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Review article

Nitrogen, sustainable agriculture and food security. A review

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Abstract – The impact of modern agriculture on natural resources has become a major global concern. Population growth and expanding demand for agricultural products constantly increase the pressure on land and water resources. A major point of concern for many intensively managed agricultural systems with high external inputs is the low resource-use efficiency, especially for nitrogen. A high input combined with a low efficiency ultimately results in environmental problems such as soil degradation, eutrophication, pollution of groundwater, and emission of ammonia and greenhouse gases. Evidently, there is a need for a transition of current agricultural systems into highly resource-use efficient systems that are profitable, but at the same time ecologically safe and socially acceptable. Here, opportunities to improve nitrogen-use efficiency in cropping and farming systems are analyzed and discussed. In the past and present, increased productivity of the major plant production systems has been derived from genetic improvement, and from greater use of external inputs such as energy, fertilizers, pesticides and irrigation water. Aiming at improving resource-use efficiencies, in high-input systems the focus should be on more yield with less fertilizer N. In low-input systems additional use of N fertilizer may be required to increase yield level and yield stability. Developing production systems that meet the goals of sustainable agriculture requires research on different scales, from single crops to diverse cropping and farming systems. It is concluded that N supply should match N demand in time and space, not only for single crops but for a crop rotation as an integrated system, in order to achieve a higher agronomic N-use efficiency. A combination of quantitative systems research, development of best practices and legislation will be needed to develop more environmentally-friendly agricultural systems. The growing complexity of managing N in sustainable agricultural systems calls for problem-oriented, interdisciplinary research.

productivity / nitrogen-use efficiency / cropping systems / biodiversity / land use / environment

1. INTRODUCTION

Population growth and expanding demand for agricultural products constantly increase the pressure on land and water resources. Today, global agriculture feeds a population of approximately 6.4 billion and delivers a wide range of additional services such as rural employment, bioenergy and biodiversity. The world's population is increasing by about 1 billion people every 12 years. In 2050, the population is projected to be about 9 billion (UNEP, 2007). However, the main question is not if we can feed 9 million people in 2050, but can we do it sustainably, equitably and on time in the face of the growing demand for biofuel and the probable changes in climate? Agriculture has to meet at a global level a rising demand for bio-based commodities such as food, feed, fiber and fuel, while satisfying even tighter constraints with respect to the safety of products, the environment, nature and the landscape. Currently, policy-makers in countries of the European Union are focusing strongly on the concept of multifunctional land use. Indeed, besides agriculture other economic activities such as recreation, producing regional products with a special brand, and ecological services such as maintenance of landscape, biodiversity and water harvesting, contribute to employment and income (Tait, 2001). Furthermore, high standards for food safety and quality are imposed to control food scares (Knowles et al., 2007).

Sustainability is based on the principle that we meet the needs of the present without compromising the needs of the future. Sustainable agriculture combines three main objectives: economic profitability, environmental health and ethical soundness. It is often presented as a conceptual 3-P framework: People-Planet-Profit (Fig. 1). The changes in agriculture from a purely profit-oriented activity into a triple-P-based production sector, trying to meet productivity, efficiency and efficacy aims, have been of considerable importance during the last few decades.

The concerns of scientists and consumers about the large-scale use of chemical external inputs such as fertilizer nitrogen and pesticides from the 1950s onwards led to movements that searched for alternatives to conventional agricultural practices (Matson et al., 1997). Besides the organic movement, the

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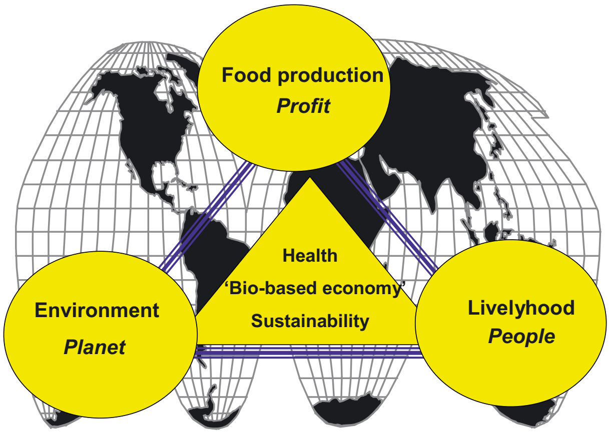

Figure 1. Framework to relate substainability, bio-based economy and health goals boundaries for objectives in the domains of *People*, *Planet* & *Profit*.

agricultural research community invested in the development of systems, such as: integrated agriculture, and low-input and sustainable agriculture (Altieri, 1995). The aim is to reduce the environmental impact and to enhance food quality while maintaining acceptable yields. Generally, the use of pesticides is controlled by legislation and inspection services. However, the use of N is mainly determined by economic incentives such as profitability and subsidies, and less by environmental costs. An ecosystem-based approach to manage nutrients and productivity of agroecosystems was proposed by Drinkwater and Snapp (2007). They stated that N losses would be minimal in systems where yields and soil reserves are maintained with nutrient inputs approximately equal to harvested exports. The critical question remains, what productivity levels can be supported by these technologies? Generally, low external inputs of nutrients will result in reduced yields when soil nutrients cannot buffer the gap between demand and supply. Sustainable crop management cannot be a "blue-print", but best practices should be adjusted to the specific agroecological conditions such as land availability, soil quality, water resources, weather patterns, labor requirements and markets. Scarcity of land and water is becoming a dominant factor for major cropping systems (Bouman et al., 2007a).

Land that is suitable for agricultural production is a finite and vulnerable resource on a global scale; however, there are big contrasts between regions. The availability of arable land per capita amounts currently to about 0.45 ha as a global average; however, a more severe decline to < 0.10 ha has taken place in densely populated regions of China (Zhao et al., 2008). China is becoming more dependent on import of commodities, because it has to feed over 20% of the world's population with only 7% of the arable land. Globally, the agricultural land suited for growing crops can be expanded by some 180 million ha, especially in South America, North America, and Central and Eastern Europe (Hansen and De Ridder, 2007). In Argentina and Brazil vast acreages of semi-natural grassland are reclaimed to grow arable crops, mainly soybeans.

Historically, increases in crop yield potential, intensification of cropping systems and expansion in the area of cultivated land have all contributed to the enhancement of world food production. The levelling off per capita grain production during the last two decades means that increases in grain production are only keeping pace with population growth. At the same time the rise in meat consumption causes a sharp increase in the use of cereals for feed. Currently, the world market of cereals has become volatile due to a growing demand and declining stocks of major commodities: rice, maize and wheat. The increase in grain prices will lead to an expansion of the acreage sown with cereals, especially maize and wheat. To avoid expansion of cultivation into fragile natural ecosystems, Cassman et al. (2003) concluded that raising yields should get more priority. Improved resource-use efficiencies are pivotal components of a sustainable agriculture that meets human needs and protects natural resources. The excess use of N fertilizers, available at low cost, causes environmental pollution (Eickhout et al., 2006).

In this review I will discuss the driving forces for intensification and diversification of major food production systems. Furthermore, options in strategic and tactical crop management to meet sustainability goals will be presented. The following topics are addressed:

– Food security, and land and nitrogen use,
– Nitrogen use, crop growth and yield,
– Primary productivity and biodiversity,
– Nitrogen use at the farm and global levels,
– Environmental boundaries and N management.

The review will be concluded with some recommendations for improving cropping systems and management practices.

2. FOOD SECURITY, AND LAND AND NITROGEN USE

Agriculture has broadened and diversified its objectives. Good agricultural practice, where farmers aim at an ecologically and economically sustainable use of resources, should be the guiding principle in achieving sustainability goals. Furthermore, there are a range of technologies and practices that aim at resource conservation, such as: agroforestry, conservation agriculture, integrated aquaculture (fish-rice systems), integrated cropping management (ICM), integrated nutrient management (INM), integrated pest management (IPM) and water harvesting (Pretty, 2008; Hobbs et al., 2008; Gupta and Seth, 2007; Oehme et al., 2007; Tipraqsa et al., 2007; Yang H.S., 2006). Consequences of climate change for the occurrence of heat or drought stresses should also be taken into account (Olesen and Bindi, 2002).

A general consensus exists that sustainable agriculture should focus primarily on:

– maximization of the use of ecological processes, such as: plant-microbial interactions, biological pest and disease control (IPM), crop-weed competition, and cycling of organic matter and nutrients (INM) within farming systems and agroecosystems;

Figure 2. High yielding wheat cultivars grown under temperate climatic conditions in the Flevopolder, The Netherlands (photo taken by the author). For details: see Spiertz and Ellen (1978).

- optimal use of natural resources, e.g. soil fertility, soil water content, above- and below-ground biodiversity, and of genetic diversity in plant traits;
- restricted use of external resources such as synthetic chemicals, fossil energy and fresh water.

Given the growing population and the limited area of fertile cropland globally there is an urgent need for further increasing the yields of crops combined with a sustainable use of nonrenewable resources.

The question if the world is approaching the biophysical limits of food production was addressed by Penning-de-Vries et al. (1997). They analyzed the potential supply of food in different parts of the world. It was shown that there still exists a huge potential for expanding and increasing crop production, especially in Latin America. Within less than 10 years after this study, Brazil and Argentina have become major exporters of soybean and cereals to Asia and Europe (Hansen and De Ridder, 2007). Globally, food production has risen since the 1960s by 65% (in Europe) to 280% (Asia), while world population has grown from 3 million to 6.4 million (Pretty, 2008; Hazell and Wood, 2008). Thus, per capita food production has outpaced population growth. The per capita grain production increased up to 1980 and has kept stable since then. Borlaug (2007) showed that a tripling of the world cereal production since the 1950s was achieved through only a 10% increase in area planted to cereals. The majority of the gain came from yield increase per unit land area resulting from the introduction of high-yielding cultivars that responded very well to supply of fertilizer nitrogen and irrigation water. It was concluded that intensification of cereal production saved about one billion ha of agricultural land. Therefore, in regions with scarcity of land agronomic intensification will no doubt continue, with more nutrients, water and other inputs applied to crops in an appropriate form, with a better timing and a more targeted site-specific application (Evans, 1999).

In food crop systems nitrogen plays a key role, because it is the main yield-determining nutrient. The rise in food production did have a price: more external N inputs and more environmental harm. Until 1960 N fertilizer was used at a relatively low rate; then, crop nitrogen uptake depended strongly on manure applications, biological N fixation and indigenous N supply through mineralization of soil organic matter. Since the early 1960s, the use of nitrogen fertilizers has grown approximately sevenfold and nowadays 30–80% of nitrogen applied to farmland is lost to surface and ground-waters, and to the atmosphere (Goulding et al., 2008). In the atmosphere the nonreactive form (N_2) is already present abundantly; only the reactive N forms (NH_3, NO_x) are harmful. Goudriaan et al. (2001) analyzed that in 1990 fertilizer N accounted for 60% of the net primary production (NPP) and since 1980 has exceeded the amount taken up by crops globally. The economic response in crop yield far outweighs the cost of fertilizer, which led to over-applications when only yield improvement was considered and not environmental sustainability.

The role of nitrogen in future world food production and environmental sustainability was explored by Eickhout et al. (2006). Based on FAO projections they concluded that despite improvements in nitrogen-use efficiency of food production systems in developed countries, total reactive N loss will grow strongly towards 2030 because of the intensification of animal and crop production systems in developing countries. Herridge et al. (2008) estimated the global inputs of nitrogen fixed biologically in agricultural systems by pulses, oilseed legumes and other cropping systems at 50–70 Tg N (Tg: million tons). Soybean represents 50% of global crop legume area and contributes to about 75% of the N fixed by crop legumes. The increasing global trade of commodities such as soybean is also accompanied by a flow of nutrients. The annual total N flow in traded cereals from exporting to importing countries was estimated to amount to 11.5 Tg N in 2004; mainly from Brazil and the US to China and Europe (UNEP, 2007).

So, there is a need for a great leap forward in a balanced use of fertilizer N. Only economic optimization of fertilizer use does not control over-use; therefore, communication about the risks of N excess in agro-ecosystems and legislation should be implemented. Unfortunately, in many developing countries adequate environmental policies are still in their infancy.

3. NITROGEN USE, CROP GROWTH AND YIELD

Long-term experiments, such as at Rothamsted Research in the UK, show that wheat yields with fertilizers exceed those without external N input by a factor of 2–3 (Rasmussen et al., 1998). It was found for on-farm and research station experiments that grain yields of maize increased from 3 to 14 t ha^{-1} with a rise in plant N accumulation from 50 to 300 kg N ha^{-1}, while rice yields increased from 2 to 8 t ha^{-1} with a rise in plant N accumulation from 25 to 200 kg N ha^{-1}, respectively (Dobermann and Cassman, 2002). The increased use of fertilizers, especially nitrogen, strongly enhanced crop growth and yield, and as a consequence, the associated resource-use efficiencies such as light-use efficiency ($g \cdot MJ^{-1}$) and water productivity (kg dry matter per unit of evapotranspiration).

In complex cropping systems, such as multiple cropping and relay intercropping, the response of the component crops to N is less than for sole crops (Van Noordwijk and Cadish, 2002). This was clearly shown for rice-wheat cropping systems (Fan et al., 2007). The total N efficiency of relay intercropping systems of wheat and cotton was assessed by comparing the relative nitrogen yield to the relative yield total (Zhang et al., 2008). The relative nitrogen yield varied from 1.4 to 1.7, while the relative yield total ranged from 1.3 to 1.4, indicating that intercrops used more N per unit produce than monocrops. Thus, component crops in intercropping systems should get less fertilizer N than a monocrop.

Higher yields of cereal crops (e.g.: rice and wheat) were derived from the breeding of high-yielding and N-responsive cultivars and a greater use of agrochemical inputs such as fertilizer and pesticides, and irrigation (Evans and Fischer, 1999; Peng et al., 1999). The optimal N use for growth and maximizing yields is determined by plant traits, physiological processes, environmental conditions and nutrient management. The most significant increases in nitrogen-use efficiency (NUE) have come from improved plant genotypes and agronomic practices. Opportunities for improving NUE are:

- *improved genotypes*; modern plant biotechnology and classical plant breeding show opportunities to improve NUE by selection for specific traits (root architecture, integrative traits (Laperche et al., 2006; Van Ginkel et al., 2001) and adaptation to stress conditions (Cabrera-Bosquet, 2007)).
- *improved resource use*; a better timing of nitrogen and water supply by time- and site-specific management can avoid stress at critical growth stages. More productivity per unit of water will lead to increased yields and thus higher NUE (Peng and Bouman, 2007).
- *improved cropping systems*; farmers can vary the timing of sowing/planting and the choice of crops in a cropping sequence to make a better match of the genetic make-up of a crop and the growing conditions determined by climate, soil and pests (Hobbs et al., 2008; Ladha et al., 2005).

Under high land pressure the emphasis will be on growing high-yielding genotypes and optimizing the management of external inputs, while under low-input conditions adapting cropping systems, including cultivar choice, to the variability and resource availability of contrasting agroecological conditions will become more important.

3.1. Nitrogen, photosynthesis and plant growth

Nitrogen is the key element in plant nutrition limiting plant growth and crop yields in many agroecosystems, rainfed as well as irrigated systems. Crop photosynthesis is closely associated with light capture by the canopy and leaf N content depending strongly on the availability of nitrogen (Lemaire et al., 2007; Hikosaka, 2004). Leaf N content is strongly associated with the rate of photosynthesis (Cabrera-Bosquet, 2007; Dreccer et al., 2000; Sinclair and Horie, 1989). An early canopy closure and a delay of canopy senescence will enhance the amount of light intercepted, while a very high leaf area index (LAI) increases mutual shading and therefore decreases light-use efficiency (Russell et al., 1989). In reproductive crops, such as cereals and pulses, the duration of canopy photosynthesis is also determined by the functional balance between sink strength and source capacity (Yin and Van Laar, 2005; Sinclair and De Wit, 1975) and by the ability of roots to capture N at the end of the growing season (Kichey et al., 2007; Spiertz and De Vos, 1983).

The amount of N in the harvested part of the crop is determined by the sink strength of the storage organs and expressed as N harvest index. This value is usually high in cereals and tuber crops, e.g.: 0.60–0.80 for wheat (López-Bellido et al., 2008; Spiertz and Ellen, 1978) and 0.70–0.80 for potato (Biemond and Vos, 1992)), but somewhat lower in legumes (Chapman et al., 1985). Cereals do reallocate N from the leaves to the grains, while in root crops most N is retained in crop residues. Generally, dry matter and nitrogen partitioning in wheat differ between old and modern cultivars; however, both parameters are not always genetically associated (Van Ginkel et al., 2001). Martre et al. (2007) found that variations in weather and N treatments also affected the nitrogen harvest index of wheat. Further improvement will require a good understanding of genotype × environment interactions.

3.2. Synchronization of N demand and N supply

To secure crop yields and avoid N losses the N supply should match the crop N demand in dose and time. The concept of *synlocation* and *synchronization* in plant nutrition was proposed by De Willigen and Van Noordwijk (1987) some 20 years ago. However, implementation of this concept seems to be difficult. A more generic approach to achieve a demand-based N supply of crops is based on the functional relationship between N uptake and carbon acquisition through canopy photosynthesis of a sole crop or a multiple cropping system. This relationship can be illustrated with the following simple equations:

(1) Total C acquisition = $\sum$ LI × LUE
where $\sum$ LI is the total amount of light intercepted by the canopy of a sole crop or intercrop ($MJ.m^{-2}$) and LUE is the light-use efficiency (g. MJ^{-1}). The $\sum$ LI is mainly determined by the amount of incoming radiation and the growth duration of a sole crop or a sequence of crops (Keating and Carberry, 1993).

(2) Total N uptake = f × C-acquisition
where f is a parameter determined by the maximum N content of the biomass. This parameter depends on species- or cultivar-specific plant traits (Lemaire et al., 2007).

(3) Total N-supply = a × (N soil reserve + manure + mineralization) + b × (N fertilizer) where a and b are parameters determined by plant traits, such as: root length, rooting depth, etc., that affect the recovery of applied N (Van Delden, 2001).

More sophisticated algorithms were developed for describing the relationship between crop dry weight and nitrogen uptake (Van Delden, 2001; Booij et al., 1996). To get an optimal match of N demand and N supply crop growth models can assist in predicting the yield potential under specific climatic

Figure 3. High yielding rice cultivars grown under subtropical conditions in Jiangsu Province, China. (photo taken by the author).

conditions and take into account the risk of growth-limiting (e.g.: drought, heat) and growth-reducing (e.g.: weeds, pests, diseases) conditions.

In irrigated rice systems, the use of water and fertilizers, especially nitrogen, has increased dramatically; a major point of concern for these systems is the agronomic efficiency of the use of water and nutrients (Belder et al., 2005a, b). In a study on strategies for increasing rice yield potential using ORYZA models, Aggarwal et al. (1997) found that only with growth-rate-driven N management the yield potential of high-yielding (9–10 t ha^{-1}) cultivars can be realized. By applying a simple rice-nitrogen model, MANAGE-N, it was possible to improve the timing of nitrogen dressing (ten Berge and Riethoven, 1997). For each user-defined fertilizer N dose, the model identifies the timing and amount of applications, associated with maximum grain yield and maximum agronomic N efficiency (kg grain per kg N applied). Improved timing of nitrogen on irrigated rice resulted in yield increases of 4–10%, at a fixed total dose. Changing the N dose to the predicted economic optimum rate resulted in additional increases up to 13%. Thus, in rice it appeared essential to match the seasonal pattern of N supply to the N demand of the crop at each stage of development to achieve maximum yields, but also to minimize N losses to the environment. Integrated nutrient management and precision farming have shown to be effective tools to improve NUE (Pierce and Nowak, 1999). Smart farming technologies aiming at both productivity and efficiency gains have been promoted. A vast number of experiments have been carried out with site-specific nutrient management (SSNM) in rice, but this method did not change fertilizer use significantly and therefore N losses continue to harm the environment (Ladha et al., 2005). To facilitate site-specific decision-making long-term multiple crop yield-map datasets have been transformed into profit maps that contain economic thresholds (Massey et al., 2008). However, environmental thresholds are still lacking, and as a consequence farmers are not informed about the risk of N losses.

Generally, the emphasis in N management is too strong on tactical fine-tuning of the N dose and too weak on strategic choices to make the cropping system less leaky. The transformation of flooded to aerobic rice systems (Bouman et al., 2007a, b) in regions with water scarcity is one of the best examples of a strategic approach to achieve a more sustainable use of limited natural resources. Benchmarking of low- and high-input cropping systems is needed to make a full assessment of economic benefits and environmental harm; an example for various rice ecosystems is presented in Table I. Rice yields vary from 2 000 to 12 000 kg ha^{-1} with an associated N input ranging from 50 to 260 kg ha^{-1}.

Surprisingly, the variation in parameter values for nitrogen-use efficiencies does not differ much between low- and high-input systems. Genetic improvements of rice are most effective in enhancing physiological N-use efficiencies (Peng and Bouman, 2007), while applying best management practices can raise apparent N recoveries (Campbell et al., 1995; Cassman et al., 1993)

It is concluded that N supply should match N demand in time and space – not only for single crops, but for a crop rotation as an integrated system – to achieve a higher agronomic NUE. Alleviating factors that limit growth – such as drought, flooding, pests and diseases – will be most effective in increasing the apparent N recovery.

4. PRIMARY PRODUCTIVITY AND BIODIVERSITY

Net primary productivity (NPP) in terrestrial temperate ecosystems is generally limited by N availability. However, excessive levels of reactive N in the soil, water and atmosphere constitute a major threat to biodiversity in natural ecosystems (Suding et al., 2005). There is increasing evidence that diversity of soil biota as well as plants contributes to ecosystem functioning and improved nutrient-use efficiency (Brussaard et al., 2007; Barrios, 2007; Van Ruijven and Berendse, 2005). Diversity and functional complementarity leads to greater soil C and N accumulation on agricultural degraded soils (Fornara and Tilman, 2008). Most of the research on improved ecosystem functioning by an increased diversity were carried out in vegetations with relatively low external inputs and biomass yield. However, Oerlemans et al. (2007) studied the impact of long-term nutrient supply on plant diversity in grassland; they found that increased N fertilization reduced the number of species site-independently. A unimodal relationship was observed between productivity and species number. The highest number of species was found when N and K were co-limited.

The challenge for the future is how can we combine a high land productivity – the capacity of agricultural land to produce biomass on a sustainable long-term basis – with the provision of ecosystem services and soil biodiversity (Barrios, 2007)? The use of crop genetic diversity in maintaining ecosystems services was reviewed by Hajjar et al. (2008). They concluded that crop genetic diversity can enhance agroecosystem functioning and provide ecosystem services, especially by contributing to stability in crop and soil health. As a consequence, crop productivity and resource-use efficiencies will also become more stable.

There are still many gaps related to methodological, experimental and conceptual approaches that prevent quick progress in the guidance for policy- and decision-making on changes

Table I. Estimated rice yields and N-use parameters for different rice cropping systems. NUE: nitrogen use efficiency.

Parameters	Irrigated lowland rice[a]	Irrigated Rice – wheat systems[b]	Aerobic rice systems[c]	Rainfed rice systems[d]
1. Rice yield (kg. ha^{-1})	9–12.000	5–9.000	4–6.000	2–4.000
2. Grain N uptake (kg. ha^{-1})	100–150	60–100	50–85	30–60
3. Apparent N recovery (kg. kg^{-1})	0.30–0.40	0.25–0.40	0.30–0.50	0.40–0.60
4. Physiological NUE (kg. kg^{-1})	50–80	50–70	40–60	30–50
5. Agronomical NUE (kg. kg^{-1})	30–60	20–30	25–50	25–30
6. Crop N demand (kg. ha^{-1})	150–200	100–150	80–125	40–80
7. Recommended fertilizer N supply (kg. ha^{-1})	200–260	150–200	120–160	50–80

Sources:
[a] Samonte et al., 2006; Belder et al., 2005a; Jiang et al., 2004; Cassman et al., 1993.
[b] Becker et al., 2007; Ladha et al. , 2005; Pande and Becker, 2003.
[c] Belder et al, 2005b; Yang X. et al., 2005.
[d] Saito et al., 2007; Boling et al., 2004.

needed in developing highly productive, sustainable agricultural systems. Swift et al. (2004) concluded that maintaining ecosystem services and biodiversity outside conservation areas lies in promoting diversity of land use on the landscape and farm rather than field scale. Good examples are arable and grassland field margins (Sheridan et al., 2008; Asteraki et al., 2004); these field margins can provide multiple ecological services, such as biodiversity and pest control (Olson et al., 2007). Biodiversity effects can be managed (Storkey and Westbury, 2007). It was reported that these effects increase linearly with biotope space (Dimitrakopoulos and Schmid, 2004). By spatially allocating land (2–5% of the area) for ecosystem services complementary to land used for crop cultivation, biodiversity can be enhanced within intensive cropping systems without a severe loss of production potential. In areas with hilly or rolling land, strips or banks dedicated to developing biodiversity richness may also reduce run-off of nutrients and soil erosion.

5. NITROGEN USE AT THE FARM AND GLOBAL LEVELS

A high nitrogen-use efficiency is no guarantee that N losses do not exceed critical environmental thresholds. The most important factor determining the risk of potential N losses is the total amount of mineral N left over after the harvest in crop residues and in the soil. To assess the environmental impacts the N dynamics should not be studied in one crop, but in a diversity of cropping cycles and in mixed plant-animal systems.

5.1. Arable cropping systems

The main objectives for ecologically and economically sustainable agriculture are maintaining soil fertility and improving crop productivity and stability. Management options are: site- and time-specific nutrient and water management, crop protection measures and the choice of adapted, high-yielding cultivars. The effects of the various measures that are of importance for the maintenance and use of the resource base cannot easily be assessed within one growing cycle but should be evaluated over a sequence of crops. Crop rotation is an important component of an integrated approach of sustainable agriculture and resource conservation. Short- and long-term effects of a cropping sequence and related management practices can be expressed in physical soil properties such as water-holding capacity and bulk density; chemical soil properties such as pH, carbon content and nutrient contents, and biological soil properties such as microbial activity (Lal, 2008; Shibu et al., 2006).

Growing special crops in a rotation can improve the sustainability of the cropping system (Struik and Bonciarelli, 1997); examples are:

- legumes for improving the nitrogen availability,
- green manure crops for improving the physical and biological soil fertility,
- cover crops to prevent soil erosion and to store nutrients prone to leaching or run- off.

The potential of legumes can be established by comparing yields and N uptake under the same agroecological conditions. Sibma and Spiertz (1986) carried out field experiments with three forage crops – grass (*Lolium perenne*), lucerne (*Medicago* sativa) and maize (*Zea mays*) – over 3 years on a fertile clay soil under temperate climatic conditions. It was found that above-ground DM yields ranged from 13.4 to 19.8, from 13.4 to 18.1 and from 13.7 to 17.1 t ha^{-1} for grass, lucerne and maize, respectively (DM: dry matter). The associated N yields ranged from 413 to 452, from 392 to 577 and from 188 to 220 kg ha^{-1} (Spiertz and Sibma, 1986).

Table II. Sustainability parameters for benchmarking of contrasting food production systems in temperate, non-water-limited regions

Parameters	Technological high-input systems	Ecological low-input systems	Mixed animal-plant systems	Dairy-grazing systems
A. Quantitative parameters[1]				
1. Biomass - NPP ($t.ha^{-1}$)[a]	12–20	8–12	10–18	12–20
2. Total N supply (kg. ha^{-1})[b]	150–300	100–150	200–350	200–400
3. N use (NUE) (N_{output}/ N_{input})[c]	0.30–0.60	0.40–0.70	0.25–0.50	0.15–0.35
B. Qualitative parameters[2]				
1. Marketable yield (kg. ha^{-1})	High	Low	Moderate	High
2. Ecological stability/diversity	Low	Moderate	High	Moderate
3. Nutrient recycling	Low	Moderate	Moderate	High
4. Environmental N load	Moderate	Low	Moderate	High
5. Profitability (net returns)	High	Moderate	High	Moderate
6. Sustainability (planet issues)	Low	High	Moderate	Moderate
7. Ethical acceptance	Moderate	High	Moderate	High

[1] Best guesses of the author.
[2] After Pretty (2008); Principles of agricultural sustainability.
[a] Aboveground biomass or net primary productivity (NPP) , expressed as ton dry matter per ha.
[b] N supply by manure and fertilizer use.
[c] N use defined as overall system recovery, expressed as the ratio between output (N in harvestable crop parts, meat or milk) and input (N in manure and fertilizers).

Grass showed the highest productivity in the first year and lucerne in the last year. N fixation by lucerne varied between 462 and 507 kg ha^{-1} without and between 107 and 195 kg $ha^{-1}$with a N fertilizer application. The after-effects from soil N reserves of a 1-, 2- and 3-year cropping sequence of lucerne (no N fertilizer) and grass (300 kg N ha^{-1}), measured as N uptake by an unfertilized maize crop, amounted to 140–175 and 110–140 kg N ha^{-1}, respectively. For comparison, the N after-effect of a preceding maize crop centered around 110 kg N ha^{-1}. Even higher DM yields were reported by Lloveras et al. (2008) for irrigated lucerne under Mediterranean conditions; they found a range from 16 to 21 t ha^{-1} averaged for three years. These data show the high potential of a legume crop for N fixation and DM production under favorable growing conditions.

5.2. Mixed farming systems

Besides crop rotation, integration of crop and animal production on the farm and regional scales may be an opportunity to increase *eco-efficiency* (Wilkins, 2008). Nitrogen is mobile in the soil-plant-animal system and with the required N inputs for high crop yields and intensive livestock production the risk of N losses increases (Van Keulen et al., 2000). Traditionally, nutrient management has been concerned with optimizing the economic return from nutrients used for crop production. The main emphasis was on the expected crop response from adding nutrients to the soil. In practice, however, nutrients, particularly manure, are not always applied to optimize plant nutrient use. Such practice or the improper or untimely application of manure and fertilizer may release nutrients into the air and water. The problems are most significant in regions with an intensive animal production (Aarts et al., 1992). The excess of nitrogen compounds in manure has become an issue of major concern in many European countries and will also become an increasing problem in other countries, such as India and China, with high stocking rates of animals. The problems with nutrient pollution are not generally the result of mismanagement by farmers, but are a result of how agricultural systems have evolved, with no direct costs associated with environmental quality and conservation of natural resources. Beegle et al. (2000) concluded that nutrient management strategies will not be the same for all farms. They classified farms on a nutrient balance basis into three groups:

- Nutrient-deficient farms; nutrient imports are less than exports. Thus, additional nutrients in the form of purchased fertilizer or other sources are required for achieving optimum crop yields. A well-planned nutrient management program emphasizing economic and agronomic efficiency should reduce the need for purchased inputs and thus should improve farm profitability.
- Nutrient-balanced farms; nutrient imports are approximately equal to exports. Because these farms are often at the upper limit of being able to safely handle all the nutrients in the production system, nutrient management planning may offer potential environmental benefit.
- Nutrient-surplus farms; nutrient imports significantly exceed exports. The nutrients in the manure generally exceed those required for crop production on the farm. A significant component of a nutrient management program involves acceptable off-farm uses for the excess manure.

Some countries, such as Denmark, have given priority to agro-environmental schemes, restricting the use of fertilizers and manure. The impact of these measures was studied by evaluating farm gate nutrient balances (Kyllingsbaek and Hansen, 2007). It was shown that nutrient surpluses at the farm gate were reduced; however, the effects on water quality were small. It is still not clear if there is no direct relationship or that the lag time of reducing the N load is longer than considered in the study.

5.3. Organic agriculture

In Western countries with an affluent society, organic farming has got increasing support from citizens and governments during the last three decades, because of the perceived ecological services, environmental benefits and human well-being and health (Rembialkowkska, 2007). "*The ethos of organic farming is that it forms the basis of a production system that is environmentally, socially and economically sustainable*" (Topp et al., 2007). However, consumers are reluctant to buy organic food, because of the much higher prices than of conventional products. A debate is going on if organic farming can feed a growing world population and to what extent organic farming outperforms conventional high-input farming systems in sustainability. In contrast with recent claims by Badgley et al. (2007) that organic agriculture does have the potential to produce enough food for a growing world population, Connor (2008) concluded that organic agriculture cannot feed the world. He noticed a major overestimation of the potential for N fixation by legumes, the availability of organic nutrients and the productivity of organic agriculture in a comparison with conventional low- and high-input agriculture. Furthermore, the study of Topp et al. (2007) on resource-use efficiencies made clear that the delineation of system boundaries in both space and time is critical in the compilation of resource-use budgets. The expression of output per unit of land area tends to favor low-input systems, because the impact on the regional scale may be less but may result in the need for additional land elsewhere (Van der Werf et al., 2007). Thus, on a national or even a global scale the total impact of food production may increase.

Evaluation of the advantages in sustainability performance of organic agriculture and other low-input systems, such as SRI (System of Rice Intensification, McDonald et al., 2006), should be carried out on an eco-regional and global scale over a time-span of at least 10 years. Then, the full benefits of improved soil processes and crop health as well as the costs in terms of land productivity, nutrient depletion and weed competition can be taken into account.

6. ENVIRONMENT AND N MANAGEMENT

Concerns about the environmental impact of intensive agricultural systems require an improvement in production technologies to maximize resource-use efficiencies, and to minimize the environmental impact. Nitrogen (N) fertilizers comprise almost 60% of the global reactive N load attributable to human activities; especially in China (UNEP, 2007). N use has a major impact on the functioning of the ecosystems and human well-being. In Europe, agriculture is responsible for

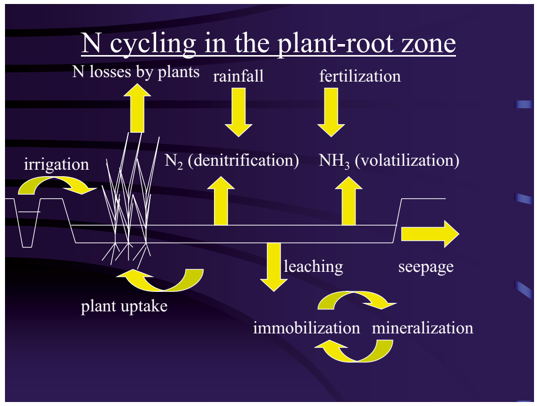

Figure 4. N cycling scheme for irrigated rice systems (modified after Bouman, 2007).

40–80% of the N loading to surface waters (OECD, 2001). Nitrogen losses associated with the application of N fertilizer can result in nitrate contamination of water resources and increased emissions of ammonia (Erisman et al., 2007; Bussink and Oenema, 1998), nitrous oxides (N_2O), a potent greenhouse gas (Stehfest and Bouwman, 2006), and NO_y, with negative human health effects (Wilkinson et al., 2007; Van Egmond et al., 2002). Today, the agronomic and economic requirements of nutrient management remain central, but in addition we must consider the potential impact of these nutrients on environmental quality. Total reactive loss will grow in the period explored until 2030, because of an increase in fertilizer consumption in developing countries to feed the growing population and concurrently a steep rise in dairy and meat consumption in emerging industrialized countries (China, India, etc.), despite improvements in overall system N recovery in developed countries (Eickhout et al., 2006).

Since land is a finite and fragile resource, its sustainable management depends on the husbandry of its different components, of which soil fertility and water availability are key factors for agricultural production. At the moment, agronomic N-use efficiencies are often very low (Spiertz and Oenema, 2005). Agronomically, farmers should aim at the minimum input of each production resource required to allow maximum utilization of all other resources (de Wit, 1992). Consequently, above a certain minimum, higher inputs of yield-increasing factors such as water and nutrients result in higher yields per unit area and are associated with higher efficiencies of other resources. Higher efficiencies, expressed as output per unit of input, might coincide with larger emissions per unit of area.

6.1. Plant-soil-atmosphere

Mathematical modeling has strongly contributed to a more quantitative understanding of the soil-plant N cycle and the soil, plant and environmental factors which govern it (Galloway, 1998). Environmental concerns are focused on nitrogen losses from soils, which may pollute the environment. Leaching is the major route by which nitrate enters the ground- and surface waters, while denitrification and nitrification are significant sources of N_2O, an important greenhouse gas. Improved efficiency of N use on a field and farm scale, both increasing crop yield and quality and reducing losses, is dependent upon dynamic optimization to match supply of N and the N requirements of the crop on a field scale. This optimization requires measurement and prediction of soil-N supply, crop uptake and their variability (Stockdale et al., 1997). Models of crop growth, the soil-N cycle and plant – soil models have been developed (Bouman et al., 1996). However, these are little used in current fertilizer and farm management recommendations. Farmers cannot wait for our understanding of plant-soil dynamics to be perfect, but need researchers to put their current knowledge to use.

6.2. Scale and systems

A system approach can be used as a research tool, but also as an instrument for training of students and scientists. Research and training networks enable the necessary development of a common language of concepts, models and databases, and allow frequent interaction among actors (Ten Berge and Kropff, 1995). System approaches were introduced in the 1970s and are used increasingly in research on food production studies, natural resource management, land use options and rural development (Van Keulen, 2007). The system approach can be described as the systematic and quantitative analysis of agricultural systems. Agricultural systems are defined as well-delineated parts of the real world, consisting of many interacting elements (Neeteson et al., 2002). The system approach uses many specific techniques, such as simulation modeling, expert systems with databases, linear programming and geographic information systems. A system approach has been applied for studies at different aggregation levels, such as:

- *the plant level*; analyses and evaluation of genotype × environment interactions in breeding programs,
- *the crop level*; optimization of nutrient and water management,
- *the farm level*; prototyping of integrated farming systems and analyzing the flows of nutrients on farms,
- *the watershed and landscape level*; optimization of water use and water saving,
- *the eco-regional level*; *ex-ante* assessment of the possible impacts of changes in technology or in the socio-economic environment on agricultural development.

Actually, in the last few decades we have witnessed the integration of process-specific knowledge into very precise, widely accepted relationships between processes in the system and driving factors from outside the system (Van Keulen et al., 2000). This applies mainly for water management at the field and catchment levels (Bouman, 2007). Mathematical quantification of N flows in space and time is more complex, because of the dynamic nature of N in the plant, soil, water and atmosphere (Erisman et al., 2007; Galloway et al., 2003). The growing complexity of managing N in sustainable agricultural systems calls for problem-oriented, interdisciplinary research. Key disciplines are: agronomy, crop science, soil science, conservation biology, environmental sciences and systems modeling.

The current assessment of the impact of climate change on agriculture and the options for adaptation relies heavily upon both crop and climatic modeling. The output of the models is greatly limited by the extent of our understanding of short- and long-term crop adaptation to changing environmental conditions, especially in soil traits and weather patterns. Howden et al. (2007) stated that complex problems require multidisciplinary solutions, with a focus on integrated rather than disciplinary science.

6.3. Policy-making and regulation

A more environmentally sensitive nutrient management on the field and farm levels can reduce nitrogen losses to a level that meets the standards (Goulding et al., 2008; Aarts et al., 1992). Decision-making related to nutrient management occurs at the strategic, tactical and operational levels. In Europe society demands more and more accountability from farmers; therefore, more legislation has been implemented by the EU and the national governments. Legislation is inevitable whenever 'profit' and 'planet' goals conflict. In Europe and especially in The Netherlands, there exists a set of regulations set up by the government to protect the environmental compartments – soil, water and air – against nutrient losses from agro-production. Legislation can only be successful when clear motivations and regulatory tools are provided to farmers (Schröder et al., 2003). There are two approaches to nutrient management planning in a regulatory situation. One approach is to specify what should be done on all farms as a recipe for nutrient management. Another approach is to establish performance criteria or goals for farmers to meet as part of their farm nutrient management plan.

Langeveld et al. (2007) concluded that agro-environmental indicators can be used for design, implementation and testing of farming systems, but it should be kept in mind that indicators are not perfect, because of the complexity and highly variable processes involved in N cycling. Transitions occur at some cost; for example, large savings on one limited resource, such as irrigation water, may have a trade-off on yield. A methodology for an integrated analysis of trade-offs between economic and environmental indicators is available (Stoorvogel et al., 2004). Integrative modeling approaches to evaluate the impact of multifunctional agriculture have been developed (Rossing et al., 2007). New approaches are needed that will integrate biophysical processes and ecological processes at the crop, farm and landscape levels (Pretty, 2008; Giller et al., 2006). A policy that will lead to N applications of manure and fertilizer balanced with crop N demand is urgently needed, not only in developed, but also in developing countries. An intensive communication between all stakeholders (environmental agencies, policy-makers, researchers and farmers) and a controlled implementation of indicators and guidelines may contribute to a balanced application of nutrients (Delgado et al., 2008). Such an approach will be needed to meet 'planet' and 'profit' objectives and to prevent nitrate levels in groundwater from exceeding the standards for human consumption (a 'people' objective).

7. CONCLUSION

Two strategies to meet sustainability goals in food production, with a safe and profitable use of N, can be followed:

a. Developing *low-input*, *high-diversity* agricultural systems. Within these systems diversity in crop choice and crop rotation minimizes the risks of yield reductions by abiotic and biotic stresses. Furthermore, the stability of the agroecosystems is enhanced by combining genetic diversity with functional biodiversity at the farm and landscape levels. The supply of nutrients, especially N, relies strongly on maintaining high levels of soil organic matter (SOM). Crop output levels will range from low to moderate; therefore, these systems require more land.
b. Developing *high-input*, *low-diversity* agricultural systems. Within these systems high-yielding, high N-responsive crop cultivars are chosen to achieve a maximum productivity per unit of land. The stability of these agroecosystems depends strongly on the management of genotype × environment × management interactions and soil quality. An optimized N management during the whole crop cycle will control N losses. The advantage of these agroecosystems is a high productivity per unit of land and therefore, less land is needed for food production. As a result, virgin and fragile soils can be saved.

For Southeast Asia the "*high-input low-diversity*" approach will be unavoidable due to scarcity of land. However, in other regions where more land per capita is available the "*low-input high-diversity*" approach is recommended. It would environmentally even be more effective when the different strategies are not applied on a global but on a regional scale.

A balanced sequence of crops with complementary functions can help to improve the N-use efficiency and to maintain the profitability and sustainability of the cropping system in the long run. Contrary to the widespread view that high-input agrosystems are homogeneous, many researchers have found large spatial and temporal differences in nutrient levels and fertilizer efficiencies, even on similar soil types. Differences between fields are in part due to historical differences in management. However, the major cause of low and varying fertilizer-use efficiency, particularly for N, is that the supply of nutrients from soil reserves and fertilizers is not well synchronized with the demands of the crops, and managing fertilizers to improve this synchrony is complicated. Despite many attempts, there has been little success correlating spatial grain yield with spatial patterns in soil fertility (Pierce and Nowak, 1999). An increasing body of knowledge suggests that spatial variation in soil water relations may be an important factor in causing spatial variation in grain yield.

More advanced diagnostics could be used to increase the specific nature of recommendations or to adjust model recommendations during the growing season. This would enable a greater use of dynamic optimization strategies in the field. An "*ecological modernization*" requires *synlocation* and *synchronization* of crop nutrient demand and supply by fertilizers. Precision farming methods will implement these concepts in practice, but at some cost. Management of the environment has moved from a command and control paradigm to a much wider perspective of regulatory means, including economics, participatory approaches and ethics. Ignorance and uncertainty still play an important role in decision-making on environmental consequences of modern farming and cropping systems. Therefore, research should not only be focused on productivity and profitability of food production systems, but also on agroecosystem functioning (nutrient cycling, stability, resilience) and ecosystem services such as biodiversity, carbon sequestration and water harvesting.

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REFERENCES

Aarts H.F.M. Biewinga E.E., van Keulen H. (1992) Dairy farming systems based on efficient nutrient management, Neth. J. Agr. Sci. 40, 285–299.

Aggarwal P.K., Kropff M.J., Cassman K.G., ten Berge H.F.M. (1997) Simulating genotypic strategies for increasing rice yield potential in irrigated, tropical environments, Field Crop. Res. 51, 5–17.

Altieri M.A. (1995) Agroecology: the science of sustainable agriculture, Boulder, CO, Westview Press.

Asteraki E.J., Hart B.J., Ings T.C., Manley W.J. (2004) Factors influencing the plant and invertebrate diversity of arable field margins, Agr. Ecosyst. Environ. 102, 219–231.

Badgley C., Moghtar J., Quintero E., Zakem E., Chappell M.J., Aviles-Vazques K., Samulon A., Perfecto I. (2007) Organic agriculture and the global food supply, Renew. Agr. Food Syst. 22, 86–101.

Barrios E. (2007) Soil biota, ecosystem services and land productivity, Ecol. Econ. 64, 269–285.

Becker M., Asch F., Maskey S.L., Pande K.R., Shah S.C., Shrestha S. (2007) Effects of transition season management on soil N dynamics and systems N balances in rice-wheat rotations of Nepal, Field Crop. Res. 103, 98–108.

Beegle D.B., Carton O.T., Bailey J.S. (2000) Nutrient management planning: justification, theory, practices, J. Environ. Qual. 29, 72–79.

Belder P., Spiertz J.H.J., Bouman B.A.M., Guoan Lu, Tuong T.P. (2005a) Nitrogen economy and water productivity of lowland rice under water saving management, Field Crop. Res. 93, 169–185.

Belder P., Bouman B.A.M., Spiertz J.H.J., Peng S., Castaneda A.R., Visperas R.M. (2005b) Crop performance, nitrogen and water use in flooded and aerobic rice, Plant Soil 273, 167–182.

Biemond H., Vos J. (1992) Effects of nitrogen and the development and growth of the potato plant. 2. The partitioning of dry matter, nitrogen and nitrate, Ann. Bot. 70, 37–45.

Boling A., Tuong T.P., Jatmiko S.Y., Burac M.A. (2004) Yield constraints of rainfed lowland rice in Central Java, Indonesia, Field Crop. Res. 90, 351–360.

Booij R., Kreuzer A.D.H., Smit A.L., van der Werf A. (1996) Effect of nitrogen availability on dry matter production, nitrogen uptake, and light interception of Brussels sprouts and leeks, Neth. J. Agr. Sci. 44, 3–19.

Borlaug N.E. (2007) Sixty-two years of fighting hunger: personal recollections, Euphytica 157, 287–297.

Bouman B.A.M. (2007) A conceptual framework for the improvement of crop water productivity at different spatial scales, Agr. Syst. 93, 43–60.

Bouman B.A.M., Van Keulen H., Van Laar H.H., Rabbinge R. (1996) The 'School of De Wit' crop growth simulation models: a pedigree and historical overview, Agr. Syst. 52, 171–198.

Bouman B.A.M., Humphreys E., Tuong T.P., Barker R. (2007a) Rice and Water, Adv. Agron. 92, 187–237.

Bouman B.A.M., Feng Liping, Tuong T.P., Lu Guoan, Wang Huaqi, Feng Yueha (2007b) Exploring options to grow rice using less water in northern China using a modelling approach II. Quantifying yield, water balance components and water productivity, Agr. Water Manage. 88, 23–33.

Brussaard L., de Ruiter P.C., Brown G.G. (2007) Soil biodiversity for agricultural sustainability, Agr. Ecosyst. Environ. 121, 233–244.

Bussink D.W., Oenema O. (1998) Ammonia volatilization from dairy farming systems in temperate areas: a review, Nutr. Cycl. Agroecosys. 51, 19–33.

Cabrera-Bosquet L., Molero G., Bort J., Nogues S., Araus J.L. (2007) The combined effect of constant water deficit and nitrogen supply on WUE, NUE and $\Delta^{13}C$ in durum wheat potted plants, Ann. Appl. Biol. 151, 277–289.

Campbell C.A., Myers R.J.K., Curtin D. (1995) Managing nitrogen for sustainable crop production, Fertil. Res. 42, 277–296.

Cassman K.G., Kropff M.J., Gaunt J., Peng S. (1993) Nitrogen use efficiency of irrigated rice: what are the key constraints, Plant Soil 155–156, 359–362.

Cassman K.G., Dobermann A., Walters D.T., Yang H.(2003) Meeting cereal demand while protecting natural resources and improving environmental quality, Ann. Rev. Env. Res. 28, 10.1–10.44.

Chapman A.L., Muchow R.C. (1985) Nitrogen accumulated and partitioned at maturity by grain legumes under different water regimes in a semi-arid tropical environment, Field Crop. Res. 11, 69–79.

Connor D.J. (2008) Organic agriculture cannot feed the world, Field Crop. Res. 106, 187–190.

De Willigen, P., van Noordwijk M. (1987) Roots for plant production and nutrient use efficiency, PhD-thesis Agricultural University Wageningen, 282 p.

De Wit C.T. (1992) Resource use efficiency, Agr. Syst. 40, 125–151.

Delgado J.A., Shaffer M., Hu C., Lavado R., Cueto-Wong J., Joosse P., Sotomayer D., Colon W., Follett R., DelGrosso S., Li X., Rimski-Korsakov H. (2008) An index approach to assess nitrogen losses to the environment, Ecol. Eng. 32, 108–120.

Dimitrakopoulos P.G., Schmid B. (2004) Biodiversity effects increase linearly with biotope space, Ecol. Lett. 7, 574–583.

Dobermann A., Cassman K.G. (2002) Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia, Plant Soil 247, 153–175.

Dreccer M.F., van Oijen M., Schapendonk A.H.C.M., Pot C.S., Rabbinge R. (2000) Dynamics of vertical nitrogen distribution in a vegetative wheat canopy. Impact on canopy photosynthesis, Ann. Bot. 86, 821–831.

Drinkwater L.E., Snapp S.S. (2007) Nutrients in Agroecosystems: rethinking the management paradigm, Adv. Agron. 92, 163–186.

Eickhout B., Bouwman A.F., van Zeijts H. (2006) The role of nitrogen in world food production and environmental sustainability, Agr. Ecosyst. Environ. 116, 4–14.

Erisman J.W., Bleeker A., Galloway J., Sutton M.S. (2007) Reduced nitrogen in ecology and the environment, Environ. Pollut. 150, 140–149.

Evans L.T. (1999) Step towards feeding the Ten Billion, Plant Prod. Sci. 2, 3–9.

Evans L.T., Fischer R.A. (1999) Yield potential: its definition, measurement and significance, Crop. Sci. 39, 1544–1551.

Fan M., Lu S., Jiang R., Liu X., Zeng X., Goulding K.W.T., Zhang F. (2007) Nitrogen input, ^{15}N balance and mineral N dynamics in a rice-wheat rotation in southwest China, Nutr. Cycl. Agroecosys. 79, 255–265.

Fornara D.A., Tilman D. (2008) Plant functional composition influences rates of soil carbon and nitrogen accumulation, J. Ecol. 96, 314–322.

Galloway J.N. (1998) The global nitrogen cycle: changes and consequences in: K.W. van der Hoek et al. (Eds.), Nitrogen, the Confer-N-s, Elsevier, Amsterdam, pp. 15–26.

Galloway J.N., Aber J.D., Erisman J.W., Seitzinger S.P., Howarth R.W., Cowling E.B., Cosby B.J., (2003) The nitrogen cascade, Bioscience 53, 341–356.

Giller K.E., Rowe E.C., de Ridder N., van Keulen H. (2006) Resource use dynamics and interactions in the tropics: Scaling up in space and time, Agr. Syst. 88, 8–27.

Goudriaan J., Groot J.J.R., Uithol P.W.J. (2001) Productivity of Agro-ecosystems in: Roy J., Saugier B., Mooney H.A. (Eds.), Terrestrial Global Productivity, Academic Press, San Diego, USA, pp. 310–313.

Goulding K., Jarvis S., Whitmore A. (2008) Optimizing nutrient management for farm systems, Philos. T. Roy. Soc. B 363, 667–680.

Gupta R., Seth A. (2007) A review of resource conserving technologies for sustainable management of the rice-wheat cropping systems of the Indo-Gangetic plains (IGP), Crop. Prot. 26, 436–447.

Hansen S., de Ridder W. (2007) Agri-based alternative energy, Risks and opportunities for the farming industry. Rabobank International, The Netherlands, 68 p.

Hajjar R., Jarvis D.I., Gemmill-Herren B. (2008) The utility of crop genetic diversity in maintaining ecosystem services, Agr. Ecosyst. Environ. 123, 261–270.

Hazell P., Wood S. (2008) Drivers of change in global agriculture Philos. T. Roy. Soc. B 363, 495–515.

Herridge D.F., Peoples M.B., Boddey R.M. (2008) Global inputs of biological nitrogen fixation in agricultural systems, Plant Soil 311, 1–18.

Hikosaka K. (2004) Interspecific differences in the photosynthesis-nitrogen relationship: patterns, physiological causes and ecological importance, J. Plant Res.117, 481–494.

Howden S.M., Soussana J.-F., Tubiello F.N., Chhetri N., Dunlop M., Meinke H. (2007) Adapting agriculture to climate change, PNAS 104, 19691–19696.

Hobbs P.R., Sayre Ken, Gupta Raj (2008) The role of conservation agriculture in sustainable agriculture Philos. T. Roy. Soc. B 363, 543–555.

Jiang L., Dai T., Jiang D., Cao W., Gan X., Wei S. (2004) Characterizing physiological N-use efficiency as influenced by nitrogen management Field Crop. Res. 2004, 239–250.

Keating B.A., Carberry P.S. (1993) Resource capture and use in intercropping – solar radiation, Field Crop. Res. 34, 273–301.

Kichey Th., Hirel B., Heumez E., Dubois F., Le Gouis J. (2007) In winter wheat (*Triticum aestivum* L.), post-anthesis nitrogen uptake and remobilization to the grain correlates with agronomic traits and nitrogen physiological markers, Field Crop. Res. 102, 22–32.

Knowles T., Moody R., McEachern M.G. (2007) European food scares and their impact on EU food policy, Brit. Food J. 1, 43–67.

Kyllingsbaek A., Hansen J.F. (2007) Development in nutrient balances in Danish agriculture 1980–2004, Nutr. Cycl. Agroecosys. 79, 267–280.

Ladha J.K., Pathak H., Krupnik T.J., Six J., van Kessel C. (2005) Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects, Adv. Agron. 87, 85–156.

Lal R. (2008) Soils and sustainable agriculture, A review, Agron. Sustain. Dev. 28, 57–64.

Langeveld J.W.A., Verhagen A., Neeteson J.J., van Keulen H., Conijn J.G., Schils R.L.M., Oenema J. (2007) Evaluating farm performance using agri-environmental indicators: Recent experiences for nitrogen management in The Netherlands, J. Environ. Manage. 82, 363–376.

Laperche A., Devienne-Barret F., Maury O., Le Gouis J., Ney B. (2006) A simplified conceptual model of carbon/nitrogen functioning for QTL analysis of winter wheat adaptation to nitrogen deficiency, Theor. Appl. Genet. 113, 1131–1146.

Lemaire G., Oosterom E., Sheehy J., Jeuffroy M.H., Massignam A., Rossato L. (2007) Is crop N demand more closely related to dry matter accumulation or leaf area expansion during vegetative growth? Field Crop. Res. 100, 91–106.

Lloveras J., Chocarro C., Freixes O., Arque E., Moreno A., Santiver F. (2008) Yield, yield components, and forage nutritive value of alfalfa as affected by seeding rate under irrigated conditions, Agron. J. 100, 191–197.

López-Bellido R.J., Castillo J.E., López-Bellido L. (2008) Comparative response of bread and durum wheat cultivars to nitrogen fertilizer in a rainfed Mediterranean environment: soil nitrate and N uptake and efficiency, Nutr. Cycl. Agroecosys. 80, 121–130.

Martre P., Semenov M.A., Jamieson P.D. (2007) Simulation analysis of physiological traits to improve yield, nitrogen use efficiency and grain protein concentration in wheat, in: Spiertz J.H.J., Struik P.C., Van Laar H.H. (Eds.), Scale and Complexity in Plant Systems Research: Gene-Plant-Crop Relations, Wageningen UR Frontis Series, Springer, pp. 181–201.

Massey R.E., Myers D.B., Kitchen N.R., Sudduth K.A. (2008) Profitability maps as an input for site- specific management decision making, Agron. J. 100, 52–59.

Matson P.A., Parton W.J., Power A.G., Swift M.J. (1997) Agricultural intensification and ecosystems properties, Science 277, 504–509.

McDonald A.J., Hobbs P.R., Riha S.J. (2006) Does the system of rice intensification outperform conventional best management, A synopsis of the empirical record, Field Crop. Res. 96, 31–36.

Neeteson J.J., Schröder J.J., Ten Berge H.F.M. (2002) A multi-scale system approach to nutrient management research in the Netherlands, NJAS Wageningen J. Life Sci. 50, 141–151.

OECD (2001) Environmental Indicators for Agriculture: Methods and Results, Vol. 3, OECD, Paris.

Oehme M., Frei M., Razzak M.A., Dewan S., Becker K. (2007) Studies on nitrogen cycling under different nitrogen inputs in integrated rice-fish culture in Bangladesh, Nutr. Cycl. Agroecosys. 79, 181–191.

Oerlemans J., Von Oberfeld W.O., Wolf D. (2007) Impact of long-term nutrient supply on plant species diversity in grassland: and experimental approach on conventionally used pastures, J. Appl. Bot. Food Qual. 81, 151–157.

Olesen J.E., Bindi M. (2002) Consequences of climate change for European Agricultural productivity, land use and policy, Eur. J. Agron. 16, 239–262.

Olson D.M., Wäckers F.G. (2007) Management of field margins to maximize multiple ecological services, J. Appl. Ecol. 44, 13–21.

Pande K.R., Becker M. (2003) Seasonal soil nitrogen dynamics in rice-wheat cropping systems of Nepal, J. Plant Nutr. Soil Sci. 166, 499–506.

Peng S., Bouman B.A.M. (2007) Prospects for genetic improvement to increase lowland rice yields with less water and nitrogen, in: Spiertz J.H.J., Struik P.C., Van Laar H.H. (Eds.), Scale and Complexity in Plant Systems Research: Gene-Plant-Crop Relations, Springer, pp. 251–266.

Peng S., Cassman K.G., Virmani S.S., Sheehy J., Khush G.S. (1999) Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential, Crop. Sci. 39, 1552–1559.

Penning de Vries F.W.T., Rabbinge R., Groot J.J.R. (1997) Potential and attainable food production and food security in different regions, Philos. T. Roy. Soc. B 352, 917–928.

Pierce F.P., Nowak P. (1999) Aspects of precision farming, Adv. Agron. 67, 1–85.

Pretty J. (2008) Agricultural sustainability: concepts, principles and evidence, Philos. T. Roy. Soc. B 363, 447–465.

Rasmussen P.E., Goulding K.W.T., Brown J.R., Grace P.R., Janzen H.H., Körschens M. (1998) Long-term agroecosystems experiments: assessing agricultural sustainability and global change, Science 282, 893–896.

Rembialkowska E. (2007) Quality of plant products from organic agriculture, J. Sci. Food Agr. 87, 2757–2762.

Rossing W.A.H., Zander P., Josien E., Groot J.C.J., Neyer B.C., Knierim A. (2007) Intergrative modelling approaches for analysis of impact of multifunctional agriculture: A review for France, Germany and The Netherlands, Agr. Ecosyst. Environ. 120, 41–57.

Russell G., Jarvis P.G., Monteith J.L. (1989) Absorption of radiation by canopies and stand growth, in: Russell G. (Ed.), Plant canopy: their growth, form and function, Cambridge University Press, Cambridge, pp. 21–39.

Saito K., Atlin G.N., Linquist B., Phanthaboon K., Shiraiwa T., Horie T. (2007) Performance of traditional and improved upland rice cultivars under nonfertilized and fertilized conditions in northern Laos, Crop. Sci. 47, 2473–2481.

Samonte S.O.P.B., Wilson L.T., Medley J.C., Pinson S.R.M., Clung A.M., Lales J.S. (2006) Nitrogen utilization efficiency: Relationships with grain yield, grain protein and yield-related traits in rice, Agron. J. 98, 168–176.

Schröder J.J., Aarts H.F.M., ten Berge H.F.M., van Keulen H., Neeteson J.J. (2003) An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use, Eur. J. Agron. 20, 33–44.

Sheridan H., Finn J.A., Culleton N. O'Donovan G. (2008) Plant and invertebrate diversity in grassland field margins, Agr. Ecosyst. Environ. 123, 225–232.

Shibu M.E., Leffelaar P.A., van Keulen H., Aggerwal P.K. (2006) Quantitative description of soil organic matter dynamics – A review of approaches with reference to rice-based cropping systems, Geoderma 137, 1–18.

Sibma L., Spiertz J.H.J. (1986) Dry matter production and nitrogen utilization in cropping systems with grass, lucerne and maize. 1. Comparison of crop characteristics, growth and production, Neth. J. Agr. Sci. 34, 25–35.

Sinclair T.R., Horie T. (1989) Leaf nitrogen, photosynthesis, and crop radiation use efficiency – A review, Crop Sci. 29, 90–98.

Sinclair T.R., De Wit C.T. (1975) Photosynthate and nitrogen requirements for seed production by various crops, Science 189, 565–567.

Spiertz J.H.J., Ellen J. (1978) Effects of nitrogen on crop development and grain growth of winter wheat in relation to assimilation and utilization of assimilates and nutrients, Neth. J. Agr. Sci. 26, 210–231.

Spiertz J.H.J., De Vos N.M. (1983) Agronomical and physiological aspects of the role of nitrogen in yield formation of cereals, Plant Soil 75, 379–391.

Spiertz J.H.J., Sibma L. (1986) Dry matter production and nitrogen utilization in cropping systems with grass, lucerne and maize. 2. Nitrogen yield and utilization with various cropping systems and their after-effects, Neth. J. Agr. Sci. 34, 37–47.

Spiertz J.H.J., Oenema O. (2005) Resource use efficiency and management of nutrients in agricultural systems in: ERSEC Ecological Book Series – 1. On sustainable agricultural systems. Publishers: Tsinghua University Press and Springer, pp. 171–183.

Stehfest E., Bouwman L. (2006) N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions, Nutr. Cycl. Agroecosys. 74, 207–228.

Stockdale E.A., Gaunt J.L., Vos J. (1997) Soil-plant nitrogen dynamics: what concepts are required? Eur. J. Agron. 7, 145–159.

Stoorvogel J.J., Antle J.M., Crissman C.C., Bowen W. (2004) The trade-off analysis model: integrated bio-physical and economic modelling of agricultural production systems, Agr. Syst. 80, 43–66.

Storkey J., Westbury D.B. (2007) Managing arable weeds for biodiversity, Pest Manage. Sci. 63, 517–523.

Struik P.C., Bonciarelli F. (1997) Resource use at the cropping system level, Eur. J. Agron.7, 133–143.

Suding K.N., Collins S.L., Gough L., Clark Ch., Cleland E.E., Gross K.L., Milchunas D.G., Pennings S. (2005) Functional- and abundance-based mechanisms explain diversity loss due to N fertilization, PNAS 102, 4387–4392.

Swift M.J., Izac A.-M.N., van Noordwijk M. (2004) Biodiversity and ecosystem services in agricultural landscapes, Agr. Ecosyst. Environ. 104, 113–134.

Tait J. (2001) Science, governance and multifunctionality of European agriculture, Outlook Agr. 30, 91–95.

Ten Berge H.F.M., Kropff M.J. (1995) Founding a systems research network for rice in: Bouma et al. (Eds.), Eco-regional approaches for sustainable land use and food production, Kluwer Academic Publ., pp. 263–282.

Ten Berge H.F.M., Riethoven J.J.M. (1997) Applications of a simple rice-nitrogen model in: Ando T. et al. (Eds.), Plant nutrition for sustainable food production and environment, Kluwer Acad. Publ., pp. 793–798.

Tipraqsa P., Craswell E.T., Noble A.T., Schmidt-Vogt D. (2007) Resource integration for multiple benefits: Multifunctionality of integrated farming systems in northeast Thailand, Agr. Syst. 94, 694–703.

Topp C.F.E., Stockdale E.A., Watson C.A., Rees R.M. (2007) Estimating resource use efficiencies in organic agriculture: a review of budgeting approaches, J. Sci. Food Agr. 87, 2782–2790.

UNEP (2007) Reactive Nitrogen in the Environment, Too Much or too Little of a good Thing. The Woods Hole Research Center, USA and UNEP DTIE Sustainable Consumption and Production Branch, Paris, France, 51 p. [ISBN 978 92 807 2783 8].

Van Delden A. (2001) Yield and growth components of potato and wheat under organic nitrogen management, Agron. J. 93, 1370–1385.

Van Egmond K., Bresser T. , Bouwman L. (2002) The European Nitrogen Case, Ambio 31, 72–78.

Van der Werf H.M.G., Tzilivakis J., Lewis K., Basset-Mens C. (2007) Environmental impacts of farm scenarios according to five assessment methods, Agr. Ecosyst. Environ. 118, 327–338.

Van Ginkel M., Ortiz-Monasterio I., Trethowan R., Hernandez E. (2001) Methodology for selecting segregating populations for improved N-use efficiency in bread wheat, Euphytica 119, 223–230.

Van Keulen H. (2007) Quantitative analyses of natural resource management options at different scales, Agr. Syst. 94, 768–783.

Van Keulen H., Aarts H.F.M., Habekotte B., van der Meer H.G., Spiertz J.H.J. (2000) Soil-plant- animal relations in nutrient cycling: the case of dairy farming system 'De Marke', Eur. J. Agron. 13, 245–261.

Van Noordwijk M., Cadish G. (2002) Access and excess problems in plant nutrition, Plant Soil 247, 25–40.

Van Ruijven J., Berendse F. (2005) Diversity-productivity relationships: Initial effects, long-term patterns, and underlying mechanisms, PNAS 102, 695–700.

Wilkins R.J. (2008) Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems, Philos. T. Roy. Soc. B 363, 517–525.

Wilkinson P., Smith K.R., Joffe M., Haines A. (2007) Energy and Health 1: A global perspective on energy: health effects and injustices, The Lancet 370, 965–978.

Yang H.S. (2006) Resource management, soil fertility and sustainable crop production: Experiences of China, Agr. Ecosyst. Environ. 116, 27–33.

Yang X., Bouman B.A.M., Wang H., Wang Z., Zhao J., Chen B. (2005) Performance of temperate aerobic rice under different water regimes, Agr. Water Manage. 74, 107–122.

Yin X., Van Laar H.H. (2005) Crop Systems Dynamics: An ecophysiological simulation model for genotype-by-environment interactions. Wageningen Academic Publishers, The Netherlands, 153 p. [ISBN 907 69 985 82].

Zhang L., Spiertz J.H.J., Zhang S., Li B., van der Werf W. (2008) Nitrogen economy in relay intercropping systems of wheat and cotton, Plant Soil 303, 55–68.

Zhao J., Luo Q., Deng H., Yan Y. (2008) Opportunities and challenges of sustainable agricultural development in China, Philos. T. Roy. Soc. B 363, 893–904.