Agroecological Intelligence Needed to Prepare Agriculture for Climate Change

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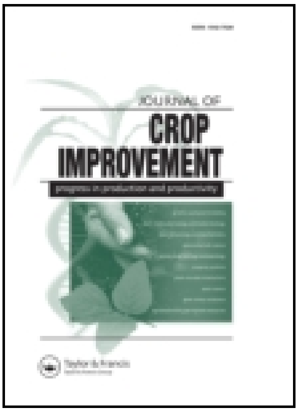

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The Need for Agro-Ecological Intelligence to Preparing Agriculture for Climate Change

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The Need for Agro-Ecological Intelligence to Preparing Agriculture for Climate Change

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Gratefully, the quality of life for billions of people will improve drastically during the coming decades. This implies that the production of virtually every commodity will have to increase dramatically. Agriculture-related activities ought to provide food, feed, and non-edible plant-based products. The availability of natural resources per person will, however, continue to decline. Resource degradation like erosion, soil fertility decline, and water pollution further constrain production increases. Hence, the use efficiency of natural resources will have to be boosted drastically, while variability should be curtailed through enhanced buffering capacity of the production base to prevent shock in food systems. These changes in agricultural strategies also call for interdisciplinary research groups to seek for synergies between production factors. This paper provides an overview of the challenges to meet the above mentioned production conditions and stresses the need for agro-ecological intelligence in choosing agricultural development strategies and, therefore, in designing agro-ecosystems. Plant production is taken as a starting point where global change, including climate, are considered in an integral manner.

KEYWORDS Resource requirement, resource use efficiency, buffering capacity of agro-ecosystems, plant production, climate and production variability

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GLOBAL DEVELOPMENT

Great successes in increasing total food volumes were obtained during the green revolutions in virtually all continents starting from the 1950s (e.g., Bindraban & Rabbinge 2011), though these successes were not obtained in sub-Saharan Africa (InterAcademy Council 2004). Advanced technologies, principally high-yielding varieties, large-scale irrigation development, and agronomic inputs, including fertilizers, biocides, and other agro-chemicals, were at the base of this success. Simultaneously, supportive economic and socio-institutional conditions were put in place for the technologies to work.

Yet, the production of food and other agriculture-based non-food commodities will have to drastically increase further during the coming decades to meet the growing demand of the increasing and ever wealthier population. These booming commodity volumes call for agro-productions systems with increasing use efficiency of natural resources because of the ever-declining base of natural resources per person. The current high food prices and those of 2008 show the fragility of the world food system and hit hardest on the poor. The buffering capacity of the world food system to cope with temporary shortages has decreased, and variability in production is expected to further increase because of increasing environmental variability, especially rainfall, and continued convergence of food supply and demand. The latter may occur because it becomes increasingly difficult for supply to keep pace with the rapidly growing demand.

Increasing the use efficiency of natural resources, including land, water, nutrients, air, and biodiversity, boosting supply to exceed demand for agro-commodities, and mitigating variability and risk, however, will not be easily attained. Anyhow, it calls for smart use of our resources through in-depth knowledge of production ecological principles (Ittersum & Rabbinge 1997). Some currently proposed strategies to resolve foreseen global problems tend to reject basic eco-physiological processes and even basic physical, chemical, and biological laws. They are given in by economic arguments, by ignorance or sentiments, or by vested interest of, for instance, powerful industries. This may generate false hope (e.g., organic agriculture), stimulation of counterproductive measures (e.g., biofuels), and pleas for unnecessary extreme options (e.g., vegetarian diet) to resolve the global pressure on natural resources. While the intentions may be precious, the means could be erroneous. Ecologically durable options can be arrived at only when basic processes and laws are respected.

This paper reviews current and projected claims on natural resources and revisits some of the current strategies to meet human food, feed, and fuel needs to arrive at options that limit pressure on the world's natural resource base in view of global change. Climate change is dealt with as an integral component of global change, and plant production ecology of terrestrial systems is the point of departure, as it forms the basis for secondary (animal) production.

REQUIREMENT OF NATURAL RESOURCES

To be able to calculate resource requirement for food and to ease comparison of diets and production systems, food components can be converted into grain equivalents (GE). This aggregation is justified because cereals account for 60% of global carbon fixation in agriculture and because the carbon fixation per unit area per year is at 87% of the global average carbon fixation rate (Goudriaan, Groot, & Uithol 2001). A healthy vegetarian diet requires approximately 1.5 kg GE per person per day (GE p^{-1} d^{-1}), while it takes 4.2 kg GE p^{-1} d^{-1} for a meat-rich, European diet (Wetenschappelijke Raad voor het Regeringsbeleid 1995).

For global analyses, plant growth can be estimated fairly accurately based on a few processes. The conversion of the production factors of radiation, water, and nutrients into crop growth appears to be relatively stable (Monteith 1990; Sinclair 1990). Absorbed radiation is converted into biomass with crop-specific radiation use efficiencies. This efficiency, however, reduces under insufficient availability of production factors like nitrogen (e.g., Bindraban 1999) or water. Water for crop transpiration can be calculated from crop-specific transpiration coefficients (Monteith 1990), with water use approximating to 1,000 liters of water for 1 kilogram of grains. It therefore takes from 1,500 liters water to produce a vegetarian diet to more than 4,000 liters for a meat-rich diet per person per day. Plant nutrient concentrations remain within certain margins, which allows the estimation of crop growth on the basis of the combined availability of soil nutrients (e.g., Jansen et al. 1990).

It is essential to consider both the availability of individual production factors as well as their interactions when analyzing resource requirements. Production ecological principles suggest that "most production resources are used more efficiently under improving conditions of resource endowment" (De Wit 1992). Crop and soil models that integrate the impact of production factors on growth provide powerful analytical tools to analyze plant growth and resource requirements (e.g., Boote, Kropff, & Bindraban 2001). However, interactions appear more difficult to quantity and are not always sufficiently taken into consideration, resulting in erratic growth estimates such as in Hoogwijk et al. 2005.

Land

The availability of suitable agricultural land is severely limiting in most Asian countries with little space for expansion (FAO 2009). Agricultural land per person has steadily decreased and will continue to decrease due to population growth. India has virtually no permanent pasture into which to expand its arable land and little natural land to take into cultivation. So far, the acreage per person could be maintained in China by conversion of natural lands into pasture and arable land. Bangladesh is worse off and has to feed its population of over 150 million people with 635 m^2 per person. Obtaining a vegetarian diet of 1.5 kg GE p^{-1} d^{-1} from this area implies a grain yield per hectare of more than 9 t ha^{-1} y^{-1}, while a meat-rich diet would require more than 24 t ha^{-1} y^{-1}, which exceeds biological limits. Rice yielded 3.9 t ha^{-1} in Bangladesh over the 2006 season, which indicates the lack of land to be self-sufficient and a need for food imports. Even though China has twice as much land per person and 50% higher rice yields than Bangladesh, the figures indicate the overall need for food imports by Asian countries. Furthermore, much of the most suitable fertile lands are being occupied by growing cities and other hard infrastructure (e.g., Chen 2007; Yang & Li 2000).

Land is abundantly available in Latin America reflecting the large potential to export food, certainly with expansion of the agricultural frontier (Wetenschappelijke Raad voor het Regeringsbeleid 1995; International Institute for Applied Systems Analysis 2011). Agro-ecological production potential of Northern America, the former Soviet Union, Australia, and Europe also exceed food requirement. In sub-Saharan African countries, land is abundantly available relative to the low population densities, though soil quality is poor, heavily depressing yield levels (Bindraban et al. 1999). Expansion, however, comes at the expense of biodiversity (Gibbs et al. 2010) and causes large amounts of greenhouse gas emission (Fargione et al. 2008; Searchinger et al. 2008). These effects might reduction the capacity of the land to provide ecosystem goods and services over a longer period of time. These tradeoffs should therefore be carefully balanced with the need for food production.

The claim on land (and water) resources depends heavily on the level of wealth. The average consumption by Europeans of 4.2 kg GE p^{-1} d^{-1} puts a claim on about 1,000 m^2 for plant products and some 2,000 m^2 for feed, of which about half is for crop-based feed and the remainder for grassland for meat and dairy products at European yield levels (Jing Qi, personal communication). Though consumption rates are much less in sub-Sahara Africa at 1.4 kg GE p^{-1} d^{-1}, total land requirement is higher at about 1,500 m^2 for plant products and 2,500 m^2 for feed, of which about 20% is for crop-based feed and the remainder for grassland for meat and dairy products, because of the low yields.

Hence, yield is a key factor that determines the claims on land that in turn will heavily depend on land quality. Land quality indicators (Dumanski, Gameda, & Pieri 1998) relevant for agriculture should integrate biophysical production factors (Bindraban et al. 2000). Even with continued increase in overall yield levels, the total arable area will increase by about 200 to 300 Mha in the coming two decades just to meet food demand (e.g., Organization for Economic Cooperation and Development [OECD]/Food and Agriculture Organization of the United Nations [FAO] 2008; International Assessment of Agricultural Science, Technology for Development (IAASTD) 2008). Other claims such as from agro-energy have not even been considered. In addition, soil lost due to urbanization, physical, and chemical degradation will have to be replaced to sustain the current agricultural area of about 1.4 billion hectares. Often fertile lands are lost and are being replaced by less fertile ones (e.g., Döös 2002).

Water

On average, 70% of water withdrawals from natural systems is used for agriculture. Water withdrawn is not necessarily 'lost,' and may be available for reuse, though generally with degraded quality, and not at the appropriate time. Any diversion of water from its natural course will affect ecosystems. Some rivers, for instance, do not even reach the sea anymore because their water is completely withdrawn for human activities, creating ecological and environmental problems (Steduto, Hsiao, & Fereres 2007b). Salt intrusion, water pollution, erosion, declining levels of groundwater, and drying up of lakes and wetlands are emerging phenomena deteriorating the quality of land. Water withdrawals should be more strategically targeted.

There is a well-established linear relation between plant biomass and transpiration (de Wit 1958; Tanner & Sinclair 1983; Steduto, Hsiao, & Fereres 2007a), which implies that more biomass production requires more transpiration. Plant breeding improved the harvest index for wheat, rice, and maize from about 0.35 before the 1960s to 0.5 in the 1980s (e.g., Sayre, Rajaram, & Fischer 1997), and that has raised water productivity gains more than any other agronomic practice over the last 40 years (Keller & Seckler 2004). The rate of increase in harvest index has slowed over the last 20 years as physiological limits are being reached (Bindraban 1997), depressing further gains in water productivity by this route. Water-limited yield levels in the semi-arid Sahelian region can be as high as 5 t ha^{-1}, while nutrient-limited yield levels range from 0.5 to 2 t ha^{-1} (Bindraban et al. 1999, 2000; Conijn et al. 2011). Actual yield levels in Sahelian countries range from only 0.5 to 1.5 t ha^{-1}. There are significant opportunities therefore to increase crop productivity and with that the utilization efficiency of rainwater through improvement of non-water factors such as soil fertility (Tanner & Sinclair 1983; Breman, Groot, & van Keulen 2001). These synergistic effects between water management and other agronomic practices such as maintaining soil health and fertility, controlling weeds and disease, and timing of planting, should be exploited. The author therefore launched the slogan "The best irrigation is fertilization," as it points to such synergistic interactions between production factors to raise water productivity. These findings are true in general for semi-arid regions (French & Schultz 1984), eastern Africa (Smaling et al. 1992), sub-Saharan Africa (Rockström 2001), southern India (Ahlawat & Rana 1998), and western China (Li et al. 2001).

These agricultural potentials under rainfed conditions will have to be exploited to contribute to future food and water needs. Production systems that rely entirely on (highly variable and erratic) rainfall are, however, exposed to high risks of crop failure or dramatic reductions in yield due to dry spells (Jagtap & Chan 2000; Hulme 2001). These conditions are projected to worsen with climate change (Hanrja & Qureshi 2010; Jin & Zhu 2008; Cooper et al. 2008). Measures like mulching, water harvesting and conservation, crop selection, timing of planting, etc. (Singh 1998; Li et al. 2001), can help to retain soil water in order to help the crop to withstand longer periods of drought. Supplemental irrigation during prolonged drought periods by using underground water, even if of poor quality, or rainwater harvested in tanks stabilizes and improves rainfed yields (Joshi et al. 1998; Singh 1998; Savenije 1998).

Current practices of inundated rice cultivation require 2,000 to 5,000 (and even up to 10,000 under poor management conditions) liters of water per kilogram of rice produced (Bouman & Tuong 2001), as compared to some 1,000 liters for a kilogram of dry grains (Rockström 2003). Water use in rice cultivation can be reduced by about 50% without yield loss when other agronomic measures are taken simultaneously, such as additional weeding, adjusting planting method, and the like (Bindraban et al. 2006a; Boumanet al. 2007). Hengsdijk et al. (2006) analyzed that up to 40% more water could be supplied to the urban area of the Jabotabek-Citarum region on Java, Indonesia, if water-saving rice cultivation practices were to be implemented in northwestern Java. Rapid adoption of such practices appears difficult as changing practices that have existed for thousands of years and are an integral part of the entire socio-economic and institutional design of a society is highly complex (Senthilkumar et al. 2008).

Molden et al. (2009) summarize that 20% of agricultural evapotranspiration is used for livestock production, and this proportion is projected to grow substantially with the increasing consumption of animal products. The water requirement for animal products mainly is determined by the water required for feed. The production of 1 kilogram of animal products is estimated to vary widely between 3,000 and 20,000 liters because it depends on management practices, the kind of feed, how crop residues are used, the processing system, and how well the animals convert feed into the animal product. Gains in water productivity can be made by adjusting each of these factors (Peden et al. 2007).

Even with efficiency gains, demands will result in increased water withdrawal from natural systems. Required amount for food production in 2005 of 4,800 (Bindraban, Jongschaap, & van Keulen 2010) to

7,000 km^3 (Rockström 2003; Molden 2007) per year comprises both irrigation and precipitation volumes. With 1,800 (Shiklomanov 2000) to some 2,660 km^3 y^{-1} (Oki & Kanae 2006) provided by irrigation water, some 3,000 to 4,000 km^3 y^{-1} of water for crop growth is obtained from rainwater. Feeding 9 billion in 2050 with an average diet of 2.0 or 2.5 kg GE p^{-1} d^{-1}, up from the average of 1.6 in 2005, implies a total water requirement of 6,800 or 8,500 km^3 (Bindraban, Jongschaap, & van Keulen 2010). With withdrawal for irrigation to remain within the current range of 1,800–2,660 km^3 y^{-1}, a total of approximately 5,000 or 6,500 km^3 should be provided by rainwater. Also assuming the food to be grown on the same arable land area of 1.4 billion hectares in order to refrain from further clearing of natural lands, some 40% or 55% of the rainwater falling on those arable lands of 11,970 km^3 y^{-1} (Oki & Kanae 2006) should be used as evapotranspiration. When correcting for the seasonal effect, i.e., assuming that 60% of annual precipitation is received during the growing season, the efficiency of rainwater would have to increase to 70% or 90%. It is not likely that these efficiency levels can be achieved for rainwater. Alternatively, expansion of agricultural land will be needed to "collect" rainwater and/or grasslands will have to be use more effectively (see section on vegetarianism).

Nutrients

Generally, the availability of several nutrients in soils allows low yield levels only, and needs to be supplemented by external inputs. In Africa, where food production systems are constrained by overwhelmingly low soil fertility (McCownet al. 1992; Giller et al. 2006), eco-efficient use of other resources are low as well, which is consistent with de Wit's (1992) observation. Because of farming strategies in many African systems to continuously improve the soil conditions on fields closest to the homestead, N use efficiency for maize on these fields is found to exceed 50 kg grain per kg N applied as fertilizer, while the efficiency is less than 5 kg grain per kg N on fields far away from the homestead (Tittonell et al. 2005; Zingore et al. 2007a; Vanlauwe, Tittonell, & Mukulama 2006).

Tilman et al. (2001) show that global nitrogen fertilizer use on field crops increased by seven-fold between 1960 and 1995, while cereal yields more than doubled, resulting in a decline of the nitrogen fertilizer efficiency from over 70 to around 25 kg grain per kg N. The response curve for any single factor is, however, that the highest increments in output are achieved for the first increments in inputs and efficiency declines thereafter. Part of this decline can be offset through simultaneous improvement of other production conditions. When a broad package of agronomic measures is introduced in a production system, such as in the Gezira, Sudan (Ahmed, Sanders, & Nell 2000), more pronounced yield increases are realized then with improvements of single factors (Ahmed & Sanders 1998). Farmers'

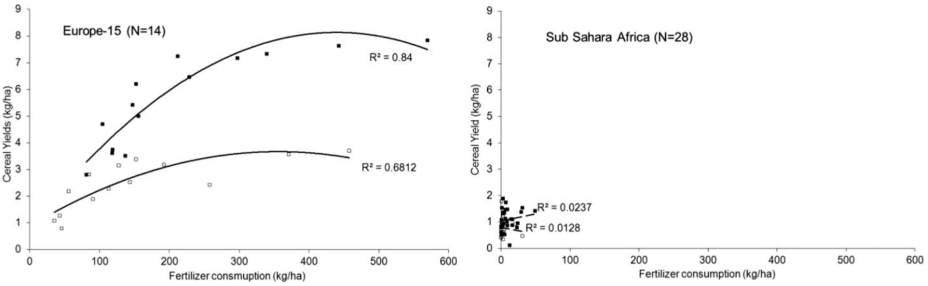

FIGURE 1 Cereal yields (t ha–1) as associated with fertilizer consumption (kg ha–1) for 1961 (open dots) and 2000 (closed dots) for sub-Saharan Africa and Europe. Only countries with data for both years and both variables are presented.
From Bindraban, Löffler, and Rabbinge 2008.

yields in Europe were 3 t ha^{-1} in 1961 even at high fertilizer rates and increased to 8 t ha^{-1} in 2000 at similar fertilizer rates because of improved overall management practice and advanced technologies such as improved varieties (Figure 1) (Bindraban, Löffler, & Rabbinge 2008).

Low eco-efficiency can also occur through excess use of fertilizers, in particularly nitrogen, leading to heavy costs to the economy and environment (e.g., Liu & Diamond 2005). From 1977 to 2005, grain production in China increased by 71% (from 283 to 484 million tons), while N fertilizer application increased by 271% (from 7.07 to 26.21 million tons). This overuse of N fertilizer is further exacerbated by high levels of N inputs from the atmosphere, water supplies, animal manures, and legume sources in the range of 89 to 104 kg N ha^{-1} y^{-1} (Ju et al. 2009). The excess nitrogen applied to cereals in China is estimated in the order of 11.8 million tons. If this 'excess' N fertilizer was instead used in sub-Saharan Africa, it would represent an average annual N fertilization rate of 68 kg N ha^{-1} over 174 Mha of cropland. If nutrients of this magnitude were available (and rebalanced to address other nutrient needs), a potential doubling of cereal productivity could be realized in sub-Saharan Africa (McCown et al. 1992; Twomlow et al. 2008a, b).

The current economically exploitable P resources have been estimated to be depleted within 100 (Smit et al. 2009) to over 300 years (Van Kauwenbergh 2010). Phosphorus (P) accumulates in soils when fertilization exceeds crop removal, especially with additional animal manure in intensive livestock regions. Often excess amounts are applied to increase the P-status of the soil and to anticipate the P-fixing properties of the soil. Generally P recovery is low at the short term, while it may be significantly higher at the longer term due to delayed delivery (Wolf et al. 1987). Also, losses occur in the entire agricultural chain through food waste. Smit et al. (2009) propose a mix of measures for a more sustainable use of P. Prevention of erosion is essential. Livestock production systems should be balanced with arable land in their vicinity for effective (re)use of P. Technologies should be developed to recycle P in waste streams, especially in the urbanized areas.

Fertilizer recommendation schemes should be critically revisited; P-fertilizer application methods should be tuned to the specific location of the production system, e.g., better timing and spacing, and plant breeding could seek to improve the ability of plants to better exploit soil P. While gains in efficient use of P are feasible, they call for fundamental changes in the design of production systems, land use patterns, and even of economic sectors, such as the need to better interlink livestock and arable production. Currently over 40 million tonnes of soybeans are imported by Europe, primarily from Latin American countries, to feed its animals in the intensive meat industry. A ban on imports would have economic consequences for the meat industry in Europe but hardly for the total meat consumption (Bindraban et al. 2008), while the flow of soybean causes a dramatic imbalance in nutrient extraction and accumulation in soils. Similarly significant translocation of potassium (K) also occurs as a result of international agricultural trade, frequently resulting in severe local negative balances.

Increasingly micronutrients are found to limit crop production and need macro-attention in our fertilization strategy (Production Ecology–Resource Conservation 2011). Crop responses to micronutrients are more frequently observed increasing the use efficiency of macronutrients, though the magnitude varies between regions and soil types, which call for location-specific recommendations. It is hypothesized that micronutrient deficiencies could have been human induced. Increasing deficiencies are, for instance, detected with increasing intensity (of NPK use) in India, while micronutrient deficiency shows up sporadically in many African production systems where NPK use has been low up to now.

Interactions

Synergies and interactions between production factors at various scales (de Wit 1992; Ahmed, Sanders, & Nell 2000; Bindraban, Löffler, & Rabbinge 2008) suggest the need for careful analysis of production systems to arrive at agro-technical suggestions for enhancing productivity. Even the use of a small amount of fertilizer can be extremely effective as long as access to other production factors such as water and labor is ensured and biotic stresses such as pests, weeds, and diseases can be controlled (de Ridder & van Keulen 1990; Ahmed & Sanders 1998; Ahmed, Sanders, & Nell 2000; Breman, Groot, & van Keulen 2001; Rowe et al. 2006; Rufino et al. 2007). Breman, Groot, and van Keulen (2001) illustrate that only the synergistic effect of the combined use of organic and inorganic fertilization was able to increase yield over time in the semi-arid Sahelian region, whereas recycling of organic matter alone could not sustain soil quality. Zingore et al. (2007b) show that maize response to N fertilizer is much higher with the simultaneous application of P. Application of lime to increase soil pH is essential in the Cerrado for P to have a favorable impact on soybean yield. Van Astenet al. (2004) found synergistic effects of joint application of zinc (Zn) and P on nutrient uptake that led to increases in crop yield, whereas application of either P or Zn alone gave little response. Increasing attention should be paid to these interactions and micronutrients in the future as expansion of agricultural land will take place more and more in less favorable areas with deficiencies of various kinds in soils and with strong interactions with rainfall.

Some 82% of world agriculture is rainfed, implying a large dependence on rainfall amounts and patterns. Annual rainfall patterns may vary considerably from year to year and from place to place, which complicates 'one-size-fits-all' measures. Figure 2 shows how yields vary with annual rainfall patterns at a site in Zimbabwe. While in most years fertilizer has a positive effect on production, it has zero or even a negative effect in the dry years. As result, many African farmers apply risk-adverse strategies that secure a minimum production in any year but that fail to capitalize on good seasonal conditions.

While investment in expanding irrigation has significantly improved agricultural productivity in the past, with 40% of world food currently being produced on 18% of irrigated agricultural land, there is little scope for much expansion of large-scale irrigation (Molden 2007; de Fraiture et al. 2007; de Fraiture & Wichelns 2010). Hence, small-scale water management and storage approaches are likely to be a key component in future efforts to increase agricultural production (Brown & Hansen 2008). Small-scale irrigation schemes have, however, a patchy history due to the lack of attention to institutional aspects, which ought to be overcome in future.

Extreme climatic events such as years of extreme drought, excessive rainfall leading to flooding, or days with extreme temperature can have dramatic effects on production (Wheeler, Craufurd et al. 2000; Porter & Semenov 2005), and there is emerging consensus that the semi-arid regions

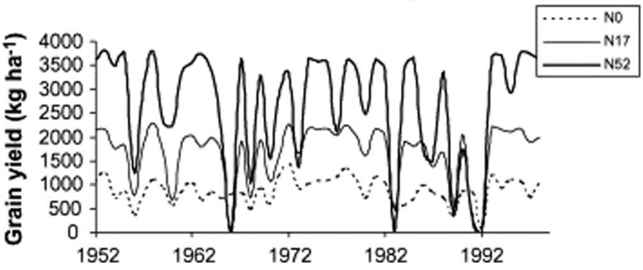

FIGURE 2 Yield response of maize varying with annual rainfall patterns at three levels of fertilizer application (0, 17, and 52 kg N/ha).
From Cooper et al. 2008.

will experience a high degree of climate variability in the future (Held, Delworthet al. 2005; Kamga et al. 2005). Climate science has reached a level where some of the forecast events can now be used operationally at farm level, such as in Australia (Meinke et al. 2006; Howden et al. 2007; Lo & Wheeler 2007). The approaches already account for spatial and temporal variability. Twomlow et al. (2008a, b) note that farmers, for instance, simply ignore fertilizer recommendations if these are not tuned to their local conditions and strategies for coping with risks.

The above examples reveal that, for a sensible assessment of the potential gains in efficiency that can be achieved in agriculture, production ecology concepts have to be used that account for eco-physiological processes in crop growth. In studies that review how sustainability in agriculture can be enhanced, production factors should be considered in an integral manner rather than in isolation as single factors such as by Tilman et al. (2002).

REVISITING CURRENT STRATEGIES

Agriculture has been successful in its primary role as food supplier, and global food production per person has increased by 27% over the past five decades despite a doubling of the world population. Not only has the productivity increased per unit land area and other inputs, but the productivity per labor hour has also increased. Production systems therefore are the result of the interplay between biophysical, socio-economic, and cultural factors. Dixon, Gulliver, and Gibbon (2001) provide an overview of agricultural production systems in the world. Vereijken (2002) classified production systems that have evolved over the past decades in Europe based on their core objectives. Starting off as systems to secure food production along with work and income, integrated systems have evolved to take environmental issue into consideration as well.

Integrated Agriculture

The full emphasis to raise food production after the Second World War pushed yields up in the EU15 at rates of 171, 105, and 433 kg ha^{-1} y^{-1} for maize, wheat, and potato, respectively (Bindraban, Löffler, & Rabbinge 2008). However, ecologically unbalanced amounts of inputs caused pollution of ground and surface water (Admiraal, de Ruyter Van Steveninck, & de Kruijf 1989), as is currently the case in China (Chen 2007). In Europe, total use of fertilizers and agrochemicals has been reduced absolutely and per unit of output since the mid-1980s, while yield levels have increased because applications are more precisely adjusted in time and space to crop demand (e.g., Tsiouris et al. 2002). Crop modeling techniques can help identify optimal timing strategies for fertilizer application, and nutrient balances can be further tightened to minimize losses. Insights into ecological predator-prey principles permit the reduction of agrochemical use to a minimum (Van Roermund, van Lenteren, & Rabbinge 1997; Kempenaar 2002). Close sensing allows early detection of plant stress from diseases and timely action to prevent losses from water or nutrient shortages, while global positioning systems with close- and remote-sensing facilitate precise spatial applications (Jongschaap 2006). Farming systems can be redesigned to minimize environmental impact, while maintaining high and economically viable production levels (e.g., Aarts 2000). These advances in technology support practices to optimize input use through integrated nutrient (INM), pest (IPM), and crop (ICM) management that is essential to enhancing use efficiency of natural resources while limiting adverse impact on the environment. Integrated approaches result in high production systems to be most effective in resource use efficiency (e.g., Glendining et al. 2009).

Organic Agriculture

Yields from organic agriculture are often presented as reaching 60% to even 80% of yields under conventional agriculture in Europe (e.g., Van Mansvelt & Mulder 1993; Tamis & Van den Brink 1999), but Bos (2005) showed that these yields can be attained only when nutrients from at least another hectare are used as input. Kirchmann and Thorvaldsson (2000) showed that many environmental problems might be even worse than in conventional agriculture. The release of nutrients from organic manure is not synchronized with crop uptake, leading, for instance, to higher nutrient losses. While total losses per unit area may be lower at lower production levels, losses per unit of product are higher in organic agriculture (Basset-Mens & van der Werf 2005). Exclusion of pesticides does not guarantee less toxic components in products, e.g., due to increased concentrations of plant metabolites and of mycotoxins of fungi, while food quality is not superior to conventionally produced items either (Warman & Havard 1997; 1998). Organic agriculture might house a higher degree of biodiversity of plant species and worms in the field (e.g., Van Elsen 2000; Siegrist et al. 1998), though others find no proof for such claims (Trewavas 2004). No increased nutrient use efficiency is found in long-term trials for organically and conventionally treated soils (Langmeier et al. 2002).

Yet, there is much debate about the production level of organic agriculture. As the application of artificial fertilizers is rejected (as is the use of most biocides), nitrogen can enter the production system through biological fixation by legumes only. Nutrients can also be concentrated on the production field from surrounding areas, such as through grazing animals, but this implies unsustainable practices of depletion of the grazing areas. Nitrogen also enters countries with net balances of biomass imports, such as the Netherlands, but this also leads to depletion in the exporting regions. Hence for organic agriculture to be sustainable and comply with its strict conditions, the ultimate amount of nitrogen that can enter the production system is through N-fixation. Nitrogen can also enter the system through deposition, though this pool is not consistent with the view of avoiding pollution. Under optimal growth conditions, i.e. with sufficient availability of water and other nutrients, primarily P, N-fixation rates of legumes range from 1 to 3 kg N ha^{-1} d^{-1} (e.g., Giller 2001). Based on the availability of nitrogen through N-fixation by legumes, the Wetenschappelijke Raad voor het Regeringsbeleid (1995) showed that the acreage required for the production of a similar amount of food is four to five times larger for organic agriculture than for integrated agriculture. A simplified calculation provides an estimate of the order of magnitude in yield levels between organic and integrated systems to explain these findings. Given a period of maximum growth of some 100 days in temperate regions, total N-fixation can reach 300 kg N ha^{-1}. Assuming a crop rotation of two cereal crops following the legume, on average 100 kg N ha^{-1} is available per year. With nitrogen recovery of 50%, a total amount of 50 kg N can be contained in the grains. At N contents in grains of 1.5%–2%, a maximum yield level of 2.5–3 tons grains can be obtained per hectare. Grain yields under integrated agriculture reach 10 t ha^{-1}. The difference in yield will be larger under the poor soil fertility status of tropical soils, primarily low P availability, as it further reduces the production potential of organic agriculture. Organic agriculture will therefore put a much larger claim on land and other resources due to lower use efficiencies, revealing the large trade-off with biodiversity.

Organic agriculture can rather be perceived as a system that integrates social and cultural values, aiming at plant and animal production with environmental care, conservation of nature, and care for health and well-being, including tourism and recreation. These values may be relevant in wealthy societies, but claims on natural resources will be displaced to other regions when consumers do not lower their consumption patterns.

Bio-Energy

Worldwide, many nations impose blending of their transport fuels with biofuels, approximating 10% globally by 2020, to contribute to energy security while reducing emission of greenhouse gasses (FAO 2008). Scientific evidence is rapidly accumulating and questioning the environmental benefits of biofuels (Bindraban, Bulte, & Conijn 2009; Bindraban et al. 2009). The Achilles' heel of biofuels production is the low utilization efficiency of sunlight by plants. The maximum attainable efficiency (Spedding 1988) of around 2.5%, with year-round cultivation in the tropics and about 1.5% in temperate regions, ultimately reduces to 0.2%–0.8% for biofuels after correction for non-harvestable crop parts and energy needed during production, transport, and processing of the biomass (Corré & Conijn 2008). This applies to crops grown under optimal conditions, and efficiencies will be even lower under marginal growing conditions, when crop radiation use efficiency declines due to yield-reducing factors (Sinclair & Horie 1989).

Net savings of greenhouse gas emissions up to 10 t CO_2 $ha^{-1}y^{-1}$ in the production chain for biofuels from feedstocks like sugarcane and palm oil have been calculated (Righelato & Spracklen 2007). Savings will be lower under poor management, when soil organic matter is lost during production, or when too much nitrogen fertilizer is used (Crutzenet al. 2007; Smeets et al. 2007). Worse, when cultivation of biomass leads to the direct or indirect clearing of natural lands, emissions 30 to 200 times the amount potentially saved in the chain may occur (Searchingeret al. 2008; Fargioneet al. 2008).

Hence, the critical question is whether agricultural productivity can be increased to such an extent that sufficient agricultural land can be freed up for the production of energy crops while meeting global demand for food. Most studies indicate that this is unlikely and argue that both arable land and grassland acreage will have to increase (OECD/FAO 2008; IAASTD 2008). Moreover, these studies may be too optimistic as they are partly based on extrapolating existing trends, whereas a deteriorating resource base (notably water availability and physical and chemical soil fertility) will limit future productivity increases in biomass production. Arguably more rather than less land will be necessary for food production to meet future food demand, certainly until 2020 (e.g., Bruinsma 2003), the year for which the obligatory blending targets are set. This implies that the production of biofuels will lead to net clearing of natural lands, resulting in carbon emissions as well as a loss of biodiversity. The use of marginal lands is unlikely to create significant volumes of biomass.

Many advocates of biofuels have vested their hopes on so-called second-generation technologies, i.e., the production of biofuels from non-edible plant parts (e.g., EEA 2008). However, the implementation of such technologies, in terms of timing and volumes, remains highly uncertain until 2020 (Deurwaarder, Lensink, & Londo 2007). Moreover, second-generation feedstock also put claims on scarce natural resources, with continued competition with food for these resources.

The availability of energy to the world is basically infinite, as the world receives over 8,000 times more energy than is currently used. Because energy is a pure physical phenomenon and is used in physical processes like horizontal movement, rotations, lightening, and heating, a direct conversion of physical process (also using some chemical processes) into physical processes, without the interference of biological processes, would yield highest use efficiencies, such as with solar energy. Because of the low radiation use efficiency of plants, the interference in the world's ecological systems will be infinite when our energy is to be produced with biomass. The production of 10% biofuels for the transport sector, i.e. some 2% of our total energy use, puts a claim on 100 million to 200 million hectares of fertile lands (Bindraban et al. 2009), while others suggest even 600 million hectares as production will take place on less favorable land (Murphy et al. 2011). Much of our global environmental problems might be solved when our energy provision is entirely disconnected from biological and ecological processes.

Vegetarianism

Presently, vegetarianism is claimed to make a large contribution to reduce claims on natural resources. A purely vegetarian diet indeed requires about a third of the land and water of a meat-rich diet. Access for wealthy people to a wide diversity of food items allows them to compose balanced diets. However, food-insecure people under poor conditions generally rely on unbalanced diets. Meat and animal products provide high-quality foods rich in micronutrients and essential amino acids. This is important for supplementing proteins from plant sources, which typically have low levels of essential amino acids. Children that consume a little amount of meat benefit from a more balanced diet and exhibit less stunting, are less prone to diseases, and gaining weight (Gryseels 1988; Abassa 1995).

Meat production is even essential in securing sufficient food, as much grassland cannot be converted into arable land but can be utilized through conversion of grass into valuable food items by ruminants. In addition, grasslands will serve as an essential surface to collect part of the future water required for food production.

Enhancing the use of grasslands for increasing red meat production by ruminants may be an essential way to capture part of this additional water to increase the availability of healthy food products for poor and food-insecure people. The production of ruminant meat on improved grasslands can make a significant contribution to substitute expansion of arable land area (Bindraban, Jongschaap, & van Keulen 2010; Steinfeld 2006).

Hence, rather than calling for vegetarianism, poor people should be given the opportunity to eat more meat, primarily from ruminants. This does not hold for people in current wealthy societies that consume excessive amounts of meat, including pork and chicken, putting a large claim on arable land (Bindraban, Löffler, & Rabbinge 2008).

ENHANCING THE BUFFERING CAPACITY OF AGRO- ECOSYSTEMS

The supply and demand for agro-produce (food, feed, fuel, and the like) have converged to an extent that food reserves have been continuously depleted over the past decade. With that, the buffering capacity to cope with temporary shortages that in themselves have not been uncommon in the past, has decreased. The fragility of this new world food equilibrium has increased, making the poor even more vulnerable to food shortages as has recently been experienced. This fragility is likely to become even greater because of expected increases in environmental variability, the expansion of agriculture into less favorable environments, and the continued convergence of food supply and demand as it becomes increasingly difficult for supply to keep pace with the rapidly growing demand. Therefore, an increase in both use efficiency and storage capacity of agro-ecosystems should be realized simultaneously to secure sufficient and stable food supplies.

Much emphasis has been placed during the green revolution on increasing the yield potential of a limited number of major crops, primarily rice, wheat, maize, and potato. The increase in harvest index of cereal crops has basically been the most fundamental change that has been achieved to obtain higher yields (e.g., Sayre, Rajaram, & Fischer 1997). However, total biomass production has not changed, nor has the efficiency of the photosynthesis apparatus. The potential for further increases in crop yield is limited (Bindraban 1997). Increasingly important will be the increased resistance to pests and diseases and the tolerance level of crops to drought and other biophysical threats to stabilize yield (Figure 3).

Van Ginkel, Baum, and Ogbonnaya (2009) argue that input efficiency can be combined with input responsiveness in several crops: varieties with relatively high yields under low fertility/water conditions and significantly higher yields under more favorable conditions. Yield potential is not necessarily in conflict with adaptation to abiotic stress, as has been shown recently for New Rice for Africa (NERICA) rice varieties bred in West Africa (Balasubramanian et al. 2007). These types of robust varieties may further reduce yield variability. Broadening the number of improved crops may further help to stabilize production. Crops specific to sub-Saharan Africa that were bypassed by the Green Revolution, such as plantains, roots, and tuber crops like cassava and yams, and small cereals such as millet and sorghum, especially ought to receive breeding attention.

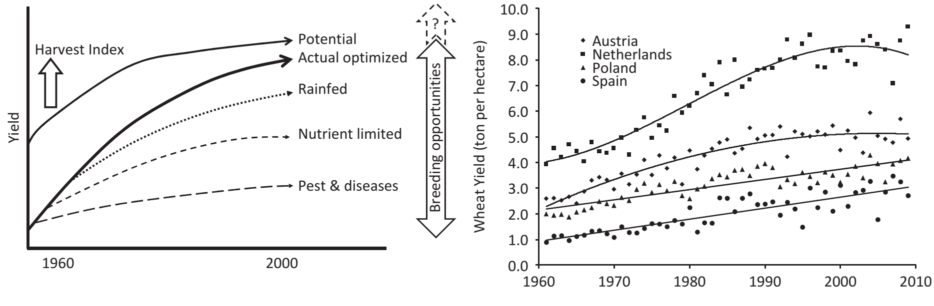

FIGURE 3 Schematic presentation of options to increase crop yields (left) and observed wheat yields in several European countries (right).
Based on FAO data; April 2011.

Biotechnological approaches that speed up the process of breeding and can better target the incorporation of required traits into new varieties should be exploited to accelerate this process. Bindraban et al. (2006b) do, however, argue for broad scope in breeding by introducing considerations related to the entire production system within which a crop is cultivated. This approach will better reveal the functioning of species and support identification of the genetic characteristics necessary to enhance productivity in a given agro-ecological context.

Nearly all investments for water provision in agriculture are made in abstraction of water from streams and groundwater, i.e. ‘blue’ water. Globally, however, 60% of fresh water is contained by soils, described as ‘green’ water (Cosgrove and Rijsberman 2000). With decreasing blue water resources, the importance of rainfed agriculture will increase. Often total amounts of rainwater in a growing season suffice to obtain high yields (Conijn et al. 2011), but erratic rainfall, with few heavy showers, for instance, causes much water to run off or to percolate below the root zone. Key in increasing and stabilizing yields will be the ability to store water in soils. Other benefits may simultaneously be obtained. Sustainable land and water management practices upstream reduce erosion, which leads to less sedimentation in rivers and reservoirs. More water becomes available downstream and production of hydro-electricity can be significantly increased (Dent & Kauffman 2007). In general, designing and managing agricultural water for multiple uses—drinking water, industries, livestock, fisheries—raises the economic productivity of water in water management systems (Meinzen-Dick 1997; Bhatnagar et al. 2004; van Koppen, Moriarty, & Boelee 2006).

Soil organic matter (SOM) and clay determine many soil characteristics necessary for plant growth, such as banking of nutrient stocks, cation exchange capacity, and water-holding capacity. Maintaining and increasing SOM is important to enhance the buffering capacity of soils; therefore, using biomass residues cannot be considered a sustainable source for the production of bio-energy. Without return flow of these residues, soil organic matter may decrease by up to 50% of the initial level prior to removing straw from the field, which depends on interacting processes within the cropping system, the share of straw crop in the rotation, management, use of organic fertilizer, weather conditions, soil type, hydrology, and fertilizer use. The reducing effect on future crop yields and the loss of N, S, P, and other nutrients may have to be compensated by increasing external inputs and hampering the buffering capacity of agro-ecosystems.

Integrated agro-production systems may catalyze the optimal rather than the maximal use efficiency of resources, certainly so under unfavorable environmental conditions, as a means to enhance the buffering ability of agro-ecosystems. While growing, there is still little systematic insight into production-ecological aspects of such complex systems at both a field and regional scale. Ecological synergies may be exploited, such as the creation of refuges in non-productive areas for natural enemies of pests on crops in adjacent production fields (e.g., Landis et al. 2008). The combined growth of two or more crops might make more effective use of natural resources (e.g., light and water) and added resources (e.g., fertilizer), raising the productivity of the entire system. The different crops would optimize sharing of resources over time and space, but then various combinations could also exacerbate drought or disease and pest incidence (e.g., Keating & Carberry 1993; Marshall & Willey 1983; Morris & Garrity 1993; Trenbath 1993; Tsubo & Walker 2002). Skelsey et al. (2005) only recently developed a model to systematically assess the impact of crop combinations on disease infestation and dispersion. Similarly, no priority has been placed on the development of machines equipped to harvest two or more crops simultaneously or to harvest a single crop in a mixture. But unless mechanization is tailored to diversified farming systems, their land and labor productivity will remain virtually stagnant at a low level.

CONCLUDING REMARKS

It is likely that we have already reaped the low hanging fruits in terms of rapidly increasing yields over the past decades. High-yielding varieties have been bred that could excel on our best soils supplemented with fertilizers and with sufficient water in favorable rainfall areas and from well and surface irrigation. While the yield gap, i.e., the difference between actual yield and yield that can be obtained under optimal management conditions, is still large, closing that gap will not be easily attained. These gaps generally occur under current less favorable conditions, such as erratic rainfall and high spatial variability of soil fertility, that call for knowledge-intensive management of scarce resources in time and space. Securing future food production will therefore require intelligent agro-ecological solutions. In this paper, some counterintuitive suggestions have been made that may not be in line with common understanding, but do intend to follow basic production and ecological principles.

Much more emphasis should be put on understanding and exploiting the benefit from interactions between production factors. Synergies and methodologies that prevent increased variability in production under increased levels of inputs should be fostered, certainly so under environmentally less favorable production areas, primarily rainfall. Buffering strategies by integrating production systems and practices should be pursued. Plant breeding strategies would best be focused on increasing the resilience of plants to harsh conditions. The production potential of grasslands should be exploited. These systems are indispensable for world food security, as the area under grass is needed for the collection and conversion of rainwater into food items. Moreover, conversion of grass by ruminants result in high-quality food items essential to improving the health of billions of poor people. Organic agriculture per se is not an answer toward more sustainable use of resources. Organic fertilizers improve soil structure and fertility and contribute to stabilized yields, but are insufficient to increase overall yield levels. Inorganic fertilizers should be applied to increase the productivity of production systems. The extremely low radiation use efficiency of plants implies that much land, water, and other resources will be needed for the production of little amounts of bio-energy, leading to excessive claims on natural resources. Moreover, rather than reducing greenhouse gas emissions, biofuels may worsen climate change and lead to the loss of biodiversity through direct and indirect effects. Competition with food will continue—directly with food as feedstock and indirectly through competition for resources. Our energy provision should be disconnected from biological and ecological processes.

The current crises in the financial, energy, climate, and food sector have created a sense of urgency in the search for unconventional concepts and novel information to pursue strategies for development and growth that are truly sustainable. An overriding influence of economic arguments on decisions in policymaking and in private enterprises have stimulated short-term gains, thereby systematically undervaluing the importance of the world's natural resource base. Policymakers, private enterprises, and society at large should be better informed about agro-ecological processes to make the best use of the world's natural resources. Land, water, air, and biodiversity are among the precious resources now being used to the benefit of human welfare. However, their quality and quantity should also be maintained to allow sustained exploitation for generations to come. The research community should maintain its independence, reflect critically on proposed strategies taking fundamental physical, chemical, and biological processes as a starting point, and identify ecologically more durable option to meet future food and non-food demands while making the most efficient use of natural resources.

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