Avenues to meet food security. The role of agronomy on solving complexity in food production and resource use

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Abstract

Food security has determined the history of mankind. The global population will increase to about 9 billion during the next four decades. Food and feed demands have been projected to double in the 21st century, which will further increase the pressure on the use of land, water and nutrients. Clearly, there are gaps in our knowledge regarding the global capacity for a sustainable plant-based production to meet the demands of a bio-based economy, while maintaining food security. Complexity in the demand and supply of food, feed and fuel at local, regional and global scales asks for tailor-made solutions. The rapidly growing demand for food, feed and fuel will require transitions in land and water management, improving crop productivity and resource-use efficiencies.

The present review discusses achievements and shortcomings in meeting food security at a global and regional scale. Next, the avenues for future research in agronomy to enhance food production are presented. Progress should be made in:

- Improving yield security and closing yield gaps by plant–soil–crop management practices based on knowledge-based support systems for contrasting conditions in land use and climatic conditions.
- Making cropping systems adaptive to climate change and to biotic and abiotic stresses by genetic improvement of crops and increasing agro-diversity. Carrying out integrated assessments of biophysical and socio-economic constraints and opportunities to improve the productivity and sustainability of agricultural systems.
- The ultimate objective is to achieve food security, sustainability and ecosystem services at regional and global scale on a cost-effective way.

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1. History of agriculture in a global and regional context

The evolution from primitive to modern farming systems determined the live of mankind. The history of agriculture dates back to 8–10,000 years ago. Written history of agriculture dates back to the inscriptions on bones or shells made during the Shang Dynasty (1500–1050 BC) in China, which can be seen in museum of the old capital Anyang, Henan Province (http://en.wikipedia.org/wiki/Agricultural_science). Farming practices were also documented in books by Roman writers, e.g.: Cato in ‘De Agricultura’ (On Farming). In the Roman Empire a family with 6 persons would need to cultivate 3 ha to meet the minimum food requirement; taking into account the requirements of the animals, the area had to be expanded to 5 ha. Fraser (2011) analysed that medieval Europe (11–14th century) shifted from the subsistence agrarian economy to one where spatially dispersed trade in agricultural commodities could support societies that devoted resources to develop monastic institutions and guilds in cities.

The ratio of seed to grain yield centred in the Roman time around 1–10. In the Middle Ages this ratio was even lower (1–5) when wheat yields stagnated at a level of less than 1 tonne ha−1 probably due to lack of animal manure and more severe competition by weeds in the expanded cereal farming systems. Currently, the ratio will centre around 1–30 for low-input rainfed systems with yields of about 3.5 tonne ha−1 and 1–100 for high-input wheat cropping systems with yields ranging from 8 to 12 tonne ha−1. As a consequence of progress made in breeding (semi-dwarf cultivars), agronomy (use of nitrogen, herbicides, fungicides, etc.) and technology (advanced equipment for soil tillage, sowing, spraying and harvesting) during the last century not only yields per ha increased with a factor 10, but even more labour productivity (grain yield per hour) with a factor 200 (De Wit et al., 1987; Evans, 1998).

Global land use and economic globalization are intertwined. Land use change through population growth, agricultural intensification and urbanization has transformed natural ecosystems locally, regionally and globally (Ellis et al., 2010). From 1700 to 2000 land used for agriculture and urban settlements increased from 5% to 39% of the total ice-free land area. Globally, scarcity of fertile land becomes increasingly a serious constraint to producing food, feed and fuel; as a consequence more marginal land and semi-natural land will be brought under cultivation. The pressure on fertile land does vary for different parts of the world: relatively low in Europe compared to South-East Asia, where the available fertile land per capita decreased to <0.20 ha (Tong et al., 2003). In Europe, urbanization, agricultural policies and environmental legislation did increase the value of agricultural land in spite of forecasts that less land would be needed for food production (Van Latensteijn, 1995). During the last two decades, the value of land for dairy farming in the Netherlands was primarily determined by dairy quota and the legislation for manure applications and not by the capacity to produce feed.

2. Global food security and regional diversity

The general trend in global food security during the last century was characterized by a change from shortages to surpluses, resulting in food affluence in the developed world. In Western Europe price guarantees for major commodities (cereals, dairy, meat, oil, wine, etc.) aggravated the problems with food surpluses. The trend in an increased availability of food per capita globally was interrupted during the last decade. Food scarcity continued to persist for poor people in regions with severe drought, diseases, low availability of nutrients, and political instability (Herdt, 2006). The number of people suffering hunger and poverty decreased to about 800 million in the period from 1985 to 2005, but showed a rise to about 1.2 billion afterwards due to price volatility and regional food shortages. For some commodities, like rice, the relatively small world market compared to the demands of importing countries, such as the Philippines, makes food security fragile. The price spike (“bubble”) of the main food crops (maize, rice and wheat) in 2008 and the current trends show the risks and uncertainties in global food security. Also, in the long term food prices for poor people are at risk; in many low-income countries, food expenditures average over 50% of the household income and higher prices will push more people into undernourishment (Lam, 2011). A plea for a more nuanced debate on how global developments and policies affect food security was presented by Swinnen and Squicciarini (2012). They concluded that “impacts of price changes on the number of hungry people are projections based on models and assumptions, which include uncertainties and should be interpreted with caution”.

The awareness of the food shortages in Africa came much too late; from the seventies of the last century onwards aid agencies mainly associated food shortages with severe drought spells or political unrest, but not with lagging behind in investments in agricultural research and infrastructure. Since the agreement on the Millennium Goals in 2007 more concerted actions by public (World Bank) and private (Melinda and Bill Gates Foundation) donor agencies are taken to solve the problems in Africa. Especially in Asia, a revolutionary change in cereal production – the solid base of global food security – took place when large-scale investments were made in agricultural research, land reclamation and supporting infrastructure (e.g., irrigation systems) from 1960 onwards by national governments and the World Bank as well as foundations such as the Ford and Rockefeller Foundations (Mu and Khan, 2009; Zeigler and Mohanty, 2010).

3. Constraints in meeting global demands for food and feed

In a recent study, it was estimated that global food demand will increase with 50% and the area of cultivated land with 10% (excluding land needed for the production of biofuel) by 2030 assuming yield increases of 40% for major commodity crops (Anonymous, 2007; Godfray et al., 2010). A more specific assessment was made for China by Fan et al. (2012); they concluded that yields should increase by at least 2% annually to meet the extra demand for grain of 580 Mt. Thus, yield increases per unit of land by breeding more adapted, high-yielding cultivars and implementing best farming practices are needed to save fragile land and nature (Cassman et al., 2003; Tilman et al., 2002). An assessment of long-term global availability of food has recently been carried out by Wageningen scientists (Koning et al., 2008; Koning and Van Ittersum, 2009). They concluded that globally there is a biophysical potential for feeding two or three times as many people as anticipated for the year 2050. However, the actual level of food supply will be determined by a great complexity of factors of diverse nature at different scales as shown in Fig. 1. Amongst those are socio-economic constraints, environmental legislation, food preferences, climate change induced weather extremes, scarcity of resources (irrigation water, phosphorus, fertile land) and fossil energy.

The relative importance of drought and other water-related constraints as a major source of risk for food crops in South Asian farming systems already contribute to 20–30% of current yield gaps (Li et al., 2011). In case of emergencies (flooding, drought, etc.) food aid should be provided across regions. Even when natural hazards do have a minor impact on the average food self-sufficiency at national level, the consequences for vulnerable regions can be severe. To balance the risk of crop failures two measures seem to be effective: a stable grain stock and a higher degree of diversity.
in grain crops. When considering also the need of a balanced diet in nutritive terms a broader range of crops, e.g. potatoes, pulses and legumes, should be taken into account. Wright (2011) concluded that the balance between consumption, available supply, and stocks should be understood to give good guidance to policymakers confronted with a bewildering variety of expensive policy prescriptions.

The rapidly growing demand for food, feed and fuel will also require further improvements of resource use efficiencies (nutrient-use efficiencies and water productivity) over the next 20–30 years (Spiertz and Ewert, 2009; Spiertz, 2010). Nowadays there is a growing concern on a looming phosphorus crisis (Schröder et al., 2011); however, regional differences are large. Taking into account residual soil phosphorus in the global phosphorus budget, Sattari et al. (2012) estimated that in the next four decades globally a cumulative P application of about 20 kg ha\(^{-1}\) y\(^{-1}\) of cropland is required to meet the projected food production in the Millennium Ecosystem Assessments. This is 50% less than in studies that did not take into account the contribution by residual P.

Enhancing grain production requires not only progress in agronomy and breeding, but also investments in irrigation, technology and skilled labour. Constraints and opportunities for improving production efficiencies of the major cereals – rice, wheat and maize – differ strongly between world-regions (Neumann et al., 2010; Strzepek and Boehlert, 2010), and views for releasing these constraints differ among scientists. Agronomists tend to have a one-sided view on food security. They consider the improvement of crop yields per unit of land as the major factor to match supply and demand in staple foods. There is quite some evidence that the green revolution resulted in improved crop yields of the three major grain crops: maize, rice and wheat (Fischer and Edmeades, 2010). At the end of the 60s to the beginning of the 70s new technology packages, including split dressings of nitrogen, use of growth retardants and the use of systemic fungicides and insecticides, were introduced in cereal cropping to enhance yields. During the last three decades, the emphasis was on reducing the side-effects of the use of external inputs. As a consequence, the external inputs were reduced and yields did reach a plateau. Interestingly, new cultivars continued to outyield their predecessors.

In the future we will face a greater complexity. Meeting food security will involve many biophysical and ecological aspects, such as: genetic plant improvement, sustainable land use, water saving irrigation, integrated nutrient management, control of pests, diseases and weeds. Furthermore, socio-economic factors (poverty, affluent societies) and consumer behaviour (change of diets) are already playing a major role in a more urbanized world. A conceptual framework of supply and demand factors is presented in Table 1. Among the supply factors the most important related to the primary production are: availability of fertile land, crop productivity, availability and efficient use of resources, losses by biotic and abiotic factors.

The demand for food and feed is not only driven by a growing population, but even more by diet choice, food safety regulations and lifestyle (e.g. easiness). A shift from a cereal-legume or potato-based diet towards a more protein-rich diet with dairy and meat has already taken place. When considering food security at the local, national and regional level post-harvest losses, stocks and trade are playing an important role. In the Western world food waste by consumers is estimated to centre around 30%, while in developing countries food waste by consumers is low, but post-harvest losses in the food chain during transportation and storage are high (Parfitt et al., 2010).

### Table 1

A conceptual framework with factors that determine supply and demand of food at a regional and global scale.

<table>
<thead>
<tr>
<th>Supply</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global available fertile land (ha)</td>
<td>Global population (number of people)</td>
</tr>
<tr>
<td>Crop yields per unit of land (kg ha(^{-1}) y(^{-1}))</td>
<td>Human consumption (kJ capita(^{-1}) y(^{-1}))</td>
</tr>
<tr>
<td>Dairy and meat supply (kg y(^{-1}))</td>
<td>Feed use (kJ y(^{-1}))</td>
</tr>
<tr>
<td>Resource use efficiencies (kg kg(^{-1}))</td>
<td>Conversion efficiencies (kJ kg(^{-1}))</td>
</tr>
<tr>
<td>Losses by weeds, pests and diseases (kg ha(^{-1}) y(^{-1}))</td>
<td>Waste by consumers (kJ capita(^{-1}) y(^{-1}))</td>
</tr>
<tr>
<td>Harvest and storage losses (tonne y(^{-1}))</td>
<td>Waste in the food chain (tonne y(^{-1}))</td>
</tr>
<tr>
<td>Depletion of stocks (tonne y(^{-1}))</td>
<td>Accumulation of stocks (tonne y(^{-1}))</td>
</tr>
<tr>
<td>Imports (tonne y(^{-1}))</td>
<td>Exports (tonne y(^{-1}))</td>
</tr>
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4. Challenges at the national, regional, and global scale

Taking into consideration the world-wide growing demand for food, feed and bio-based products (bio-energy, compostable packaging, etc.), it will be necessary to raise the production per unit of land in order to save land for forest and nature (Parry and Hawkesford, 2010). Food security will increasingly be affected by the extent, to which supply and demand of food are balanced at temporal and spatial scales. This is clearly illustrated in the study by Simelton (2011) on food self-sufficiency and natural hazards (floods and droughts) in China. In a “theoretical worst-case scenario”, when all experienced crop failures over a period of 10 years were to happen in one year, China’s cereal harvest may drop by 140 million tonnes. The overall impact of natural hazards on food production does differ between regions.

Since the implementation of the General Agreement on Tariffs and Trade (GATT) and the Uruguay Round of the World Trade Organization (WTO) agriculture became an important global issue. Free trade became dominant in matching demand and supply in agricultural produce, mainly based on cost-effectiveness. Regions with ample fertile land and a low population density like South America (Argentina and Brazil) are nowadays the main suppliers of protein-rich animal feed for Europe and China (Anonymous, 2010). Global free trade aiming at maximizing profits has become important for countries that export grains (USA, Australia, Argentina, Brazil, Russia, France, etc.), dairy, meat and fish (Argentina, Denmark, Ireland, The Netherlands, Vietnam, etc.) and high-value crop produce such

![Food security: a complex network. Source: Economic Research Department Rabobank Group (Anonymous, 2010).](image-url)
as seeds, vegetables and flowers (China, The Netherlands). During the last five decades global trade in cereals (especially maize and wheat), soybean, meat, dairy and vegetables have increased considerably at the global scale (Anonymous, 2010; Fig. 2). This approach is not sustainable, because of energy costs, plant nutrient imbalances, virtual water use, and environmental concerns and dependence on political stability. A paradigm shift in thinking on securing food supply is needed from global trade to regional balancing of demand and supply. The question if regionalism in food production and trade will be an alternative is strongly rejected by economists (Oladi and Beladi, 2008), but gets increasingly support from ecologists and social scientists (Röling, 2009) concerned with the effects for the environment and poor people. The conflicting views partly result from a lack of quantitative underpinning of the trade-offs between food production and environmental side-effects.

Considering the potential in Europe to grow feed and food for humans and animals, major savings will be possible on energy use and nutrient losses, when a regional approach would replace the world free trade paradigm. In principle, there is no need for importing huge quantities of feed stocks from Southern America (Brazil and Argentina) to Europe. In Western Europe, the conditions for food and feed production are favourable, but the demand for food is decreasing because of a stagnating population growth and a rapid aging of the population. As a consequence, government policies shifted from food security to quality of life, especially food safety, health and well-being. The EU Common Agricultural Policy (CAP) replaced price support for major commodities (cereals, meat, dairy, etc.) by a multifunctionality policy with subsidies for maintaining agricultural land and for ecosystem services (Brouwer and Lowe, 1998). However, the compatibility of the policy combining multifunctionality with market liberalization and the consequences for land use remain unresolved (Potter and Tilzey, 2007; Hermans et al., 2010). A shift to regional specialties (food products with a local brand) and a multifunctional use of land and buildings were developed to curb the trend of declining revenues. Historical farm buildings were converted into restaurants, party centres, or estates. A government scheme “green for red” made it possible to pull down pig houses that were constructed during the booming business in the pig industry in the 1980s. The erosion of small-scale farming activities in the countryside from the 1950s onwards has been a gradual process initially, but accelerated during the last two decades. The question is if diversification and multifunctionality can compensate the loss in income from farm activities on the long run (Potter and Tilzey, 2007). It might be the case in peri-urban areas of high-income countries. Globally, poor farmers migrate to industrial urban areas to acquire an income and hopefully a more decent life (Sachs et al., 2010).

Scale of operations does matter; without government support farmers, processing companies and food retailers can only survive when they expand their size of operations. Less farmers produce more than in the past; the volume of production continued to grow. A further expansion is not primarily determined by biophysical factors, but increasingly by economic competition at a global scale and by environmental and food safety regulations. This is clearly illustrated by the developments in dairy farming in The Netherlands during the last three decades: the average milk production increased per cow from 6000 to 8000 L, per ha from 10,000 to 15,000 L and per farm from 300,000 to 800,000 L. A further increase is not limited by production factors, but by environmental regulation; especially, the levy-free excess on nitrogen and phosphor budgets (Aarts et al., 2000). As a consequence of raising costs of labour and land – e.g. in The Netherlands, agrosectors have to develop strongly in commodities with a high added value (horticulture, dairy, meat, etc.). The growing international competition will put many small- and middle-sized farms out of business. Small farms can only survive when producing for special niche markets (organic products, products with a regional brand) or developing complementary activities, like care taking for children and disabled people, recreation, etc. These activities are still listed as farming, but the share of income from primary farming activities has been decreasing for more than 20 years. The scaling-up in farming...
affected strongly the number of people employed in farming, the economic viability of the countryside and last but least the diversity of cropping systems in the countryside.

Fertilizer N-use boosted since the 1960s in the temperate growing areas as well as in the irrigated rice and wheat systems (Dobermann and Cassman, 2002). A vast amount of papers is dealing with the consequences of the change from traditional low-input to modern high-input farming systems. In a comprehensive review Gomeroio et al. (2011) recognize that agricultural productivity per unit land made a great leap forward; however, most attention was paid to environmental costs, loss of biodiversity, loss of soil organic matter, depletion of fresh water resources and use of agrochemicals. A shortcoming of these types of studies is that most impacts of highly productive farming systems are presented in a negative connotation without presenting a quantitative underpinning. Instead, non-sustainable solutions are presented; such as: “Organic production of corn and soybeans in the US without ‘commercial’ nitrogen, soil erosion and insecticides or herbicides and 30% less fossil energy gave equal yields to conventional production methods” (Pimentel et al., 2005). More recently De Ponti et al. (2012) reported that yields of organic grown crops are on average 80% of conventional yields. This analysis was based on a meta-dataset of 362 comparisons for a wide range of crops. Taking into account differences in rotation between organic and conventional, it is evident that the yield gap between the cropping systems will be more than 20% The often incomplete N budget and short term analysis of advantages of organic systems do not prove the economic and agro-ecological sustainability on the long term.

Clearly, there are gaps in our knowledge regarding the local, regional and global capacity for a sustainable plant-based production to meet the demands of a bio-based economy, while maintaining food security (Burgess et al., 2012; Langeveld et al., 2010). The rapidly growing demand for food, feed and fuel will require a combination of further improvements of land and water management, crop productivity and resource-use efficiencies. Cases of land use change in developing countries (China, Vietnam, Costa Rica, and El Salvador) as a consequence of economic globalization show that policies and innovations can reconcile forest preservation with food production (Lambin and Meyfroidt, 2011).

5. Integrated research on improving plant-soil-crop management

Major contributions to achieve higher and more stable yields in small cereals, especially wheat and rice, were achieved by technology transitions based on the introduction of dwarfing genes and optimizing water and nitrogen supply. These transitions caused a jump in the annual yield increase from about 1 to 3% for two decades from around 1970 to 1990. Another type of technological transitions, like mechanization and chemical weed control that resulted in more stable yields, but also a much higher labour productivity got less attention. Fresco (2009) concluded that the immediate challenge is to adapt food systems to changing abiotic conditions (temperature, nutrients and water). A better quantitative understanding is needed to assess the trade-offs between productivity increase and environmental side-effects (Stoorvogel et al., 2004). The magnitude of the trade-offs can show a window of opportunities for improving crop productivity in a sustainable way.

It is clear that strong investments in research, development and extension are needed to meet the future challenges. Integration requires bridging scales in time and space. Therefore, attention is given to the field and landscape level:

6. Innovations of cropping systems

Maximizing interception of solar radiation by growing more crops during one growing season gets priority when fertile land is scarce and food demand is high. Multiple cropping systems can convert a greater proportion of the potential land productivity in crop yield, which is shown by an increase of the land equivalence ratio (LER > 1). Examples are: double- and intercropping (e.g.: rice–wheat (Iijima et al., 2005); maize–wheat (Jin et al., 2011), wheat–soybean (Caviglia et al., 2004, etc.) and relay-strip intercropping of wheat and cotton (Zhang, 2007)). Improvements in interception of light by multiple crops in one growing season should be based on the total PAR available per year within the window for favourable growing conditions. To realize the potential of multiple cropping systems in terms of an optimized spacing and timing of planting and application of external inputs (irrigation, fertilizers, etc.) a science-based crop management support is required. Timing will become the most important management factor; next, the dosage of seed rates and external inputs has to be adjusted to the target yield levels.

Not only productivity should be increased, but also the efficient use of natural resources and external inputs in cropping systems. Jat et al. (2009) carried out an extensive study of the impact of advanced land levelling and double zero-till on water use, productivity, profitability and soil physical properties in a rice–wheat rotation. Their study in a semi-arid tropical environment (hot summers and cool winters) of Uttar Pradesh, India – showed that conservation and precision agriculture based resource conserving technologies can contributed to sustain rice–wheat systems in a more profitable and resource-use efficient way.

7. Resource saving and resource-use efficiency

The growing demand for food, feed, bio-energy, etc. will not only require more land and higher crop productivity, but also fresh water and nutrients. Worldwide water use patterns will change significantly as a consequence of regional shift in rainfall, temperature and atmospheric CO₂ concentration. Many regions are projected to become less water use efficient (Fader et al., 2010). Virtual water use is already playing a significant role to compensate for water shortage and low water use efficiencies. The potential for water saving in irrigated rice systems has been extensively explored (Bouman and Tuong, 2001; Belder et al., 2004; De Vries et al., 2010). Water savings in rice ranged from 5 to 40% without much impact on the yield level. An improved water management based on a quantitative understanding of unnecessary evaporative and seepage losses, can result in a great leap forward in water saving and in water-use efficiency and water productivity.

A vast amount of experimental work has been carried out to co-develop an optimum management of water regime and nitrogen use. It was estimated that yield gaps in rainfed rice systems ranged from 0 to 28% due to water shortage and from 35 to 63% due to nitrogen deficiency. Currently, there is still an overuse of nitrogen and water in irrigated cropping systems, despite many years of experimental and modelling research on a better dosing and timing of nitrogen (e.g.: Belder et al., 2005; Liu et al., 2011). The agronomic nitrogen-use efficiency amounts to 0.50 on average for crops under temperate conditions; however, there exists a wide variation ranging from 0.20 to 0.80. Especially the efficiency in rice–wheat systems with alternating anaerobic and aerobic soil conditions is very low (Timsina and Connor, 2001). De Wit (1992) already stated: “farmers should aim at the minimum input of each production resource required to allow maximum utilisation of all other resources”.

Next to nitrogen, phosphorus is the nutrient that limits plant production most; especially the growth of maize and legumes. Schröder et al. (2011) suggested a concerted set of measures to reduce the demand for phosphorus while maintaining crop productivity. Most of the measures, such as land use and nutrient management, require an integrated approach at the farm level. Currently, inefficiencies in the use of nutrients and water in agriculture are the result of a lack of effective government policies and legislation to encourage sustainable use of scarce resources and to protect the environment. Clear incentives and legislation are needed to encourage savings on water and nutrients. Agronomist should provide the knowledge en the decision-support tools to optimize resource-use efficiencies within the boundaries for cropping systems set by the market and government policies. Closing the gap between actual and attainable resource use efficiencies should become as important as closing yield gaps.

8. Adaptation to global change and sustainable land use

A transition towards food and feed systems that rely less on water and fertilizer N will be promising. One example is the replacement of wheat by maize in double cropping rice systems in warmer and dryer climates (Timsina et al., 2010). Another example is the introduction of legumes in cropping systems in Africa (Giller et al., 2011) and of growing faba beans to produce feed (Jensen et al., 2010). Thinking in terms of functioning of agricultural and natural systems at the field and landscape level will help to bridge the gap in understanding between agronomists and ecologists. Doré et al. (2011) suggested analyzing farms and cropping systems in terms of complex networks and learning lessons from the functioning of natural ecosystems. This will be not an easy task, because natural ecosystems and cropping systems differ not only in temporal and spatial scales (Giller et al., 2006), but also in the interference of carbon and nutrient flows by external inputs and harvesting a major part of the biomass within an annual cycle. However, major improvements in resource use efficiency can only come from a paradigm shift towards food productions systems that rely less on external inputs.

Adaptation science was coined by Meinke et al. (2009) as: “the process defining and assessing threats, risks, uncertainties and opportunities that generates the information, knowledge and insight required to affect changes in systems to increase their adaptive capacity and performance”. At the crop level most progress may be expected by taking genotype × environment into account (Chenu et al., 2011). At the field level the production function of the soil can be improved by integrating management practices that are able to increase productivity per unit of land while maintaining the long-term fertility of the soil (Giller et al., 1997; Powlson et al., 2011). Development of resource-use efficient cropping systems should be carried out for well-defined regions on the basis of physical and socio-economic conditions (Challinor et al., 2009; Röling, 2009; Doré et al., 2011).

9. Improving crop management practices

Crop management is a strong tool to make better use of natural resources and external inputs. The success of best management practices on the short term can be assessed by monitoring crop productivity and quality on the one hand and resource-use efficiencies on the other. In the long run, yield stability, control of pest, diseases and weeds, and maintaining soil fertility and soil health are useful indicators. An example of such approach is the study by Chen et al. (2011) on developing an integrated soil-crop management system for maize that doubled maize yields to 13.0 tonne ha⁻¹ without increasing N fertilizer use. As a consequence the agronomic N-use efficiency increased considerably. Such combined experimental and modelling approaches do yield a quantitative insight in the performance of different management practices.

In the study of Carberry et al. (2011) on innovation and productivity in dryland farming for Australia the following priorities in developing future technologies for the period 2010–30 were identified:

- remove system inefficiencies related to poor management and the functioning of soils.
- increase the efficiency of resource use by managing climate risk, precision farming, information and communication technology (ICT) and integrating arable cropping and livestock production.
- develop break-through technologies to convert crops from annual to perennial, and to improve the diversity in functions and services.

Often the causes of heterogeneity in crop productivity and resource use efficiency are not clear. Tittonell et al. (2007) showed that within smallholder Kenyan farms the interaction between soil fertility and management decisions should be taken into account. Indeed, these interactions should be known to advance precision farming for small and large farms.

A more comprehensive assessment was carried out by De Vries et al. (2012) who studied the resource use efficiencies and environmental performance of first and second generation biofuel cropping systems. Based on a set of production-ecological sustainability indicators relating to resource use efficiencies, soil quality, net energy production and greenhouse gas emissions, he could compare productivity and sustainability of contrasting cropping systems. This type of assessment could also be carried out for various food and feed production systems.

10. Connecting disciplines and goals

The ultimate objective is to bridge different level playing fields; especially: combining production goals and eco-services. A plea for interdisciplinary research to understand interactions between environmental quality, food production and food insecurity was made by Acevedo and Miguel (2011). He concluded that “it provides many opportunities for synergies including conservation agriculture, efficient use of inputs, smarter land use taking into account spatial patterns and landscape ecology principles, and improved water management”. This study shows that complex multi- and interdisciplinary conceptual research frameworks can stimulate the scientific debate, but lacks a quantitative underpinning of the suggested outcomes. New tools, such as the integrated assessment of agricultural systems, are developed that may overcome these shortcomings (Kropff et al., 2001; Van Ittersum et al., 2008). To evaluate the impact for different agro-ecological conditions and a longer time-frame it is necessary to combine experimental research and explorative studies based on biophysical and/or economic models (Chen et al., 2010). There is no magic bullet to identify ideal cropping systems on a scale that exceeds field experiments in space and time.

11. Conclusions

The rapidly growing demand for food, feed and fuel will require a combination of further improvements of land and water management, crop productivity and resource-use efficiencies. Adaptation of cropping systems to climate change and a better tolerance to biotic and abiotic stresses by genetic improvement and by managing diverse cropping systems in a sustainable way will be of key importance. A systems approach to perform integrated...
assessments of resource-use efficiencies, ecological services and economic profitability is needed to guide the choice of crop species and cultivars to be grown in a target environments and regions.

It is concluded that progress should be made at three levels:

1. At the plant/crop level:
   - Improving resource-capture and -use efficiency, especially for water and nutrients.
   - Improving the adaptation of crops to climate change: especially, to extreme weather conditions.

2. At the farm level: a greater diversity in cropping systems to ensure ecological processes that contribute to short term yield stability and long term productivity and sustainability. Furthermore, a more dedicated plant–soil–crop management for optimizing crop performance under contrasting conditions in land use (rainfed, irrigated) and climatic conditions.

3. At the landscape and regional level: integrating biophysical and socio-economic research on productivity and sustainability of cropping systems, taking into account land use and global change.

The ultimate objective is to achieve food security, sustainability and ecosystem services at regional and global scale on a cost-effective way. A quantitative system approach is needed to perform integrated assessments of resource-use efficiencies, ecological services and economic profitability to guide the choice of crop species and cultivars to be grown in a target environment and region.

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