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Review

Footprints[1] of water and energy inputs in food production – Global perspectives

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ABSTRACT

During the second half of the 20th century the global food production more than doubled and thus responded to the doubling of world population. But the gains in food production came at a cost, leaving a significant environmental footprint on the ecosystem. Global cropland, plantations and pastures expanded, with large increases in fossil energy, water, and fertilizer inputs, imprinting considerable footprint on the environment. Information from pre eminent publications such as *Nature*, *Science*, *PNAS* and scholarly journals is synthesized to assess the water and energy footprints of global food production. The data show that the footprints are significant, both locally, national and globally and have consequences for global food security and ecosystem health and productivity. The literature nearly agrees that global food production system generates considerable environmental footprints and the situation would likely get worrisome, as global population grows by 50% by 2050. Investments are needed today to buffer the negative impacts of food production on the environment. Investments to boost water productivity and improve energy use efficiency in crop production are two pathways to reduce the environmental footprint.

Introduction

Many environmental factors and international forces are working against agriculture today. These emerging challenges include reduced genetic diversity of food crops; build up of pesticide resistance; HIV/AIDS pandemic; increasing feminization of agriculture; ozone depletion; climatic shifts; global climate change; volatile food prices; and falling investment in agriculture. Together these factors pose immense challenges to local food security, with serious implications for the environment and global peace and security. Major changes in agricultural technology, infrastructure, and farming management practices are needed now. With falling investments and surmounting challenges, the prospectus for global sustainability in food production systems seem daunting. This paper distills lessons from history and from existing studies to choose the right investments, policies, and institutional structures to ensure that water and energy resources are used wisely in the challenging years ahead.

Global water cycles, carbon energy cycle, food production, and climate change are inextricably linked. Climate change is expected to accelerate water cycle, slowing the increase in number of people living under water stress, but changes in seasonal and spatial patterns and surge in the probability of extreme events may offset this effect (Oki and Kanae, 2006). Prolonged droughts and extreme rainfall events can cause a step change in water supplies and worsen the risk pervasive in agriculture (Pannell et al., 2000). Both climate normals (average long-term surface wetness and temperature) and interannual climate variance impact farm cropland and revenue (Mendelsohn et al., 2007a) but interannual climate variability is much more important than climate normals (Easterling et al., 2000). There is a larger degree of uncertainty on the future impacts of climate change on water resources than climate variability. Greater interannual rainfall variability may be associated with lower GDP particularly in poor countries (Brown and Lall, 2006). Rising water demand may greatly overweigh greenhouse warming in defining the state of global water systems (Vorosmarty and Sahagian, 2000). Climate change and population growth may have significant implications for agricultural production and its environmental footprint, especially for irrigated agriculture which provides about 40% of global food production from just 18% of cropland. Rainfed food production systems will also come under intense pressure due to shifts in weather patterns and changes in rainfall events and hydrological regimes and greater dependency on land and water resources, causing further resources degradation and eroding productivity.

Agricultural production accounted for about 90% of global freshwater consumption during the past century (Shiklomanov, 2000). Water requirements for food production will increase to

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meet demands of a 50% larger global population projected to increase from 6 billion in year 2000 to 9 billion in 2050 (UNDP, 2006). Meeting the 2015 Millennium Development Goals of reducing the share of people living in hunger by 50% will put further stress on water resources. A wealthier and richer population with changing diet preferences to higher meat consumption will also put significant pressure on water resources because meat production requires several multiples of water (4000–15,000 l/kg) than grain production (1000–2000 l/kg) to meet daily nutritional energy needs. An estimated 2.5–10 times more energy is required to produce the same amount of calorie energy and protein from livestock than grain (Molden et al., 2007). Direct consumption of cereals by humans can boost energy efficiency of the global food system, because one third of world's cereal supply is used for feed resulting in lower energy efficiency (de Fraiture et al., 2007; Renault and Wallender, 2000), but influencing diets of a richer population is difficult. Vegetarian diets may well have an environmental advantage, exceptions may also occur. Environmental costs associated with long-distance transport, freezing, and some agricultural practices may lead to environmental burdens for vegetarian foods exceeding those form locally produced organic meats (Reijnders and Soret, 2003). Growing consumption can cause major environmental damage (Myers and Kent, 2003) and have major implications for global water security and food security (Pimentel et al., 2004).

Global cropland, plantations and pastures have expanded in recent decades accompanied by large increases in fossil energy, water, and fertilizer consumption, imprinting considerable footprint on the environment. Should past dependences of the global environmental impacts of agriculture on human population and consumption continue, another 10^9 ha of natural ecosystems would be converted to agriculture by 2050 (Tilman, 1999; Tilman et al., 2001), introducing larger uncertainties for water demands and climate projections for irrigated agricultural regions (Bonfils and Lobell, 2007). Lower than expected crop yield with rising CO_2 concentrations will create further uncertainty (Long et al., 2006). In semiarid areas such as Africa where rainfall already is unreliable, this might have severe impacts on crop production (Mendelsohn et al., 2007b). Other projects such as agricultural production for carbon sequestration and energy production including biofuel crops will also increase demand for water resources (Burnes et al., 2005). The energy balance, economics, and environmental impacts of ethanol fuels are negative (Pimentel, 2003). Thus these pressures are likely to amplify the environmental footprint of agricultural production on ecosystem productivity and services (Scanlon et al., 2007). Some studies predict that the impacts of land use changes on water resources, specifically those associated with agricultural production may rival or exceed those of climate change (Barnett et al., 2005). Much will depend on how additional agricultural production takes place and what adaptation strategies could be adopted (Pannell et al., 2006; Parry et al., 1998). In any case the costs of adaptation to climate change are likely to be substantial and have implications for distributional and social issues such as effects on poverty and equity, and preservation of land and water resources and the environment (Kandlikar and Risbey, 2000).

This paper sketches the environmental footprints of water and energy use in food production systems through a review of information published in pre eminent journals. The literature nearly agrees that the footprints of global food production systems could be significant, particularly where policy and institutional infrastructure to protect the environment are weak. Investments to boost water productivity and improve energy use efficiency in crop production operations are the two possible pathways to reduce the environmental footprints.

Global agricultural water footprint

Food factor

Rising water scarcity is partially a consequence of the increasing demand for food or "food factor". Feeding a growing and affluent population will increase food demand and further intensify the scramble for water (Molden et al., 2007). The calories produced per cubic meter of water range from 1000 to 7000 for corn and 1260–3360 for legumes such as fava beans compared to 500–2000 for rice and 60–210 for beef (Molden et al., 2007); nutritional transition to more meat based diets will require far larger quantities of water to meet the same daily calorie requirements. Growing more food requires more water, as gains in yield, when yield is already beyond the 50% potential, come at a near proportionate increase in water depletion. More water depletion for extending the crop yield- or area-frontier may exact significant costs on the environment. The environmental footprints associated with increased water use for food production are often not taken in account partly because the links between crop production processes and the environment are poorly understood; agricultural water input often does not reflect the full opportunity cost of water use to the society and the environment; and policies and institutional infrastructure to protect the environment are weak or lacking and above all food security concerns dominate domestic political agenda such that negative externality issues rarely feed into the policy processes.

Agricultural production has a significant environmental footprint, as a result of expansion in cropland and pastures at the expense of forests, grasslands, and ecotones (Pimentel et al., 2004). Over the past three centuries, global crop and pasture land increased by four and five orders of magnitude respectively (Goldewijk and Ramankutty, 2004). Limits are being met on further expansion in the area as much of the land suitable for agricultural production has already been developed. Crop intensification through high inputs of water, energy and macro nutrients has been articulated as the way forward, especially in land scarce regions, but this has profound implications for global water and energy cycles. For instance, in many of the world's most important crop producing regions (Brazil, China, India, Iran, Pakistan, and Western Europe) the historical sources of growth in agricultural productivity are being rapidly exhausted, yield growth are stagnating or decelerating, and a significant share of irrigated land is now jeopardized by scarce water resources, groundwater depletion, a fertility sapping build up of salts in the soil, or some combination of these factors (Khan et al., 2008b; Postel, 2000). Further intensification can have adverse impacts on land and water quality and thus worsen the environmental footprint.

Today rainfed agriculture accounts for about 80% of global cultivated area and produces 60% of world's food, whereas irrigated agriculture which is more intensively managed produces 40% of world's food from just 18% of global cropland (Rockstrom et al., 2007). Irrigated agriculture has significant impacts on water resources, for instance, it accounts for 67% of global freshwater withdrawals and 87% of consumptive water use (Döll and Siebert, 2002). Irrigated agriculture has expanded by 480% during the past century and is projected to expand by 20% by 2030 (FAO, 2003). Ecosystem needs and environmental flows requirements are unlikely to be met in large parts of the world (Smakhtin et al., 2004).

The FAO (2007) data show that for the 90 developing countries, the water requirement ratio (irrigation water requirements in km^3/total agricultural water withdrawals in km^3) was around 38% in 2000, varying from 25% in areas of abundant water resources (Latin America) to 40% in Near East/North Africa and 44% in South Asia where water scarcity results in higher ratio. At the country level, variations are even higher: 10 countries used more than 40% of their water resources for irrigation in 2000, a situation which FAO (2007) considers critical based on its comprehensive global water balance approach calculated in a uniform way and comparable across countries. An additional nine countries used more than 20% of their water resources, a threshold that could be used to indicate impending water scarcity (Fig. 1). Already by 2000, irrigation water use was several times larger than their annual renewable water resources for three countries not shown here; Libya (712%), Saudi Arabia (643%) and Yemen (154%). None of these countries is a major agricultural producer; all are quite arid. Libya relies largely on fossil groundwater withdrawn from the desert and transported a substantial distance to water users. These countries desalinize water to meet their water needs. Groundwater mining also occurs at the local level in several other countries (Giordano and Vilholth, 2007). Intra country variations are large; China, for instance, is facing severe water shortage in the north including the Yellow River Basin while the south still has abundant water resources. Water rivalry poses huge challenges as water shortages rise and the scramble for water intensifies among contending uses for water. Intense water sharing issues could be in the making as transboundry water conflict spreads to lower level across India (Gujja et al., 2006), for instance.

Crop intensification

The expansion in irrigated agriculture brought tremendous benefits to billions of poor people (Narayanamoorthy and Hanjra, 2006). These include higher production and productivity; significant gains in food security and rural development; lower food prices for the rural and urban poor; better nutrition and health; better education; improved access to rural infrastructure; higher and more stable rural employment and reduced pressure on urban services; resettlement of population to high potential agricultural areas; moderation of socioeconomic inequality; and community cohesiveness (Hussain and Hanjra, 2003; 2004). Macro level benefits include gains in agricultural and food exports and strategic regional/global interests (Khan, 2007). Irrigated agriculture also had substantial unintended social, economic, and environmental costs.

The intensification of land use increased dramatically during the Green Revolution, feeding billions. For example, in the past 40 years global food production more than doubled (Falcon and Naylor, 2005), although global cropland area increased only by 12%, mainly through the use of high yielding varieties of grain, massive increases in nitrogen (~700%) and phosphorous (~350%) fertilization and comparable increases in pesticide use, increased reliance on irrigated land (a 70% increase), and increased fossil energy input due to agricultural mechanization (Foley et al., 2007; Fox et al., 2007). Although modern agriculture increased food production manifolds, it also caused extensive environmental damage. The key environmental footprints of agricultural production include:

- Loss of natural habitat on agriculturally usable land (Green et al., 2005).
- Increase in continental water storage formerly flowing to deltas, wetland and inland sinks and its impacts on greenhouse gases (Milly et al., 2003).
- Homogenization of regionally distinct environmental templates/landscapes, due to excessive construction of dams (Poff et al., 2007), thereby altering natural dynamics in ecologically important flows on continental (Fig. 2) to global scale (Arthington et al., 2006).
- Loss or extinction of freshwater fauna populations and habitat for native fisheries, plummeting population of birds due to inadequate water flows, and loss of riverine biodiversity due to large scale hydrological changes in tropical regions (Dudgeon, 2000).
- Biodiversity loss associated with agricultural intensification (Butler et al., 2007; Kremen et al., 2002).
- Enhanced global movement of various forms of nitrogen between the living world and the soil, water, and atmosphere with serious and long-term environmental consequences for large regions of the Earth (Vitousek et al., 1997).
- Nitrate pollution of agricultural landscapes and groundwater resources, and nitrogen- and phosphorous-driven eutrophication of terrestrial, freshwater, and near-shore marine ecosystems, causing unprecedented ecosystem simplification, loss of ecosystem services, species extinctions, outbreaks of nuisance species, shifts in the structure of food chains, and contribution to atmospheric accumulation of greenhouse gases (Correll, 1998; Tilman et al., 2001).
- Synthetic chemicals compromising symbiotic nitrogen fixation, thus increasing dependence on synthetic agrochemicals and unsustainable long-term crop yields (Fox et al., 2007).
- Soil salinity and water logging and impaired natural drainage, and associated damages to infrastructure and lost opportunities for regional growth and economic development (Khan et al., 2006; Kijne, 2006; Wichelns and Oster, 2006).
- Depletion of groundwater aquifer and reduced stream flows (Khan et al., 2008a) and associated impacts on drinking water supplies, health and rural livelihoods (Meijer et al., 2006).

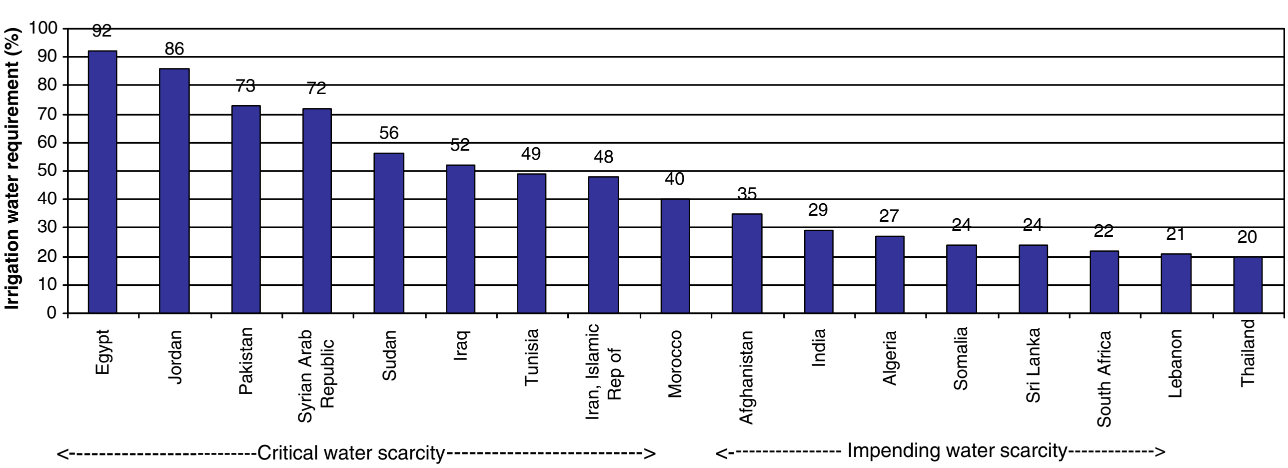

Fig. 1. Water scarcity: Irrigation water withdrawal as percentage of renewable water resources.

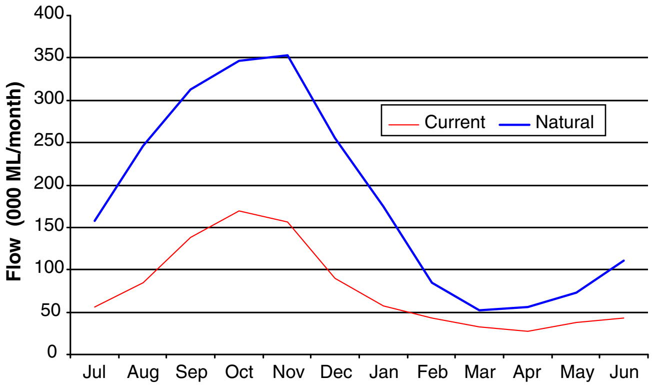

Fig. 2. Human alterations of the natural flow regime: Comparison of the natural and current median monthly flows in Murrumbidgee River at Balranald, Australia.

- Displacement of population due to dam construction (Cernea, 2003), and higher incidence of vector-borne diseases in some irrigation areas and loss of human productivity (Lautze et al., 2007).
- Reduced capacity of the ecosystems to sustain food production, maintain freshwater and forest resources, purify water, regulate climate and air quality, or ameliorate infectious diseases (Foley et al., 2005).
- Global accelerated erosion from plowed agricultural fields and hill slope production – greater than 1–2 orders of magnitude than rates of soil production; and erosion under native vegetation, and long-term geological erosion (Montgomery, 2007).
- Erosion caused by human transport of larger amounts of sediment and rocks for construction and agricultural activities exceeding all other natural process operating on the surface of the planet (Wilkinson and Mcelroy, 2007).
- Surge in extreme hydrological events such as storms, droughts and floods (Illangasekare et al., 2006).
- Global, inter- and intra-state conflict over freshwater resources and potential for social instability (Yoffe et al., 2004).
- Raised threat level of global terrorism to water resources due to elevated risk to dams and reservoirs (Gleick, 2006; Mustafa, 2005).

The potentially negative implications of intensive agriculture warrant policy action but it is necessary to note also that alternative approach of less intensive agriculture likely would require much more land and resources, possibly with greater aggregate damage to the environment. Investments must be targeted to address these potential negative implications and protect food security.

Resource degradation

Irrigated areas are the major food basket of the world, producing 40% of the world's food from just 18% of the global cropland (Khan and Hanjra, 2008). Despite the need to achieve sustainability in food crop production and to raise staple crop yields, important to achieving the Millennium Development Goals of eradicating extreme poverty and hunger (Goal 1) and environmental sustainability (Goal 7), productivity in irrigated areas have been declining in recent decades, threatening food security of millions of smallholders (Hussain and Hanjra, 2003; 2004). Some 15 million ha – almost 9% of the global irrigated land – in developing countries have experienced significant yield declines as a result of soil salinity and water logging. (Postel, 1999), and salinization is becoming a major problem on an additional 2 million ha per year at minimum, severely reducing or entirely destroying yields and thus offsetting a large proportion of the benefits to agricultural productivity achieved from crop intensification and area expansion in irrigated agriculture. A deepening agro-ecological crisis threatens to shrink productivity and adversely affect food security in irrigated agro-ecosystems (Khan et al., 2006). Resource degradation and productivity decline are twin issues facing irrigated agriculture. Environmental footprints of unsustainable land and water management are found in many irrigated systems in developing world, but their effect on overall productivity so far may be limited, partly because farmers react to the signs of salinity in their field by changing land and water management practices (Kijne, 2006). Almost 3/4th of irrigated land is in developing countries, supporting 60% of rice and 40% of wheat grown there, but is facing significant challenges due to water logging and salinity. Well regarded estimate (Murgai et al., 2001) show that crop intensification, especially in the rice–wheat system, resulted in resource degradation in both Indian and Pakistani Punjab and reduced the overall productivity growth from technological change and from educational and infrastructural investments by about 1/3rd in the latter's case. For the left bank main canal of Tungabhadra project in south west India (Janmaat, 2004), where approximately half of the water is being used to grow water-intensive crops, about 15% of the system's productive potential is lost due to land degradation while inequitable water distribution accounts for 37% of lost production value. A case study of wheat farmers in the upper Indus basin in Pakistani Punjab (Hussain et al., 2004) show that land, water, and other factors, account for productivity differences among farmers. In particular, locational inequities in canal water distribution, use of saline groundwater, differences in the use of inputs all result in significant losses in productivity. The adverse impacts of poorly-managed canal water supplies are stronger for tail-end farmers and in settings with poor quality groundwater. Consequently food productivity is low and the depth and severity of poverty are higher for these farmers (Hussain and Hanjra, 2003, 2004).

Instances of other negative externality due to poorly managed irrigation water such as flooding, malaria, population displacement and livelihood loss, social unrest and conflict in irrigation schemes, and such are also documented in the Asian literature (Hussain and Hanjra, 2003; 2004) and elsewhere (Cernea, 2003). These externalities of irrigation point largely to the software or operational and policy issues in irrigation management (Easter, 1993; Saleth and Dinar, 2004). Inappropriate policies and inadequate institutions create an environment in which farmers and other water users lack incentive to use scarce resources in a socially optimal fashion. Many of the potential impacts described above result from institutional and policy failures, rather than mere technical or agronomic factors.

Cropland degradation has an enormous environmental footprint as well. It also poses a major threat to the sustainability of agriculture all around the world (Crosson, 1995). Although no firm global data on these problems exist, about 2 billion ha of land under crops, pasture, and rangeland through out the world or about 17% of Earth's vegetated land are now degraded, mostly as a result of water and wind erosion (World Bank, 2003). Widely reported data show that salinization, erosion, compaction, and other forms of soil degradation affect 30% of the global irrigated land, 40% of rainfed land, and 70% of rangelands. Cumulative global productivity loss due to land degradation over three decades has been estimated at 11% of total production from irrigated, rainfed, and rangeland or about 0.5% per year (Crosson, 1995). This calculation is consistent with other estimate (Daily, 1995) showing a 10% reduction in potential direct instrumental value, defined as the potential to yield direct benefits to humans in the form of agricultural, forestry, industrial, and medicinal products. Others have argued that in most agro-ecosystems, declining crop yield is exponentially related to loss of soil quality (Stocking, 2003). This funding is based on a series of experiments since 1984 on major tropical soil types that attempted to determine the relationship between crop yield and cumulative soil loss. Results indicate that yield decline follows a curvilinear, negative exponential that holds true for most tropical and many temperate soils. In general, the underlying degradation estimates are weak both because time series data on land degradation are lacking and farmers bring new land under cultivation. Large regional differences also exist in the extent of degradation, with almost 3/4th of Central American and 2/3rd of African land base partially degraded. Land degradation in Africa is grave, widespread and poverty induced (Sanchez, 2002).

Extractive farming practices

The traditional shifting cultivation practised mainly in Africa, but also in parts of Asia, is becoming unsustainable as rising population density shortens fallow periods, which lowers fertility, such that more land is needed each year partly because to offset the effect of a decline in crop yield and higher population. Population growth is putting more and more pressure on land and water resources – the two agents that are responsible for 85% of land degradation globally. For instance, arable land per capita in Africa shrunk from 0.5 ha in 1960s to 0.32 ha in 2001 (Harsch, 2004). Most parts of Africa continue to experience plant nutrient mining, lowering soil nutrient stocks to level that can not sustain yield. These practices have resulted in a very high average annual depletion rate – 22 kg of nitrogen, 2.5 kg of phosphorous, and 15 kg of potassium per ha of cultivated land over the past 30 years in 37 African countries. This annual loss is equivalent of US$4 billions in fertilizer terms (Sanchez and Swaminathan, 2005). The widespread nutrient mining has decreased soil organic matter; lowered the ability of microorganisms to recycle nutrients; and impaired the water holding capacity of soil. Cutting African and world hunger requires decisive action to replenish soil fertility (Sanchez, 2002). Increases in soil fertility or organic carbon pool improves soil quality; reduces groundwater pollution of agriculture; moderates gaseous emissions; improves water quality; and enhances biodiversity – managing soil organic matter holds the key to water, soil, and air pollution (Lal, 2007). Unsustainable water and land management practices present a threat to global environment and food production systems as well (Daily et al., 1998). Policies and programs are needed to support sustainable land and water management practices, promote technological change, boost crop yields, provide social safety nets, and reduce the environmental footprint in smallholder food systems. Most of today's water problems can not be solved without a truly integrated Triple Bottom Line approach, which addresses economic, social, and environmental issues simultaneously.

Environmental flows

The environmental footprints of increased agricultural production are significant. Ecosystem water needs are increasingly being recognized as environmental flow programs attempt to establish flow requirements to maintain ecosystem productivity and regulatory and provisioning services (Gordon et al., 2005). A transition is underway to a "soft path" to water management that balances efficiency, equity, and environmental protection gaols (Gleick, 2003; Ruttan, 1999) complemented by innovations in the "hard path" including advances in agricultural biotechnology that reduces dependence on external inputs such as pesticides to mitigate the environmental impacts of agricultural intensification (Basu and Qaim, 2007; Cattaneo et al., 2006).

Societal values and hidden benefits

The Comprehensive Assessment of Water Management in Agriculture was released in March 2007. It critically evaluates the benefits, costs, and impacts of the past 50 years of water development, the water management challenges communities are facing today, and solutions people have developed. The assessment is produced by a broad partnership of about 700 practitioners, researchers and policy makers. The CA estimates suggest that, because renewable fresh water is scarce, the projected 70–90% increase in food demand by 2050 (de Fraiture et al., 2007; Rockstrom et al., 2007) must be met by improving output per unit of water from the existing irrigated land or with the same or less water. Yield improvements increase the required water diversions by 30%, but irrigated area expansion requires an increase of 55%. This would have serious impacts on water scarcity and the provisioning of environmental services. Part of the increase in food production can be achieved by improving crop yields and increasing output per unit of water through appropriate investments in both irrigated and rainfed agriculture. One challenge is to manage this additional water in a way that does not impact on environmental services, while meeting additional food requirements. Linking the hydrological cycle with the carbon cycle is crucial to improving yield and to soil carbon sink in the dryland agriculture. Investments are needed now to protect the natural ecosystems and food security. Feeding billions while maintaining the climate within habitable boundaries is probably the greatest "public goods game" played by human (Milinski et al., 2006), and greatest gift to future generations.

Global agricultural energy footprint

Energy factor

Energy resources are an essential ingredient of global economic growth and development (Goldemberg, 1995). Energy is the lifeblood of technology and development. Yet no primary energy source, be it renewable or non-renewable, is free of economic or environmental consequences (Chow et al., 2003). Energy consumption has implications for economic growth; the local, national, and global environment, and even for the global peace and security.

Global energy consumption can be categorized into five major sectors: industry, transportation, agriculture, commercial and public services, and residential. Agriculture is a major producer of energy as well, generating a large amount of energy through photosynthesis activity by crops and plantations. Solar energy dominates the energy balance on food production, accounting for ~90% of total energy inputs even in intensive systems (Goldemberg, 1995). Widely quoted phrases such as "man is eating potatoes indirectly made from oil" draw attention to the ongoing substitution of solar energy with fossil fuel energy in high productivity agriculture (Naylor, 1996). Early literature on the energetics of world food production (Pimentel et al., 1973) suggested that energy was a potential constraint on agricultural productivity and that global food systems were increasingly vulnerable to changes in the availability and use/prices of energy inputs.

The World Bank (2007) reports that on-farm crop production uses about 2–5% of the commercial energy in almost all countries, irrespective of their level of development. Agricultural operations make a fairly small contribution to the overall energy use. For instance, the use of farm machinery, irrigation, fertilization and chemical pesticides amounts to merely 3.9% of the commercial energy use. Of this, 70% is associated with the production and use of chemical fertilizers (Vlek et al., 2004). However, energy inputs have increased disproportionately over time. A series of cross-sectional studies on farming systems suggest that crop intensification show declining returns to energy inputs after a certain point. A seminal paper on US maize production (Pimentel et al., 1973) showed that maize yield more than doubled over the period

1945–1970 but energy inputs rose at a proportionately faster rate and thus caused the energy ratio of inputs to outputs to fall from 3.7 to 2.82. Surely the energy requirements have changed in notable ways during the past 35 years but energy inputs have continued to increase overall.

Stabilizing the carbon dioxide induced component of anthropogenic climate change is an energy problem (Raupach et al., 2007) and a major pathway to reducing the environmental footprint of energy use. From agricultural standpoint this includes optimal use of fertilizer energy; soil carbon sequestration projects; and biofuel crops.

Biofuel crops

Biofuel crops offer potential but encounter limits to their ability to lowering the environmental footprint of energy consumption. Globally escalating demands for both food and energy have raised concerns about the lower environmental footprint of biofuels, due to competition for fertile land, increased pollution from fertilizers and pesticides, and threats to biodiversity when natural lands are converted to biofuel production. The energy balance, economics, and environmental impacts of ethanol fuels are shown to be net negative (Pimentel, 2003). The carbon sequestered by restoring forests is greater than the emissions avoided by the use of the liquid biofuels (Righelato and Spracklen, 2007); demand for water is higher; competition for land devoted to food production is intense.

Biofuels from grassland biomass can provide more usable energy, greater greenhouse gas reduction, and less agrochemical pollution per hectare than can corn ethanol or soybean biodiesel (Tilman et al., 2006). Moreover these biofuels can be produced on agriculturally degraded or abandoned lands, which need to neither displace population nor cause loss of biodiversity via habitat destruction (Francis et al., 2005). Other benefits may include ecosystem services such as stable energy production, renewal of soil fertility, cleaner ground and surface waters, and wildlife habitat and recreation (Tilman et al., 2006). There may be some interlinked issues; for instance, converting all grass on US grasslands into ethanol as proposed by Tilman et al. (2006), might have serious consequences for millions of cattle and sheep grazing on this grass, which already have overgrazing problem. New technologies are required to produce ethanol from cellulose, such as wood chips and agricultural by products rather than valuable food and feed grains or grass. But technological constraints such as the integration of agroenergy crops and biorefinery manufacturing technologies (Ragauskas et al., 2006), limit the production and use of the latter type of biofuels; and constraints on the availability of degraded lands in suitable locations for biofuel crop production would mean stronger competition for land and water resources currently devoted to food production with a real possibility of net negative environmental footprint (Hoffert et al., 2002). Choosing among the host of strategies for reducing anthropogenic carbon emissions, for instance biofuels, is not easy. There are competing environmental priorities, social and economic factor, and commercial and political interests (Righelato and Spracklen, 2007) that must be balanced carefully to achieve positive sum solutions.

Agricultural chemicals

Fertilizers are an important indirect energy input for food production. Global fertilizer consumption increased by several orders of magnitude over the past 50 years (Fig. 3). By far nitrogen fertilizer is the largest fertilizer energy input. Nitrogen fertilizers require about 10 times more energy to produce per ton than phosphorous and potassium fertilizers, and they typically account for 55–65% of on-farm energy use for high yield crops. The role of nutrients such as nitrogen and phosphorous in maintaining crop yields is well accepted (Jayne et al., 2003). The data from 362 seasons of crop production support the off-cited generalization that at least 30–50% of crop yield is attributable to commercial fertilizers (Stewart et al., 2005). The rate of accumulation of soil organic matter is often higher on fertilized fields due to higher biomass production, but it carries a carbon "cost" that is rarely assessed in the form of carbon emissions during the production and application of inorganic fertilizer. Carbon accounting using a life cycle approach can provide a more informed view of such omissions.

Soil carbon sequestration

Minimizing the environmental footprint of fertilizer is an intricate balance between maximizing food production and enhancing environmental quality. The addition of nitrogen fertilizer leads to increased crop biomass, while augmenting carbon inputs to the soil and hence increases soil organic matter. The efficient use of nitrogen fertilizer has been found valuable for enhancing food production and sequestering atmospheric carbon in the soil. For instance, non-fertilizer corn in Kentucky experiment removed about 65 kg nitrogen/ha/year; whereas corn fertilized with 84 kg/ha/year removed 97 kg/ha/year (Izaurralde et al., 2000). The sequestration of carbon far outweighs the emissions that are associated with the production of the extra fertilizer needed. Proper utilization in combination with reduced tillage can produce net positive carbon sequestration in soil and sustain productivity, and thus reduce environmental footprint as well as enhance food

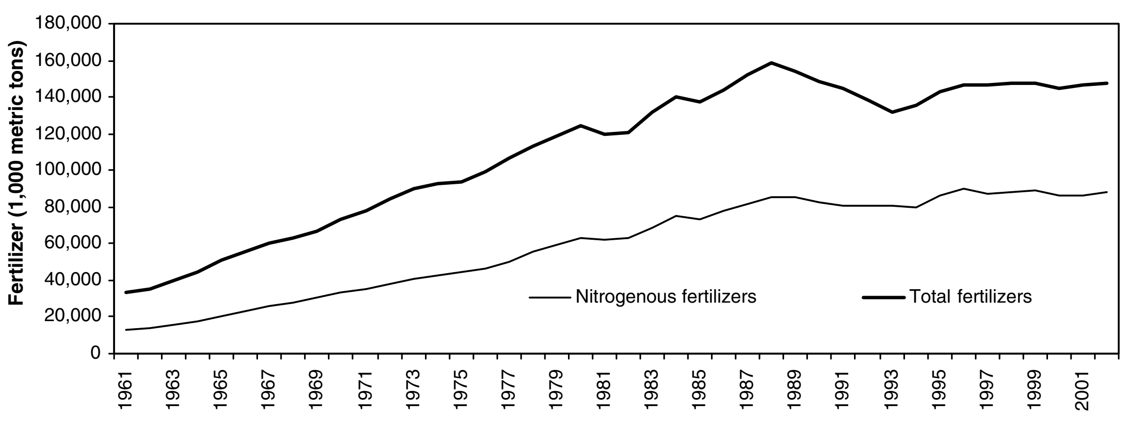

Fig. 3. Global consumption of fertilizers (1000 metric tons).

security (Lal, 2007). In irrigation systems with already high fertilizer inputs such as in South Asia, an efficient use of fertilizer must be warranted. Reduced tillage as well as soil fertility management practices, where inorganic fertilizer is not used much, can improve on-farm profitability and food security in smallholder production systems such as in sub-Saharan Africa (Kaizzi et al., 2007).

However, fertilizer use for carbon sequestration has its limits, and is sensitive to soil condition, land management practices, and climate (Lal, 2007). Excessive additions of nitrogen to the environment can be associated with increased environmental problems. Some authors (Schlesinger, 2000) have argued that the marginal carbon cost of nitrogen fertilizer use exceeds the marginal gains in carbon sequestration in soils, even under no-till management. For instance, the mean use of nitrogen fertilizer on corn in the US (150 kg/ha/year) already exceeds the economic optimum level (133 kg kg/ha/year). The conversion from no-till farming to conventional till increases emission by 30–35 kg C/ha/season (Lal, 2007). Furthermore the full carbon cost of nitrogen fertilizer may effectively negate any net carbon sink. These costs include the carbon emissions during fertilizer manufacture, storage transport, and application (estimated at 1.436 moles of carbon emitted per mole of nitrogen applied). A greater use of nitrogen fertilizer for boosting food production is likely to contribute to excessive loss of nitrogen to surface and ground waters, thus increasing environmental footprint (Schlesinger et al., 2006). This is typically the case in large parts of developing world, where excessive nitrogen have serious and long term environmental consequences. Credible studies (Vitousek et al., 1997) show that human alteration of the nitrogen cycle have: nearly doubled the rate of nitrogen input into the terrestrial cycle and the rate is still increasing; caused loss of soil nutrients; contributed substantially to the acidification of soils, streams and lakes in several regions; accelerated losses of biodiversity; caused changes in the composition and functioning of estuarine and nearshore ecosystems; and derived the formation of photochemical smog over large regions of the Earth.

Strategies that increase soil carbon sequestration have impacts on global climate change and food security, since it increases yield even in high input commercial agriculture, but especially in regions with depleted soils facing intense food security issues. For instance, an increase of 1 ton of soil carbon in degraded cropland increased crop yield by 20–40 kg/ha for wheat and 10–20 kg/ha for maize in selected settings (Lal, 2007). Carbon sequestration can thus enhance food security, and has the potential to lower environmental footprint (Table 1) by offsetting fossil-fuel emissions by 5–15% annually (Lal, 2007).

Table 1
Potential of carbon sequestration in world soils

Item	C sequestration potential (kg C/ha/yr)
Irrigated soils: 275 Mha (0.01–0.03 Gt C/yr)	
Using drip/sub-surface irrigation	
Providing drainage	100–200
Controlling salinity	60–200
Enhancing water use efficiency	100–200
Cropland soils: 1350 Mha (0.4–0.8 Gt C/yr)	
Conservation tillage	100–1000
Cover crops	50–250
Manuring and integrated resource management	50–150
Diverse cropping system	50–250
Mixed farming	50–200
Agroforestry	100–200
Rangeland and grasslands: 3.7 billion ha (0.01–0.3 Gt C/yr)	
Grazing management	50–150
Improved species	50–100
Fire management	50–100
Nutrient management	
Restoration of degraded and desertified soils: 1.1 billion ha (0.2–0.4 Gt C/yr)	
Erosion control by water	100–200
Erosion control by wind	50–100
Afforestation on marginal lands	50–300
Water conservation/harvesting	100–200

Data source: Lal (2004b), p. 1624.

Hydrologic and carbon cycle

With out fertilizer use, the tropical countries would have cleared even more land for cultivation. Low input food production systems that do not use nitrogen fertilizer are less efficient converters of sun light, and they do not utilize water or soil nutrients as effectively as high input farming systems. Other strategies to increase soil carbon pool include soil restoration and vegetation regeneration, no till farming, cover crops, nutrient management, manuring and sludging, better grazing schedule, agroforestry, growing energy crops on wasteland, water harvesting and conservation, and efficient irrigation (Lal, 2007).

However the co-benefits and tradeoffs of various strategies need to be taken into account. Plantations are increasingly advocated/grown for carbon sequestration. A synthesis of more than 600 observations and climate and economic modelling studies documents substantial losses in stream flows, and increased soil salinization and acidification with afforestation resulting in what is termed as "water trading for carbon" with biological carbon sequestration (Jackson et al., 2005). Soil restorative farm policies are win–win and must be implemented to mitigate environmental footprints and enhance food security. However the challenges are immense because of weak institutions, limited infrastructure, and predominantly resource-poor farming systems especially in Asia and Africa (Lal, 2004a).

Carbon farming

Carbon farming could become the New Agriculture, as humans respond to climate change. It is water, land and livestock management designed for the era of climate change. Growers face the challenge of emissions from livestock (methane) and fertilizer (nitrous oxide). The farm plan which incorporates both carbon capture and emission reduction is called Carbon Farming (Williams, 2007). These are methods of capturing and holding carbon in the soil, including: grazing management, pasture cropping; low/no till; mulching; biological or organic farming; natural sequence farming; alternatives to nitrogen fertilizers; composting; and biodynamics. Adopting environmentally friendly farming practices can reduce the environmental footprint, at a much lower cost, and give farmers a chance to be part of the solution. Required are the instruments to support a carbon farming payments program, much like existing farm subsidy programs, and to integrate these with national and international carbon trading schemes.

Australian farmers have made some headway towards carbon farming. A conservative estimate suggest that the farmers and landowners could earn $25 per tonne for carbon dioxide stored in soil, plants and trees, native vegetation and sustainable cropping techniques (Williams, 2007).

Alongside, attention is also called for to the clearing of native ecosystems for agricultural use in the tropics which is the largest non-fossil fuel source of carbon emissions. Reforestation in these countries can sequester large amounts of carbon even to mitigate excessive emissions elsewhere (Dixon et al., 1994; Smaling and Dixon, 2006). The environmental footprint of shifting cultivation, widespread in tropical agriculture, is believed to be quite large. About half of the tropical deforestation is commonly explained by shifting cultivation (Angelsen, 1995). Little is known about its long-term effects including the potential to sustain rural population. Data spanning 200 years form selected sites in Indonesia show that the shifting cultivation enhanced the availability of phosphorous due to an increase in stable organic phosphorous fraction (Lawrence and Schlesinger, 2001). This suggests that long-fallow shifting cultivation can continue to support rural population for some time. Pressures arising from increased population and the need to maintain real incomes can result in a general failure to continue sustainable agricultural practices which can cause slope instability, loss of soil fertility and land degradation, and excessive depletion of water resources (Costanza et al., 1998; Gichuki, 2004). Policies and interventions that focus on agricultural diversification through development of infrastructure and provision of support services as well as on capacity building can assist in dealing with farmer's vulnerability and reducing environmental footprints in the uplands (Rasul and Thapa, 2003).

Agricultural water and energy linkages

Global water and carbon energy cycle

Carbon sequestration in soil organic matter is increasingly advocated as a possible win–win strategy in the rehabilitation of degraded soils and dryland agro-ecosystems, while increasing productivity and improving water quality. For instance, food production under irrigated conditions with optimal inputs of fertilizer can lower the net environmental footprint, because it simultaneously contributes to the reduction of global atmospheric greenhouse gas concentrations while enhancing local land productivity. This may typically be the case in nutrient deficient soils. In other settings where soils are rich, even rainfed production can lower the environmental impact. For example, data for irrigated corn production in western Nebraska confirms that it take three times more fossil energy for the irrigated corn compared with the non-irrigated corn in eastern Nebraska. Both had the similar yields (Wortmann et al., 2006). The additional fossil energy in irrigated production will not reduce the environmental footprint. Irrigation of semiarid lands may also produce a sink for carbon in food production, but its contribution to a sink for carbon in soils must be discounted by carbon dioxide emitted when energy is used to pump irrigation water and when calcium carbonate precipitates in the soil profile, or where land management changes the availability of phosphorus in the soil (Izaurralde et al., 2000; Lawrence and Schlesinger, 2001). Pumping irrigation has an environmental footprint as well. For instance, it takes 0.86 kg C/kg N; 0.17 kg C/kg P_2O_5; 0.12 kg C/kg K_2O; 0.36 kg C/kg lime; 4.7 kg C/kg herbicide; 5.2 kg C/kg fungicides; 4.9 kg C/kg insecticide; where as 150 kg C/ha are emitted for pumping groundwater for irrigation (Lal, 2004b).

Power pricing and social equity

Irrigation is commonly regarded as a primary consumer of energy on-farm. The carbon footprint of energy input in groundwater irrigation is also substantial, but government policies have supported groundwater use to enhance food security while the negative externalities associated with the pumping have often been ignored. Farmer investments in wells and pumps had driven the rapid expansion of groundwater irrigation; however the supply of cheap diesel or free electricity was a critical though often over looked driver of the groundwater boom (Scott and Shah, 2004). For instance, agricultural pumping accounts for 1/3rd of the total power consumption in India (Kumar, 2005). Another serious outcome in many regions around the world has been groundwater overdraft, where pumping exceeds aquifer recharge, water tables have declined and water quality has deteriorated (Shah et al., 2006) generating substantial negative externalities (Chandrakanth and Arun, 1997). Considering that groundwater is a critical input for livelihoods and food security, irrigating about 70% of the cropped area and supplying 80% of domestic water, for instance in India, the implications of groundwater depletion for social equity for the poor and communities dependent on groundwater for drinking and irrigation are quite large (EPW, 2007). China, India, Mexico and hard-rock areas in Pakistan face critical challenges in groundwater overdraft. With subsidized energy, farmers have few incentives to limit pumping (Scott and Shah, 2004).

The linkages between power pricing and energy and groundwater footprints and social equity are complex and highly debated. Many argue that pro rata electricity tariff with built in positive marginal cost of pumping could lessen environmental footprint by promoting efficient use of groundwater and by delivering gains in agricultural productivity (Kumar, 2005). Others argue that levels of tariffs to influence demand would be too high to be viable from the political and equity perspective (Saleth, 1997). It could, for instance, reduce net social welfare as a result of: reduction in demand for electricity and groundwater; lower net surpluses individual farmers could generate from cropping; and upward pressure on food prices, impacting the livelihood and food security of millions and making it socially unviable (Malik, 2002).

Power pricing and geopolitics

Agricultural water use and energy consumption are linked. A range of emerging issues are affecting water management via the energy pathway, hence their environmental footprints. For instance, geopolitical events affect energy prices and rising energy prices impact water use and the environment in several ways. Crude oil prices have risen sharply in the past few years (Ghouri, 2006), and jumped to $100 a barrel in the last quarter of 2007. Higher energy prices may affect agricultural water footprint in four ways (de Fraiture et al., 2007, p. 137):

- The cost of pumping groundwater increases; and the cost of transporting agricultural inputs and outputs increases, extending the agricultural production frontier into fragile areas and limiting opportunities and incentives to protect the environment by smallholders as higher energy costs would encourage them to expand production into new areas rather than investing in expensive inputs.
- Fertilizer prices and the unit costs of other oil-based inputs increase. Some farmers choose to expand irrigated area rather than improving yields, possibly leading to higher aggregate water demand and environmental footprint.
- The viability of desalinization as a source of alternative water declines, generating further pressure on freshwater resources.
- The demand for alternative energy sources, such as hydropower and bioenergy, increases, with potential impacts on the environment.

Pumping irrigation water is a major consumptive use of fossil energy in agriculture. Hydropower and bioenergy require substantial water, although hydropower production does not consume water. Multipurpose dams can produce energy, sustain irrigation and fisheries, enhance river regulation, and increase storage. However, dams often have adverse impacts on river ecosystems and contribute to greenhouse gas emissions. Bioenergy production is a consumptive use of water such that biofuel use for pumping would compete with land and water resources currently devoted to food crop production (Berndes, 2002). With rising energy prices groundwater pumping may become unaffordable, leaving smallholders dry and hungry. If India and other countries discontinue energy price subsidies, irrigation might become unaffordable for millions of smallholder farmers, with consequences for food security and social stability (Narayanamoorthy and Hanjra, 2006).

Higher use of irrigation water is almost always associated with higher energy input. Global surge in fossil energy consumption and geopolitical events and global economics impact energy prices, such that many of the drivers of water and energy footprints will come from outside the sector. The pathway to limiting the environmental footprints and ensuring food security is not a single neatly defined vector. Instead, the aggregate, global pathway may represent many smaller paths representing unified and integrated approaches seeking to ensure domestic food security and enhanced social welfare, with minimal environmental footprints both locally and globally.

Conclusions and policy implications

The data show that the footprints are significant, both locally, national and globally and have consequences for global food security and ecosystem health and productivity. The literature nearly agrees that global food production system generates considerable environmental footprints and the situation would likely get worrisome, as global population grows by 50% by 2050. Water and soil resources are being unsustainably used and depleted; yields of food crops are stagnating or even declining in some major food producing areas; agricultural or total factor productivity growth is falling in many systems; and agrochemical use and fossil energy inputs are rising with consequent impacts on the ecosystem and humans. The WHO reports that 3.7 billion people are malnourished in the world – the largest number ever in history. The FAO reports that only 800 million people are malnourished but they are only measuring protein/calorie malnourishment. Addressing malnutrition and food security issues poses huge challenges (Castillo et al., 2007).

A key finding from the review was that higher energy efficiency and the use of alternative energy sources as well as carbon sequestration by the avoidance of deforestation and better cropping systems are the main pathways to reduce the carbon emissions and environmental footprints of food production.

But there is no single solution to alleviate the environmental footprints of food production. Not all unintended consequences of production are avoidable. Some of the productivity loss and footprints can be offset in the short run, for instance through efficiency improvements; but in the long run the cumulative loss of soil fertility and productivity and water holding capacity are far more difficult to restore. Degradation of irrigated land throughout the world poses serious challenges to food security and the environment. Salinization, waterlogging and alkalinization of irrigated land and depletion of groundwater are affecting ~10–20% of total irrigated land, causing losses in crop productivity and thus offsetting the large proportion of benefits to food security achieved from irrigation expansion. Almost three quarters of irrigated land is in developing world, supporting almost 40% of wheat and 60% of rice production there. Globally irrigated area have declined after a peak in 1978; global lending to irrigation sector also declined then onwards (Hussain and Hanjra, 2004). Investments are needed now to raise food crop yields to improve the management of existing irrigation systems, develop new systems, and restore degraded land and water resources. These investments must avoid the ills of the past to generate positive-sum solution in efficiency, social equity, and environmental quality, and should thus be fully compliant with the Triple Bottom Line framework.

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