CHAPTER

1

Resource Use Efficiency Revisited

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Contents

Abstract

The notion of "eco-efficiency" can provide a solid basis for developing a conceptual understanding of rational and effective use of resources in agriculture and a set of tools to move us toward these objectives. It will not, however, be the magic bullet to solve the overuse of resources in agriculture. A wide range of concepts and approaches need to come together if we are to succeed in solving this problem. Both high-input intensive agriculture and low-input agriculture need to evolve based on agroecological principles. In broad terms, high-input agriculture should aim at becoming more eco-efficient, and low-input agriculture needs to increase in productivity while retaining high efficiency of input use.

This chapter looks at eco-efficiency from a perspective of experiences and lessons in resource use, research for development, climate change adaptation and mitigation, policies and incentives, and social equity and gender. The narrative: (1) points out the key roles of research and potential research breakthroughs to alleviate food shortages in the future; (2) suggests following the path of "resource use efficiency" in terms of strategies and management practices; (3) suggests the need for changes in land use; and (4) indicates the importance of investing in gender equity as a means to improve food production and food security and achieve greater social equity.

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Background and Historical Perspective

> *In the long run the planet has the upper hand. In the short run humans act as if they do and as if this will continue to be the case (Hall, 2008)*

The concept of "eco-efficiency" originates from the field of natural resources research. However, in this chapter, while giving particular attention to natural resources, we adopt the more inclusive description used by CIAT and elaborated in its Medium-Term Plan 2010-2012, p.3. This states the following:

> "Eco-efficient agriculture increases productivity while reducing environmental impacts. Eco-efficient agriculture meets economic, social, and environmental needs of the rural poor by being profitable, competitive, sustainable, and resilient. It harmonizes the economic, environmental, and social elements of development, and strives toward solutions that are competitive and profitable, sustainable, and resilient, and generate benefits for the poor. Eco-efficient agriculture cannot effectively address the needs of the poor without taking into account the particular needs of women."

This definition follows suggestions of authors such as Park et al. (2010) to explicitly include social criteria as well as economic and environmental criteria in order to improve rates of uptake of eco-efficiency technologies, to promote practices that improve the effectiveness of hunger-reduction efforts, and to minimize environmental degradation. Chapter 2 of this volume goes into detail on conceptual foundations and frameworks for eco-efficiency.

The seminal work of Meadows et al. (1972)—*The limits to growth*—impacted academia and society at large, although perhaps not so much the political process. Using what was then an advanced model of interactions between human population, industrial growth, food production, and ecosystems—World3—the authors warned that growth without limits would have serious consequences on earth's finite resources. Twenty years later the authors followed up with another significant piece, *Beyond the limits* (Meadows et al., 1992), in which they argued that humans were overshooting the capacity and availability of earth's resources. This research sparked, and has become a cornerstone of, the intense debate on sustainable development. More recently, *Limits to growth: The 30-year update* (Meadows et al., 2004) attempted once more to provide data and make a compelling case for a significant debate and urgent actions to limit and to make rational use of scarce resources.

The experiences and lessons learned from the Green Revolution of the 1960s and beyond point to significant trade-offs in resource use. While there were ample benefits from targeted plant breeding and the application of external inputs in terms of increased productivity, income, and food production, this strategy placed significant pressures on natural resources and the environment.

During the last 4 decades recognition of unsustainable resource use and the increasing concerns expressed by producers, consumers, and civil society have prompted the development and testing of approaches to optimize resource use, such as minimum tillage, precision agriculture, plant breeding for input use efficiency (water, nitrogen), marker-assisted breeding, and transgenic crops and animals. This volume highlights a number of these accomplishments as well as related experiences and lessons learned.

Despite the advances in agricultural productivity, wasteful and contaminating systems continue to coexist with eco-efficiency-based approaches. Population growth, market forces, productivity levels, and incentives all impact on the balance between positive and negative forces driving agricultural innovation. Policies and incentives at the local, national, and international levels exert a strong influence on outputs and outcomes.

We need to consider eco-efficiency beyond the farm, crop, or animal enterprise level, and extend the concepts to include the whole food chain. This will include the full life cycle of inputs to the farm and products leaving the farm, i.e., nutrient and energy flows that include transport and processing.

While there are great opportunities for increasing eco-efficiency by adoption of mixed farming systems, particularly those involving both crops and livestock, the trend, particularly in developed countries, has been for increased specialization and separation of crop and livestock enterprises. Increasingly there may also be market opportunities based on consumer preferences for products from eco-efficient systems. Currently the proportion of food marketed as being from such systems is very small.

Several authors (Pimentel et al., 2005; Hobbs et al., 2008; Horrigan et al., 2002) have made the case for moving high-input agriculture toward greater sustainability. The arguments for this include the beneficial effects of high levels of soil organic matter, which help conserve soil and water resources and are particularly beneficial during drought years; the unsustainability of current levels of use of fossil fuels, water, and topsoil; and the documented benefits to both the environment and productivity of direct seeding, conservation tillage, integrated systems, bed planting, and mulching.

Ultimately, there will not be a simple, single solution to increasing the eco-efficiency of agriculture. There are practical advantages for intensive agriculture and low-input agriculture to each adapt and adopt the best practices of the other. High-input agriculture should aim at becoming more eco-efficient, and low-input agriculture needs to aim at higher productivity, often based on more intensive practices. To meet the growing demands for food, feed, fiber, and fuels from agriculture in the long term, this combination of higher productivity and sustainability through eco-efficient practices is imperative.

The Need for Eco-Efficiency in Agriculture

The question "why worry about producing more food?" needs to be considered from several angles.

First is how much we are currently producing. Despite constraints in water availability, land, and fertilizers (particularly nitrogen), the world should be able to feed itself. According to *The Economist* (2011), allowing for the staggering amounts of food wasted and all the food that could be eaten but is instead turned into biofuels, farmers are producing much more food than is required—more than twice the minimum nutritional needs of about 2100 calories a day.

The Food and Agriculture Organization of the United Nations (FAO) estimated that we need to increase food supplies by 70% by 2050 if we are to feed a population of 9 billion (FAO, 2009). This is a major challenge, and even more so with the constraints of available water, land, and fertilizer.

Currently, every 9 months we consume what the planet's ecology can provide sustainably in any given year (Global Footprint Network, 2011). From that point until the end of the year, we meet our ecological demand by liquidating resource stocks and accumulating CO_2 in the atmosphere. This cannot continue.

Another way to visualize this imbalance in resource use is humanity's ecological footprint. The *Living planet report 2010* (WWF, 2010) reveals that this footprint has more than doubled since 1966. In 2007, the most recent year for which data are available, humanity used the equivalent of 1.5 planet earths to support its activities. Even with modest United Nations (UN) projections for population growth, consumption patterns, and climate change, humanity will need the capacity of two earths by 2030 to absorb CO_2 waste and keep up with natural resource consumption. The report illustrates the scope of the challenges humanity faces, not only for preserving biodiversity, but also for halting climate change and meeting basic human development aspirations, such as reducing worldwide hunger and poverty.

The increased food insecurity and vulnerability of a large number of people worldwide point to a broken food production and distribution system. We need to look at the contribution agriculture should make not only to feed a growing population but also to impact less on the planet's resources. The future food supply equation needs to consider the current reality of lower growth rates for major crop yields in conventional agriculture, eco-efficient approaches to diminish impacts on natural resources, the climate change challenge, and the volatility of energy prices. Intensive, oil-dependent agriculture is reaching worrisome yield plateaus and water tables keep decreasing.

The world needs a new paradigm for the ways that we use natural resources—a new set of tools and policies. Should we eat less? Should we eat smarter (e.g., less protein of animal origin, with its high demands for energy, land, and water)? Should we create incentives to use fewer resources and implement legal directives to push for eco-efficiency? Should we put in place measures to control population growth? Pimentel et al. (2008) demonstrate that use of fossil energy in the United States' food system could be reduced by about 50% if appropriate technologies were adopted in food production, processing, packaging, transportation, and consumption.

Higher Productivity with Lower Negative Impact

Agricultural productivity must increase if we are to meet the increasing demands of a growing and more affluent population for food, feed, fiber, and fuels in the context of limited land available for expansion of agriculture (Hubert et al., 2010). Humans have always attempted to raise the efficiency of agroecosystems, aiming to harvest more per unit of input, mainly water, nutrients, energy, or agrobiodiversity (see Chapter 2 of this volume). Efforts to increase productivity should therefore consider crop breeding (particularly for maximizing input use efficiency and for host plant resistance for reducing pesticide use), eco-friendly husbandry, and the sustainable use of natural resources (especially agrobiodiversity), while enhancing ecosystem services. This volume explores many ways that this can be accomplished.

Sustainable intensification of agriculture should reduce the need to expand into environmentally vulnerable areas, thereby sparing some lands from further degradation by concentrating production in others. However, the result of this approach is not always clear cut. Rudel et al. (2009) analyzed trends in area planted to 10 major crops between 1970 and 2005, with particular emphasis on the 1990–2005 period. The data suggest that agricultural intensification was not often accompanied by decline or even stasis in cultivated area on a national scale, except in countries that imported grain and implemented conservation set-aside programs. Thus, policies and innovations aimed at increasing land use efficiency must be carefully designed and monitored to assure they have the desired impact, rather than leading to uncontrolled land use expansion (Lambin and Meyfroidt, 2011).

Humans face the challenge of managing trade-offs between immediate needs and maintaining the capacity of the biosphere to provide goods and services in the long term (Foley et al., 2005). Policy measures are needed that provide incentives for development and adoption of more diverse, eco-efficient farming; such measures include premium prices for products from eco-efficient systems, and price supports for the provision of their environmental services. Innovative education is needed on whole-system approaches that feature resource-use efficiency and resilient farming systems to train a new generation of practitioners whose main aim will be ensuring productivity, profitability, and security of food value chains (Francis et al., 2011).

There are numerous approaches for increasing agricultural productivity using eco-efficient production systems. For example, integrating livestock, crops, and forestry systems can lead to higher productivity and lower negative impact. In such integrated systems, livestock are reared mostly on grass, browse on nonfood biomass from maize, millets, rice, and sorghum and in turn supply manure and traction (Herrero et al., 2010). Wilkins (2008) argues that eco-efficiency can be increased either by altering the management of individual crop and livestock enterprises or by altering the land use system, for example by adopting mixed crop-livestock systems that incorporate biological nitrogen fixation and use of manure as fertilizer. Combining intensification, better integration of animal manure in crop production, and matching nitrogen and phosphorous supply to livestock requirements can effectively improve nutrient flows (Bouwman et al., 2011). Furthermore, a shift in human diets (e.g., poultry or pork replacing beef) can reduce nutrient use in countries with intensive ruminant production.

Implications of Major Land Use Changes, Scale of Production, Biofuels, and Global Farmland

Land use changes

Land use changes impact the quality and availability of soils, water, and biodiversity. Globally, croplands, pastures, plantations, and urban areas have expanded in recent decades, accompanied by large increases in energy, water, and fertilizer consumption, and significant losses of biodiversity (Foley et al., 2005). These changes can also lead to changes in atmospheric concentration of CO_2, and may therefore be a contributor to climate change (see discussion below).

As noted by Lambin and Meyfroidt (2011), Bhutan, Chile, China, Costa Rica, El Salvador, India, and Vietnam managed to increase both agricultural production and the area of forests in their territories. In doing this, they relied on various mixes of agricultural intensification, land use zoning, forest protection, increased reliance on imported food and wood products, creation of off-farm jobs, foreign capital investments, and remittances. The authors conclude that sound policies and innovations can, therefore, reconcile forest preservation with food production.

According to FAO (1993), there is an increasingly urgent need to match land types and land uses in the most rational way possible, so as to maximize sustainable production and satisfy the diverse needs of society while at the same time conserving fragile ecosystems and our genetic heritage. Land use planning is fundamental to this process. It is a basic component, whether we are considering mountain ecosystems, savannas, or coastal zones, and underlies the development and conservation of forestry, range, inland, and coastal resources (FAO, 1993). For example, land use allocation has contributed to protecting the Peruvian Amazon, in spite of recent increases in disturbance and deforestation rates (Oliveira et al., 2007). Likewise, protection of productive agricultural land has become a major priority in many regions of the world. Overgrazing and intensive agriculture on marginal lands are a major driver of land loss through degradation. Policies are in place in many countries to avoid this loss of production, but their effectiveness in the face of economic demand is often limited (Ellis and Pontious, 2010).

Scale of production

The assumption that large-scale mechanized agriculture is more productive and efficient than small, family farms may be influencing agricultural development policy around the world. In several continents, developing countries are moving toward large-scale, corporate farming as a way to boost production and jump-start agricultural development (Landesa, 2011).

In the case of Canada, Maynard and Nault (2005) propose to maintain both big and small farms, given the current situation where 2% of farms produce 35% of the food. The authors propose overall strategies to keep and expand the number of small enterprises, for example, maintaining vibrant rural communities, investing in research and extension, and implementing incentives, regulations, and indicators. Current regulations are not properly differentiated and tend to favor big farms. They also examine the term “sustainability” in the context of big and small farms and find that conclusions are difficult, as the term is open to multiple interpretations. The daily reality of farming asks the questions of tradeoffs between sustainability and profitability.

Biofuels

The debate about the costs and benefits of biofuels (economically and environmentally) now focuses squarely on whether their use causes too much conversion of natural lands into crop and livestock production around the world. According to Babcock (2009), "the worry is that the loss of carbon stocks on the converted land would more than offset the direct reduction in greenhouse gas emissions caused by lower gasoline use. The California Air Resources Board has concluded that corn ethanol causes such large amounts of land conversion that it does not qualify as a low-carbon fuel. In its recent analysis of greenhouse gas emissions from biofuels, the U.S. Environmental Protection Agency estimates that corn ethanol and biodiesel made from soybean oil cause enough land use changes to call into question whether these biofuels meet required greenhouse gas reductions."

New technology, crop management changes, and renewable energy are playing important roles in increasing the energy efficiency of agriculture and reducing its reliance of fossil resources (Woods et al., 2010). Alternative renewable energy sources also bring diverse opportunities and challenges, such as how to integrate potential biofuel markets, deal with impacts on food security, alleviate poverty, and manage crop and natural resources sustainably (FAO, 2010). The agricultural systems used to produce feedstock for biofuels must use biomass sustainably, and partition it among energy, feed, food, and CO_2 fixation demands (Tilman et al., 2009). Hill et al. (2006) indicate that biofuels produced from low-input biomass plants grown on marginal land or from waste biomass, could provide much greater supplies and environmental benefits than staple food-based biofuels. Appropriate life-cycle analysis will therefore be needed to determine the use of land resources and estimate net carbon emissions of each suggested renewable energy technology (Vonblottnitz and Curran, 2007).

Global farmland

There has been a dramatic rise in interest of investors in acquiring farmland, particularly in Africa, as a result of the escalating food prices at the end of the first decade of the 21st century. The focus of this interest has largely been on land with agricultural potential that is either uncultivated or producing less than its potential. This food crisis pointed to new players, challenges, and perhaps some opportunities associated with land use changes. This phenomenal development, if considered by the sheer size of the lands being acquired (some 56 million hectares in 2009), has prompted specific proposals on the ethics and principles that should be applied by all interested parties (Deininger et al., 2011). Three key principles that are closely related to the issue of land use change are:

- *Respecting land and resource rights.* Existing rights to land and associated natural resources should be recognized and respected.
- *Responsible agro-investing.* Investors should ensure that projects respect the rule of law, reflect industry best practice, are economically viable, and result in durable shared value.
- *Environmental sustainability.* Environmental impacts of a project should be quantified and measures taken to encourage sustainable resource use while minimizing and mitigating the risk and magnitude of negative impacts.

A recent report from the World Bank (2009) examines commercial agriculture in the Guinea savanna and elsewhere in Africa. The report claims that African agriculture continues to lag, as reflected in the decline in international competitiveness of many traditional African export crops during the past 30 years, as well as in the competitiveness of some food crops for which import dependence has increased. In contrast, over the same period two agricultural regions in the developing world have shown the way—the Cerrado region of Brazil (see Chapter 4 of this volume) and the Northeast Region of Thailand. Both have developed at a rapid pace and conquered important world markets. Their success defied the predictions of many skeptics, who had asserted that the two regions' challenging agroecological characteristics, remote locations, and high levels of poverty would prove impossible to overcome.

Two recent developments have led to a change in thinking about the potential of African agriculture (The World Bank, 2009). First, during the past decade, strong agricultural growth has been recorded in many African countries, suggesting that the sector can indeed be a driver of growth when the conditions are right. Second, the steep rise in prices of food and agricultural commodities that occurred in 2008 has led to a realization that new opportunities may be opening for countries that are endowed with the land, labor, and other resources needed to respond to the growing demand for food.

Climate Change Adaptation and Mitigation

Although there may be a large regional variability, models suggest that changes in temperature and precipitation patterns due to climate change and increasing concentrations of atmospheric CO_2 will significantly affect agroecosystems and yields (Battisti and Naylor, 2009; Lobell and Field, 2007), reducing food availability and thereby jeopardizing food security and farm incomes (Lobell et al. 2008) (see also Chapter 3 of this volume). There will be shifts of plant distributions because some species will expand into newly favorable areas and others will decline in increasingly adverse locations. Climate change may increase global timber production as a result of changes of forestry locations (shifting from low-latitude regions in the short term to high-latitude regions in the long term as climate changes), whereas demand for forest products will rise slightly (Kirilenko and Sedjo, 2007).

Agriculture contributes to carbon emissions through the direct use of fossil fuels in farming, the indirect use of energy in inputs that are energy-intensive to manufacture (e.g., fertilizers), and the cultivation of soils resulting in the loss of soil organic matter (Pretty and Ball, 2001). Agricultural management explains historic changes in regional soil carbon stocks. Agriculture is also a major contributor of atmospheric nitrous oxide (N_2O), a potent greenhouse gas (GHG) commonly generated by the use of manure or nitrogen (N) fertilizers. In intensive wheat-cropping systems, common N fertilizer practices may lead to high fluxes of N_2O and NO (nitric oxide). Several groups of heterotrophic bacteria use NO_3^- as a source of energy by converting it to the gaseous forms N_2, NO, and NO_2. N_2O is therefore often unavailable for crop uptake or utilization.

Land use change contributes considerably to increases in atmospheric CO_2. The IPCC (2007) estimates the land use change (e.g., conversion of forest to agricultural land) contributes 1.6 ± 0.8 gigatons of carbon per year to the atmosphere, compared with 6.3 ± 0.6 gigatons of carbon from fossil fuel combustion and cement production.

The total biomass carbon stock of tropical forests is estimated to be 247 gigatons, with 193 gigatons stored above ground and 54 gigatons stored below ground in roots. Latin American, sub-Saharan African, and Southeast Asian forests account for 49, 25, and 26% of the total stock, respectively (Saatchi et al., 2011). Deforestation and degradation of tropical forests accounted for 12 to 20% of global anthropogenic GHG emissions in the 1990s and early 2000s. Reducing deforestation and forest degradation would thus both reduce GHG emissions and increase the potential of forests to remove additional carbon from the atmosphere.

Expansion of cattle ranching has been identified as a major cause of deforestation and a major contributor to CO_2 emissions (see Chapter 10 of this volume). The carbon footprint of beef produced on newly deforested land in the Amazon exceeds 700 kg CO_2 equivalents per kilogram of carcass weight if direct land use emissions are annualized over 20 years (Cederberg et al., 2011). Enteric fermentation is also a major contributor to GHG emissions, particularly in the developing world, which accounts for almost three-quarters of such emissions (Thorpe, 2009). Intensive ruminant-based meat production systems consume large amounts of high-value feed but suffer from low feed conversion rates and long reproductive intervals, making them inefficient users of resources. Changing from ruminants to monogastrics could significantly reduce the contribution of livestock to GHG production (Steinfeld and Gerber, 2010).

Eco-Efficient Practices to Resolve Land Use and Climate Change Challenges

Adoption of eco-efficient practices would contribute immensely to solving land use and climate change challenges noted in the previous sections. Agriculture can sequester carbon when organic matter is built up in the soil or when above-ground woody biomass acts either as a permanent sink or is used as an energy source that substitutes fossil fuels. The mitigation effects of adoption of improved pastures, intensifying ruminant diets, changes in land use practices, and changing breeds of large ruminants could account for 4 to 7% of the global agricultural mitigation potential to 2030, or US$1.3 billion per year at a price of US$20/t of CO_2 equivalents (Thornton and Herrero, 2010).

Expanding cropland onto areas under natural ecosystems reduces carbon stocks in natural vegetation and soils, with the amount of carbon released and crop yields differing markedly between temperate regions and the tropics (West et al., 2010): for each unit of land cleared, land in the tropics releases nearly twice as much carbon (~120 t/ha vs. ~63 t/ha) and produces less than half the annual crop yield as land in temperate regions (1.71 t/ha per year vs. 3.84 t/ha per year). However, high-input industrialized agriculture uses far more energy, in the form of nitrogen fertilizers, pumped irrigation, and mechanical power, than does low-input, sustainable agriculture, making it less energy efficient. Production of 1 ton of cereals or vegetables from high-input farming consumes 3000–10,000 MJ of energy, compared with only 500–1000 MJ using sustainable farming practices (Pretty and Ball, 2001).

Van Wesemael et al. (2010) studied changes in soil organic carbon (SOC) stocks in soils in Belgium between 1960 and 2006, and found a large reduction in SOC in grassland soils that had been drained after 1960, and large gains in croplands in sandy lowland soils due to manure additions.

Cassman (1999) indicates that precise management and improvements in soil quality are needed to achieve high yields without causing environmental damage. Conservation agriculture, green manures, and cover crops contribute to organic matter and carbon accumulation in the soil, physically protect the soil from the action of sun, rain, and wind, and help feed soil biota. No-tillage systems result in accumulation of 0.3–0.6 t C/ha per year, but no-tillage combined with rotations and cover crops may double the amount of carbon accumulated, to 0.66–1.3 t C/ha per year (Pretty and Ball, 2001).

No-tillage has revolutionized agricultural systems because it allows individual producers to manage larger amounts of land with fewer inputs of energy, labor, and machinery (Tripplet and Dick, 2008). Lal (2010) points out that not all conservation agriculture practices and other resource conservation technologies are applicable across all farming systems. However, he reports that increasing SOC in the root zone can increase grain yields (kg/ha per ton of C) of bean (30–60), maize (200–300), rice (20–50), soybean (20–50), and wheat (20–40). Such increases in SOC also improve soil quality, increase eco-efficiency, and enhance ecosystem services. Such soil sinks must become permanent if they are to contribute to mitigating climate change; if lands under conservation agriculture are ploughed all the gains in soil carbon and organic matter would be lost.

Using the correct amount and timing of N application can halve NO_2 emissions in intensive irrigated agroecosystems without significantly affecting crop yields (Ruan and Johnson, 1999). Using a handheld optical sensor that calculates the normalized differential vegetation index (NDVI), thereby assessing yield potential as plants grow, can reduce unnecessary N-fertilizer inputs, saving farmers money and protecting the environment by reducing trace gas emissions.

Some plants produce chemicals that inhibit nitrification in the soil, reducing loss of fertilizer N (Fillery, 2007). This ability, which is referred to as biological nitrification inhibition or BNI (Subbarao et al., 2006), seems to vary widely among and within species, and appears likely to be a widespread phenomenon in tropical pasture grasses (Subbarao et al., 2007).

Nitrification inhibition enhances agroecosystem fertility in a sustainable way, especially under high nitrate leaching and denitrification fluxes, which may account for the ecological advantage of African grasses over indigenous grasses in South American pastures (Boudsocq et al., 2009). These deep-rooted grasses (e.g., *Brachiaria humidicola*) also sequester significant amounts of organic carbon deep in the soil and help offset anthropogenic CO_2 emissions (Fisher et al., 1994). *Brachiaria humidicola,* an African forage grass found from southern Sudan and Ethiopia in the north to South Africa and Namibia in the south, shows particularly high BNI capacity (Ishikawa et al., 2003; Subbarao et al., 2009).

Local agrobiodiversity will be an important coping mechanism for climate change, especially for the most vulnerable people (Ortiz, 2011a). Agro-silvo-pastoral systems can also be designed to optimize agrobiodiversity and attain production benefits without adding pressure to convert natural habitat to farmland (Ortiz, 2011b; see also Chapter 4 of this volume). However, in some areas locally available agrobiodiversity may not able to adapt quickly to changing conditions, and therefore new crop cultivars, livestock breeds, or other species better suited to the new environments will be needed to cope with climate change.

Nitrogen use efficiency (NUE) of agricultural systems can be increased by growing plant species or genotypes with high N uptake and utilization abilities (Fageria and Baligar, 2005). Whole-plant physiology, quantitative genetics, and forward- and reverse-genetics approaches are providing a better understanding of the physiological and molecular controls of N assimilation in crops under varying environments (Hirel et al., 2007). Crops are being bred for NUE because this trait will be a key factor in reducing N fertilizer pollution and increasing yields in N-limiting environments.

Besides sophisticated approaches to make photosynthesis more efficient, a number of already well-developed biotechnologies such as plant micropropagation, virus-free planting materials, molecular diagnostics of plant and livestock diseases, and molecular markers to identify superior lines and populations in conventional breeding operations must continue to be improved and disseminated, particularly in those countries with limited research infrastructure and low rates of adoption. Production of genetically modified organisms (GMOs), undoubtedly the most controversial approach of the new biotechnologies, holds significant promise for contributing to eco-efficient agriculture, but there is an urgent need to focus investment on the needs of the poor (The World Bank, 2008). This is likely to require increased public investment in these technologies. It will also be necessary to increase the capacity to evaluate the risks and regulate these technologies in ways that are cost effective and inspire public confidence in them.

However, conventional breeding, benefitting from techniques such as marker-assisted selection, is likely to be at the center of agricultural developments in the immediate future. Unfortunately, the number of plant and livestock breeders continues to decline. This will affect our capacity to improve crops and animals in the future, and urgent measures are needed to reverse this trend.

Policies, Capacity Building, and Capitalizing on Market Forces

Eco-efficient agriculture will only be adopted and implemented if conducive policies and incentives are in place. This will require that lessons be learned from prior experiences, alignment with market forces, clear communication and engagement with public opinion, development of public-private partnerships, and strong leadership.

Any eco-efficiency approach must recognize and exploit the impact of multidimensional economic, environmental, and social interactions on the four components of the food system, i.e., availability, utilization, accessibility, and stability (Park et al., 2009). Failing to do so will impede uptake of adaptation and efficiency strategies.

There is an urgent need to intensify, diversify, and integrate production systems to achieve eco-efficiency, but this will require more than just technical solutions. A new vision, combined with policies and incentives, needs to be part of the mix. Reverting to mixed farming will not be easy (Wilkins, 2008). Persuading farmers to do so will require evidence of clear economic advantages from linking crop and livestock systems, cost-effective ways of handling and incorporating animal manures, and systems that are managerially simple to operate. It may also require conducive policies and support payments. For example, the European Union's Nitrate Directive and the Water Framework Directive, by limiting inputs, have provided a very direct incentive for the adoption of eco-efficient practices, while support payments have promoted conversion of land to organic farming and maintenance of organic systems (Wilkins, 2008).

The food requirements of the expected population levels in 2050 cannot be met exclusively by the intensive agriculture of today, simply because the natural resource base would either collapse or be placed under very severe stress. Likewise, less input-intensive, agroecological approaches—in particular integrated livestock, crop, and tree systems—could not be utilized everywhere due to limitations in labor, land, water, markets, and infrastructure. Technology, innovation, and policies are essential components of the mix in order to reach acceptable social, economic, and environmental outputs and outcomes in the future. Consumers exert significant pressure on the market and are ultimately one of the main drivers of the agricultural agenda (Gopalan, 2001).

Policies and subsidies are sensitive and controversial issues. Developed-country agricultural policies cost developing countries about US$17 billion per year, a cost equivalent to about five times the current levels of overseas development assistance to agriculture, while subsidies in developing countries divert funds from high-return investments in public goods (The World Bank, 2008). Investment in infrastructure (irrigation, roads, transport, power, and telecommunications), markets, rural finance, and research would boost agricultural productivity in developing countries while being less distorting than price subsidies and incentives.

How best to promote products from eco-efficient systems is an area that requires further research and more systematic analyses in order to guide both producers and consumers on food grown using eco-efficient approaches. For example, there are learning opportunities from the experiences of the organic markets and locally produced foodstuffs, as well as consideration of non-price incentives and the power of consumers to guide production towards a more eco-efficient path.

Meeting Challenges to Social Equity

Eco-efficient agriculture can deliver quality products that meet consumers' needs with a low ecological impact. However, to ensure that it does so equitably and sustainably it is imperative that assessments address social and economic performance as well as ecological criteria (Park et al., 2010).

Research on and implementation of the concept and practices of eco-efficiency must be sensitive to gender issues. Women play a major role in agriculture, accounting for about 70 to 80% of household food production in sub-Saharan Africa, 65% in Asia, and 45% in Latin America, cultivating food crops and commonly contributing to production of commercial crops (The World Bank et al., 2009). Women are generally responsible for food selection and preparation and for the care and feeding of children. They are thus key to food security for their households (Quisumbing et al., 1995).

Women also commonly play active roles as traders, processors, laborers, and entrepreneurs. However, many development policies and projects continue to assume that farmers and rural workers are mainly men (The World Bank et al., 2009). According to Deere and Leon (2003), about 70 to 90% of formal owners of farmland are men in many Latin American locations.

A World Bank water and sanitation study (Fong et al., 1996) concluded that gender is an issue not only of equity but of efficiency, because involving both women and men enhances project results, increases cost recovery, and improves sustainability. A review of 121 rural water supply projects found that women's participation was among the variables strongly associated with project effectiveness in the sector. Women's participation serves both practical and strategic gender needs. The practical gender needs of women are needs based on existing divisions of labor and authority, whereas the strategic gender needs are those that require redress of gender inequalities and redistributing power more equitably.

A closer look at women's roles in agricultural production (Table 1-1) illustrates the important part they play in every aspect of agriculture and food production, the significant challenges they face, and why gender-neutral strategies alone will not be sufficient to meet future needs and expectations.

Both men and women play critical and often complementary roles, both at the farm-level in smallholder agricultural systems and downstream in more intensive production systems, where processing, packaging, and overall value-adding require the complementary abilities and knowledge of women and men. Interventions must address the specific needs and opportunities of both women and men, particularly the poorest, if they are to reduce inequalities, stimulate growth, and contribute to reducing environmental degradation (The World Bank et al., 2009). To achieve this it is vital to understand and change natural resource tenure and governance and address gender-based inequalities in access to and control over natural resources.

The World Bank (2006) sums up the importance of addressing gender issues, stating that "Gains in women's economic opportunities lag behind those on women's capabilities. This is inefficient, since increased women's labor force participation and earnings are associated with reduced poverty and faster growth. In sum, the business case for expanding women's economic opportunities is becoming increasingly evident; this is nothing more than smart economics and appropriate social policy."

Monitoring and Evaluation

Eco-efficiency monitoring requires disciplined record-keeping and managed conservation to ensure long-term environmental improvement (Reith and Guidry, 2003).

Life-cycle analysis (LCA) helps to assess potential environmental impacts along the value chain (McGregor et al., 2003). LCA quantifies inputs (e.g., water, nutrients, energy, and agrochemicals) and outputs (e.g., grain, stubble, flour, oil, waste), assesses the environmental performance relative to input use and outputs, analyzes and explains the environmental performance of the supply chain, and suggests where and what measures can improve performance. LCA helps the individual actors (farmers, food processors, farm suppliers, retailers, and end users) to manage their environment along the value chain, to set their own environmental performance goals and indicators, and to identify practical, cost-effective measures to improve environmental performance. It can also be used to improve the quality of extension services, increase the profitability of farms by green marketing, and support the regional transition to sustainable agricultural systems (Hayashi et al., 2007).

In agriculture, water, energy, and land use intensity are used as resource intensity indicators, whereas NO_x pollution, CO_2, and CH_4 intensity are used to measure environmental impacts (United Nations, 2009). Wießner et al. (2010) introduced a set of practical indicators reflecting ecological and agronomic performance to describe the current eco-efficiency of sugar-beet cultivation,

Table 1-1. Roles, needs, and challenges faced by women in agriculture.

Activities	Key characteristics
Agricultural production	Rural women are the main producers of the world's staple crops—rice, wheat, and maize—which provide up to 90% of the food consumed by the rural poor. Women sow, weed, apply fertilizer and pesticides, and harvest and thresh crops. Their contribution to growing secondary crops such as legumes and vegetables is even greater. Grown mainly in home gardens, these crops provide essential nutrients and are often the only food available when major crops fail.
Water ownership and tenure	Women have much less access to water than men. The distribution of water and land is a major determinant of poverty, and inheritance laws that deprive women of access are often the cause of women's poverty.
Selection, improvement, and adaptation of local cultivars	Women are typically involved in the selection, improvement, and adaptation of local cultivars, as well as seed exchange, management, and saving. They often keep home gardens where they grow traditional cultivars of vegetables, herbs, and spices selected for their nutritional, medicinal, and culinary benefits. Women, therefore, play an important role in maintaining biodiversity. Women are also the primary collectors of wild foods that provide important micronutrients in diets and that are vital for the survival of households during food shortages.
Climate change	Least-developed countries are more reliant on rainfed agriculture and natural resources than more developed countries, and are therefore the most vulnerable to climate change. These countries generally lack the necessary adaptive capacities to cope with climate change. Poor people tend to live on marginal lands that are subject to frequent droughts or floods and are most likely to be affected by even small changes in climate variability. Because of gender-based inequalities in accessing critical livelihood assets (such as land, credit, technology, information, markets, and organizations), women are more exposed to these risks.
Biomass and fuelwood	Over one-third of the world's population (2.4 billion people) relies on fuelwood, agricultural residues, and animal wastes for their primary energy needs. Many women spend up to 3 to 4 hours a day collecting fuel for household use, sometimes traveling 5 to 10 km a day. In many African, Asian, and Latin American countries, rural women carry approximately 20 kg of fuelwood every day. This work burden limits time available for food production and preparation, household-related duties, and women's participation in income-generating activities and educational opportunities.
Weeds, pests, and diseases	Some 20–40% of the world's potential crop production is lost annually because of the effects of weeds, pests, and diseases. Attempts to control agricultural pests have been dominated by chemical control strategies, but the overuse of chemicals has adversely affected human health, the environment, international trade, and farm budgets. It is broadly estimated that between 1 million and 5 million cases of pesticide poisoning occur each year, resulting in several thousand fatalities. Pesticide fatalities are overwhelmingly a developing-country phenomenon and children and women are especially at risk.

SOURCE: Summarized and adapted from The World Bank et al. (2009).

and showed that eco-efficiency could be enhanced by reducing input levels. Recently, BASF (2010) announced its first eco-efficiency analysis for maize grown with or without a fungicide. The analysis compared both economic and environmental aspects of products and processes, and took the product's entire life cycle into account, from sourcing raw materials to product manufacture, use, and disposal. They found that using the fungicide reduced costs and energy and resource use and delivered high yields, i.e., farmers could both earn more by using this fungicide and protect the environment.

Conclusions

Those agricultural systems and practices that release less C to the atmosphere, conserve organic matter, utilize biological methods for disease and pest control, use clever rotations, pursue recycling opportunities by means of crop, tree and animal components and interactions, and use water rationally tend to be inherently eco-efficient. Humankind—given prospective demands and socio-economic, political and environmental challenges—will not be able to sustain and survive based solely on low-input agricultural systems. Intensive and high-input agriculture also has a key present and future role to play; however, it must attempt to do more with less and, as argued by several authors, it should aim at being more sustainable (Pimentel et al., 2005; Hobbs et al., 2008; Horrigan et al., 2002).

In summary:

- In view of the challenge to enhance productivity and counteract current yield plateaus in key crop and animal systems by means of eco-efficient methods, technology must be at the forefront of political, strategic, and investment priorities.
- Policies and incentives should be also of high priority, in order to tilt the balance towards eco-efficiency, food security, food safety, and reduced waste.
- Researchers and policy-makers need to consider the more-from-less, the more-from-more, and even the same-from-less scenarios to define priorities and goals at the national, regional, and local levels. In this context, eco-efficiency needs to be considered at wider scales than the farm or individual crop or animal production system.
- The widely assumed notion that developed countries are the ones that tend to specialize in few intensive production systems no longer holds. A growing number of large and intensive crop and animal enterprises (in particular fruits, vegetables, poultry, and beef for the export markets) are nowadays commonly found in the tropical belt.
- Generation and dissemination of eco-efficiency knowledge and adoption will greatly benefit from active participation of farmers in research and development, enhanced extension methods (including the new information technologies), and producer and consumer education.
- The current and potential impact of climate change on achieving a higher degree of eco-efficiency needs to be better researched and understood. There are both challenges and opportunities that must be worked out, particularly in relation to how eco-efficiency may or may not impact diversification and systems adaptability.
- Research and implementation of the concepts and practices of eco-efficiency cannot and should not be made with a gender-neutral approach. Lessons learned all over the world and abundant literature clearly show the advantages—smart economics as depicted by the World Bank (2006)—of considering and designing research and implementation of eco-efficient systems based on gender roles and inherent advantages.

In the lines of thought outlined above the best possible outcome is for high-input intensive agriculture and low-input agriculture to come closer to each other. High-input agriculture should certainly aim at becoming more environmentally friendly and low-input agriculture should adopt, whenever possible, a more intensive approach leading to higher productivity

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