Is There a Need for a More Sustainable Agriculture?

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In this paper the environmental impact of current agriculture practices is reviewed. Soil loss (along with soil fertility), increasing water demand from agricultural practices and environmental pollution caused by the intensive use of agrochemicals, are among the most pressing issues concerning agriculture sustainability. Biodiversity loss due to land use change and emission of greenhouse gases from agricultural activities are also causes for concern. A
number of alternative agricultural practices are also presented that can help to make agriculture less environmentally damaging by reducing the use of natural resources, limiting inputs and preserving soil fertility and biodiversity. We think that there is room for a different and more ecological agriculture and that research should be implemented in order to better assess the potential and constraints of the different options. However, notwithstanding the great achievements of the “Green Revolution,” the world will need 70 to 100% more food by 2050. So a new challenge lies ahead: how to feed nine billion with less land, water and energy, while at the same time preserving natural resources and soil fertility? Technical advances are important in order to meet the future needs, but addressing key socioeconomic issues, such as the inequality in the access to resources, population growth, and access to education are also a priority if we want to properly deal with sustainability. It may require our society to change some of its paradigms and “values” if we wish to preserve our support system, the soil and its health, for the future generations.

Keywords sustainable agriculture, agroecology, food security, environmental impact, natural resources, multifunctionality, multi-criteria

I. AGRICULTURE: PRODUCTIVITY VS. SUSTAINABILITY

In the twentieth century agricultural productivity experienced an incredible leap forward: fossil fuels became available as a cheap and (deemed) unlimited energy source, allowing the industrial production of chemical fertilizers and pesticides, and the mechanization of agriculture (Smil, 2000; 2004). In the 1970s, Norman Borlaug (1914–2009, Nobel Peace Prize in 1970) and colleagues developed new high-yielding wheat varieties (HYVs, termed also high-response varieties), which could benefit from the availability of these new fertilizers, and boost productivity. HYV grains had shorter stems than traditional cultivars, were genetically homogeneous, and were more productive but needed a higher rate of fertilizer intake (e.g., nitrogen). However, they resulted in crops more prone to pests and diseases. Even if some varieties have certain kinds of disease resistance built in, newly developed synthetic pesticides were necessary to keep pests out of the crops.

With the “green revolution” (as this period is referred to), the productivity of the main agriculture crops, on average, more than doubled and some cereals reached a staggering 4 to 5 times (Smil, 1991; 2000; Tilman et al., 2002; Pimentel and Pimentel, 2008), helping to meet world food demand and saving hundreds of millions from starvation. Asia, for example, which was threatened by hunger and mass starvation as late as the mid-1960s, became self-sufficient in staple foods within 20 years even though its population more than doubled (Hazell and Wood, 2008). However, along with the increase in food production, population levels kept increasing (Cohen, 2003), and paradoxically this huge boost eventually has not solved the problem of the hungry world. Late official statistics (WFP, 2008; Fao, 2010) estimates that in the last years form about 920 to 1,020 million people were undernourished and chronically hungry (based only on calorie and protein malnutrition). The real figure, however, is much larger. When other forms of nutritional deficiency are included (e.g., those caused by lack of vitamins and minerals), 3.7 billion people can be considered malnourished (FAO, 2008; UNEP, 2009).

Recent studies suggest that the world will need 70 to 100% more food by 2050 (World Bank, 2008). So a new challenge lies ahead: how to feed 9 billion with less land, water, and energy (Borlaug, 2007; Godfray et al., 2010)? The quest for higher food production is more active than ever, to the point that a new “Green Revolution” is persistently called for (e.g., Conway, 1997; Borlaug, 2007; Hahlbrock, 2007; Phelan, 2009; Godfray et al., 2010).

At present, however, malnutrition is more a matter of access to food rather than one of insufficient availability (Sen, 1982; Conway, 1997; Smil, 2000; Stone, 2002; Patel, 2008). Hunger is more a problem of income distribution rather than of food shortage. Stone (2002, p. 615) states that “The fact that so many go hungry while the granaries are bursting is widely recognized in India.” But even in countries of food plenty, such as the United States and those in Europe, a larger and larger fraction of poor people suffer from malnutrition due to food shortage. A survey of the U.S. Department of Agriculture states that in 2008, 49 million people went without access to sufficient food in the United States, and more than one in five children went without enough food during the same year (Nord et al., 2009). This cannot be attributable to lack of food supply due to low crop yields in the United States, especially when by 2012, 30% of American corn production is expected to be devoted to generating ethanol, accounting for 7.4 % of projected American total gasoline consumption (USGEOA, 2007; Koplow and Steenblik, 2008).

This famine tragedy in many developing countries clashes with the obesity epidemic in the industrialised countries, and among the newly rich people in developing countries. According to the WHO’s latest projections globally in 2005 approximately 1.6 billion adults (ages 15+) were overweight, and at least 400 million adults were obese (WHO, 2005). WHO further projects that by 2015, approximately 2.3 billion adults will be overweight and more than 700 million will be obese. Obesity is related to a number of diseases such as different types of cancer, kidney problems, and many adverse metabolic effects on blood pressure, cholesterol, triglycerides, and insulin resistance among others. This new epidemic is also very costly for the society, so that consumption of sugary and fatty foods should be a matter of concern for national health policy (Nestle, 2003).

A vegetarian diet of an equivalent 2,200 kcal per day requires 33% less fossil energy than the average American diet with meat (Pimentel and Pimentel, 2008). The Food and Drug Administration (FDA, 2007) recommends an average daily consumption of 2,000 kcal for females and 2,500 kcal per day for males, much less than the average American is consuming today. Reducing the caloric intake would significantly reduce the total energy expended for food production as well as help lessen the obesity problem.
When coming to the food system, it is disturbing that 30−40% of the food produced in the field is wasted through the food system; in industrialized countries it is estimated that 15−20% just passes directly from our refrigerators to the bin (Smil, 2000; Stuart, 2009; Godfray et al., 2010). Food wastage clashes with the increasing costs of intensive agricultural practices. Costs are being paid in terms of loss of soil and fertility, reduction of water supply, threat to biodiversity, and pollution from agrochemicals (Tilman et al., 2001; 2002; Jackson et al., 2005; Millennium Ecosystem Assessment, 2005; Molden, 2007; Vitousek et al., 2009).

All this calls for a time of careful re-evaluation: should we try to understand how our food system became this perverse? Why are we pushing for intensive agriculture to produce more crops, when we throw a lot away? Why has this increased production and consumption made us sick and unhealthy? Why do we accept a food system that impoverishes the soil, threatens biodiversity, and contaminates our environment?

II. ENVIRONMENTAL COSTS

The huge agriculture productivity boost achieved with the introduction of modern agriculture did not come without a cost. The environmental impact of agricultural activity increased too, and the overall efficiency (as output/input) declined sharply (Tilman et al., 2001; 2002; Millennium Ecosystem Assessment, 2005; Hazell and Wood, 2008; Pimentel and Pimentel, 2008).

A. Human Appropriation of Net Primary Productivity

Croplands and pastures have become one of the largest terrestrial biomes on the planet, rivaling forest cover in extent and occupying about 50% of the land surface (Foley et al., 2005). The coming 50 years are likely to be a period of rapidly expanding, global human environmental impacts. Future agricultural practices will shape, perhaps irreversibly, the surface of the Earth, including its species, biogeochemistry, and utility to society (Tilman et al., 2001; Foley et al., 2005).

Vitousek et al. (1986) proposed to use the Human Appropriation of Net Primary Productivity (HANPP) as an indicator of human pressure on the environment. Vitousek et al. (1986; 1997) estimated that until 1700, millions of humans used less than 5% of nature’s Net Primary Productivity (NPP) while in the second half of the 1900s, the HANPP already reached 40%. In 2000, it has been estimated that HANPP reached 50% (Haberl et al., 2002; Imhoff et al., 2004). However, other authors suggest a wider range. Rojstaczer et al. (2001) estimate that humans appropriate 10 to 55% of terrestrial photosynthesis products, the broad range reflecting uncertainty in key parameters and making it difficult to ascertain whether we are approaching crisis levels in our use of the planet’s resources.

Also, other indicators of sustainability (or better of unsustainability) such as the Ecological Footprint (Wackernagel and Rees, 1996) are telling us that the ecological overshoot has already reached an alarming stage. Today, humanity uses the equivalent of 1.3 planets to provide the resources we use and absorb our waste (Global Footprint Network, 2009), which dramatically indicates that humans are already living far beyond sustainability (Wackernagel et al., 2002). [The Ecological Footprint measuring system has been criticized by some scholars (e.g., van den Bergh and Verbruggen, 1999; Fiala, 2008a) on the basis that it underestimates the real impact of agricultural activities on long-term resource sustainability, and presents a logical flaw in the comparison of consumption levels and earth biocapacity].

With a human population that will grow from 6.8 billion in 2007 (PRB, 2009) to a staggering figure of 8.3 billion by the 2030 (FAO, 2002) and 9.2 billion in 2050 (UN, 2007a; Godfray et al., 2010), we have to expect HANPP to further increase just to keep pace with the production of food and fiber. In addition, more land will be lost to urbanization, leading to the destruction of vast areas along with its ecosystems.

B. Soil

Agricultural intensification leads to increasing water use and loss of soil fertility, threatening long-term crop productivity by increasing soil degradation and causing water shortages.

About 40% of global croplands may be experiencing some degree of soil erosion, reduced fertility, or overgrazing (Pimentel et al., 1995; Wood et al., 2000; Montgomery, 2007; Reynolds et al., 2007). Soil erosion has been estimated to reduce yields on about 16% of agricultural land, especially cropland in Africa and Central America and pastures in Africa (Wood et al., 2000). Dry land prone to degradation covers about 40% of the earth’s land surface and is tied with the subsistence of 2.5 billion people. In such areas agricultural management plays a key role in guaranteeing fertility conservation (Reynolds et al., 2007).

At present, the accelerated rates of erosion experienced are causing major modifications to carbon, nitrogen, and phosphorus biogeochemical cycles (Vitousek et al., 2009; Quinton et al., 2010). Resistance of soils to erosion is closely linked to the stabilizing influence of organic matter and vegetation cover. In regions such as Asia and Africa, where soil erosion is associated with reduced vegetation cover, the loss of soil carbon can trigger catastrophic shifts to severely degraded landscapes (Berhe et al., 2007; Quinton et al., 2010).

Most of the Soil Organic Matter (SOM) is found in the topsoil (15−25 cm of the A horizon) in the form of decaying leaves and stem material. SOM is of key importance for soil fertility (Allison, 1973; Altieri, 1987; Pimentel et al., 1995; Pimentel and Kounang, 1998; Lal, 2004; Bot, 2005).

The Soil Organic Carbon (SOC) pool to 1 m depth ranges from 30 tons ha−1 in arid climates, to 800 tons ha−1 in organic soils in cold regions, and a predominant range of 50 to 150 tons ha−1 (Lal, 2004). Fertile agricultural soils can contain up to 100 tons of organic matter per hectare (or 4% of the total soil weight), and in the case of most agricultural soils, SOM represents 1−5% of topsoil (Russell, 1977). Conventional agricultural practices
that tend to leave soil uncovered for long periods of the year are responsible for topsoil erosion and reduction of its SOM content. Soil removed by either wind or water erosion is 1.3–5.0 times richer in organic matter than the soil left behind (Barrows and Kilmer 1963; Allison 1973; Lal, 2004; 2010). About 95% of soil nitrogen and 25–50% of soil phosphorus are contained in the SOM-containing topsoil layer (Allison, 1973; Lal, 2010), the importance of which is such that in one study it was estimated that the reduction of SOM from 1.4% to 0.9% lowered the grain yield potential by 50% (Libert, 1995).

When poorly practiced, intensive agriculture poses a threat to soil ecology in two ways: it accelerates SOM matter oxidation and depletion, and predisposes soil to increased erosion, leading to mandatory application of nitrogen fertilizers (Allison, 1973; Pimentel et al., 1995; Matson et al., 1997; Rasmussen et al., 1998; Lal, 2004; Montgomerie, 2007; NRC, 2010). Agricultural practices such as no-till agriculture, or minimum tillage, can help to reduce soil loss and restore soil fertility (Lal, 2004; 2007; 2010; NRC, 2010).

C. Water Resources

Currently, on a global scale, 70% of the 3,800 km$^3$ of water that humans use is directed towards agriculture, 20% towards industry and 10% towards urbanized areas (Molden, 2007). By 2050 agricultural water use is expected to increase by 13% (Molden, 2007).

The production of common crops in many parts of the world requires a great amount of water, from a few hundreds to a few thousands times the final crop mass (Pimentel et al., 2004; Smil, 2002; Molden, 2007; Rockstrom et al., 2007). Estimated average values range from 0.65 m$^3$ kg$^{-1}$ for corn, 1 m$^3$ kg$^{-1}$ for wheat, 2 m$^3$ kg$^{-1}$ for soybeans, up to 6 m$^3$ kg$^{-1}$ for pork and 43 m$^3$ kg$^{-1}$ for beef (Pimentel et al., 2004; Pimentel and Pimentel, 2008). However, current levels of water productivity show large variations by commodity: 6.6–0.6 m$^3$ kg$^{-1}$ for rice, 5–1 m$^3$ kg$^{-1}$ for wheat, 3.3–0.5 m$^3$ kg$^{-1}$ for corn, 0.33–0.15 m$^3$ kg$^{-1}$ for potatoes, 33–10 m$^3$ kg$^{-1}$ for beef (e.g., Molden, 2007, tab 7.3). The concepts of “virtual water” (Allan, 1998; FAO, 2002; Smil, 2008) and “water footprint” (Khan and Hanjra, 2009; Hoekstra et al., 2009) have been proposed to assess the real cost of agricultural commodities in terms of water use.

Intensive irrigated agriculture can lead to waterlogging and salinization. Some irrigated lands have become heavily salinized, causing the worldwide loss of about 1.5 million hectares of arable land per year, along with an estimated $11 billion in lost production (Postel, 1999; Wood et al., 2000), as well as the depletion and chemical contamination of surface and groundwater supplies (Wood et al., 2000; Pimentel et al., 2004; Moss, 2008). Approximately 40% of U.S. fresh water is deemed unfit for drinking or recreational use because of contamination by dangerous microorganisms, pesticides, and fertilizers (Pimentel et al., 2004).

Agricultural impacts on freshwater and marine systems might include: effects on water composition (nutrient loss, with consequent eutrophication and food web modification), biocide leaching, suspended loads from soil erosion, hydrological cycle alteration (changed evapotranspiration rates and hence run-off and modification of river courses and irrigation water losses), effects of exotic species used, particularly in fish and crustacean culture, and physical habitat modification (channelization, channel modification, embankment and drainage) (Moss, 2008).

According to recent analysis, experts report that agricultural expansion and intensification have altered the quantity and quality of global water ways, and that these changes have increased the risk of catastrophic ecosystem regime shifts (Gordon et al., 2007). For example, during the twentieth century, humans increased the diversion of river water six-fold (Pretty et al., 2006; Molden et al., 2007).

As water becomes increasingly scarce in certain regions of the world, it will be important to increase water efficiency in irrigation and rain-fed agriculture. It is estimated that 2.8 billion people currently live in areas facing water scarcity, with agricultural water use expected to increase by 70–90% by 2050, because of changes in evapotranspiration (Molden et al., 2007). Increasing water use efficiency is then needed as well as increasing concern about the pattern of our food consumption. In this regard, above-mentioned indicators such as “virtual water” and “water footprint” will help assess the effect of human consumption patterns on water use (Molden et al., 2007; Hoekstra et al., 2009).

D. Agrochemicals

The Haber-Bosh industrial synthesis of ammonia in 1913 (Smil, 2004), and the discovery in 1939 of the insecticidal qualities of DichloroDiphenylTrichloroethane (DDT) by Swiss chemist Paul Hermann Müller (Müller, 1948), have revolutionized agriculture, and led to the production of cheap synthetic fertilizers and pesticides. The use of agrochemicals spread in the United States and Europe after World War II, following an exponential trend (Smil, 2004; Pretty, 2005; Vitousek et al., 2009).

Synthetic fertilizers have been at the core of the green revolution, but there is awareness that their widespread use can represent a serious threat for the environment (Smil, 2002; 2004; Tilman et al., 2002; Dalton and Brand-Hardy, 2003; Beman et al., 2005; Eickhout et al., 2006; Erismann et al., 2008; Vitousek et al., 2009). Pre-agricultural terrestrial Nitrogen (N) fixation has been estimated to have been 150–190 Mt N per year, while, at present, the aggregate anthropogenic fixation of N amounts to 160–170 Mt N per year (Cleveland et al., 1999; Smil, 2004).

Between 1960 and 1995, at a global scale, N fertilizer use on cereals increased sevenfold, whilst cereal yields more than doubled; however, N fertilizer efficiency (cereal yields divided by N fertilizer inputs) declined from over 70% to around 25 kg grain per kg N (Tilman et al., 2001; Cassman et al., 2002). The overall global nitrogen use efficiency of cereals decreased from ~80% in 1960 to ~30% in 2000 (Tilman et al., 2001; Erisman et al., 2008).

Global data for maize, rice, and wheat indicate that only 18% to 49% of nitrogen applied as fertilizer is taken up by crops; the
remainder is lost to runoff, leaching, or volatilization (Cassman et al., 2002). In this case, in order to improve efficiency (both on energetic and economical bases, because producing synthetic N requires energy and costs money), and greatly benefit the environment, a more rational use of fertilizers would suffice. Actually, some authors demonstrated how N application can be reduced up to 50% without compromising yield or grain quality (Madson et al., 1998; Ju et al., 2009; Vitousek et al., 2009; Ahrens et al., 2010), in turn reducing N losses into the environment.

It has been estimated that in 2005 approximately 100 Mt N from the Haber-Bosch process was used in global agriculture: only 17 Mt N was consumed by humans in crop, dairy and meat products, the remainder ending up dispersed in the environment (Erisman et al., 2008).

Eickhout et al. (2006) estimated that NH₃, N₂O and NO emissions and nitrate leaching to groundwater will grow strongly towards 2030 because of the intensification of animal and crop production systems in developing countries. In the light of the above statements, a more careful and rational use N would be a win-win solution, being of agronomical, economical, and environmental benefit (Erisman et al., 2008; Vitousek et al., 2009).

Widespread use of pesticides on crops has lead to the emergence of many pesticide-resistant pests and pathogens (Hoy, 1998; Pimentel, 1997; Krebs et al., 1999; Johansen, 2003; Pretty, 2005). Concerning pest resistance, some authors argue for the need to embrace a “mitigation” strategy, contrary to the belief that we can manage it, such as Integrated Pest Management (IPM). However, in order for mitigation measures to be effective, a holistic approach to pest management is needed, requiring the management of the global environment. As Holy (1998, p. 1799) points out: “An effective paradigm for resistance mitigation has not yet been widely deployed. This is because we have failed to accept that satisfactory resistance mitigation is based on the development of effective, fully integrated multi-tactic IPM programmes. Such programmes ideally will consider the entire agroecosystem and acknowledge the role of monitoring, economic injury levels, biological controls, genetic controls, cultural controls, and biorational controls such as mating disruption, insect growth regulators and mass trapping. A key issue in such programmes should always be whether pesticides can be used in a precise and selective manner without disrupting natural enemies. Disruption of natural enemies is not limited to acute toxicity, but can occur if pesticides are applied over a sufficiently large area so that natural enemies are limited in abundance by available food resources. It is time we recognize, as Stern et al. (1959) did, that true resistance mitigation requires a holistic approach to pest management.”

Moreover, pesticides also have a major impact on animal and human health. The book Silent Spring by Rachel Carson has been a landmark on this issue, raising public awareness of the side effects of chemicals that seemed to be a silver bullet to defeat pests. People can be exposed to excessive pesticide levels while working; via food, soil, water or air; or by directly ingesting pesticide products. Pesticides are known to cause 26 million human poisonings per year and 220,000 deaths (Richter, 2000). Along with other synthetic chemicals, some pesticides have a direct effect on the reproductive system of many high organisms, acting as endocrine disruptors, and inducing severe reproductive problems and modifying sexual behavior (Colborn et al., 1997; Lyons, 2009). Lu et al. (2006) demonstrate that an organic diet provides a dramatic and immediate protective effect against exposures to organophosphorus pesticides that are commonly used in agricultural production, in children who were most likely exposed to these compounds exclusively through their diet.

Dietary accumulation through the tropic chain, or biomagnification, can cause additional bioaccumulation, resulting in a thousand-fold increase in toxic substance chemical concentration and in increasing trophic levels in food webs, even at very low concentrations of the toxic chemicals in the environment (Kelly et al., 2007).

In the last decades efforts have been produced to reduce the use of pesticides (Pretty, 2005; Pimentel and Cilveti, 2007; Ekström and Ekborn, this issue).

In both Sweden and Indonesia, for instance, there have been notable reductions in pesticide use. Sweden has reduced pesticide use by 68% and Indonesia by 65% (Pesticides News, 435, 2001; Pimentel and Cilveti, 2007). Integrated Pest Management (IPM), a technique that combines biological control, improving host plant resistance and adopting appropriate farming practices to minimizing the use of pesticides, is regarded as the best option for the future (Ekström and Ekborn, this issue).

E. Biodiversity

Agricultural expansion has a direct impact on local biodiversity through landscape modification which in turn results in displacement of local populations and loss of ecosystem services.

The loss of native habitats and agricultural intensification, which displaces traditional varieties of seeds with modern high-yielding, but genetically uniform crops, are threatening biodiversity (both wild and domesticated) all over the globe (Wilson, 1988; Paolletti and Pimentel, 1992; Paolletti et al., 1992; Matson et al., 1997; Pimentel et al., 1997; Krebs et al., 1999; Wood et al., 2000; Donald et al., 2001; Tilmann et al., 2001, 2002; Green et al., 2004; Foley et al., 2005; Jackson et al., 2005; Millennium Ecosystem Assessment, 2005a; Chivian and Bernstein, 2008; Sachs et al., 2009). Farming, including land conversion to farmland, for instance, accounts for 37% of threats to bird species listed as threatened species (Green et al., 2005). Extensive industrialized agriculture also greatly contributes to impoverishing crop biodiversity, with the loss of a large number of agricultural species and varieties (Jackson et al., 2005; Fowler and Hodgkin, 2005).

This agricultural expansion threatens the benefit that biodiversity provides to crops by, for instance, pest control and other...
environmental services (Paoletti et al., 1992; Sommaggio et al., 1995; Altieri and Nicholls, 2004; Hillel and Rosenzweig, 2005; Bianchi et al., 2006; Sachs et al., 2009; Crowder et al., 2010). Furthermore, land use change has also a direct impact on rising CO$_2$ on global river run-off (Piao et al., 2007).

Aboveground and belowground components of ecosystems have traditionally been considered in isolation from one another, but it is now clear that there is strong interplay between them (Wardle et al., 2004). Many beneficial insects and parasitoids, for instance, spend most of their lifecycle underground before being active aboveground on the crops; preserving soil quality is, then, of foremost importance, so as to take advantage of those beneficial organisms for control of crop pests (Paoletti and Bressan, 1996). Stable litter on topsoil can encourage pests such as slugs, but can also feed detritivores and polyphagous predators and parasitoids, which would otherwise damage crops (Paoletti and Bressan, 1996). It has been reported that removing shelterbelts in rural settings can cause a loss of litter in topsoil and this can lead to a shift of feeding habits among some detritivores such as the case of the slider, Australioidillo bifrons, in NSW, Australia, which is becoming a cereal pest (Paoletti et al., 2007a; 2007b).

Agriculture intensification, along with the widespread use of chemicals, is also curtailing the benefits provided by pollinators, especially bees (Kremen et al., 2002; Biesmeijer et al., 2006; Klein et al., 2007). This is a critical issue, because although 60% of global production comes from crops that do not depend on animal pollination, still 35% of crop production depends on pollinators (5% are unevaluated yet) (Pimentel et al., 1997; Klein et al., 2007).

F. The Role of Animal Production

Worldwide, an estimated 2 billion people live partly on a meat-based diet, while an estimated 4 billion people live primarily on a plant-based diet (Pimentel and Pimentel, 2008).

Meat consumption is matter of extensive debate because the environmental impact of livestock is enormous (Rifkin, 1992; Rosegrant et al., 1999, Smil, 2000, 2002; Brown, 2005; Naylor et al., 2005; FAO, 2006; Fiala, 2008b; Pimentel and Pimentel, 2008; Stokstad, 2010).

It has been estimated that if the world’s population today were to eat a Western diet of roughly 80 kg meat per capita per year, the global agricultural land required for production would be about 2.5 billion hectares, two-thirds more than is presently used (Smil, 2002; Keyzr et al., 2005; Naylor et al., 2005). FAO (2006) estimates that global production of meat and milk will more than double in 2050, with meat rising from 229 million tonnes in 1999/2001 to 465 million tonnes in 2050, and milk from 580 to 1043 million tonnes in the same period.

Livestock production accounts for 70% of all agricultural land and 30% of the land surface of the planet (FAO, 2006). Expansion of livestock production is a key factor in deforestation, especially in Latin America where the greatest amount of deforestation is occurring; 70% of previous forested land in the Amazon is occupied by pastures, and feed crops cover a large part of the remainder. In the United States, with the world’s fourth largest land area, livestock are responsible for an estimated 55% of erosion and sediment, 37% of pesticide use, 50% of antibiotic use, and 30% of the high amount nitrogen and phosphorus contaminating freshwater ecosystems (FAO, 2006; Stokstad, 2010).

FAO (2006) estimates that in 2002 a total of 670 million tonnes of cereals were fed to livestock, representing about 30% of the global cereal harvest. According to Brown (2005), while the consumption of animal protein has grown, that share of the world grain harvest used for livestock feed has remained at about 37%. Among the cereals, FAO (2006) estimates that more than 60% of maize and barley is used mainly as feed. In addition 350 million tonnes of protein-rich processing by-products are used as feed (mainly brans, oilcakes and fishmeal). More than 97% of the soymeal produced globally is also fed to livestock (FAO, 2006). According to Smil (2002), in 1900 just over 10% of the world’s grain harvest was fed to animals, most of it going to energize the field work of draft animals rather than to produce meat while in the late 1990s it surpassed 40%, and in the United States it reached 60% in the late 1990s.

In the United States as a whole, about 300 million hectares are in pasture and about 30 million hectares are in cultivated grains for livestock production (USDA, 2007). In addition, to large amount of forage that are unsuitable for human consumption and are fed to livestock, about 323 million tons of grains, or about 816 kg per American are fed to American livestock (USDA, 2007).

It has to be stressed that typical efficiencies of protein production via animal feeding are very wasteful: at least 80% and as much as 96% of all protein in cereal and leguminous grains fed to animals are not converted to edible protein (Smil, 2000, 2002).

Increasing meat consumption would also put significant pressure on water resources. An estimated 2.5–10 times more energy is required to produce the same amount of calorie energy and protein from livestock than grain (Smil, 2000; Molden, 2007; Pimentel and Pimentel, 2008). Meeting daily nutritional energy needs would also require much higher water consumption because meat production requires 4,000–15,000 l kg$^{-1}$, while grain production just 1,000–2,000 l kg$^{-1}$.

Rockstrom et al. (2007) estimated water requirement per energy unit at 0.47 m$^3$ 1,000 kcal$^{-1}$ for cereals and 4 m$^3$ 1,000 kcal$^{-1}$ for meat.

Intensive livestock production has created problems of manure disposal and water pollution, as well as greatly contributing to GHGs emissions (Subak 1999; FAO, 2006; Pimentel and Pimentel, 2008; Koneswaran and Nierenberg, 2008). Subak (1999) estimated that the social costs of the feedlot system for beef production at 15 kg CO$_2$ equivalent kg$^{-1}$ beef are more than double that of the pastoralist system. According to estimates from FAO (2006), the amount of fossil fuels burned varies
depending on the species and type of animal product. For example, processing 1 kg of beef requires 4.37 megajoules (MJ), or 1.21 kilowatt-hours, and processing 1 dozen eggs requires > 6 MJ, or 1.66 kilowatt-hours. When considering the entire commodity chain, livestock production is estimated to release every year in the atmosphere 6.5 billions of CO₂-equivalent GHGs, accounting for 18% of GHGs emissions, a bigger share than that of transport (FAO, 2006; Fiala, 2008b) and less than only energy production [according to Fiala (2008b), GHGs emission from human activities are: Energy production 21%; Livestock production 18%; Transportation 14%; Fossil fuel retrieval 12%; Agriculture 12%; Residential 10%; Manufacturing 7%; Land use 4%; Waste disposal and treatment 3%].

In intensive animal production, drugs are often used to speed up fattening and milk production. The use of antibiotics as growth promoters destroys or inhibits bacterial populations.

In the United States (the practice is prohibited in European Union), the injection of bovine growth hormone (BGH) into dairy cattle is reported to increase milk production from 10% to 15% in dairy cows (Capper et al., 2008), but its effect on human health are still debated.

The high animal stocking rate, together with the high amount of milk production in cows, forces farmers to use antibiotics to lower the risk of epidemics spreading among animals. Livestock in the United States, for instance, are treated with 8 times more antibiotics than the human population (Pimentel and Pimentel, 2008). Such a large use of antibiotics in agriculture poses a threat to human health because it induces the spread of resistance in pathogens and has been a central issue in the medical field for decades (Cohen, 1992; Vaquero and Blázquez, 1997; FAO, 2005; Lipsitch et al., 2002; Smith et al., 2005). In the United States 70% to 80% of the antibiotics are used in livestock production, causing an estimated death of 5,000 people each year (Pimentel, 2010).

In order to work for a more sustainable agriculture, major actions should be taken concerning animal production and meat consumption in our diets, as it directly affects our impact on the planet and its resources, as well as our health (Subak, 1999; Smil, 2000, 2002; FAO, 2006; Baroni et al., 2007; McMichael et al., 2007; Fiala, 2008b; Pimentel and Pimentel, 2008).

The matter, however, is far from simple and reducing meat consumption with the view to make cereals more available and cheaper for poor people may not be easily accomplished given the current social expectations. Some scholars (e.g. Rosegrant et al., 1999; Stokstad, 2010), for instance, argue that when the farmers produce less meat, demand for corn and soy drops and the grains become more affordable. That may be good for people in the parts of Africa and Latin America where corn is a dietary staple. But people in many developing countries, particularly in Asia, eat rice and wheat as staple food, rather than corn. So, if consumers in developed countries replace meat with pasta and bread, world wheat prices may rise and that may increase malnutrition in developing countries that rely on wheat, such as India. The use of mini-livestock can be less resource-consuming, and if properly managed could represent an alternative to the current livestock production system, especially in tropical countries (Paoletti, 2005; Ochatt and Jain, 2007).

G. Concern for the Future

As pointed out by Foley et al. (2005, pp. 570–571) “In short, modern agricultural land use practices may be trading short-term increases in food production for long-term losses, in ecosystem services, including many that are important to agriculture.” Such an impact, however, although too often neglected in the accounting system, when properly assessed turns out to be very costly for society (e.g., Pimentel et al., 1995; Pimentel, 1997; Buttel, 2003; Pretty et al., 2000; 2003; McCandless et al., 2008). Policies aimed at internalizing agricultural externalities would much benefit both resource allocation and natural resource conservation. If the impact of agriculture practices on the soil and the environment cannot be mitigated, in the long run we may pose a serious threat to our living support system and to the food security of a large part of humanity. More research should be carried out in order to improve the efficiency of agricultural systems and reduce their impact on the environment and on natural resources. As stated by NRC (2010) in the case of American agriculture, for instance, only one-third of public research spending is devoted to exploring environmental, natural resource, social, and economic aspects of farming practices.

Agriculture should also aim to guarantee food security for people. As stated by FAO (2008), food security is defined as a state when “all people, at all times, have physical and economic access to sufficient, safe and nutritious food for a healthy and active life.” So, in order to guarantee food security to humanity we have to be concerned with the health of earth’s natural resources, soil fertility to start with. The World Bank in its World Development Report (2008) indicates the urgency of dealing with climate change, and highlights the fact that “Poor people who depend on agriculture are most vulnerable to climate change.” (World Bank, 2008, p. 17).

According to UNEP (2009) up to 25% of the world’s food production may become lost due to environmental breakdown by 2050 unless action is taken. And action is even more urgent when the possible effects of climate change are taken into account: these are likely to hit billions of people in developing countries, mostly those already suffering for food shortages (Parry et al., 2007; FAO, 2008; Lobell et al., 2008; UNEP, 2009; Barrett, 2010; Godfray et al., 2010).

Of course, it would be naïve to believe that our environmental concern is all that matters. We cannot dismiss the importance of social and economic forces as constraints and driving forces affecting food security, such as: access to food (Sen, 1982; Drèze and Sen, 1989), population dynamics (Smil, 1991, 2000; Hardin, 1993; Cohen, 2003), market forces (Patel, 2008), agriculture research (Smil, 2000; Pardey et al., 2006; Alston et al., 2009), access to credit (Yunus, 2009), subsidies and commodity price distortion (Peterson, 2009; Anderson et al., 2010), availability
of natural resources (Tilman et al., 2002; Pimentel and Pimentel, 2008; Smil, 2008; UNEP, 2009), production lost in post harvest storage and management (Smil, 2000; PHLIS, 2010).

III. THE CALL FOR SUSTAINABILITY IN AGRICULTURE

The definition of “sustainable agriculture,” in its modern approach, can be traced back to the United States in the early 1980s, indicating a way of farming that should mimic natural ecosystems. Within the domain of sustainable agriculture fall some other definitions and practices such as agroecology, integrated agriculture, low input, precision agriculture and organic agriculture (Pretty, 2008). In the last decades, in order to face the challenge to feed 9 billion people by 2050, a concept called “sustainable intensification” has been discussed, meaning producing more food from the same area of land while reducing the environmental impacts (Pretty, 2002; 2008; Royal Society of London, 2009; Godfray et al., 2010).

A. Development and Goals of Sustainable Agriculture

The conceptual setting for the definition of sustainable agriculture has been posed by Wes Jackson who is credited to have been the first to use the term “sustainable agriculture” in his publication New Roots for Agriculture in 1980 (Harwood, 1990; Kirschenmann, 2004). In a 1983 paper, Rodale proposed the concept of “regenerative agriculture” referring to the need for an agriculture based on the principle of ecological interactions (Harwood, 1990).

The term “sustainable agriculture” did not emerge in popular usage until the late 1980s. Sustainable agriculture must, as defined by the U.S. Department of Agriculture in the 1990 Farm Bill: “… over the long term, satisfy human needs, enhance environmental quality and natural resource base, make the most efficient use of nonrenewable resources and integrate natural biological processes, sustain economic viability, and enhance quality of life.” (USDA, 1990). The early idea of a sustainable agriculture was for a farming system that mimics natural ecosystems (e.g., Jackson, 1980; Soule and Piper, 1991; Scherr and McNeely, 2007). We remember also the lesson of Eugene P. Odum (one of the fathers of modern ecology), who in his talks and books made the point that American agriculture has to mimic native forests and prairies to become more sustainable (Odum, 1993). Over time, nature tends to establish more diversity than humans do with most of their agricultural systems. In a productive hectare of agricultural land there may be tens of thousands of species of organisms that weigh up to 10 tons (Lavelle and Spain, 2002; Pimentel, 2006). Thus, agriculture, when properly managed, still can preserve a great deal of biodiversity. Lately the term “ecoagriculture” has also been proposed (e.g., Scherr and McNeely, 2007).

Sustainable agriculture should aim at: preserving the natural resource base, especially soil and water, relying on minimum artificial inputs from outside the farm system, recovering from the disturbances caused by cultivation and harvest while at the same time being economically and socially viable (Poincelot, 1986; Altieri, 1987; Edwards et al., 1990; Soule and Piper, 1991; Dunlap et al., 1992; Francis et al., 2006; Pimentel et al., 2005; Gliessman, 2007). Sustainable agriculture does not refer to a prescribed set of practices and it differs from organic agriculture because, in sustainable agriculture, agrochemicals (synthetic fertilizers and pesticides) may or may not still play a role. However, their use is kept to a minimum or not used at all, and conservative practices (crop rotation, integrated pest management, natural fertilization methods, minimum tillage, biological control) are fully integrated in farm management.

As summarized by Pretty (2008, p. 451) the key principles for sustainability can be summarized as:

(i) integrate biological and ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration, allelopathy, competition, predation and parasitism into food production processes,

(ii) minimize the use of those non-renewable inputs that cause harm to the environment or to the health of farmers and consumers,

(iii) make productive use of the knowledge and skills of farmers, thus improving their self-reliance and substituting human capital for costly external inputs, and

(iv) make productive use of people’s collective capacities to work together to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management.

According to many authors there is much room for improvement toward a more sustainable agriculture, both in developed and developing countries (Smil, 2000; Altieri, 2002; Cassman et al., 2002; Jackson, 2002; Pimentel et al., 2005; Jordan et al., 2007; Pretty, 2008; Bohlen and House, 2009; Glover et al., 2010a). Recent research in the United States, for instance, has demonstrated that organic production of the two most important crops (corn and soybeans) can be produced without commercial nitrogen, without soil erosion, without insecticides or herbicides and with 30% less fossil energy (Pimentel et al., 2005). The corn and soybean yields were equal to yields using conventional production methods.

B. Assessing Sustainability: A Complex Issue

For sustainable agriculture, the major challenges to be addressed are (Lowrance et al., 1986; Conway, 1987; Hansen, 1996; McConnell and Dillon, 1997; Bland, 1999; Ruttan, 1999; Kropff et al., 2001; von Wieren-Lehr, 2001; Altieri, 2002; López-Ridaura et al., 2002; Pretty, 2002; Giampietro, 2004; Gomiero et al., 2006; Bland and Bell, 2007; Jordan et al., 2007; Bohlen and House, 2009):

- The multifunctional nature of agriculture (not only producing commodities, but also preserving the health of ecosystems, consumers and rural communities),
The multi-scale nature of the complex network of relations among ecosystems and socioeconomic systems, which requires considering simultaneously different but relevant dynamics operating at different hierarchical levels.

However, as already noted by some authors (e.g., Lowrance et al., 1986; Hansen, 1996; Park and Seaton, 1996; Gomiero et al., 2004; Sydorovych and Wossink, 2008), sustainable agriculture means many things to different people, and definitions abound. Goldman (1995), lists fourteen definitions of sustainability in the field of agriculture, and argues, for instance, that the concepts of sustainable agriculture are based mainly on the experiences and norms of western industrial nations and may not be appropriate to sub-Saharan Africa and other developing regions. Beets (1990, p. 723), for instance, referring to subsistence agriculture state that sustainable agriculture is: “The ability of a system to maintain productivity in spite of a major disturbance, such as caused by intensive stress or a large perturbation,” and that perfectly fits the needs of subsistence farmers.

What is “sustainable” may be also culture-oriented. For instance, when the Western agriculture package is transferred to other continents, it tends to dismiss, or overlook, many sorts of traditional local resources – such as insects and other arthropods, earthworms, small vertebrates and wild plants (insects and earthworms, for instance, may total more than 3,000 kg/ha; Pimentel and Pimentel, 2008). These local resources can play an important role in guaranteeing food security in poor rural areas, but are often neglected because of the Western perception that these are not “proper food” for people (Paolelli and Bukkens, 1997; Paolelli, 2005; Ochatt and Jain, 2007).

Being a complex issue, “sustainability” depends on the perspective taken when looking at the system. This lead to some key considerations when attempting sustainability assessment (Giampietro, 2004; Gomiero et al., 2006):

- Farming systems are not steady-state systems but highly adaptable and evolving systems (ceteris are never paribus),
- Any representation of these systems depends on a set of choices made by the observer when framing the identity of what is observed,
- It is impossible to reach the best/optimal solution to a problem of sustainability, we should address the issue of “sustainable/optimal for whom and in which sense,” as there is no solution that optimizes all the possible criteria of performance for all the relevant actors (who decides who are the relevant actors and how?),
- Any assessment implying a value judgment (such as good or bad) cannot be made by the application of an algorithm within an optimization protocol. Rather, value judgments must be made within a participatory process of multi-criterial assessment,
- When dealing with participatory processes of multi-criterial assessment, it is crucial to be able to guarantee not only the quality of the scientific analysis used for characterizing options and scenarios, but also the quality of the process of participatory assessment itself.

This implies that an adequate representation of a farming system requires a multi-dimensional, or multi-criterial, approach, in which many dimensions (e.g., economic, environmental, social, cultural dimension), and many levels of analysis (e.g., farmers, consumers, governments, international agreements) have to be simultaneously taken into account. This is what can be defined also as “Integrated Assessment” as defined by Rotmans and van Asselt (1996, p. 327): “an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena” Beddoe et al. (2009) discuss even the need to redefine the very institutional structure of society in view to meet the call for sustainability.

Because of its complex, multi-dimensional nature, it is widely recognized that assessing farming systems and agricultural sustainability requires to embrace a number of different scales, criteria and sets of indicators. Such a complex approach has been developed both theoretically (e.g., Lowrance et al., 1986; Ikerd, 1993; Wolf and Allen, 1995; Bland, 1999; Morris and Winter, 1999; Kropff et al., 2001; von Wirén-Lehr, 2001; Piorr, 2003; Gomiero, 2004; Gomiero et al., 2006; Verburg et al., 2006; van Cauwenbergh et al., 2007; Sydorovych and Wossink, 2008), as well as applied in a number of case studies both in developed and developing countries (e.g., Beets, 1990; McConnell and Dillon, 1997; Gomiero et al., 1997; Beinat and Nijkamp, 1998; Giampietro and Pastore, 1999; Gliessman, 2000; Gomiero and Giampietro, 2001; López-Ridaura et al., 2002; Giampietro and Ugliati, 2005; Gafsi et al., 2006; More et al., 2007; Groot et al., 2007; Janssen and van Ittersum, 2007; van Ittersum et al., 2008). The interested reader could refer to Collinson (2000) for a history of farming systems research.

NRC (2010, p. 528) argues that: “To pursue systemic changes in farming systems, research and development have to address multiple dimensions of sustainability (productivity, and environmental, economic, and social sustainability) and to explore agroecosystem properties, such as complex cropping rotations, integrated crop and livestock production, and enhanced reliance on ecological processes to manage pests, weeds, and diseases (recognizing their interconnectedness and interactions with the environment), that could make systems robust and resilient over time.”

IV. POSSIBLE ACTIONS TOWARDS A MORE SUSTAINABLE AGRICULTURE

There is an urge to develop more ecological agriculture practices able to preserve soil fertility, reduce the consumption of nonrenewable natural resources and integrated with local...
biodiversity and landscape. The Millennium Ecosystem Assessment (2005) recommended the promotion of agricultural methods that increase food production without harmful trade-offs from soil erosion, excessive use of water, nutrients, or pesticides. FAO (2002; 2003; 2004) also stressed the need to reduce the environmental impact of agriculture practice as it poses a risk to the sustainability of agriculture and food security itself.

In the last decades, a number of different philosophical approaches to agriculture management and novel agronomic techniques have been proposed and implemented in order to meet the demand for a more sustainable agriculture. Here we list the main approaches in alphabetic order.

A. Agroecology

The use of the term agroecology can be traced back to the 1930s (Wezel et al., 2009), and by the 1980s had reached a broad diffusion. The scales and dimensions of agroecological investigations changed over the past 80 years from the plot and field scale to the farm and agroecosystem scale.

In the 1980s some scholars argued that in order to move towards a more sustainable agriculture a whole-farm holistic approach needed to be embraced. Such an approach stands at the basis of the science of agroecology (Altieri et al., 1983; Altieri, 1987; 2002; Conway, 1987; Gliessman, 1990). As defined by Altieri (2002, p. 8, bold in original) “Agro-ecosystems are communities of plants and animals interacting with their physical and chemical environments that have been modified by people to produce food, fiber, fuel and other products for human consumption and processing. Agro-ecology is the holistic study of agro-ecosystems including all the environmental and human elements. It focuses on the form, dynamics and functions of their interrelationship and the processes in which they are involved.” Lately the term agroecology has been used to include the agrifood system (see Francis et al. this issue).

The new concept and approach found wide audience among scholars, and established agroecology as a respected scientific field in its own right (Paoletti et al., 1989; Carrol et al., 1990; Altieri, 2002; Francis et al., 2003; Altieri and Nicholls, 2004; Giampietro, 2004; Wojtkowski, 2006; Gliessman, 2007; Bohlen and House, 2009; Wezel and Soldat, 2009; Wezel et al., 2009).

According to Wezel et al. (2009), three approaches can be distinguished: (1) investigations at plot and field scale, (2) investigations at the agroecosystem and farm scale, and (3) investigations covering the whole food system.

In order to properly study agroecosystem functioning and management, integrated scale analysis has to be performed along with the multiple scales and dimensions of agrosystems (Conway, 1987; Lowrance et al., 1986; McConnell and Dillon, 1997; Gomiero et al., 1997; 2006; Bland, 1999; Kropp et al., 2001; Altieri, 2002; López-Ridaura et al., 2002; Giampietro, 2004; Bland and Bell, 2007; Vadrevu et al., 2008).

B. Agriculture Intensification

With world food demand doubling by 2050, how to preserve natural habitats will become a critical challenge. Two competing solutions are proposed: (1) a wildlife-friendly farming, which boosts densities of wild population on farmland but may decrease agricultural yields; and (2) land sparing, which minimizes demand for farmland by increasing yield by improving crop efficiency (Trewavas, 2001; Pretty, 2002; 2008; Tilman et al., 2002; Cassman et al., 2003; Green et al., 2004; Burney et al., 2010). The term “eco-efficiency” has been used by some scholars (Groot et al., 2007; Wilkins, 2008; Keating et al., 2010; Lal, 2010) to address the interrelationships and trade-offs among a host of production, conservation, economic, and social values at landscape scale.

Some authors (e.g., Cassman et al., 2003) warn that although harvested cereal production area has remained relatively constant during the past 20 years, evidence of yield stagnation in several major cropping systems will make it increasingly difficult to sustain increases in food production without an expansion in cultivated areas. They conclude that increased nitrogen use and water use efficiency, and improved soil quality, are key factors in order to avoid expansion of cultivation into natural ecosystems, while meeting human needs. However, such an issue is very complex and simple models, which, for instance, claim that technological advance can lead to sparing land has been proven untrue in a number of cases (García-Barrios et al., 2009; Perfecto and Vandermeer, 2010). Perfecto and Vandermeer (2010), for instance, in the case of tropical agriculture and forest conservation, claim that social context makes a difference in the direction as well as the degree of impact of agricultural intensification on deforestation.

However, whether increasing agriculture intensity (crops yield) results in a reduction of cultivated land is a matter of debate, as some authors do not find any correlation between agriculture intensification and sparing land (e.g., Ewers et al., 2009; Rudel et al., 2009). Ewers et al. (2009), for instance, argue that in developing countries there is a tendency for the area used to grow crops other than staples to increase in the countries where staple crop yields increased. There remained a weak tendency in developing countries for the per capita area of all cropland to decline as staple crop yield increased, a pattern that was most evident in developing countries with the highest per capita food supplies. In developed countries, there was no evidence that higher staple crop yields were associated with decreases in per capita cropland area.

C. Integrated Agriculture

Integrated agriculture is a farming method that combines management practices from conventional and organic agriculture. As an example, animal manure may be used instead of chemical fertilizer when possible. Pest management (integrated pest management) is carried on combining several methods: using crop rotation, the release of parasitoids, cultivating
pest-resistant varieties, and using various physical techniques, leaving pesticides as the last resort (Edens, 1984; Poincelot, 1986; Pimentel, 1997; Mason, 2003; Pretty, 2005; Altieri and Nicholls, 2004; Francis et al., 2006).

Weeds can be managed through tillage and cultivation practices, using competitive cultivars, crop diversification and other factors can be used to reduce weed germination, growth, competitive ability, reproduction, and dispersal. Introducing arthropod and microbial biocontrol agents can also be successfully employed (Altieri, 1987; Pimentel, 1997; Liebman et al., 2001; Lampkin, 2002; Gliessman, 2007). Integrated agriculture is not governed by specific regulations but its goal is still to reduce as much as possible both farm management costs and its environmental impact, aiming at the long term sustainability of farming practices.

D. Organic Agriculture

A different alternative to sustainable agriculture has been proposed and implemented by the organic agriculture movement. Although sustainable agriculture practices are adopted by an increasing number of farmers only organic agriculture is regulated by laws and needs to strictly follow a specific set of norms. Such norms, among other, forbid the use of agrochemicals and strictly regulate the use of drugs in animal rearing; they also forbid the use of GMO. Because of this topic will be widely dealt with in a specific paper in this issue (see Gomiero et al., this issue), in this section we will give just a very brief introduction.

The organic movement appeared in Europe in the 1920s and in the United States in the 1940s representing farmers and citizens refusing the use of agrochemicals, and willing to persevere with traditional agricultural practices (Conford, 2001; Lotter, 2003; Lockeretz, 2007). The organic movement has national and international representatives. The International Federation of Organic Agriculture Movements (IFOAM), is based in Bonn, Germany (http://www.ifoam.org/).

Organic agriculture has been officially recognized by the European Union in 1991 and by the America federal government in 1995. Internationally, the Codex Commission approved the Codex Guidelines for plant production in June 1999, followed by animal production in July 2001. The Codex Alimentarius Commission at point 5 states that: “Organic Agriculture is one among the broad spectrum of methodologies which are supportive of the environment. Organic production systems are based on specific and precise standards of production which aim at achieving optimal agroecosystems which are socially, ecologically and economically sustainable.” (Codex Alimentarius, 2004, p. 4).

Organic agriculture other than crops productivity aims at preserving soil fertility, reducing soil erosion, conserving water, biodiversity, landscape, ecological functionality, and reducing global change (Reganold et al., 1987; FAO, 2002; 2004; Mäder et al., 2002; Pimentel et al., 2005; Kristiansen et al., 2006; Niggli et al., 2009; Crowder et al., 2010).

Organic agriculture can represent a valuable option in order to work for a more sustainable agriculture, and deserves wide experimentation to fully explore and understand its potentialities as well as constraints and limitations.

E. Permaculture

Mollison and Holmgren, in their book Permaculture One: A Perennial Agriculture for Human Settlements (Mollison and Holmgren, 1978) coined the term “permaculture”, a contraction of “permanent agriculture.” Permaculture puts the emphasis on management design and on the integration of the elements in a landscape, considering the evolution of landscape over time. The goal of permaculture is to produce an efficient, low-input integrated culture of plants, animals, people and structure, and integration that is applied at all scales from home garden to large farm (see also http://www.permaculture-info.co.uk/). However, one problem with permaculture is that biomass from surrounding areas is used to fertilize the permaculture areas. Thus, this is depleting resources in the surrounding areas.

F. Precision Agriculture

Precision agriculture (also known as “precision farming,” “site-specific crop management,” “prescription farming,” and “variable rate technology”) has developed since the 1990s, and refers to agricultural management systems carefully tailoring soil and crop management to fit the different conditions found in each field. Precision agriculture is an information and technology based agricultural management system (e.g., using remote sensing, geographic information systems, global positioning systems and robotics) to identify, analyze and manage site soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment (Lowenberg-DeBoer, 1996; National Research Council, 1998; Srinivasan, 2006; Gebbers and Adamchuk, 2010). Precision agriculture is now taught in many universities around the world (see for instance http://precision.agri.umn.edu/links.shtml).

G. Perennial Crops

Because of the dramatic consequences of plowing on soil conservation, in the United States since the 1980s some authors (Jackson, 1980; 2002; Soule and Piper, 1991; Glover, 2005; Glover et al., 2007, 2010a; 2010b) began suggesting to move from an agriculture based on annual crops to an agriculture relying on the cultivation of perennial crops, so that the detrimental effect of soil tillage and agrochemical usage could be avoided or at least greatly reduced.

Perennial crops [e.g., Intermediate wheatgrass (Thinopyrum intermedium) and other perennial Th. species, Maximilian sunflower (Helianthus maximiliani), Illinois bundleflower (Desmanthus illinoensis) and Flax (a perennial species of the Linum genus)] have been proposed in order to reduce nitrogen loss
and improve soil conservation. Perennial crops, with their roots exceeding depths of two meters, can improve ecosystem functions, such as water conservation, nitrogen cycling and carbon sequestration; more than 50% when compared to conventional crops. Perennial crops are reported to be 50 times more effective than annual crops in maintaining topsoil, reduce N losses from 30 to 50 times, and store about 300 up to 1,100 kg C/ha per year compared to 0 to 300–400 kg C/ha per year as do annual crops. It is believed they could help restrain climate change (Cassman et al., 2002; Cox et al., 2005; Glover et al., 2007; 2010a; 2010b).

Management costs are also reduced because perennial crops do not need to be replanted every year, so they require fewer passes of farm machinery and fewer inputs of pesticides and fertilizers as well, which reduces fossil-fuel use. Glover et al. (2007) report that herbicide costs for annual crop production may be 4 to 8.5 times the herbicide costs for perennial crop production, so fewer inputs in perennial systems mean lower cash expenditures for the farmer.

Perennial crops are predicted to better adapt to temperature increases as the magnitude predicted by most climate-change models. Cassman et al. (2002) report that increases of 3 to 8 degrees Celsius are predicted to increase yields of switchgrass (Panicum virgatum), a perennial forage and energy crop, by 5,000 kg per ha, whereas for annual species yields are predicted to decline (e.g., maize, −1,500 kg per ha; soy-bean, −800 kg per ha; sorghum, −1,000 kg per ha).

H. Transgenic Technology

Technological advancements in the field of genetics have made it possible to manipulate gene expression and operate gene transfers from an organism to another. Such possibility opened the doors for a wide number of practical applications, mainly in medicine and agriculture.

It is beyond the scope of the present paper to provide a review of genetic engineering in agriculture and related debates on social, political and ethical issues (e.g., patenting life and intellectual property rights, biopiracy, bio-safety and the precautionary principle). However, because of its relevance on agriculture sustainability we wish to briefly introduce the topic.

Genetic Modified Organism (GMO) or Transgenic Organisms (TO) are considered by many a chance to meet the food demand while at the same time preserving the environment and limiting agriculture environmental impact. According to many authors GMOs can represent a new “green revolution”, especially for developing countries facing food scarcity, as they could be able to boost agriculture productivity and cope with new environmental challenges, such as climate change and soil exhaustion, while at the same time benefiting the conservation of natural resources (Conway, 1997; Ejeta, 2010; Enserink, 2010; Fedoroff et al., 2010; Gilbert, 2010).

Crops, could, for instance, be engineered to resist pest, improve water use efficiency, cope with drought or salty soil, self fix N, or to produce more or novel important nutritional elements (e.g., the case of golden rice, Enserink, 2010) (Conway, 1997; Chrispeels and Sadava, 2002; Hails, 2002; Hahlbrock, 2007; Murphy, 2007; Ferry and Gatehouse, 2009; Royal Society of London, 2009; Fedoroff et al., 2010; Gilbert, 2010; Pennisi, 2010; Tester and Langridge, 2010).

In Bt corn, a toxin-encoding gene from the bacterium Bacillus thuringiensis has been successfully transferred to corn to defend it from stem borer (Ostrinia nubilalis), a major corn pest. Crops can also be engineered to be resistant to herbicides; in this way weeds can be reduced without affecting crops. Such is the case, for instance, of soybean tolerant to the herbicide Round Up®. About 90% of U.S. corn and soybeans are herbicide tolerant in the United States, since the introduction of herbicide-tolerant plants, the use of herbicides has been reported to be increasing (Benbrook, 2009), and the excessive use of herbicides can have a negative impacts on the environment.

According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA, 2010), the use of plant transgenics is the fastest adopted crop technology: in 2009 there were 134 million ha of biotech crops, with an underlying 80-fold land increase from 1996 to 2009 and a year-to-year growth of 9 million hectares or 7% on average. Developing countries have increased their share of global biotech crops to almost 50% and are expected to continue to significantly increase biotech hectarage in the future. Figures supplied by ISAAA (2010) for 2009 indicate that Round Up® soybean is the principal biotech crop, accounting for 69.2 million ha or 52% of global biotech crop area (65.8 million ha in 2008), followed by Bt maize (41.7 million hectares or 31%, 37.3 million ha in 2008), Bt cotton (16.1 million hectares or 12%, 15.5 million ha in 2008) and Round Up® canola (6.4 million hectares or 5%, 5.9 million ha in 2008).

While GMOs such as Bt corn and cotton, and herbicide-tolerant soybean have been cultivated in USA since 1990s, most of the European countries are still against their approval for cultivation. In Europe the environmental release of GMO, generated an extensive and intense social and political debate, concerning the environment and food safety and the ethical acceptability of engineered crops (Wolfenbarger and Phifer, 2000; Hails, 2002; Altieri et al., 2004; Borlaug, 2007; Stokstad, 2008; Waltz, 2009), and a precautionary approach to their release has been invoked by some stakeholders (Aslaksen and Ingeborg Myhr, 2007). It has to be pointed out that the use of GM technology in medical screening and therapy is not met with the same level of hostility, and this holds true even amongst radical environmentalist movements.

Some researchers hold that even organic farming could benefit from using transgenic crops because of the benefit for the environment and reduction of farming costs (Amman, 2008). Some authors (e.g., Stone, 2002) criticize the fact that genetic research is mostly in private hands, and does not pursue what may really benefit the poor: the genetic improvement of staple-subsistence crops, such as: cassava (Manihot esculenta), sorghum, pearl millet, because of companies could not make money out of that.
Environmental risks directly related GMO cropping concerns two main issues: (1) the effect of gene flow to non target organisms, and (2) the probability of gene flow to relative wild plants (leading, for instance, to weed resistance to herbicides) (Ellstrand, 2003; Chandler and Dunwell, 2008; Romeis et al., 2008). A further issue concerns the development of resistance in weeds and pests, as happened with agrochemicals.

Concerning the first issue, it is reported that large international initiatives are already under way to develop a scientifically rigorous approach to evaluate the potential risks to non target arthropods posed by insect-resistant and genetically modified crops (Romeis et al., 2008).

Transgene flow (introgression) from GRCs to non-GM crops or wild weeds is the largest risk posed by glyphosate resistant crops (GRCs). Glyphosate resistance transgenes have been found in fields of canola that was supposed to be non-transgenic (Cerdeira and Duke, 2006).

Spread of weeds and pests resistance is an issue that deserves much attention. It has been reported that about a dozen different varieties of weeds are known to have developed resistance to glyphosate, and that the spread of resistance to new weed species is increasing in countries like the United States, Argentina, South Africa, Israel, and Australia (Cerdeira and Duke, 2006; Service, 2007; Phelan, 2009; Nandula, 2010). Pest resistance in Bt cotton has also been reported in the United States (Tabashnik et al., 2009). According to some authors, resistance spread could be overcome by improving regulatory systems and adopting genetic techniques that can find wider approval among the public (Fedoroff et al., 2010; Tester and Langridge, 2010).

Pest ecology is a very complex issue, and our knowledge of the matter is still quite limited. Transgenic crops should not to be considered a magic bullet for pest control (Lu et al., 2010).

For instance, whenever a primary pest is targeted and controlled, other species are likely to rise in its place. It has been reported, for example, that the boll weevil (Anthonomus grandis) was once the main worldwide threat to cotton. As farmers sprayed pesticides against the weevils, bollworms (Pectinophora gossypiella) developed resistance and rose to become the primary pest. Similarly, stink bugs Euschistus servus (Say), E. tristigmus (Say), Acrocer numhilar (Say), Nezara viridula (L.), and leaf-footed bugs such as Leptoglossus spp. (primarily L. phyllopus) have recently grown back again to be important primary pests of most fruit, nut, vegetable and grain/seed crops in the Southeast and other areas of the United States. Since Bt cotton was introduced, they have replaced bollworms as the primary pest in southeastern United States (Hollis, 2006; Benbrook, 2009; VV. AA. 2009; Qiu, 2010). Use of refuge may help to prevent the spread of resistance (Tabashnik et al., 2008). Refugia work by maintaining populations of susceptible insects, some of which will mate with resistant insects, thereby diluting the presence of Bt-resistant genes in insect populations. However, refugia contamination has also been reported (e.g., Chilcutt and Tabashnik, 2004) and vigilance should be maintained to make sure that farmers comply with the recommendations given on this matter by the agronomists.

The recent experience with Bt cotton in China should be of concern. More than 4 million hectares of Bt cotton are grown in China. Bt cotton was planted in order to fight the bollworm Helicoverpa armigera. However, since the introduction of Bt cotton and the ensuing reduction in pesticide use, the numbers of mirid bugs (insects of the Miridae family), which are not susceptible to the Bt toxin, from being only minor pests in northern China in 1997, have increased 12-fold. Mirids are now becoming a major pest in the region, reducing cotton yields by up to 50% in the absence of further pest control. Moreover, differently from bollworms, mirid bugs are also a threat to crops such as green beans, cereals, vegetables and various fruits (Lu et al., 2010), resulting in the new pest causing an overall greater crop and economic loss.

According to some authors (e.g., Kiers et al., 2008), GM technology is not to be rejected on principle. Its contribution being promising in some contexts, unpromising in others, and unproven in many more. For instance, genetic engineering may prove beneficial is in the development of annual grains becoming perennial grains. Naturally occurring genes that permit exchange of DNA between chromosomes of different species or genera can be used to obtain offspring with desirable traits from both parents. Plant breeders can use genetic modification to introduce new genes, to modify existing genes, or to interfere with gene expression in specific cases (Glover et al., 2010b).

Chrispeels and Sadava (2002) point out that GM technology can play an important role in enhancing agriculture performances and benefit humanity. At the same time, they highlight also that in a world of plenty, distribution of food, and not its production, is the main culprit for current hunger and malnutrition.

V. CONCLUSION

In this paper we have examined some issues concerning the environmental impact of current agricultural practices. Warnings are issued by many experts, regarding the high impact that current agricultural practices are posing on the environment and on long-term soil fertility.

Moving our agriculture toward a more sustainable path is not an easy task, because we need to simultaneously deal with a number of different environmental, social, economic, technical issues, and tackle these at many different levels, from individual farms to the global agro-food system.

We presented a number of alternative agricultural practices that can be adopted, to make agriculture less environmentally damaging, reducing the use of natural resources and preserving soil fertility and biodiversity.

We think that there is room for a different and more ecological agriculture and that research should be conducted in order to better assess the potential and the constraints of the different options available to us.
Eventually, however, it might be required of our society that it changes some of its paradigms and “values” in order to preserve our support system, the soil and its health, for the future generations.

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