

# Eco-efficient Agriculture: Concepts, Challenges, and Opportunities

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## ABSTRACT

Eco-efficiency in the simplest of terms is about achieving more with less—more agricultural outputs, in terms of quantity and quality, for less input of land, water, nutrients, energy, labor, or capital. The concept of eco-efficiency encompasses both the ecological and economic dimensions of sustainable agriculture. Social and institutional dimensions of sustainability, while not explicitly captured in eco-efficiency measures, remain critical barriers and opportunities on the pathway toward more eco-efficient agriculture. This paper explores the multidimensionality of the eco-efficiency concept as it applies to agriculture across diverse spatial and temporal scales, from cellular metabolisms through to crops, farms, regions, and ecosystems. These dimensions of eco-efficiency are integrated through the presentation and exploration of a framework that explores an efficiency frontier between agricultural outputs and inputs, investment, or risk. The challenge for agriculture in the coming decades will be to increase productivity of agricultural lands in line with the increasing demands for food and fiber. Achieving such eco-efficiency, while addressing risk and variability, will be a major challenge for future agriculture. Often, risk will be a critical issue influencing adoption; it needs explicit attention in the diagnosis and intervention steps toward enhancing eco-efficiency. To ensure food security, systems analysis and modeling approaches, combined with farmer-focused experimentation and resource assessment, will provide the necessary robust approaches to raise the eco-efficiency of agricultural systems.

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**Abbreviations:** GM, genetically modified; NGO, nongovernmental organization; WUE, water use efficiency.

**E**FFICIENCY in use of natural resources has been central to agricultural practice for over 10,000 yr. Ever since humans intervened in natural ecosystems to gather food, there has been interest in raising the efficiency of agro-ecosystems. If efficiency is simply the level of output per unit of input, “eco-efficiency” targets this simple notion toward the production of food and fiber products relative to the ecological resources used as inputs, mainly land, water, nutrients, energy, or biological diversity. Such focus should not be considered in isolation of the critical human and economic dimensions of labor and capital nor ignoring outputs such as environmental loads on wider ecosystems—nutrient, salt, acid, or sediment losses to terrestrial, aquatic, or marine ecosystems, greenhouse gas emissions to the atmosphere—or other ecosystem services that might be positively or negatively influenced by agricultural practice. It is generally considered that the term eco-efficiency was coined by the World Business Council for Sustainable Development around the 1992 Rio Earth Summit (WBCSD, 2000) to provide a concept for the engagement of the private sector. During the past decade the concept has been

Published in *Crop Sci.* 50:S-109–S-119 (2010).

doi: 10.2135/cropsci2009.10.0594

Published online 8 Feb. 2010.

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applied more directly to agriculture and specifically eco-efficient agriculture for the rural poor (CIAT, 2009).

Yield per unit land area is the simplest and most widely used eco-efficiency measure for field crops. However, there are inevitably multiple efficiency measures at play at the same time, such as water use efficiency (yield per unit of water used, e.g., rainfall, stored soil moisture, and/or irrigation), nutrient use efficiency (yield per unit nutrient uptake or nutrient supplied), radiation use efficiency (biomass produced per unit radiation intercepted), labor efficiency (production per unit labor invested), return on capital (profit as a fraction of capital invested), and so on.

Even within these simple ratios, there are multiple ways that efficiency can be measured. For example, nutrient use efficiencies can be defined in a number of different ways: crop yield per unit of nutrient applied (partial factor productivity); crop yield increase per unit of nutrient applied (agronomic efficiency); nutrient in harvested crop per unit of nutrient applied (partial nutrient budget); or increase in above-ground crop uptake per unit of nutrient applied (recovery efficiency). Additionally, nutrient use efficiency calculations may only consider nutrient inputs derived from chemical fertilizers or may include contributions from the mineralization of nutrients in soil organic matter, crop residues, or manures and over several crop cycles. Such calculations could also be undertaken in terms of economic return per cost invested to quantify the financial benefits to farmers of enhancing nutrient use efficiency.

Broadly, eco-efficiency can cover the interrelationships and trade-offs among a host of production, conservation, economic, and social values at landscape scale (e.g., Groot et al., 2007). In this context, some efficiency measures can relate two or more system outputs, such as harvested product per unit nutrient lost by leaching or per unit of habitat loss or biodiversity impact or value per unit greenhouse gas emissions.

In this paper we first review the eco-efficiency concept as it applies to agriculture today, its multidimensionality, and its relevance over diverse spatial and temporal scales. Second, we examine contemporary food production challenges through the eco-efficiency lens. What role will efficiency of natural resource use need to play in addressing emerging global challenges around food security for our growing population? Finally, we look for guidance for agricultural science. How can we better diagnose the nature of resource use inefficiency in the diverse agricultural systems of the world, and what agro-technical solutions are likely to have greatest benefit for human development and food security?

## MULTIDIMENSIONALITY OF ECO-EFFICIENCY

Eco-efficiency is invariably influenced by multiple factors interacting on growth and development processes in nonlinear and nonadditive ways. In a classic paper on

“Resource Use Efficiency in Agriculture,” C.T. de Wit (1992) explores the interactive nature of different production factors in terms of Liebig’s Law of the Minimum, Liebscher’s Law of the Optimum, and Mitscherlich’s Law of Constant Activity. All these yield response functions reflect, *ceteris paribus*, decreasing returns to increases in the supply of one production factor. While these response curves differ in the way multiple growth factors interact to determine growth or yield, de Wit concluded that Liebscher’s Law of the Optimum best described the observed growth responses: “*It may be concluded, with some reservations regarding the control of pests, diseases and weeds, that no production resource is used with any less efficiency and that most production resources are used more efficiently with increasing yield level due to further optimizing of growing conditions.*”

While de Wit (1992) argues that the totality of resources are utilized most efficiently when their supplies are all close to yield-optimizing levels, the reality of a response curve for any single factor is that the highest increments in output are achieved for the first increments in inputs and efficiency declines thereafter. The phenomenon of decreasing efficiencies with increasing inputs is well illustrated for yield response to N fertilization. At a global scale, N fertilizer use on cereals increased by sevenfold between 1960 and 1995, cereal yields more than doubled, and the N fertilizer efficiency (partial factor productivity: cereal yields divided by N fertilizer inputs) declined from over 70 to around 25 kg grain per kg N (Tilman et al., 2001).

Eco-efficiency can also be examined at different spatial scales. At the cellular level, the efficiency with which solar radiation drives the transformation of atmospheric CO<sub>2</sub> to carbohydrates can be expressed in terms of photosynthetic rates, which in turn are influenced by ambient CO<sub>2</sub> concentrations, climatic conditions (such as light and temperature), and genetic factors (such as photosynthetic metabolic pathways) as well as other growth factors (such as water or nutrient stress that directly influence the effective functionality of the cellular photosynthetic apparatus). At the crop level, dry matter production is frequently expressed as the product of radiation intercepted and “radiation use efficiency”—the latter being a key component of many crop simulation models—and an efficiency function that is influenced by other environmental stresses (Sinclair and Muchow, 1999). Also at the crop level, harvested yield can be interpreted in terms of efficiency of water transpired, water lost via evapotranspiration, or water supplied as rain or irrigation (Sinclair et al., 1984). Likewise nutrient use efficiencies frequently express yield per unit of nutrient taken up or supplied (Baligar et al., 2001; Asseng et al., 2001).

At the farm level, eco-efficiency might be represented in terms as diverse as the food output per unit labor, the biodiversity benefits provided by retention of natural habitat

per unit food production, or the aggregate food output per unit water or fertilizer applied. Regional level analyses might target differences in the relationships between agricultural inputs and outputs associated with a diverse range of impacts on the natural resource base. At the global scale, the ultimate measure of eco-efficiency of agriculture emerges from the complex interrelationships among global food supplies to meet human needs, avoidance of land degradation to sustain long-term productivity, provision of ecosystem services beyond agriculture such as biodiversity conservation, healthy waters, and atmosphere.

Farming system eco-efficiency can vary with time. A farming system that is mining soil nutrient reserves or depreciating the productive capacity of soils through physical or chemical degradation may appear highly efficient at the outset but progressively deteriorates as degradation intensifies. Agro-ecological systems are generally nonlinear and subject to relatively rapid change when thresholds are breached. Classic examples of such thresholds include:

- rising water tables or irrigation leading to salinization in dryland (McFarlane and George, 1992) or irrigated systems, often long after shifts in water balance first occurred;
- acidification of soils due to nitrate leaching and cation removal in harvested products; this can reach thresholds where plants can no longer adapt, thus further intensifying degradation (Tang et al., 2000); and
- a farming system that depletes soil nutrients (De Jager et al., 2001) or exposes the soil to degradation via wind or water erosion may pass a soil health or fertility threshold that quickly switches the system from profit to financial loss.

## AN EFFICIENCY FRONTIER FRAMEWORK

Effective application of the eco-efficiency concept requires an understanding of the production functions that relate agricultural outputs to the level of resource and other inputs (Dillon, 1977). Figure 1 illustrates three production functions that relate production to inputs at any spatial or temporal scale. The lowest production function depicts the current efficiencies observed on farms in a particular agro-ecological or farming system setting and may represent the performance of the best managed farms across a range of input usage. While efficiency is the ratio of the output achieved to the input applied, the slope of the function represents the marginal efficiency gain from moving along the production function. The second higher function represents the achievable efficiencies through the deployment of the best known technologies for that setting. This function is a styled example of such a frontier based on currently known technologies and practices adapted to local circumstances. The gap between the observable farm efficiencies and those obtainable with known technologies is caused in the main

by economic, social, and institutional factors. One of the most commonly analyzed gaps is the yield gap between typical farms and best farms or research stations (Evenson et al., 1996). Through successful agricultural research even greater efficiencies are continually sought for a given level of input (the third highest curve in Fig. 1). Generally such production or efficiency functions exhibit the diminishing returns curve displayed in Fig. 1.

In most agricultural output–input relationships, however, there is a probability distribution of responses driven by sources of variability, primarily climate but also due to the inherent diversity in biological systems and different management across farms and years. The higher the climate variability the more pronounced will be the risk dimension of any eco-efficiency enhancing strategy. One approach to exploring relationships between risks and returns has been the concept of “mean-variance (E–V) space” (Anderson et al., 1977; Parton and Carberry, 1995). For any system, a scatter plot of expected or mean economic returns against their associated variance over a range of input levels will elicit an efficiency frontier of outermost points where mean returns can be maximized for any given level of variance in returns. The statistical variance (or standard deviation) in returns is used as a surrogate for risk.

An eco-efficiency diagnosis framework, based on the return–risk approach, is presented in Fig. 2. This framework provides for the notion of an “efficiency frontier” whereby the return with existing knowledge and technology is maximized for different levels of risk, defined as the variance of output. The curve in Fig. 2 joining points C–D–A is a styled example of such a frontier based on currently known technologies and practices adapted to local circumstances. This curve shows returns (profit or yields) approaching a plateau while risks of increased investment (due to variability or some other measure of risk such as rates of crop failure, rates of economic loss, or in some cases level of environmental damage) continue to rise. Note that it is not generally possible to map input level and risk one-on-one because of system nonlinearity and thresholds.

Based on both the input–output space in Fig. 1 and the return–risk space in Fig. 2, we can explore three specific pathways to address productivity improvement:

- (i) Moving along the efficiency frontier (moving from C to D toward A) but with associated increase in inputs and riskiness;
- (ii) Addressing system inefficiencies through best practice for a certain level of input and risk (moving from B to D); and
- (iii) Breakthrough technologies or practices to redefine a new efficiency frontier (from D to F onto a new frontier C–F).

These simple input–output and return–risk frameworks can be employed to diagnose the most promising

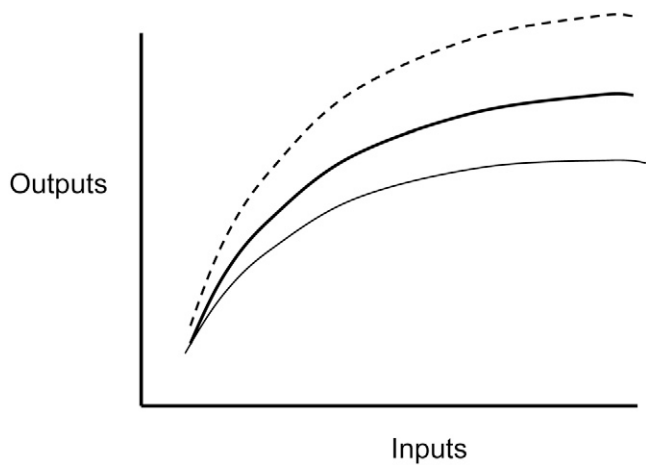


Fig. 1. Production functions that relate agricultural outputs to the level of inputs for observed farm performance (—), for current best technologies (—), and for foreseen new technologies (—).

pathways for intervention into agricultural systems to improve their performance.

## EXAMPLES OF CURRENT ECO-EFFICIENCIES IN AGRICULTURE

### Soil Fertility in Africa

In Africa, there is compelling evidence that food production systems are constrained by overwhelmingly low soil fertility (McCown et al., 1992; Giller et al., 2006; Sanginga and Woomer, 2009) and unless ways are found to relieve this constraint, eco-efficient use of other natural and human resources will remain low. This is consistent with de Wit's (1992) conclusion that resource use efficiency is maximized when the level of all inputs is close to their optima and confirmed by Bindraban et al. (2008), who have analyzed temporal trends in crop yields in Africa.

There would appear to be two linked pathways for action immediately with soil fertility and smallholder agriculture in Africa. One path is to move along the efficiency frontier (from C to D in Fig. 2) through farmers taking on additional risk in terms of nutrient inputs (from fertilizers, manures, legumes, or a combination of all three), with the prospect of higher long-term returns but also higher variability of returns. Another path is to identify agronomic practices that currently cause crop performance to fall below the technically feasible efficiency frontier (i.e., moving from B to D in Fig. 2).

In terms of increasing returns while taking on greater (but acceptable) risk, the work of Keating et al. (1991), McCown et al. (1992), Dimes et al. (2003), Robertson et al. (2005), and Twomlow et al. (2008) illustrate the possibilities arising from small amounts of carefully targeted fertilizer inputs. Some important facts emerge from this set of interrelated studies conducted on African smallholder farms, supplemented with modeling analyses over the last

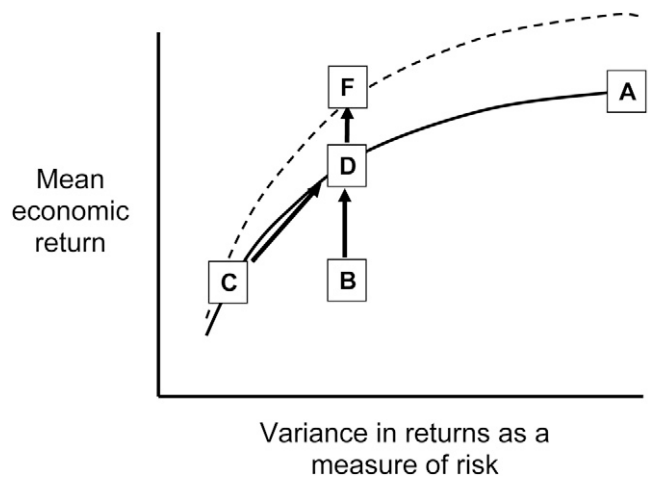


Fig. 2. A stylized return–risk framework for the diagnosis of system state and opportunities to enhance eco-efficiency. Points A, C, and D are representative points on the efficiency frontier for current best technologies (—) and point F is a specific point on the efficiency frontier for a hypothesized new technology (—). Point B represents a position below the efficiency frontier.

25 yr. First, the soil fertility constraint is often a dominant ecological factor constraining productivity at any given level of moisture availability. In Africa, N is almost universally limiting and phosphorus and other nutrients are limiting in many situations. Within-farm variability is high (Giller et al., 2006) and many farms have only small areas of higher nutrient supply, usually associated with household areas and livestock containment yards.

Rainfall variability is often extreme, yet seemingly attractive responses to fertilizer are still possible. In particular, there are high returns possible from small amounts of targeted fertilizer additions (Twomlow et al., 2008). Some gains in reducing risk associated with fertilizer inputs have been identified through the use of various forms of climate information, including seasonal forecasts (Keating et al., 1991; McCown et al., 1992), but a major hurdle remains in the lack of access to fertilizer by smallholder farmers. Poor agronomic practices (such as late sowing, weed competition, and suboptimal plant populations) reduce fertilizer use efficiency. Nevertheless, significant gains in maize yield (50–80%) can be achieved from open pollinated varieties and small inputs of fertilizer by smallholder farmers (Twomlow et al., 2008). Further modest gains are possible using improved maize varieties (Bänziger et al., 2000). However the African “green revolution” will need to be first a revolution based on improved soil fertility, albeit supplemented and reinforced by new germplasm development and agronomy for improved water management.

Despite what appears to be a strongly attractive technical opportunity to significantly raise yields on African smallholder farms, large-scale uptake and growth in fertilizer use remains painfully slow. Recently a major government intervention in Malawi provided support for fertilizer use and yields responded accordingly, but

institutional and budgetary challenges around such interventions do not confer confidence that they are sustainable (Ricker-Gilbert et al., 2009). The small but growing role of private and nongovernmental organization (NGO) sector networks in input/output markets holds promise for breaking the cycle of low inputs, low outputs, and food insecurity (Rusike and Dimes, 2004). Government policy needs to evolve to be supportive of this emerging sector and there is a role for the research and development community to consider how they will build the two-way information flows from research knowledge and technologies to application in a local context.

While the technical challenges around soil fertility in African smallholder agriculture are reasonably well defined by the work referenced above and other reports (World Bank, 2008), the solutions may lie outside the farm household at the level of input/output markets and the institutions governing them. In developed country agriculture, strategies to enable farmers to better understand and manage risks (in particular climate-related risks) associated with input use have been shown to greatly assist in this transition (Hochman et al., 2009b). In developing country agriculture, particularly in Africa, this pathway is more complex than simply improved knowledge supporting a farmer's decision to take on higher risks (Meinke et al., 2006). In many situations, the input/output markets are poorly developed or distorted to the point that even very modest inputs that could be highly effective have not been possible (Rohrbach, 1998). The emergence of private sector and/or NGO sector markets for agri-inputs and -outputs holds great promise for African smallholder agriculture to break out of the vicious cycle of soil-fertility-constrained low productivity.

### **Nitrogen Use in the United States and China**

Recent U.S. experience demonstrates that significant improvements in fertilizer use efficiency are possible. For U.S.-grown maize, the ratio of crop yield per unit of applied N fertilizer (i.e., the partial factor productivity for N fertilizer) has increased by 36%, from 42 kg kg<sup>-1</sup> in 1980 to 57 kg kg<sup>-1</sup> in 2000 (Cassman et al., 2002). The drivers of this improvement would appear to reside in the combination of continuing yield improvement through technological change and flat N fertilization rates since the concerns over environmental consequences of excess fertilizer use emerged in the 1980s. Such changes are clear evidence that agricultural research has continually created new efficiency frontiers (from D to F in Fig. 2).

In contrast in China, a problem of low eco-efficiency is generated through excess use of fertilizers, particularly N, on cereal crops, leading to heavy costs to the economy and environment (Liu and Diamond, 2005; Ju et al., 2009). The national average in N fertilizer use efficiency in China is around 20 kg kg<sup>-1</sup> N (Zhu and Chen, 2002; Ju et al., 2009).

From 1977 to 2005, grain production in China increased by 71% (from 283 to 484 million tonnes). Over this same period, N fertilizer application increased by 271% (from 7.07 to 26.21 million tonnes) (Ju et al., 2009) encouraged by strong policy support. This overuse of N fertilizer is further exacerbated by high levels of organic N inputs from the atmosphere, water supplies, animal manures, and legume sources. Nitrogen inputs from atmospheric and irrigation water sources in the range of 89 to 104 kg N ha<sup>-1</sup> yr<sup>-1</sup> have been measured in two study regions (Ju et al., 2009). Here, inefficiencies in system performance have widened the gap between farmer practice and the attainable efficiency frontier (between B and D in Fig. 2).

The excess N applied to cereals in China may be in the order of 11.8M tonnes. This figure is based on an average N rate of 250 kg N ha<sup>-1</sup>, a cereal cropping area of 104 M ha, and rates of overfertilization in the range of 30 to 60% (average 45% used in these estimates) (Ju et al., 2009). The solution to the overuse of N fertilizer in China might be a reform of fertilizer pricing policies or other institutional arrangements (OECD, 2003; Zhu et al., 2006). This appears to be an area under active policy review with the recent cessation of price controls on fertilizers, despite retention of production subsidies, and the expanded efforts to improve fertilizer use efficiency (The Economist, 2008).

It is sobering to reflect on the thought that if this "excess" N fertilizer used in China was instead used in sub-Saharan Africa, it represents an average annual N fertilization rate of 68 kg N ha<sup>-1</sup> over 174 million ha of cropland. If nutrients of this magnitude were available (and rebalanced to address other nutrient needs), the studies referenced above (McCown et al., 1992; Twomlow et al., 2008) would suggest a potential doubling of cereal production in sub-Saharan Africa. In other words, fertilizer use of this order could lay a very solid foundation for Africa's "green revolution." Of course there is no direct link between overfertilization in China and underfertilization in Africa, but the comparison places the African challenge in perspective. Modest fertilizer inputs, carefully targeted and matched with other soil enrichment strategies involving legumes and manure, are not beyond the realms of possibility for Africa.

### **Water Use in Australia**

In many environments, water supply is a major source of variability in crop yields (Ritchie, 1983). Total water use or total evapotranspiration by a crop can vary substantially due to variable soil water and rainfall. It can also vary as a result of variation in crop transpiration resulting from management such as nutrient supply (Shepherd et al., 1987) and sowing time (Connor et al., 1992) or from use of different species (Gregory et al., 1992) or cultivars (Richards and Townley-Smith, 1987). The seasonal water use of a crop consists of both crop transpiration and

soil evaporation (French and Schultz, 1984), with the latter varying between 14% (Angus et al., 1980) and 75% (Cooper et al., 1987) of total water use. The ratio between grain yield and evapotranspiration, the generally accepted definition of water use efficiency (WUE) for grain production, can be an important parameter defining the productivity of crops in water-limited environments (Fischer and Turner, 1978; Tanner and Sinclair, 1983).

In the dryland wheat systems of southern Australia, on-farm monitoring and systems simulation modeling have been effectively deployed to benchmark farms and fields relative to a rainfall-driven efficiency frontier (Hochman et al., 2009a; Carberry et al., 2009). The uniqueness of these studies lies in their effort to directly measure accurately the soil water resource available to commercially-managed crops and relate this to both actual crop performance and management.

Hochman et al. (2009a) measured the actual WUE (in kg grain ha<sup>-1</sup> mm<sup>-1</sup>) of 334 commercial wheat crops in Australia and compared their performance to the APSIM model (Keating et al., 2003). They found an average WUE of 15.2 kg grain ha<sup>-1</sup> mm<sup>-1</sup> for harvested crop yields while APSIM simulated a higher WUE of 16.9 kg grain ha<sup>-1</sup> mm<sup>-1</sup> for these same crops. The differential is attributed to factors influencing the actual crop that are not simulated by APSIM (e.g., weeds, pests, diseases, and impacts of severe weather). APSIM was used to explore if these crops could have achieved higher WUE through changed management, such as higher sowing rates, earlier sowing time, or high input levels. A maximum WUE of 21.4 kg grain ha<sup>-1</sup> mm<sup>-1</sup> is suggested as the potential WUE for this dataset of crops. Their study demonstrates opportunities for these farmers to improve WUE using two pathways of the stylized return-risk framework introduced earlier (Fig. 2). Clearly there is some opportunity to further close the average “yield gap” of 1.7 kg grain ha<sup>-1</sup> mm<sup>-1</sup> and move crop yields up onto the efficiency frontier by better controlling biotic stresses. And second, there are options for farmers to move along the efficiency frontier and increase WUE by 4.5 kg grain ha<sup>-1</sup> mm<sup>-1</sup> with a yield-maximizing strategy. In this latter case, each suggested intervention would require farmers to increase their investment risk either by increasing inputs (seed and/or fertilizer) or the chance of crop failure (sowing early increases the risk of frost damage during grain filling).

In fact, the study of Carberry et al. (2009) suggests that the better farmers in Australia are quite close to the efficiency frontier for crop yields and so are performing at their best for the level of investment risk they are willing to accept under current market circumstances. For over 700 commercial crops grown under a wide range of environmental and agronomic conditions from all cropping regions of Australia, APSIM simulations showed close agreement to measured commercial yields. This shows that the best

Australian farmers have a very low yield gap, and it appears that most of their crops are not seriously affected by yield-reducing factors such as weeds, pests, and diseases or poor agronomic management. This study suggested that the supply of water and N can account for most of the variation in crop yield, while farmers are mostly controlling other yield-limiting factors such as weeds and diseases. If true, then the only pathways for these farmers to increase production are either to move along the efficiency frontier (and so increase their investment risk) or to adopt new technologies that generate a new efficiency frontier.

## PATHWAYS TO IMPROVE ECO-EFFICIENCY

### Narrowing Yield Gaps

The term “yield gap” has often been used to describe the difference between actual yields recorded on farmer fields and the yields that are possible with known technologies and practices (identified via farm demonstration plots or a combination of on-farm experiments and simulation modeling). Yield gaps are pertinent to this discussion on eco-efficiency because they are indicative of the eco-inefficiency that persists in different food production systems of the world. One well-known study of rice yield gaps can be found in Evenson et al. (1996), which brought together a series of assessments of country and regional level constraints (as well as priority setting) for South and East Asia. Wheat yield gaps and production constraints have been documented by Kosina et al. (2007).

In terms of the simple input-output and return-risk frameworks, yield gaps would generally represent the difference between the current status and an improved situation (often the climate and genetic potential). They represent what is possible if farmers were operating on the eco-efficiency frontier and were insensitive to risk (point A in Fig. 2). Examples of yield gaps measured for maize cropping in Africa and for agricultural production more generally in various parts of the world are estimated to be in the 40 to 80% range (World Bank, 2008; Comprehensive Assessment of Water Management in Agriculture, 2007).

While yield gaps are generally large in Africa (and to a lesser degree South Asia), they have narrowed in other parts of the world such as China and in wheat and maize production areas of western Europe and North America (World Bank, 2008). The lack of inputs, in particular irrigation and nutrients, is the conspicuous explanation for the continuing large yield gaps in Africa (World Bank, 2008).

The World Development Report (World Bank, 2008) notes that exploitable yield gaps are especially high in medium- to high-potential areas and countries (i.e., in the higher rainfall areas of Africa) but that closing the gap is a matter not just of transferring known technologies and practices to farmers, but involves “*putting in place the*

*institutional structures—especially well-functioning input and output markets, access to finance, and ways to manage risks—that farmers need to adopt the technology”* (World Bank, 2008).

When viewing these remarks of the World Development Report on institutional arrangements, our return-risk framework suggests to explicitly install institutional mechanisms to deal with risk management and reduction both in agro-technical as well as socio-economic terms when aiming to close yield gaps.

## **Transformational Change**

Even the best farmers in a developed country context do not necessarily choose to operate at the point of maximum returns (i.e., point A in Fig. 2) because of the greater exposure to downside risk associated with the higher levels of investment. Under such circumstances, the only real option for these farmers to increase productivity is to break away from the current efficiency frontier by creating new production systems or practices that can increase returns for little added risk (i.e., moving from D to F in Fig. 2).

Transformational technologies that improve the efficiency of resource use will generate new frontiers of return relative to investment risk. Historically, the large step gains in agricultural productivity have resulted from an increased use of inorganic fertilizer inputs and the development of irrigation infrastructure on previously rain-fed cropping lands. Their introduction to local farming systems created new efficiency frontiers, and typically the following decades were needed for farmers to improve their practices in adapting irrigation and fertilizer technologies to approach these new productivity benchmarks (pathway B to D in Fig. 2). And as farmer practice improved, more sophisticated technologies could be introduced to continue the steady increases in the efficiency of nutrient and water use. For instance, fundamentally changing the way rice is grown can lead to drastic water savings. Among the promising new management practices are AWD (alternate wetting and drying, whereby the paddy is allowed to dry, but irrigation water is reapplied before water limitations start to impact on yields) and the aerobic rice systems, where specially developed rice varieties are grown in well-drained soil like dryland crops. This can save up to half of the normal water requirement, while with good management yields between 4 and 6 t ha<sup>-1</sup> can be routinely achieved (Bouman et al., 2005; Bindraban et al., 2006). Other examples include biodegradable mulches to restrict soil water loss from evaporation or weeds (Shogren, 2000), nitrification inhibitors to reduce fertilizer losses from leaching or denitrification (Shoji et al., 2001), removing subsoil constraints such as hard pans (Wong and Asseng, 2007), or ameliorating subsoil acidity (Tang et al., 2003).

Plant and animal breeding has been a traditional route for the creation of new efficiency frontiers in agriculture. Clearly, continued breeding effort is important for improved adaptation to current and future climates or enhanced resistance to biotic and abiotic stresses. Yet, for Africa, average yield gains of 60% are found with small inputs of fertilizer N used on open-pollinated varieties, compared to 20% gains from improved hybrid seeds (Twomlow et al., 2008). Both hybrid seed and small inputs of fertilizer N combine positively to raise the yield gains toward 80%, but these smallholder farming systems are most in need of strategies to improve soil fertility, not new plant varieties. Hence, breeding alone is unlikely to provide the transformational breakthrough required by the current low productivity, low eco-efficiency, and food insecure farming systems of the most food insecure part of the world, particularly in Africa (Twomlow et al., 2008). Hence, Meinke et al. (2009) call for “adaptation science” as a solution-oriented, scientific endeavor to facilitate adaptation actions. In contrast to conventional, disciplinary-based science, adaptation science analyses the problems in a broadly participatory mode without a predefined disciplinary lens. Adaptation science differs from science for adaptation by testing alternative solutions (often via simulation models) and developing adaptation pathways or processes as opposed to generating more data.

Gene technologies are often viewed as the source of the next generation of breakthrough innovations in agriculture. It is true that the genetically modified (GM) cotton story can be viewed as a breakthrough story in the developed world and increasingly in the developing world. In reviewing the literature on GM crops, Brookes and Barfoot (2005) reported yield increases as high as 50% for GM insect-resistant cotton in India and 10% for GM herbicide-tolerant canola in Canada. There were also a number of examples of no yield benefits, notably for GM herbicide-tolerant soybean in the United States and Argentina (Bindraban et al., 2009a) or for GM insect-resistant cotton in Australia (Brookes and Barfoot, 2005). Nevertheless, the proponents of GM crops actively promote such technology as yield frontier breaking and science should indeed be in pursuit of such outcomes.

## **ECO-EFFICIENCY AND CURRENT CHALLENGES**

### **Food Security**

Food security is defined as a state when “*all people, at all times, have physical and economic access to sufficient, safe and nutritious food for a healthy and active life*” (FAO, 2008). FAO (2008) have estimated that 923M people were undernourished in 2007—75M more than in 2005—highlighting the immediate food security challenge. Both supply and demand side perspectives are important.

The World Development Report (World Bank, 2008) estimated that cereal production will have to increase by nearly 50% and meat production by 85% from 2000 to 2030 to meet projected increases in food demand. Looking forward to 2050, this food security challenge will grow with a world population increase of approximately 35% (6.7 billion in 2008 to 9 billion in 2050). If population growth is the only force acting, an increase in food production of 35% over the next 40 yr can be expected. Economic development trajectories (including changes in diet preferences toward greater protein intake) combined with population growth suggest an increase in food demand of the order of 75% between 2010 and 2050. Nonfood uses of agricultural products and lands (such as for bio-fuels, carbon bio-sequestration, and urban development) are also growing. The demand from agriculture to supply the required amounts of biomass for bio-energy heavily depends on desired blending targets and can put a claim on many hundreds of millions of hectares of land (Bindra-ban et al., 2009b). While uncertainty is high, these forces together suggest a likely 75 to 100% increase in demand for agricultural products over the next 40 yr.

Significant production increases have been achieved in past years (e.g., Angus, 2001), but they came via a combination of increased deployment of natural resources (land, water, nutrients, and energy) and human resources (labor and capital) as well as via technological advances (varieties and agronomic practices). Globally, average yields have climbed steadily for all major cereals, at least since the 1960s (World Bank, 2008). Worryingly, the yield growth rate of wheat and rice has declined markedly since 1995 (Dixon et al., 2009). Since 1961, around 78% of the increase in production has come from increases in yields, except in Africa where about 60% of the gains have come from expanding the area of cultivation (based on Pardey et al., 2007). The yield expansion pathway of Asia contrasts dramatically with the area expansion pathway of Africa over the last 40 yr (World Bank, 2008).

The yield and production increases of the last 50 yr have been achieved with a significant cost to the natural resource base (degraded soils and ecosystem impacts) as well as the global atmosphere, that is, 31% of global greenhouse gas emissions can be attributed to agriculture and forestry (including land clearing; IPCC, 2007).

How will the world achieve the production challenge of the next 40 to 50 yr? There appears to be little alternative answer to this question other than via productivity gains—in other words, eco-efficiency gains in terms of the key natural resources of land, water, nutrients, and energy. Fischer et al. (2005) reported on the likely sources of growth in agricultural production over the 2000 to 2050 period and estimated only 7 to 12% of the projected growth in food production is likely to come from expansion in the areas of arable land. The dominant source of

production growth will need to come from intensification of agriculture, either through increased cropping intensity (13–15%) or, more significantly, yield increases (75–76%) (Fischer et al., 2005, 2007).

While yield gains dominate the future prospects for a secure world food system, the rates of gain in crop yields are slowing in developing countries (World Bank, 2008), although the same phenomenon is not apparent in U.S. maize yield data (Cassman et al., 2006).

## Climate Variability and Change

Under the current climate, agricultural production is already significantly affected by climate variability, especially in semiarid regions. Changes in climate variability with future climate change are still uncertain (Nicholls and Alexander, 2007), but rainfall variability typically increases as mean annual rainfall decreases (Nicholls and Wong, 1990). Improving the management of climate variability will have immediate benefits to improving eco-efficiency and could be a positive step toward adapting to climate change if the future climate becomes more variable (Meinke et al., 2007). For example, in water-limited environments, seasonal rainfall variability is one of the most important factors for fluctuations in agricultural production and risk. Perceptions about climatic risk and uncertainty of rainfall in the forthcoming season have led to the development of conservative, low-input management approaches, which aim to reduce the losses in poor rainfall seasons. However, such low-input approaches usually fail to capitalize on the upsides of climatic variability, that is, the good rainfall seasons (Meinke and Stone, 2005; Twomlow et al., 2008).

Crop models can assist to quantify the season- and site-specific outcomes of agricultural interventions (Matthews and Stephens, 2002; Whitbread et al., 2010) and, when integrated with long-term historical weather data, allow retrospective analysis of the potential value of climate forecasts for a particular decision issue (Meinke and Stone, 2005; Hansen, 2002). Forecasting systems linked with crop simulation models have been employed to establish optimized management strategies for improved risk management and enabled farmers to better tailor management decisions to the season and consequently improve eco-efficiency (Hammer et al., 1996; Hansen, 2005). Currently, global efforts to provide a much improved, continuous weather and climate service for agriculture and other climate sensitive sectors are expected to provide “actionable climate knowledge” for better tactical and strategic management of crops and cropping systems at interseasonal, seasonal, and decadal time scales.

Climate has changed significantly over the last century and proactively planned adaptation action is now imperative (Howden et al., 2007; Meinke et al., 2009; Wassmann et al., 2009). Faced with such complexity and uncertainty, it would appear the best strategy is to work

with the well-established efficiency constraints and test the diagnosis and solution pathways for resilience and continued relevance under a range of climate change scenarios.

## CONCLUSIONS

The term eco-efficiency has emerged relatively recently but efforts to increase the level of desired outputs from inputs of natural resources and human endeavor have characterized agriculture evolution for over 10,000 yr. What is new is the magnitude of the efficiency challenge global food systems are facing. The agricultural revolution over the next 40 yr has to be the eco-efficiency revolution, with 50 to 100% increases in the efficiency with which scarce resources of land, water, nutrients, and energy are used. Importantly, this greater output and efficiency has to be achieved without further greenhouse gases emissions while maintaining or restoring land, water, biodiversity, and agro-ecosystems.

Eco-efficiency is a “multi-factor” issue that—as shown by C.T de Wit from first principles—is maximized when all production factors approach their optimum (Law of the Optimum). However, in the case of Africa and in terms of the journey toward such optima, it is clear the critical first steps lie in getting small improvements in soil fertility in place and these first increments in fertility can produce both efficiency and production gains.

The imperative needs to be accompanied with mitigating measures to reduce risks associated with increased investments. Agricultural research is the engine for developing the technologies and practices that can lift eco-efficiency while keeping risks low by lifting the efficiency frontier. Social and economic systems and institutions are often the necessary “gears” whereby improved technologies and practices can be embedded with constant or declining production risks. Food security involves both closing the yield gap (particularly in Africa) and breakthrough technologies and practices to raise yield potential and increase efficiency of resource use. In terms of how agricultural research approaches these dual challenges, there is a critical role for more effective “systems diagnosis” of constraints and opportunities for technological and policy intervention. This need is more important than ever, given the poor adoption of existing technologies, the multiple impacts of climate change, and the decreasing availability of resources per person.

In this paper we have referred to examples where appropriately configured and validated simulation models, in conjunction with field experimentation and farmer engagement, have proven very useful in the diagnosis phase of research and development aimed at raising eco-efficiency in farming systems. Such approaches can be used to explore the likely nature of single and multifactor response surfaces and to explore opportunities for interventions including new farming practice, breeding strategies, and agricultural infrastructure and market policies.

## REFERENCES

- Anderson, J.R., J.L. Dillon, and J.B. Hardaker. 1977. *Agricultural Decision Analysis*. Iowa State Univ. Press, Ames, IA.
- Angus, J.F. 2001. Nitrogen supply and demand in Australian agriculture. *Aust. J. Exp. Agric.* 41:277–288.
- Angus, J.F., H.A. Nix, J.S. Russell, and J.E. Kruizinga. 1980. Water use, growth and yield of wheat in a sub-tropical environment. *Aust. J. Agric. Res.* 31:873–886.
- Asseng, S., N.C. Turner, and B.A. Keating. 2001. Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. *Plant Soil* 233:127–143.
- Baligar, V.C., N.K. Fageria, and Z.L. He. 2001. Nutrient use efficiency in plants. *Commun. Soil Sci. Plant Anal.* 32:921–950.
- Bänziger, M., G.O. Edmeades, D. Beck, and M. Bellon. 2000. Breeding for drought and nitrogen stress tolerance in maize: From theory to practice. CIMMYT, Mexico City, Mexico.
- Bindraban, P.S., A.C. Franke, D.O. Ferraro, C.M. Ghera, L.A.P. Lotz, A. Nepomuceno, M.J.M. Smulders, and C.C.M. van de Wiel. 2009a. GM-related sustainability: Impacts, risks and opportunities of soy production in Latin America. *Plant Res. Int. Rep.* 259. Plant Research International, Wageningen, The Netherlands.
- Bindraban, P.S., E. Bulte, and S. Conijn. 2009b. Can biofuels be sustainable by 2020? *Agric. Syst.* 101:197–199.
- Bindraban, P.S., H. Löffler, and R. Rabbinge. 2008. How to close the ever widening gap of Africa’s agriculture. *Int. J. Technol. Glob.* 4:276–295.
- Bindraban, P.S., H. Hengsdijk, W. Cao, Q. Shi, T.M. Thiyagarajan, W. Van der Krogt, and I.P. Wardana. 2006. Transforming inundated rice cultivation. *Water Resour. Dev.* 22:87–100.
- Bouman, B.A.M., S. Peng, A.R. Castañeda, and R.M. Visperas. 2005. Yield and water use of tropical aerobic rice systems. *Agric. Water Manage.* 74:87–105.
- Brookes, G., and P. Barfoot. 2005. GM crops: The global economic and environmental impact: the first nine years 1996–2004. *AgBioForum* 8:187–196.
- Carberry, P.S., Z. Hochman, J.R. Hunt, N.P. Dalgliesh, R.L. McCown, J.P.M. Whish, M.J. Robertson, M.A. Foale, P.L. Poulton, and H. van Rees. 2009. Re-inventing model-based decision support with Australian dryland farmers: 3. Relevance of APSIM to commercial crops. *Crop Pasture Sci.* 60:1044–1056.
- Cassman, K.G., A. Dobermann, and D. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31:132–140.
- Cassman, K., V. Eidman, and E. Simpson. 2006. Convergence of energy and agriculture: Implications for research and policy. CAST Report. Council for Agricultural Science and Technology, Ames, Iowa.
- Comprehensive Assessment of Water Management in Agriculture. 2007. *Water for food, water for life: A comprehensive assessment of water management*. International Water Management Institute, London, UK.
- CIAT. 2009. *CIAT strategic directions*. CIAT, Cali, Columbia.
- Connor, D.J., S. Theiveyanathan, and G.M. Rimmington. 1992. Development, growth, water-use and yield of a spring and a winter wheat in response to time of sowing. *Aust. J. Agric. Res.* 43:493–516.
- Cooper, P.J.M., P.J. Gregory, J.D.H. Keatinge, and S.C. Brown. 1987. Effects of fertilizer, variety and location on barley production under rainfed conditions in northern Syria. 2. *Soil*

- water dynamics and crop water use. *Field Crops Res.* 16:67–84.
- De Jager, A., D. Onduru, M.S. van Wijk, J. Vlaming, and G.N. Gachini. 2001. Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: A case study in Kenya. *Agric. Syst.* 69:99–118.
- de Wit, C.T. 1992. Resource use efficiency in agriculture. *Agric. Syst.* 40:125–151.
- Dillon, J.L. 1977. *An analysis of response in crop and livestock production* (2nd edition), Pergamon Press, Oxford, UK.
- Dimes, J., S. Twomlow, and P. Carberry. 2003. Application of APSIM in small holder farming systems in the semi-arid tropics. p. 85–99. *In* T. Bontkes and M. Wopereis (ed.) *Decision support tools for smallholder agriculture in sub-Saharan Africa: A practical guide*. International Center for Soil Fertility and Agricultural Development (IFDC), Muscle Shoals, AL, USA, and Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, The Netherlands.
- Dixon, J., H.-J. Braun, P. Kosina, and J. Crouch (ed.). 2009. *Wheat facts and futures – 2007*. CIMMYT, Mexico City, Mexico.
- Evenson, R.E., R.W. Herdt, and M. Hossain (ed.). 1996. *Rice research in Asia: Progress and priorities*. CABI Publ., Wallingford, UK.
- FAO. 2008. *The state of food insecurity in the developing world*. FAO, Rome.
- French, R.J., and J.E. Schultz. 1984. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Aust. J. Agric. Res.* 35:743–764.
- Fischer, G., M. Shah, F.N. Tubiello, and H. van Velhuizen. 2005. Socio-economic and climate change impacts on agriculture: An integrated assessment, 1990–2080. *Philos. Trans. R. Soc. B Biol. Sci.* 360:2067–2083.
- Fischer, G., F.N. Tubiello, H. van Velhuizen, and D.A. Wiberg. 2007. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technol. Forecast. Soc. Change* 74:1083–1107.
- Fischer, R.A., and N.C. Turner. 1978. Plant productivity in the arid and semiarid zones. *Annu. Rev. Plant Physiol.* 29:277–317.
- Giller, K.E., E.C. Rowe, N. de Ridder, and H. van Keulen. 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agric. Syst.* 88:8–27.
- Gregory, P.J., D. Tennant, and R.K. Belford. 1992. Root and shoot growth, and water and light use efficiency of barley and wheat crops grown on a shallow duplex soil in a Mediterranean-type environment. *Aust. J. Agric. Res.* 43:555–573.
- Groot, J.C.J., W.A.H. Rossing, A. Jellema, D.J. Stobbelaar, H. Renting, and M.K. van Ittersum. 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—A methodology to support discussions on land-use perspectives. *Agric. Ecosyst. Environ.* 120:58–69.
- Hammer, G.L., D.P. Holzworth, and R. Stone. 1996. The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability. *Aust. J. Agric. Res.* 47:717–737.
- Hansen, J.W. 2002. Realizing the potential benefits of climate prediction to agriculture: Issues, approaches, challenges. *Agric. Syst.* 74:309–330.
- Hansen, J.W. 2005. Integrating seasonal climate prediction and agricultural models for insights into agricultural practice. *Philos. Trans. R. Soc.* 360:2037–2047.
- Hochman, Z., D.P. Holzworth, and J.R. Hunt. 2009a. Potential to improve on-farm wheat yield and WUE in Australia. *Crop Pasture Sci.* 60:708–716.
- Hochman, Z., H. van Rees, P.S. Carberry, J.R. Hunt, R.L. McCown, A. Gartmann, D. Holzworth, S. van Rees, N.P. Dalgliesh, W. Long, A.S. Peake, P.L. Poulton, and T. McClelland. 2009b. Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. *Crop Pasture Sci.* 60:1057–1070.
- Howden, S.M., J.F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke. 2007. Adapting agriculture to climate change. *Proc. Natl. Acad. Sci. USA* 104:19691–19696.
- IPCC. 2007. *Intergovernmental Panel on Climate Change. Fourth Assessment Report*. Available at [http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4\\_syr\\_spm.pdf](http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf) (verified 23 Dec. 2009).
- Ju, X.T., G.X. Xing, X.P. Chen, S.L. Zhang, L.J. Zhang, X.J. Liu, Z.L. Cui, B. Yin, P. Christie, Z.L. Zhu, and F.S. Zhang. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl. Acad. Sci. USA* 106:3041–3046.
- Keating, B.A., D.C. Godwin, and J.M. Watiki. 1991. Optimizing nitrogen inputs in response to climatic risk. p. 329–358. *In* Muchow and J.A. Bellamy (ed.) *Climatic risk in crop production: Models and management for the Semiarid Tropics and Subtropics*. CABI Publ., Wallingford, UK.
- Keating, B.A., P.S. Carberry, G.L. Hammer, M.E. Probert, M.J. Robertson, D. Holzworth, N.I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J.P. Dimes, M. Silburn, E. Wang, S. Brown, K.L. Bristow, S. Asseng, S. Chapman, R.L. McCown, D.M. Freebairn, and C.J. Smith. 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18:267–288.
- Kosina, P., M.P. Reynolds, J. Dixon, and A. Joshi. 2007. Stakeholder perception of wheat production constraints, capacity building needs, and research partnerships in developing countries. *Euphytica* 157:475–483.
- Liu, J., and J. Diamond. 2005. China's environment in a globalizing world. *Nature* 435:1179–1186.
- Matthews, R.B., and W. Stephens. 2002. *Crop-soil simulation models: Applications in developing countries*. CABI Publ., Wallingford, UK.
- McCown, R.L., B.A. Keating, M.E. Probert, and R.K. Jones. 1992. Strategies for sustainable crop production in semi arid Africa. *Outlook Agric.* 21:21–31.
- McFarlane, D.J., and R.J. George. 1992. Factors affecting dryland salinity in two wheat belt catchments in western Australia. *Aust. J. Soil Res.* 30:85–100.
- Meinke, H., and R.C. Stone. 2005. Seasonal and inter-annual climate forecasting: The new tool for increasing preparedness to climate variability and change in agricultural planning and operations. *Clim. Change* 70:221–253.
- Meinke, H., R. Nelson, P. Kokic, R. Stone, R. Selvaraju, and W. Baethgen. 2006. Actionable climate knowledge – From analysis to synthesis. *Clim. Res.* 33:101–110.
- Meinke, H., M.V.K. Sivakumar, R.P. Motha, and R. Nelson. 2007. Preface: Climate predictions for better agricultural risk management. *Aust. J. Agric. Res.* 58:935–938.
- Meinke, H., S.M. Howden, P.C. Struik, R. Nelson, D. Rodriguez, and S.C. Chapman. 2009. Adaptation science for agricultural and natural resource management – Urgency and theoretical basis. *Curr. Opin. Environ. Sustain.* 1:69–76.
- Nicholls, N., and L. Alexander. 2007. Has the climate become

- more variable or extreme? Progress 1992–2006. *Prog. Phys. Geogr.* 31:77–87.
- Nicholls, N., and K.K. Wong. 1990. Dependence of rainfall variability on mean rainfall, latitude, and southern oscillation. *J. Clim.* 3:163–170.
- OECD. 2003. China in the world economy: An OECD statistical and economic survey. OECD Publ., Paris, France.
- Pardey, P., J. James, J. Alston, P. Glewwe, E. Binenbaum, T. Hurley, and S. Wood. 2007. Science, Technology and Skills. Background Paper for the World Development Report 2008. University of Minnesota, Minneapolis, MN.
- Parton, K.A., and P.S. Carberry. 1995. Stochastic efficiency and mean-standard deviation analysis: Some critical issues. *Aust. J. Agric. Res.* 46:1487–1491.
- Richards, R.A., and T.F. Townley-Smith. 1987. Variation in leaf area development and its effect on water use, yield and harvest index of droughted wheat. *Aust. J. Agric. Res.* 38:983–992.
- Ricker-Gilbert, J., T.S. Jayne, and J.R. Black. 2009. Does subsidizing fertilizer increase yields? Evidence from Malawi. Agricultural & Applied Economics Association 2009 AAEA & ACCI Joint Annual Meeting, 26–29 July 2009, Milwaukee, WI. Available at <http://ageconsearch.umn.edu/bitstream/49532/2/42422.pdf> (verified 23 Dec. 2009).
- Ritchie, J.T. 1983. Efficient water use in crop production: Discussion on the generality of relations between biomass production and evapotranspiration. p. 29–44. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI.
- Robertson, M.J., W. Sakala, T. Benson, and Z. Shamudzarira. 2005. Simulating response of maize to previous velvet bean (*Mucuna pruriens*) crop and nitrogen fertilizer in Malawi. *Field Crops Res.* 91:91–105.
- Rohrbach, D.D. 1998. Developing more practical fertility management recommendations. p. 237–244. *In* S.R. Waddington, H.K. Murwira, J.D.T. Kumwenda, D. Hikwa, and F. Tagwira (ed.) Soil fertility research for maize-based farming systems in Malawi and Zimbabwe. The Soil Fertility Network/CIM-MYT, Harare, Zimbabwe
- Rusike, J., and J.P. Dimes. 2004. Effecting change through private sector client services for smallholder farmers in Africa. *In* “New directions for a diverse planet” 4th International Crop Science Congress, 26 Sept.–1 Oct. 2004, Brisbane, Australia [CD-ROM]. Available at [http://www.cropscience.org.au/icsc2004/symposia/4/6/997\\_rusikej.htm](http://www.cropscience.org.au/icsc2004/symposia/4/6/997_rusikej.htm) (verified 23 Dec. 2009).
- Sanginga, N., and P.L. Woomer. 2009. Integrated soil fertility management in Africa: Principles, practices and developmental process. Tropical Soil Biology and Fertility Institute, CIAT, Nairobi, Kenya.
- Shepherd, K.D., P.J.M. Cooper, A.Y. Allan, D.S.H. Drennan, and J.D.H. Keatinge. 1987. Growth, water use and yield of barley in Mediterranean-type environments. *J. Agric. Sci. (Cambridge)* 108:365–378.
- Shogren, R.L. 2000. Biodegradable mulches from renewable resources. *J. Sustain. Agric.* 16:33–47.
- Shoji, S., J. Delgado, A. Mosier, and Y. Miura. 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. *Commun. Soil Sci. Plant Anal.* 32:1051–1070.
- Sinclair, T.R., and R.C. Muchow. 1999. Radiation use efficiency. *Adv. Agron.* 65:215–265.
- Sinclair, T.R., C.B. Tanner, and J.M. Bennett. 1984. Water-use efficiency in crop production. *Bioscience* 34:36–40.
- Tang, C., S. Asseng, E. Diatloff, and Z. Rengel. 2003. Modelling yield losses of aluminium-resistant and aluminium-sensitive wheat due to subsurface soil acidity: Effects of rainfall, liming and nitrogen application. *Plant Soil* 254:349–360.
- Tang, C., C. Raphael, Z. Rengel, and J.W. Bowden. 2000. Understanding subsoil acidification: Effect of nitrogen transformation and nitrate leaching. *Aust. J. Soil Res.* 38:837–849.
- Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? p. 1–27. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI.
- The Economist. 2008. China ends fertilizer price controls. Available at <http://www.rsc.org/chemistryworld/Issues/2009/March/ChinaEndsFertiliserPriceControls.asp> (verified 23 Dec. 2009).
- Tilman, D., J. Fargione, B. Wolff, C. D’Antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. *Science* 292:281–284.
- Twomlow, S., D. Rohrbach, J. Dimes, J. Rusike, W. Mupangwa, B. Ncube, L. Hove, M. Moyo, N. Mashingaidze, and P. Mahposa. 2008. Micro-dosing as a pathway to Africa’s Green Revolution: Evidence from broad-scale on-farm trials. *Nutr. Cycling Agroecosyst.* 10.1007/s10705–008–9200–4.
- Wassmann, R., S.V.K. Jagadish, K. Sumfleth, H. Pathak, G. Howell, A. Ismail, R. Serraj, E. Redona, R.K. Singh, and S. Heuer. 2009. Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. *Adv. Agron.* 102:91–133.
- Whitbread, A., M. Robertson, P. Carberry, and J. Dimes. 2010. Applying farming systems simulation to the development of more sustainable smallholder farming systems in Southern Africa. *Eur. J. Agron.* 32:51–58.
- World Bank. 2008. World Development Report 2008: Agriculture for Development. The World Bank, Washington, DC.
- World Business Council for Sustainable Development. 2000. Eco-efficiency—Creating more value with less impact. WBCSD. Earthprint, Hertfordshire, UK. Available at [http://www.wbcscd.org/web/publications/eco\\_efficiency\\_creating\\_more\\_value.pdf](http://www.wbcscd.org/web/publications/eco_efficiency_creating_more_value.pdf) (verified 23 Dec. 2009).
- Wong, M.T.F., and S. Asseng. 2007. Yield and environmental benefits of ameliorating subsoil constraints under variable rainfall in a Mediterranean environment. *Plant Soil* 297:29–42.
- Zhu, Z.L., and D.L. Chen. 2002. Nitrogen fertilizer use in China – Contributions to food production, impacts on the environment and best management strategies. *Nutr. Cycling Agroecosyst.* 63:117–127.
- Zhu, Z.L., D. Norse, and B. Sun. 2006. Policy for reducing non-point source pollution from crop production in China. p. 135–299. China Env. Sci. Press, Beijing, China.