates '*breeding by design*', because the impact of changing traits on crop performance can be explored for various scenarios of environmental conditions and climate change. The use of robust crop models to understand Genotype × Environment × Management (G × E × M) quantitatively did get more attention recently [30••]. Assessments of the relationship between crop productivity and climate change rely upon a combination of modeling and measurement [31•]. It was argued that the generation of knowledge for adaptation should be based on reliable quantification of uncertainty, combining diverse modeling approaches and observations and judicious calibration of models. This approach is not just an improvement of the methodology, but it also contributes to more transparency.

On the level of the crop and field a science-based understanding of the dynamics of phenology, plant physiological processes and soil conditions is required to implement precision agriculture. Adapting inputs (water, fertilizers, pesticides, etc.) site-specifically allows a better use of resources in crop production, while preventing emissions to the environment [32]. A dedicated approach with modern technologies (sensors, IT, machinery, etc.) and knowledge-intensive decision support systems (DSS) can enhance resource-use efficiencies, and enhance the quantity and quality of agricultural produce [33]. There are no easy generic solutions that fit to all agroecosystems as was nicely shown for conservation agriculture in Africa [34•]. Technologies that integrate biophysical and ecological processes into the framework of sustainable food production by an efficient use of natural resources (land, climate, and water) and minimizing the use of non-renewable inputs (especially fossil energy and phosphorus) should get strong support by making use of knowledge transfer and modern communication means engaging all actors in the food chain [35•,36,37•].

Conclusions

The concerns for the impact of agriculture on the environment are valid. However, it is not realistic to benchmark the environmental load of agroecosystems with those of nature areas. Specific threshold values are needed that meet the standards of food safety and environmental health.

Technology, especially plant breeding and crop management, and government policies have contributed to counter-balance the explosive growth in food demand during the last four decades [38•]. On average, food availability per capita improved despite the doubling of the global population in the recent past. To meet the huge future demands during the next four decades, it will be necessary to make use of the best science and technology to raise crop productivity per unit of land on average with 2% per year and resource-use efficiencies of water and nutrients by a factor 2 [39].

New insights in genetics, systems functioning, climate change and multiple stresses can guide the development of improved cultivars and highly productive farming practices to close the yield gap [40••]. So far, a combination of advanced plant breeding, systems innovations, development of best practices and legislation turned out to be effective in developing more environment-friendly agricultural systems that are profitable, ecologically safe and socially acceptable.

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