Soil and crop management to save food and enhance food security

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Chapter Outline

2.1 Introduction: enhancing food security by reducing yield loss

The coming decades will present a major challenge for the human population. Managing water, energy, and food procurement to feed the present and future population will call for our utmost ingenuity and wisdom. Although the overall population growth rate is decreasing, the population is still growing, especially in Asia and Africa. The present population of 7.5 billion (of which about 900 million are still undernourished) is expected to reach 8.5 billion in 2030 and 10 billion in 2050 (Alexandratos and Bruinsma, 2012; UN, 2017). Increasing food consumption per capita, and particularly meat intake (Smil, 2013; Godfray et al., 2018), will pose further pressure on natural resources (i.e., water, soil, energy) and exacerbate

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human impact on the environment (i.e., agrochemicals, greenhouse gas emissions (GHGs), biodiversity loss) (Pretty, 2008; Godfray et al., 2010, 2018; FAO, 2011a,b; Foley et al., 2011; Gomiero et al., 2011a; Alexandratos and Bruinsma, 2012; Gomiero, 2016; Campbell et al., 2017). It has been argued that, to meet food demand, in 2050 global agricultural production may have to increase by 70%– 110% (Bruinsma, 2003, 2011; Tilman et al., 2011; Alexandratos and Bruinsma, 2012).

Although in the last decades yields have increased dramatically, food loss and waste are still extremely high.

Food losses refer to the decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption (Parfitt et al., 2010; FAO, 2011a). FAO (2014a) defined food loss also as "the decrease in **quantity or quality** of food reflected in nutritional value, economic value or food safety of all food produced for human consumption but not eaten by humans" (bold added by the author). Therefore, in addition to yield, expressed in biomass harvested per ha, the nutritional content of produce has also to be addressed. The term *food waste* refers to food losses occurring at the end of the food chain (retail and final consumption), and relates to retailers' and consumers' behavior (Stuart, 2009; Parfitt et al., 2010; FAO, 2011a). Parfitt et al. (2010) stated that addressing moral and economic dimensions of food may lead the following to be included as food loss: crops diverted into feeding livestock, biofuels (see also Gomiero, 2015a), or biomaterials production.

It has been estimated that 30%–40% of all food harvested is lost or wasted each year (Stuart, 2009; Parfitt et al., 2010; FAO, 2011a; Royte, 2016); these estimates may vary greatly depending on the specific crops, locations, and situations involved (Parfitt et al., 2010). The figures are nevertheless indicative of a very significant issue, and reducing food losses is a key step to saving food.

Crop yields lower than potentially achievable can also be considered as food loss. Crops can perform poorly for a number of reasons, for example, weather extremes, pests, and poor agricultural practices. Poor agricultural practices such as monoculture, failing to implement proper crop rotations, intensive use of inputs, and poor water management eventually lead to soil degradation (i.e., reduced fertility and soil erosion), accumulation of toxic compounds in the soil, reduced nutritional content of produce, and a weakening of plant defenses, which in turn facilitates pest attack.

Therefore, to sustain food production in the long run, it is necessary to adopt agricultural practices that preserve soil and crop health. This also in view of the potential effect of climate change, which may dramatically impact on the performance of agriculture systems (affecting both produce yield and quality), as recent work seems to indicate (Medek et al., 2017; Myers et al., 2017; Scheelbeek et al., 2018; Tigchelaar et al., 2018; Zhu et al., 2018). Of course, reducing food losses and improving the sustainability of the food system require a rethinking of the functioning of the whole food system, including the impact of food choices, the alternative use of food such as the production of biofuels, power relations along the food chain, and the impact of the globalization process (Smil, 2000, 2013; Pretty, 2008;

Lang et al., 2009; Perfecto et al., 2009; Stuart, 2009; Conway, 2012; Nestle, 2013; Gomiero, 2015a, 2018a,b).

In this chapter, the relation between soil health, agricultural practices, and yield loss is discussed. I review how unsustainable agricultural practices' effect on soil organic matter (SOM) and soil structure is revised in spite of soil fertility reduction. The potential of agroecological agricultural practices to preserve soil health and increase yields while reducing the use of agrochemicals, as well as their potential limitations, are discussed. The concept of food security is then introduced, followed by a discussion on how unsustainable agricultural practices can reduce yields. Thereafter, soil conservation as an imperative to guarantee food security to the present and future population is denoted. The next section analyzes how unsustainable agricultural practices may impact on crop yield. Some agroecological practices that may help protect soil health and increase yields while reducing the use of inputs are also reviewed, prior to focusing on using crop genetic diversity as a means to enhance crop protection and increase yield. The potential of some technological approaches [namely precision farming and genetically modified (GM) crops] to preserve soil, increase yield, and reduce the environmental impact of food production is discussed, too. Finally, conclusions and other important issues impacting the sustainability of food production (e.g., biofuels, power relations in the food system, and the role of food choices) are presented.

2.2 Yield loss and food security

In the field, crop loss can happen at the time of harvest as edible crops are left in field, ploughed into soil, eaten by birds or rodents, or because timing of harvest is not optimal. Produce may also be damaged while harvesting due to poor harvesting technique (Cassman et al., 2003; Deguine et al., 2009; Parfitt et al., 2010). Yield loss can occur during crop growth due to the combined effect of weeds and pests (insects, rodents, plant diseases caused by bacteria, fungi, or viruses), which reduce yield in the field and may affect produce quality (pests may cause spoilage also during the postharvest phase, i.e., during storage and transportation) (Cassman et al., 2003; Deguine et al., 2009; FAO, 2011a). At the field level, harvest losses have been estimated at around 26%–30% for sugar beet, barley, soya, wheat and cotton, 35% for maize, 39% for potatoes and 40% for rice, with high regional variability (Deguine et al., 2009).

Further to that, yields can be heavily reduced by soil degradation (i.e., loss of soil fertility) (Foley et al., 2005; Montgomery, 2007b; FAO, 2015; FAO and ITPS, 2015; Lal, 2015a; Gomiero, 2016). Panagos et al. (2018) noted that soil erosion, on average, accounts for an 8% yield loss after 25–30 years cropping, notwithstanding the increasing use of inputs to replace nutrient loss due to soil erosion.

Soil compaction is also an important form of soil degradation that greatly affects yield and cost of production (Hamza and Anderson, 2005; USDA, 2008; FAO and ITPS, 2015; Sivarajan et al., 2018). Machines and farm animals are the main cause of soil compaction. Working the soil at the wrong soil water content exacerbates the compaction process. Compaction increases bulk density, and that affects plant health and yield. The more compact the soil (the higher the bulk density), the more energy plants have to spend to root in the soil and to access nutrients and water. Soil compaction is a very serious issue. Once soils undergo compaction it may be difficult to repristinate their previous structure, as such process depends on soil biological activity, which is greatly affected by the compaction process itself.

Deguine et al. (2009) argued that despite the increasing use of pesticides, harvest losses caused by pests have increased from 4% to 10% for wheat, barley, rice, and potatoes, and have remained stable or decreased slightly for maize, soya, cotton, and coffee. It has been estimated that, in the absence of any crop protection measures, about 80% of the world rice harvest, 70% of the potato harvest, and 50% of the wheat harvest might be lost (Deguine et al., 2009).

Nevertheless, den Biggelaar et al. (2004) stated that loss of productivity varies greatly, depending on crop, geographic area and soil type, and that productivity declines may not relate directly to the amount of soil loss but concern a number of erosion-induced changes in the physical, chemical, and biological qualities of soil that influence production (i.e., SOM, water-holding capacity, nutrient contents, bulk density).

Nevertheless, inappropriate agricultural practices, while potentially helping to boost yields in the short term, may expose soil to heavy erosion and put productivity at risk in the long term (under extreme weather, bare soils, low in SOM, may lose several centimeters over a very short space of time) (Morgan, 2005; Montgomery, 2007a,b; Quinton et al., 2010; Gomiero, 2016). As yield reduction tends to be compensated by using an increasing amount of inputs (i.e., fertilizers, pesticides, water), it also leads to increasing the cost of produce, and reducing farmers' profits (Fig. 2.1).

Guaranteeing food security to the world is a major challenge. FAO (2011a) defined food security as a state when "all people, at all times, have physical and

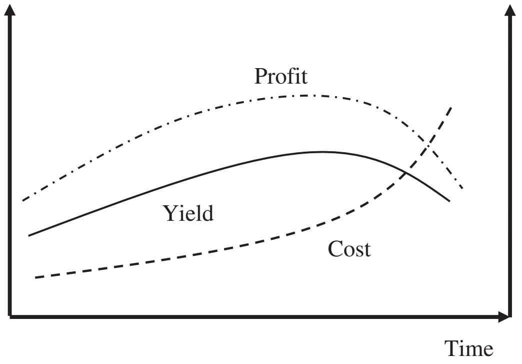

Figure 2.1 Yield loss due to unsustainable agricultural practices drives production costs up and reduces farmers' profits.
Source: Figure by T. Gomiero.

economic access to sufficient, safe and nutritious food for a healthy and active life." It requires maintaining both crop productivity (i.e., yield, which implies also ensuring enough land is available and its quality suitable to sustain production) and the quality of produce, which should be nutritious and free from toxins and other forms of contamination (Fig. 2.2).

Thus, sustainable agricultural practices should aim at reducing yield loss, stabilizing or improving long-term yields, and making the agricultural system resilient to stressors (able to recover from events such as drought and climate extremes or pest attack). At the same time, the environmental impact of agriculture should be reduced and ecosystem services preserved (Foley et al., 2011; Robertson et al., 2014; Hamilton et al., 2015; Gomiero, 2016).

In the long term, adoption of sound agricultural practices by focusing on preserving soil fertility and reducing competition by weeds and pests may help both increase yields and avoid yield loss (Fig. 2.3).

Unsustainable agricultural practices can also affect the nutritional content of produce, by reducing the density of nutrients, such as micronutrients. Nutrient-dense foods are those with a high concentration of nutrients, such as vitamins and minerals, relative to their caloric content (HLPE, 2017). Reducing nutrient density in food may pose a further threat to the health of people, especially in developing countries, where deficiencies in essential vitamins and minerals (also termed "hidden hunger"; Ruel-Bergeron et al., 2015) might affect 2 billion people. Decreasing nutritional content of produce should also be considered as a form of yield loss.

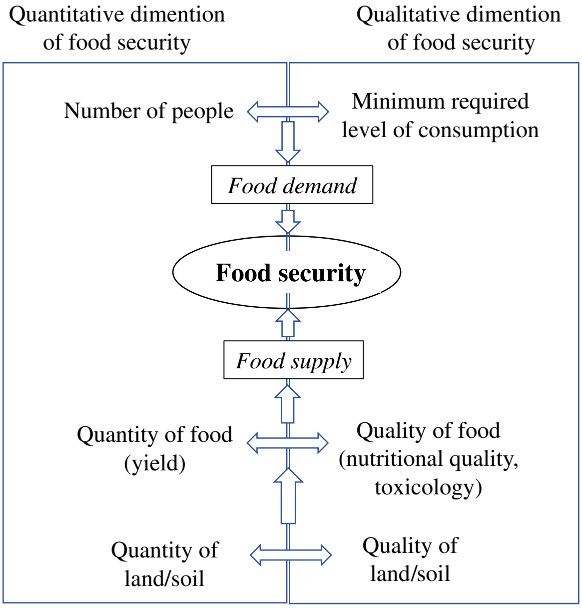

Figure 2.2 Quantitative and qualitative dimensions of food security.
Source: Figure by T. Gomiero.

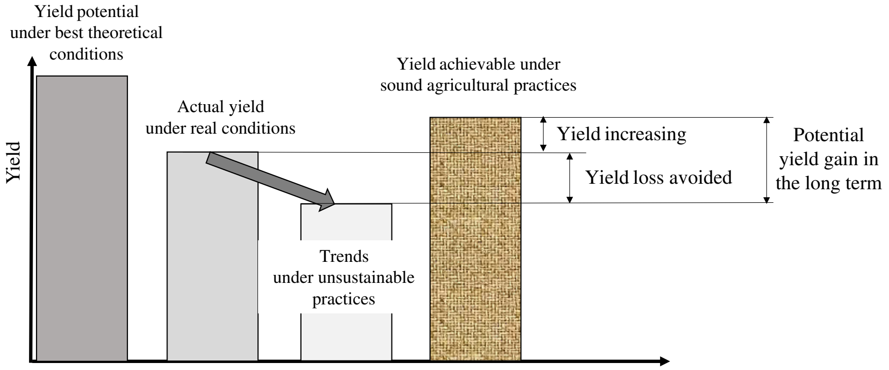

Figure 2.3 Adoption of sound agricultural practices may help both increase yield and prevent yield reduction in the long term. Theoretical yield potential refers to the achievable yield of a genotype under the best possible conditions (solar radiation, temperature, crop canopy, water, nutrients, lack of competing weeds and pests); such conditions are possible only theoretically, as they are never present in reality. Actual yield refers to the productivity of a crop in the field under local environmental conditions. In the long term, intensive or improper practices may lead to yield reduction.
Source: Figure by T. Gomiero.

As for produce quality, scholars highlight that, in the last decades, produce is less nutrient-dense than it used to be, possibly as a result of intensive agricultural practices, new crop genotypes (new high yield cultivars), and soil exhaustion (Mayer, 1997; Fan et al., 2008; Davis, 2009; Blackmore Smith and Hopkins, 2018).

According to some reviews (Mayer, 1997; Davis, 2009), in the United States and United Kingdom, nutrient content in fruit and vegetable decreased by 5%–40% in the last decades. Fan et al. (2008) reported that, from the 1960s to the present, mineral concentration in United States wheat decreased by 20%–30%. Tests reported that increased CO_2 concentration in the atmosphere could enhance yields but at the same time decrease nutritional quality of produce. According to Myers et al. (2017), a CO_2 concentration of 550 ppm can lead to a 5%–10% decrease in mineral content in cereal grains and legumes (e.g., vitB group, iron, zinc, and sulfur). Smith and Myers (2018) estimated that many food crops grown under a CO_2 level of 550 ppm have protein, iron, and zinc contents that are reduced by 3%–17% compared with current conditions. Uddling et al. (2018) claimed that increased CO_2 concentration may dramatically reduce the protein content in produce (with the exception of legumes), also altering amino acid composition.

2.3 Preserving soil health: an imperative if we want to feed the future

So far, according to some analyses, the increase in agricultural productivity (i.e., yield) has been about 70% due to the intensification of agriculture: new high yield varieties (HYV), irrigation, use of agrochemicals, and for the remaining 30% to new land being brought into production (Alexandratos and Bruinsma, 2012; Gibbs et al., 2010; Conway, 2012). Agricultural land has become one of the largest terrestrial biomes on the planet, occupying an estimated 40% of land surface (Tilman et al., 2001; Foley et al., 2005). Doubling of global food production during the past decades has been accompanied by a massive increase in the use of inputs, such as synthetic nitrogen, phosphorus, pesticides, large use of irrigation, and energy (Smil, 2000, 2003; Tilman et al., 2001; Foley et al., 2011; Gomiero et al., 2011a). Agriculture accounts for 70% of all water withdrawn from aquifers, streams, and lakes (Tilman et al., 2001; Molden, 2007; FAO, 2011b).

Since the 1990s there has been a slowdown in the growth of world agricultural production and world cereals output has stagnated and fluctuated widely (Conway, 2012; Grassini et al., 2013; Ray et al., 2012; Alexandratos and Bruinsma, 2012). Recent work by Grassini et al. (2013) seemed to indicate that some physical limits to yield productivity may have already been reached for rice, wheat, and maize, and that further attempts at increasing productivity may result in a decreasing marginal return of investment (see also Cassman et al., 2003).

Recent works (Scheelbeek et al., 2018; Tigchelaar et al., 2018) highlighted that the effects of climate change may greatly impact on crop yields. Tigchelaar et al. (2018) claim that maize yield may decrease by about 10% in Brazil and by up to 50% in the United States. The metaanalysis carried out by Scheelbeek et al. (2018), considering articles published between 1975 and 2016 concerning the effects of ambient temperature, tropospheric carbon dioxide (CO_2), ozone (O_3) concentrations, water availability, and salinization on yields and nutritional quality of vegetables and legumes, reported that in a business-as-usual scenario, predicted changes in environmental exposures would lead to reductions in yields of nonstaple vegetables and legumes.

2.3.1 Land availability and soil quality: undertaking a precautionary approach

In the last few decades, the intensification of agriculture has led to the degradation and exhaustion of soil and land. Foley et al. (2005, pp. 570−571) concluded that "[i]n 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." Soil degradation poses a major threat to food security, especially in poor regions. FAO (2011a) highlighted that there is a strong relation between land degradation and poverty. Later assessments (FAO, 2011a; Bindraban et al., 2012; Gomiero, 2016) estimated 25% of the present agricultural land to be highly degraded, about 44% to be slightly to moderately degraded, and about 10% to be recovering from degradation. Yet, the dire state of soils devoted to agriculture seems to be going unnoticed by policy makers, business, and civil society. It is urgent, therefore, to act to halt soil degradation and adopt agricultural practices that can preserve soil health.

By 2050 the demand for new agricultural land (due to population pressure, diet change, and demand for biofuels) is expected to increase by about 50%. It is very probable that tropical forests will account for that land, therefore, further deforestation is to be expected and soil degradation exacerbated (DeFries et al., 2010; Gibbs et al., 2010; Gomiero, 2015a, 2016). Furthermore, the amount of land is one aspect of the problem, while the other concerns the quality of such land. Soil quality plays a key role in determining yields, production costs, and long-term sustainability of agricultural enterprises. Marginal land, characterized by soil of poor quality, can still be cropped. Nevertheless, yields may be poor and farming may require a high use of inputs (e.g., fertilizers, water), and in the long term such land might be dismissed as it becomes infertile.

Concerning the land available for agriculture expansion, experts have different opinions. According to a review carried out by Gomiero (2016), views on the possibility of expanding agricultural land range from concerned to optimistic.

The concerned. Concerned experts pointed out that soil degradation is of major concern, and argued that, at a global level, there is not much room for the further expansion of agricultural activities and that many densely populated countries are already facing serious problems of land scarcity. They claim that most of the best agricultural land is already cropped. What is left is mostly forested land, where soil may not be very productive (actually, once deforested, such areas are highly prone to soil erosion). It is also pointed out that statistics about yields may not be reliable (an issue recognized by all experts). Some experts denoted that in many developing countries the areas harvested, yields, and production are not accurately measured, and figures may thus be affected by assumptions or political reasons. In addition, they pointed out that soil degradation reduces both actual and potential yields. Conway (2012) pointed out that in the past 50 years the population has grown by 110% and cropland by only 10%, which might be telling figures pointing to the fact that there is not much land left that can be easily cropped. The expansion of soybean (300%) and palm oil (700%) is presumably due to the clearing of the Cerrado in Brazil and of rainforests in many tropical countries (Gibbs et al., 2010; Conway, 2012; Gibbs and Salmon, 2015). It has also been stressed that the Human Appropriation of Net Primary Productivity may have reached 50% and that a further expansion of agricultural activities may erode vital space and resources away from existing biodiversity and ecosystems (Haberl et al., 2014).

The optimistic. Experts holding a more optimistic view, even though in agreement with the call to preserve soil health, argue that there is land available to sustain the further expansion of agriculture. In addition, such experts believe that in many regions of the world productivity is still very low and can be substantially increased with more inputs (i.e., fertilizers) and technology (i.e., irrigation, GM organisms). According to Mauser et al. (2015), improving crop growth management through better technology and knowledge may result in a 39% increase in estimated global production potential, while a further 30% can be achieved by the spatial reallocation of crops to their profit-maximizing locations. According to the authors, the expected yield increase will make cropland expansion redundant, and will it not be necessary to rely on GM crops. Of course, in many developing countries even a minimal investment can lead the average crop yields to rise. However, better technology and knowledge come at a cost: at present, for many developing countries such investments may be out of reach.

Given that food security is at stake, a precautionary approach should be taken, focusing on the adoption of agricultural practices that preserve soil health. Other issues should be analyzed in parallel as well, looking at the functioning of the whole of society. For example, Alexandratos and Bruinsma (2012) stated that, if social policies are not implemented, increasing productivity may spur a population growth trap (as it happened in the case of the Green Revolution), hindering further progress and locking the system into poverty.

2.3.2 The role of soil organic matter in preventing soil degradation and maintaining yields

Agricultural practices adopted in conventional agriculture tend to be poorly concerned with preserving soil health. Soil tillage increases fertility by the mineralization of soil and effectively controls weeds (although it may help the spreading of some weed species). Nevertheless, tillage, ploughing in particular, may trigger soil erosion, and the reduction in SOM that makes soil prone to erosion through the effect of rain and wind reduces soil biodiversity and destroys mycorrhiza (Morgan, 2005; Gliessman, 2014; Lal et al., 2007; Montgomery, 2007a,b; NRC, 2010; Lal, 2002, 2015a,b; Gomiero, 2016). This is exacerbated by practices that leave soil uncovered for long periods. The soil removed by either wind or water erosion is 1.3−5.0 times richer in organic matter than the soil left behind (Montgomery, 2007a). The United States Department of Agriculture (USDA) estimated that it takes 500 years to produce an inch (2.54 cm) of topsoil while it may take a few decades, or just a few years, to erode many centimeters of topsoil (Montgomery, 2007a; Gomiero, 2016).

Resistance of soils to erosion is closely linked to the stabilizing influence of SOM and vegetation cover. High organic matter content inhibits erosion because SOM binds soil particles together, generating an aggregate that resists erosion. In regions such as Asia and Africa, where soil erosion is associated with reduced vegetation cover, loss of soil carbon can trigger catastrophic shifts to severely degraded landscapes.

Soil is an extremely complex ecosystem, still poorly known. It has been estimated that, globally, SOM may contain more than three times as much carbon as either the atmosphere or terrestrial vegetation (Schmidt et al., 2011). SOM found in the topsoil (the upper 15−25 cm soil layer) is of key importance for soil fertility. It was generally believed that most of SOM was found in the topsoil (0-30 cm). Nevertheless, recent analyses proved that SOM at 0.3−1 meter may equal, or more, the amount of SOM found in the upper layer (Schmidt et al., 2011; Gregory et al., 2016). Mineral soils form most of the world's cultivated land and may contain from a trace to 30% organic matter (Bot and Benites, 2005). Fertile agricultural soils can contain up to 100 tons of organic matter per hectare (or 4% of the total soil weight); in the case of most agricultural soils, SOM represents 1%−5% of topsoil (Russell, 1977; Bot and Benites, 2005; FAO and ITPS, 2015). SOM contains roughly 55%−60% carbon by mass (FAO and ITPS, 2015.). About 95% of soil nitrogen and 25%−50% of soil phosphorus are held in the SOM-containing topsoil layer (Lal, 2010). It has been estimated that for every 1% of SOM content, soil can hold 10,000−11,000 L of plant-available water per hectare of soil down to about 30 cm (Sullivan, 2002).

SOM greatly increases the water-holding capacity of soils, which is up to 100% higher in the crop root zone (Lotter et al., 2003; Gomiero, 2016). A number of studies have shown that, under drought conditions, crops in organically managed systems, where soils have higher SOM content compared with conventionally managed fields, produce higher yields than comparable crops managed conventionally (Gomiero et al., 2011b). This advantage can result in organic crops out-yielding conventional crops by 70%−90% under severe drought conditions (Lotter et al., 2003; Pimentel et al., 2005). Other studies have shown that organically managed crop systems have lower long-term yield variability and higher cropping system stability (Pimentel et al., 2005; Reganold and Wachter, 2016).

Unsustainable soil management affects crop yield in the short term by the effect of rill or gulley erosion following intense rainfall, and in the long term by the gradual loss of soil structure and fertility. Yield losses have been reported to range from 10% to 95% per 10 cm of soil loss (Powlson et al., 2011). A review work by den Biggelaar et al. (2004), reported that that average crop yields and effects of past erosion on yields differ greatly by crop, continent and soil order, and that inappropriate soil management may amplify the effect of erosion on productivity by one or several orders of magnitude.

A metaanalysis carried out by Montgomery (2007b) highlighted that the adoption of proper agricultural practices, such as conservation agriculture, greatly reduces soil erosion (Fig. 2.4). Montgomery (2007b) reported that from a database of 39 field tests monitoring the effect of the adoption no-till on soil erosion, no-till practices showed to reduce soil erosion from 2.5 to >1000 times (median and mean values of 20 and 488 times, respectively).

Nevertheless, no-till may also lead to some problems and minimum tillage may have to be preferred (see Section 2.5.1.3). Increasing SOM also contributes to offsetting CO_2. It is generally assumed that 50−70% of soil C stocks have been lost in cultivated soils due to the effects of agricultural activities (Zomer et al., 2017). Zomer et al. (2017) reported that, globally, cropland, may store more than 140 Pg C in the top 30 cm of soil, almost 10% of the global soil organic carbon (SOC) pool. It has been estimated (Smith et al., 2008; Lal, 2015a,b) that, by adopting sustainable practices, agriculture could offset up to about 20% of total global annual CO_2 emissions. It has to be noted that carbon density in soil decreases with temperature, from less than 100 tC/ha in the equatorial belt to 400 tC/ha, or more, in the northern belt (United States, Canada, Europe, Russia) (Lal, 2002; Zomer et al., 2017). According to Zomer et al. (2017), croplands worldwide could sequester between 0.90 and 1.85 Pg C/year, accounting for 26%−53% of the target of the "4 per 1000" initiative (an initiative launched by France in 2015, aiming at achieving an

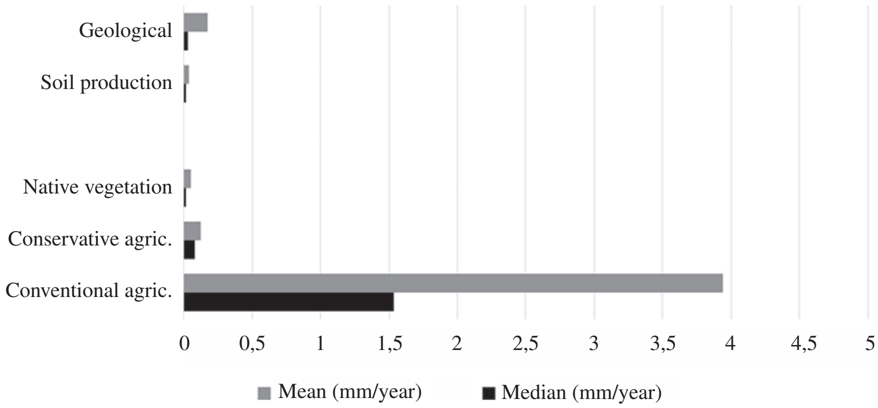

Figure 2.4 Soil erosion rate for managed and natural soils: result from a metaanalysis. Source: Figure from Gomiero, T., 2016. Soil degradation, land scarcity and food security: reviewing a complex challenge. Sustainability 8, 1–41. Available from: http://www.mdpi.com/2071-1050/8/3/281, data after Montgomery, D.R., 2007b. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. 104, 13268–13272, no permission needed for republishing.

annual growth rate of 0.4% in the soil carbon stocks, that would halt the increase in the CO_2 concentration in the atmosphere related to human activities; for details see https://www.4p1000.org/). Although such estimates may be rather optimistic (the authors did not account for differences in climate and important soil process issues, such as nutrient and water limitations), it is clear that increasing SOM in soils represents one of the most effective ways to sequester atmospheric carbon (while benefiting agricultural activities and ecosystem services).

However, it has to be pointed out that SOM can accumulate for some time (20–30 years, Zomer et al., 2017) then it levels off. Therefore, there is a limit to how much carbon the soil can capture acting as a carbon sink and conversion to more sustainable agriculture can only represent a temporary and partial solution to the problem of CO_2 emissions. Long-term solutions concerning GHGs emission abatement should rely, other than preserving C stored in soils and vegetation, also on a more general change of our development path, for instance by reducing overall fossil fuel consumption.

2.4 Unsustainable agricultural practices and their effect on yield loss

2.4.1 *"Soil fatigue" and yield decline*

Monoculture, poor rotations (i.e., short rotation, wrong species in rotation), and intensive agricultural practices (i.e., use of agrochemicals) can lead to the phenomenon known as "soil fatigue" (or "soil sickness," "yield decline"), an important cause of yield reduction. Soil fatigue is characterized by gradually decreasing yields despite fertilization and other soil preparation efforts, and is related to a complex plant−soil feedbacks (it seems that what is affected is the plants' ability to take up nutrients) (Gamliel et al., 2000; Bennett et al., 2012; van der Putten et al., 2013; Bender et al., 2016; Wolińska et al., 2018). Furthermore, soil fatigue is exacerbated when crops are grown in short rotation (Bennett et al., 2012).

Soil fatigue is a complex phenomenon that may have diverse causes (Gamliel et al., 2000; Jacob et al., 2010; Bennett et al., 2012; van der Putten et al., 2013; Bender et al., 2016; Zhao et al., 2016; Wolińska et al., 2018): (1) soil exhaustion through depletion of some essential plant nutrients, micro and macronutrients by the previous crops; (2) accumulation of soilborne pests and plant pathogens in the soil (e.g., nematodes); (3) accumulation of toxic compounds released from former crops (the effect is known as allelopathy, the production by plants of chemical compounds that affect the germination, growth, survival, and reproduction of other plants), or by soil organisms (i.e., bacteria, fungi, nematodes), affecting the health and growth of other crop species; (4) degradation of soil ecology and soil structure; (5) change in soil pH; and (6) unbalanced soil biodiversity (e.g., bacteria, reduced mycorrhizal fungi).

Soil fatigue has to be managed by restoring soil fertility (supplying micronutrients) when the problem is due to soil exhaustion, introducing proper rotations when allelopathic effects are present, and by soil sterilization in the case of soil toxicity, to eliminate soilborne pathogens. Soilborne plant pathogens have long been fought using soil fumigants, which represent a health hazard, cause environmental pollution, and can cause atmospheric ozone depletion (Gamliel et al., 2000; Dangi et al., 2017). Although some of the most problematic pesticides have been officially banned, such as methyl bromide (within the Montreal Protocol for protection of the ozone layer), they may be still in use in some regions. It has been argued that chemical soil disinfestation (use of fumigants) should be avoided, because, aside from its environmental impact, it leads to eradication of the entire microbial community, thus creating a "microbial vacuum." The latter often leads to a rebounding of pathogens, which can cause even more damage than those originally targeted for control (Gamliel et al., 2000; Dangi et al., 2017). Sound nonchemical methods have been developed that can effectively control soilborne plant pathogens and plant-parasitic nematodes. Some practices are commonly used are:

- sound crop rotations (with species that do not cause allelopathic effects) and use of cover crops (Jacob et al., 2010; Bennett et al., 2012; Zhao et al., 2016; Dangi et al., 2017; Wolińska et al., 2018),
- soil sterilization by steam treatment (180°C−200°C) provides a sound solution for the eradication of soil pests (Johnson, 1946; Gamliel et al., 2000),
- soil flooding (e.g., by introducing paddy rice in rotation) is known to suppress some soilborne pests and has been used in Asia (Momma et al., 2013).

More recently other nonchemical strategies have been developed:

- Anaerobic soil disinfestation (also known as "biological soil disinfestation" or "reductive soil disinfestation") works by creating a temporary anaerobic soil environment to stimulate the growth of facultative and obligate anaerobic microorganisms, which, under anaerobic conditions, decompose the available carbon sources, producing compounds (organic acids, aldehydes, alcohols, ammonia, metal ions that suppress soilborne pests (Blok et al., 2000; Shinmura, 2000; Momma, 2008; Butler et al., 2012; Momma et al., 2013).

- Solarization is accomplished by covering the soil surface with a clear plastic film to trap solar radiation with soil temperature that may rise above 70°C and become lethal to many plant pathogens (Gamliel et al., 2000; Butler et al., 2012; Momma et al., 2013).
- Flame soil disinfestation is a technique by which compressed fuel (i.e., natural gas) is injected into the soil, the flame temperature may reach 1200°C killing soilborne pathogens and weed seeds as well (Gamliel et al., 2000; Mao et al., 2016).
- Increasing SOM and restoring soil biodiversity through more complex cropping patterns and a reduced use of agrochemicals (Bennett et al., 2012; van der Putten et al., 2013; Bender et al., 2016; Wolińska et al., 2018).

The cost of some of these treatments (i.e., soil flooding, solarization) may limit their use to greenhouses or high value crops planted in small plots. Overall, sound preventive measures should rather be implemented.

It has to be highlighted that, although allelopathy may be a cause of soil fatigue, when properly managed it may represent an effective means to cope with weeds, as it has been the case for some rice varieties (Kong et al., 2008; Pheng et al., 2010).

2.4.2 The effect of synthetic fertilizers on pests and soil health

Intensive agriculture greatly relies on the use of synthetic fertilizers to spur plant growth. Often, fertilizers are used far beyond the real needs (Good and Beatty, 2011). Indeed, HYV was created to take full advantage of the high supply of synthetic nitrogen. Nevertheless, although a high amount of input greatly stimulates plant growth, such strategy has a number of drawbacks. It is estimated that only 30%–50% of the nitrogen applied is taken up by plants (Good and Beatty, 2011), while the rest is lost to the environment. The amount of reactive nitrogen (N compounds that support plant growth directly or indirectly) used to produce food is on average about 10-fold higher than its consumption by plants, the rest being a major cause of environmental pollution (i.e., eutrophication, water and air contamination by N-based toxic compounds) (Erisman et al., 2013).

Furthermore, plants growing on synthetic fertilizers are reported to be more prone to pest attack and to have weaker defenses. Since the 1950s, numerous studies reported that heavily fertilized crops were two to three times more prone to be attacked by pests (Altieri et al., 2012). This is possibly due to:

1. physiological changes induced in the plants by synthetic fertilizers (e.g., growth rate),
2. an altered balance between protein content (supplying high-quality food for pests) and secondary metabolite concentrations (many acting as defense compounds),
3. changes in soil ecology that affect plant nutrition (Altieri et al., 2012).

More recent studies have proven that pests prefer plants grown with synthetic fertilizer rather than those growing in organically managed soil (Phelan et al., 1995, 1996, 2009; Alyokhin et al., 2005; Hsu et al., 2009). This is explained by the "mineral balance hypothesis" (Phelan et al., 1996), which states that organic matter and microbial activity associated with organically managed soils allow enhancement of the nutrient balance in plants, which in turn can better respond to pest attack. Under greenhouse-controlled experiments, females of European corn borer (*Ostrinia nubilalis*) were found to lay consistently fewer eggs in maize on organic soil than on conventional soil (Phelan et al., 1995, 1996; Phelan, 2009). The butterfly *Pieris rapae crucivora*, a cabbage pest, prefers to lay eggs on foliage of synthetically fertilized plants (Hsu et al., 2009). Densities of Colorado potato beetle (*Leptinotarsa decemlineata*) have been reported as generally lower in plots receiving manure and soil amendments, in combination with reduced amounts of synthetic fertilizers, compared with plots receiving full rates of synthetic fertilizers, but no manure (Alyokhin et al., 2005). Staley et al. (2010) reported the case of two aphid species presenting a different response to fertilizers. *Brassica* specialist *Brevicoryne brassicae* was found to be more abundant on organically fertilized plants, while the generalist *Myzus persicae* was found more abundant on synthetically fertilized plants. Staley et al. (2010) also reported that the diamondback moth *Plutella xylostella* (a *Brassicaceae* specialist) was more abundant on synthetically fertilized plants and preferred to oviposit on these plants. The authors found that glucosinolate concentrations (a plant defense compound, widely present in *Brassicaceae*) were up to three times greater on plants grown organically, while nitrogen content was maximized on plant foliage under higher or synthetic fertilizer treatments. In China, the great population increases of major insect pests of rice were closely related to the long-term excessive application of nitrogen fertilizers (Lu et al., 2007).

A better management of inputs that avoids an overuse of synthetic fertilizers may greatly benefit crops and reduce the impact of pests (Lu et al., 2007; Good and Beatty, 2011; Erisman et al., 2013), in turn increasing farmers' profit and limiting the environmental impact caused by agrochemicals.

2.5 Agricultural practices for a more sustainable agriculture

It is urgent to work out agricultural practices that guarantee food production while preserving soil health, reducing water consumption and the use of agrochemicals. Such practices should also make crops able to withstand the potential effects of climate change (drought in particular). A number of approaches and agriculture practices have been proposed, such as no-till, minimum tillage, conservation agriculture (CA), agroecology, integrated pest management (IPM or integrated pest control), and organic agriculture (Altieri, 1987; Lampkin, 2002; Cassman et al., 2003; Altieri and Nicholls, 2004; Hobbs, 2007; Gliessman, 2014; Deguine et al., 2009; Perfecto et al., 2009; Glover et al., 2010a,b; Gomiero et al., 2011a; Lal, 2015a,b: Furlan et al., 2017).

Such practices differ in their focus and scale, some addressing specific issues. CA and no-till focus mainly on preventing soil erosion, agroecology is concerned with a more ecological management of the whole farm, which is seen as an integrated system, while organic agriculture, in addition to embracing agroecology, is also regulated by law and bans the use of synthetic agrochemicals and of GM organisms[1] (Table 2.1).

2.5.1 Conservation agriculture

The dramatic effects of the "dust bowl" that hit the US plains in the 1930s (Worster, 2004; Montgomery, 2007a; Kassam et al., 2014) forced farmers and agronomists to reflect on the use of ploughing (inversion tillage), where the soil is turned upside down by moldboard ploughing followed by disking one or more times (also referred to as "conventional tillage") (Phillips et al., 1980; Lal et al., 2007; Kassam et al., 2014; Islam and Reeder, 2014; Lal, 2015a,b). Experimentation with no-till farming practices, then defined as CA (also referred to as direct seeding, zero tillage, conservation tillage), began in the 1960s in the United States, at Ohio University (Kassam et al., 2014; Islam and Reeder, 2014). In no-till farming, soil is completely undisturbed prior to planting, except for a narrow slot used for seeding, and weed control is achieved by herbicides. In the United States, no-till began to be widely adopted in the 1980s, with the availability of better planters and cheaper herbicides.

2.5.1.1 Principles of conservation agriculture

Phillips et al. (1980, p. 1108) defined the no-till system as "one in which the crop is planted either entirely without tillage or with just sufficient tillage to allow placement and coverage of the seed with soil to allow it to germinate and emerge." Early tests provided evidence that no-till practices reduced the use of energy, labor, and machinery inputs, and provided effective soil erosion control (reducing soil erosion next to zero even in sloping land), improved soil water retention and fertilizer use efficiency, while crop yields were as high as or higher than yields from crops produced by conventional tillage (Phillips et al., 1980; Islam and Reeder, 2014). Nevertheless, drawbacks were also reported, such as a great increase in the use of herbicides (50% more for maize were reported), increase in pests resulting in crop damage, possibly higher than in the conventional tillage system, because of a more favorable habitat and lower soil temperature (Phillips et al., 1980). Early conservation agriculture tests in Ohio were based on the adoption of no-till, crops rotation, and cover crops. Most of the time farmers plant just one or two species of cover crops together, but a "cocktail" of cover crops is also used. Such cocktail consists of 5–10 species with differences in type and architecture

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[1] The term "organic agriculture" defines products that are produced according to standards established by international and national institutional bodies. Standards concerned mostly with the ban of agrochemicals (synthetic fertilizers, herbicides and pesticides), the strictly regulated use of drugs in animal rearing, and the prohibition of use of GMOs. The certification includes production, handling and processing (Codex Alimentarius 2004; EC, 2018; IFOAM, 2015; USDA, 2018).

Table 2.1 Agricultural practices, at different scales, that may help to preserve soil health, reduce the use of agrochemicals, and enhance crop production

Soil management		
Soil protection	***Reduce the impact of tillage***	***Reduce the impact of field operations and irrigation***
• Maintaining soil cover (cover crops, mulching) • Enhance soil organic matter • Enhance soil biodiversity • Sound livestock density	• Avoid soil compaction • Minimum tillage • Deep cultivation may be needed, but it has to be done in dry conditions (also to avoid compaction) • Contour tillage • Ridge tillage • Avoid turning the lower layers	• Avoid bare land • Reduce soil compaction • Prevent salinization • Drip irrigation (reduce water use)
Crop management		
Cropping pattern	***Cropping biodiversity***	***Reducing inputs***
• Avoid monoculture • Long rotations • Polyculture/multiple crops • Intercropping • Agroforestry	• Suitable landraces • Varietal mixture • Preserving agrodiversity • Preserving ecological structures	• Minimum use of agrochemicals • Integrated pest management • Managing the supply of nutrients to crops • Precision agriculture • Agroecological practices • Organic agriculture
Agroecological landscape management		
Preserving/enhancing ecological structures	***Cropping pattern***	***Land works***
• Grass strips • Hedgerows • Woodlot/forest • Wild vegetation	• Complex cropping pattern at landscape level • Integrating crops with wild vegetation	• Contour tillage • Terracing, stone walls • Irrigation/waterways • Repristinating ecological structures

(C3 vs C4), plant height and growth pattern, root distribution, nutrient and allelopathic chemical content, and adaptability. It has been reported that cover crop cocktails significantly improved soil properties and reduced soil compaction (Islam and Reeder, 2014).

Other conservation practices were subsequently tested (Lal, 2015a,b). In the 1970s, reduced tillage (mulch tillage/minimum tillage) practices were implemented (using chisels, field cultivators, discs, sweeps, blades), relying on herbicides for weed control. In the 1980s, ridge tillage was introduced: 10–15 cm high ridges are made either during the previous season during cultivation or at planting time, and crop residues are removed from ridge tops and put into the adjacent furrow.

Since the 1980s, CA has been promoted by international organizations (i.e., FAO), donors, farms, and nongovernmental organizations as a means to halt soil degradation and overcome food insecurity. FAO (2018a) defined CA as "a farming system that promotes maintenance of a permanent soil cover, minimum soil disturbance (i.e., no tillage), and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient-use efficiency and to improved and sustained crop production." CA practices are based on:

1. continuous minimum mechanical soil disturbance,
2. permanent organic soil cover (at least 30% with crop residues), and
3. diversification of crop species grown in sequences and/or associations (rotation).

Reducing soil disturbance and maintaining crop residues near the surface contributes to biological diversity both above and below the soil surface, while crop rotation reduces the risk of pest outbreaks and improves soil health (Bot and Benites, 2005; Hobbs et al., 2008; Friedrich and Kassam, 2012; Friedrich et al., 2012; Kassam et al., 2014; FAO, 2015, 2018a; Lal, 2015a,b).

It has been suggested that CA should also include integrated nutrient management (Lal, 2015a,b; Wu and Ma, 2015), that is, integrate old and modern nutrient management methods, drawing from all of their strengths to achieve an ecologically sound and economically optimal farming system. Integrated nutrient management practices, apart from increasing nutrient-use efficiency, should also aim at reducing losses incurred through leaching, runoff, volatilization, and GHGs emissions. A review of the literature indicated that adoption of integrated nutrient management practices improved yields by 8%–150% (Wu and Ma, 2015). Therefore, policies should contemplate subsidies for use of organic manures, ensuring a better balance between inorganic and organic fertilizers (Wu and Ma, 2015).

Environmental advantages of CA include soil and water conservation, carbon sequestration in the soil, landscape protection, flood mitigation, reduced pollution of waterways arising from sediments and in particular from bound phosphorus, and improved drought proofing (Friedrich and Kassam, 2012; Friedrich et al., 2012; Kassam et al., 2014; Kertész and Madarász, 2014; Wezel et al., 2014; Busari et al., 2015; Lal, 2015a,b). It has been claimed that CA is also less costly, and economically, environmentally, and socially beneficial (Kassam et al., 2014), when properly implemented. That is to say, when other than no-till, also the other two CA principles are also implemented (Hobbs et al., 2008; Friedrich and Kassam, 2012; Friedrich et al., 2012; Lal, 2015a,b). In rainfed experiments, no-till plots with residue retention resulted in higher and more stable yields than conventionally tilled plots with residues incorporated (Hobbs et al., 2008). Nevertheless, no-till farming may also cause some important problems (which I will discuss in Section 2.5.1.3).

2.5.1.2 The adoption of conservation agriculture

CA (with no-till) is practiced on more than 125 Mha around the world, covering approximately 9%–10% of the global arable land surface (Kassam et al., 2014; Kertész and Madarász, 2014). Adoption of CA practices varies among regions. According to FAO (in Kassam et al., 2014), CA accounts for about 60% of arable cropland in South America [also thanks to the introduction of herbicide-resistant (HR) crops, which are genetically engineered to resist herbicides such as glyphosate], 60% in Australia and New Zealand, 15% in the United States, 3% in Russia and Ukraine, about 1% in Asia, 0.5% in Europe, and 0.3% in Africa. According to Eurostat (2013), conventional tillage is the most widespread tillage practice in EU-27, where almost two-thirds of arable land is tilled with conventional tillage practices, about a fifth is tilled with conservation practices adopting minimum tillage, while no-till is rarely practiced.

It has been argued that CA, in particular no-till, is not equally suitable for all European agroecosystems (e.g., soil erosion risk is low in northern, cool, and temperate regions when compared with the semiarid Mediterranean regions), and that the ban on HR crops made no-till practices of little interest (Lahma, 2010; Kassam et al., 2014; Kertész and Madarász, 2014; Wezel et al., 2014; Zikeli and Gruber, 2017). Reduction in operating costs has been reported to be a major consideration in farmers' decisions to adopt conservation practices (Kertész and Madarász, 2014), even if environmental awareness is becoming an important issue for farmers. The European Common Agricultural Policy and the system of financial and institutional supports may significantly impact on farmers' decisions to adopt CA practices.

Thus, adoption of CA seems highly dependent on local societal context and farming activities. In general, CA seems to perform better in certain contexts, such as in rainfed agroecosystems in dry climates (Kertész and Madarász, 2014; Pittelkow et al., 2015a,b). Some authors (Corbeels et al., 2014; Kirkegaard et al., 2014) claimed that the existence of different biophysical and socioeconomic contexts requires a pragmatic approach to CA; for example, when mixed crop–livestock systems are widely in place, such as in Australia, Africa, and South America (where livestock are used to graze crop residues after harvest, reducing soil cover, and impacting on soil structure), or when farmers have a diverse set of objectives (i.e., protecting soil, saving time, increasing yields, increasing overall income). Nevertheless, in the case of Australia, Kirkegaard et al. (2014) reported that good livestock management within mixed crop–livestock systems can provide the same, if not greater, soil benefits as ideal CA practices.

In Africa, CA began in the 1970s in Nigeria (Kassam et al., 2014; Corbeels et al., 2014), and since then it has been increasingly promoted to preserve soil and sustain yields (both urgent priorities). Nevertheless, despite more than two decades of research and development investments, and even though CA can potentially lead to increased crop yields in the long term as a result of a gradual increase in overall soil quality, success on farms has been limited (Corbeels et al., 2014; Wezel et al., 2014; Pittelkow et al., 2015a,b), or adoption has been limited to some of the farming strategies suggested by CA (Brown et al., 2018). According to Corbeels et al. (2014) the reasons are:

1. lack of an immediate increase in farm income, deterring farmers from adopting the CA package, as, for smallholders, future benefits do not outweigh their immediate need for an income;
2. farmers owning livestock use crop harvest residues as fodder for livestock rather than as soil cover; and
3. markets for purchase of inputs and sale of produce are still lacking.

In the case of China, Zhao et al. (2017) reported that the slight decline in agronomic yield per unit area and time has deterred Chinese farmers from implementing the CA package (although, they noted that in the long term, yields may be comparable with tilled systems).

Proper assessment of local constraints to the adoption of CA is required to better meet the characteristics and needs of local farmers. In some regions it may be challenging to leave crop residues in the field due to strong pressure for residues to be used for livestock or other purposes. In the case of resource-poor and vulnerable smallholder farmers, yields should be monitored and support provided in case of yield reduction during the transition period. CA should be integrated into ad hoc conservation practices, rather than offered as a package that may fail to respond to local needs.

2.5.1.3 No-till farming: assessing the drawbacks

No-till stands at the core of CA. Nevertheless, without implementing other conservation actions (i.e., long rotation, leaving residues in the field) no-till may actually cause important problems to soil conservation, and in the long run may reduce soil health and affect yields (Bot and Benites, 2005; Friedrich and Kassam, 2012; Friedrich et al., 2012; Wezel et al., 2014; Lal, 2015a,b). Furthermore, even when properly implemented, no-till may have some important drawbacks. Therefore, CA needs to be carefully monitored and the practice might need to be adapted to different biophysical and socioeconomic contexts. Hereafter, a review of the main problems related to no-till practice follows, organized by theme.

Overall environmental benefits. In some regions and agricultural systems, energy use (i.e., fuel, use of inputs), GHG emission, and C sink in soil may not differ between conservation and conventional farming practices (Luo et al., 2010; Kirkegaard et al., 2014; Powlson et al., 2014; Lal, 2015b).

Soil compaction. No-till practice, in the long run, may exacerbate the problem due to the additive effects of equipment traffic, especially when the soil is wet or poor rotation practices are in place (Hamza and Anderson, 2005; USDA, 2008; FAO and ITPS, 2015). Nevertheless, soil compaction has been reported under minimum tillage (5–7 cm) (e.g., Peigné et al., 2018), and can happen also when the soil is tilled (the "plow pan").

Impact on soil ecology. In Argentina, negative effects of no-till on soil macrofauna and litter decomposition, as compared with natural grasslands, have been reported (Domínguez et al., 2010; Álvarez et al., 2014; Domínguez and Bedano, 2016).

Weeds ecology and use of herbicides. Although tillage (i.e., ploughing) is used to fight weeds, tillage may also incorporate weed seeds into the soil, where they can be protected and conserved for many years, and may also spread perennial weeds by cutting and distributing rhizomes and other propagating parts (Friedrich and Kassam, 2012). It has been claimed that in mature and well managed no-till systems, weeds are reduced and the use of herbicides can decrease as well, helping also to reduce management costs (Friedrich and Kassam, 2012). Nevertheless, moving from ploughing to the use of herbicides affects the weed ecology of farmed land. A new weed community could develop composed by plants that are more tolerant to herbicides (Kirkegaard et al., 2014) (tolerant plants are plant that are affected but not killed the chemicals; resistant plants are plants that are not affected by the chemicals). When no-till is poorly implemented (i.e., monocropping, or short-term rotation), weeds may quickly develop resistance to herbicides, forcing farmers to increase the dose of herbicide, eventually ending up contaminating soil and water (Chhokar and Sharma, 2008; Kirkegaard et al., 2014). This seems to be the case in the introduction of herbicide-resistant GM crops (i.e., soybean, maize, canola, cotton). Continuous use of the same product (glyphosate- and glufosinate-based herbicides) led weeds to develop resistance to the chemicals, forcing farmers to use more and more herbicides (the *herbicide treadmill*). Cases have been documented where eventually hand-weeding and deep ploughing had to be used to fight resistant weeds (Powles, 2008; Binimelis et al., 2009; Benbrook, 2016; Bonny, 2016).

Pests and fungal spores may accumulate in soil and infect the following crops. No-till may increase the number of pests that affect crops. The accumulation of residues on soil represents a microhabitat for many pests that cannot be reached by pesticides (Altieri, 1987; Altieri and Nicholls, 2004). An important issue concerns the concentration of fungal spores in the soil (most importantly molds of the genus *Aspergillus* and *Fusarium*), which may infect crops the following year. The case of genus *Aspergillus* and its toxins (aflatoxins) is highly relevant because such mold can infect both conventional and Bt maize. Bt maize was engineered to produce a toxin derived from *Bacillus thuringiensis* that is able to kill some insects (i.e., coleoptera and lepidoptera) that are maize pests, such as the corn borer (*O. nubilalis*), a moth. Such pests, when attacking maize, make it prone to be colonized by molds and then infected by the highly toxic compounds they produce. It has been known since the late 1990s that Bt maize is more resistant than conventional maize to fungi from the genus *Fusarium*, which produces a class of toxins known as fumosins. Such fungi colonize maize through the damage done by some arthropods (i.e., insects, mites). Therefore, by reducing the attack of some parasites (e.g., moths such as the European corn borer), Bt maize can reduce the presence of *Fusarium* and related toxins in maize. The presence of fumosins is reduced (by about 30%) but not eliminated. It is also well known that fungi of the genus *Aspergillus*, which produce the highly dangerous aflatoxins, colonize maize even without the damage caused by parasites. Indeed, with respect to aflatoxins there are no differences between conventional and Bt maize (Hammond et al., 2004; Williams et al., 2010; Reay-Jones and e Reisig, 2014; Abbass et al., 2016; Mitchella et al., 2017).

Limited soil organic carbon accumulation. Some studies pointed out that, although no-till increases SOC concentration in the upper layers of some soils, it does not store it more than conventional tillage for the whole soil profile (Baker, 2017; Blanco-Canqui and Lal, 2008; Powlson et al., 2014; Pittelkow et al., 2015a). Therefore, agricultural land under no-till may not represent as important a C sink as previously believed (Baker, 2017; Kirkegaard et al., 2014; Powlsen et al., 2015a,b).

Yield may be reduced and is context dependent. Although it was believed that yield was higher in no-till than in conventional tillage systems (Friedrich and Kassam, 2012), yield reduction has been reported in no-till systems, on average from 2% to 6% (but much higher in some cases, see Kirkegaard et al., 2014; Pittelkow et al., 2015a), especially during the initial stages of its implementation (Kirkegaard et al., 2014; Lal, 2015b; Pittelkow et al., 2015a; Zhao et al., 2017). This has been attributed to insufficient seed−soil contact, poor seeding equipment, and stunted seedling growth because of suboptimal soil temperatures (Lal, 2015b; Zhao et al., 2017). A global metaanalysis produced by Pittelkow et al. (2015a,b) showed that no-till performance is lower (about 5%) for most crops, and highly context dependent. For example, no-till resulted in maize yield declines at tropical latitudes, but in increased yields, relative to conventional tillage systems, in arid regions, where there is restricted water availability for crop growth (the authors did not report on profitability, which might be higher for no-till due to its potential for reducing costs, e.g., saving on fuels). Grassini et al. (2015) reported that, in the case of irrigated soybean, yields were not higher in no-till fields, and that a yield reduction was observed in no-till fields compared with minimum tillage fields, especially in regions/years with cooler early-season temperatures. Nevertheless, other authors (Hussain et al., 1999; Lal, 2015b; Zhao et al., 2017) noted that in the long term (about 10 years) yields under no-till tend to stabilize and to be comparable to crop yields under tillage.

No-till may reduce the speed of residues decomposition. No-till greatly reduces the speed at which residues are decomposed, and that may constitute a problem. Minimum tillage (or reduced tillage), where soil is tilled at depths of at most 10−20 cm, is a better means to integrate crop residues in soil and can fight weeds without the use of herbicides. Therefore, minimum tillage may substitute no-till, because when sound crop management practices are implemented, the former can still represent an effective way to reduce soil erosion.

In light of what has been discussed above, it is clear that when addressing no-till we have to address the whole management system, since its impact can be very different depending on the biophysical and social context where it is applied.

Practicing sound reduced tillage could potentially represent a more sustainable soil management practice in many contexts, while helping to reduce the use of herbicides (Kirkegaard et al., 2014; Powlson et al., 2014; Pittelkow et al., 2015a,b; Cooper et al., 2016). Ridge tillage (a technique that consists of preparing a seedbed that is elevated above the mean land surface of the field) has also been suggested as a better alternative to no-till, as it enhances soil fertility, improves water management, reduces water and wind erosion control (compared with conventional tillage), facilitates multiple cropping, enhances rooting depth, and improves pest management (Hatfield et al., 1998; Liu et al., 2018).

2.5.1.4 No-till and organic agriculture

In organic agriculture, where the use of synthetic agrochemicals is not allowed, CA, in particular no-till, is hardly practicable, due to the difficulties in controlling weeds (Delate et al., 2011; Carr et al., 2013; Wezel et al., 2014; Vincent-Caboud et al., 2017; Zikeli and Gruber, 2017). Tests on organic CA carried out in France reported a yield reduction of 25% for soybean and 75% for maize compared to ploughing (Vincent-Caboud et al., 2017). In Germany, long-term tests reported organic wheat under tillage yielding 70%−100% more than under no-till (Zikeli and Gruber, 2017). Tests carried out in the United States reported soybean under CA yielding about 10% less then under tillage, while, in the case of maize, yields in no-till fields were about 40% to 90% lower (Delate et al., 2011). Delate et al. (2011) reported that, in the case of soybean, economic return was nevertheless similar, or even higher, in no-till fields compared with tilled fields. Reduced yield in no-till tests have been attributed to weed infestation, cover crop regrowth competing with main crops, and N immobilization during cover crop decomposition (Delate et al., 2011; Vincent-Caboud et al., 2017; Zikeli and Gruber, 2017). Delate et al. (2011) pointed out that reducing tillage in organic crop production may be enhanced by “green payments” for soil conservation, which can compensate the effort needed to offset yield and economic losses. Cooper et al. (2016) noted that reduced tillage (less the 25 cm with no inversion) can represent a valid alternative to no-till to control soil erosion while preserving yield. Some authors (Carr et al., 2013; Wezel et al., 2014) did not exclude that no-till practice can be implemented in organic agriculture and point out that there are encouraging results in this sense. Nevertheless, additional research about conservation tillage effects on weed communities and on the biological, chemical, and physical properties of soils should be conducted under organic management conditions.

2.5.2 The agroecological approach

According to Wezel et al. (2009), the term *agroecology* was firstly used by Bensin, a Russian agronomist, in his work in the late 1920s: he suggested the term *agroecology* to describe the use of ecological methods to conduct research on commercial crop plants. In the 1940s and 1950s, the term *agroecology* was independently reinvented by other scholars and was adopted in both in the United States and Europe (Dalgaard et al., 2003; Francis et al., 2003; Wezel et al., 2009; Gliessman, 2014). By the 1980s, the concept of agroecology had reached a broad diffusion worldwide (Altieri, 1987, 2002; Wezel et al., 2009; Wezel and Soldat, 2009; Gliessman, 2014).

Slightly different definitions of agroecology have been proposed (Altieri, 1987, 2002; Wezel et al., 2009; Gliessman, 2014). Altieri (1987, p. 8, bold in original) defines agroecosystems as "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. *Agroecology* is the holistic study of agroecosystems 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."

Gliessman (2014, p. 345) defines *agroecosystem* as "an agricultural system understood as an ecosystem" and *agroecology* as "the science of applying ecological concepts and principles to the design and management of sustainable food systems." Gliessman (2014, p. 1) claimed that "[i]n agroecology, we move from a narrow concern with farming practices to the whole universe of interactions among crop plants, soil, soil organisms, insects, insect enemies, environmental conditions, and management actions and beyond that to the effects of farming systems on surrounding natural ecosystems."

While CA aims basically at protecting the soil, the agroecological approach aims at redesigning cropping systems and the agroecological landscape according to ecological principles, to achieve multiple objectives: protect the soil, protect crops from pests, reduce the use of inputs, increase efficiency, preserve farm and landscape biodiversity, preserve crops biodiversity, and guarantee yields and profits to farmers. In this sense, it may better respond to the call for sustainable agriculture (Altieri, 1987, 2018; Gliessman, 2014; Wezel et al., 2014). The scales and dimensions of agroecological investigations changed over the past decades, moving from addressing the field alone to integrating farm and agroecosystem (Dalgaard et al., 2003; Wezel et al., 2009, 2014). Agroecology, because of its attempt to stabilize yields while minimizing the use of inputs, has been indicated as a sound agricultural practice for smallholders and poor farmers (Altieri, 1987, 2002; Altieri et al., 2012).

To properly study the functioning and management of agroecosystems, the multiple scales and dimensions of agroecosystems have to be addressed. The relation between agroecosystems and the structure and functioning of the agrofood system and society need also to be addressed to assess the feasibility and viability of alternative production strategies (Giampietro, 2004; Giampietro et al., 2014; Gomiero, 2016, 2017, 2018c).

DeLonge et al. (2016) pointed out that in the United States, notwithstanding the alarming impact of industrial agriculture and the investments in assessing such an impact, only at best 10% of all public funds devoted to agricultural research concern projects with an emphasis on agroecology. The authors claim that there is an urgent need for additional public funding for systems-based agroecology and sustainable agriculture research. As for Europe, to my knowledge figures are not available, but the situation might not differ much from those of the United States.

(At the global level, concerning research expenditure in organic agriculture, Niggli et al. (2017) estimated that they amount at 0.5% of the total investment in all agricultural research and development).

2.5.2.1 Agroecological practices

Agroecological practices concern a more ecological management of soil, crops, farms, and landscape (Altieri, 1987, 1999, 2018; Francis, 1989; Altieri and Nicholls, 2004; Zehnder et al., 2007; Deguine et al., 2009; Glover et al., 2012; Gliessman, 2014; Wezel et al., 2014; Wojtkowski, 2016; Furlan et al., 2017):

- Reduced tillage is preferred to no-till, as it reduces the use of herbicides, avoids the insurgence of pests that find refuge in crop residues, and better integrates residues in the soil.
- Care is taken to maintain the soil covered all the time, by using cover crops, or leaving residues on the field.
- Crops are managed through long rotations, polyculture, intercropping, relay cropping (the maturing annual crop is interplanted with seedlings or seeds of the following crop), or agroforestry (the practice of including trees or shrubs in crop or animal production agroecosystems).
- Synergies among crops are used to reduce pest insurgence and dealing with weeds, as, for example, is the case for intercropping cereals with legumes, or for the *milpa* system, widespread in central America, where maize, beans, and squash are intercropped to improve soil fertility and shadowing weeds (many more species can be grown in the *milpa* system).
- Use of locally adapted landraces should be preferred when possible, as they may be more resistant to pests, and better adapted to local conditions.
- Agricultural systems should be designed so as to make effective use of sunlight, soil nutrients, rainfall, and biological resources. Fields should be reorganized in mosaics within the farm leaving nontreated strips at the field margins, or embedded within the field.
- Ecological structures such as grass strips, flowering plant corridors, hedgerows, and woodlots are preserved or created to increase biodiversity and its services in pest control (creating suitable habitats for predators and a more complex agroecological mosaic).
- In the case of conventional agriculture, any plant that does not belong to the crop is perceived as a competing weed that has to be eliminated. The agroecological approach distinguishes between species that may harm crops, and should be taken care of, and species that may actually benefit crops, and therefore can be left in the field or at its margins.
- The use of synthetic agrochemicals, although not forbidden (as in organic agriculture), is, nevertheless, reduced to a minimum. Green manure (vegetable biomass) or animal manures should be used when possible.
- Pest control should rely on IPM. IPM was developed in the 1950s, after findings higher levels of pest control in a crop of alfalfa where lower doses of insecticide were used. The lower dose of pesticide sufficed to effectively eliminate part of the pest population, while the rest was eliminated by beneficial species that had survived the treatment thanks to the low application. The term IPM was first used by Ray Smith and Robert van den Bosch in 1967 (Flint and van den Bosch, 1981, p. 6). IPM is “an ecologically based pest control strategy that relies heavily on natural mortality factors such as natural enemies and weather and seeks out control tactics that disrupt these factors as little as possible. IPM uses pesticides, but only after systematic monitoring of pest populations and natural

control factors indicates a need." (Flint and van den Bosch, 1981, p. 6). Strategies for pest control are based on a number of different techniques, including management of the crops in the agroecosystem, management of wild vegetation, biological control, adoption of proper agricultural practices and use of resistant varieties, while pesticides are used only as last resort, at minimum level, and according to established guidelines (Flint and van den Bosch, 1981; Hoy, 1998; Altieri and Nicholls, 2004; Deguine et al., 2009; Wezel et al., 2014; Furlan and Kreutzweiser, 2015; Furlan et al., 2017). IPM should rely on:

1. cultural practices compatible with natural processes (i.e., crop rotation, soil management);
2. vegetation management to enhance natural enemy impact and exert direct effects on pest populations;
3. use of trap crops for pests and host plants for indigenous natural enemies, inundative and inoculative releases of biological control agents;
4. use of mating disruption, insecticides of biological and mineral origin (as in organic agriculture), and IPM.

Monitoring should be carried out to identify pests, weeds, and other potential diseases and ecological practices that exploit the characteristics of cropped and wild species (Hoy 1998; Altieri and Nicholls, 2004; Gurr 2016; Furlan et al., 2017). A very successful practice is the "pull and push" system, that consists in intercropping species that repel pests, "push species," and plants and attract and trap them "pull species." The function of push components of the push–pull strategy is to make the protected resource hard to locate, unattractive, or unsuitable to the pest. The function of the push component is to concentrate pests in a predetermined site, so that they can be efficiently controlled (preferably through highly selective natural pesticides, which are preferred to broad spectrum, synthetic insecticides) (Altieri and Nicholls, 2004; Cook et al., 2007; Glover et al., 2012; Gliessman, 2014).

- Implementing agroecological practices at the landscape level (agricultural landscape) in order optimize the benefits of environmental services provided by the resulting extended agroecosystem (synergic effects of scale).

The adoption of agroecological practices may present some drawbacks, which may prevent farmers from their adoption. Agroecological practices require farmers to be more knowledgeable and skilled, and farmers may prefer simpler conventional practices. Poor farmers, then, may avoid taking risks involved in the adoption of more complex practices (Brookfield, 2001; Carlisle, 2016). Some agroecological practices may limit mechanization of production and may require more labor (Gliessman, 2014). Carlisle (2016) claimed that, to facilitate the adoption of agroecological practices it is necessary to carry on education and research programs, implement sound policies, adopt measures to overcome equipment barriers, and better address the complex relation between farmers and food systems.

2.5.2.2 Crop management

Other than on soil protection, the agroecological approach focuses on sound crops and whole farm management, which should also be extended to the landscape level, to better take advantage of the agroecosystem's environmental services. Crop management aims at increasing the agroecological complexity of fields by rotating crops, or by adoption of a polyculture cropping system, whereby two or more crops are grown in the same productive season. Hereafter, a brief review of the main characteristics of these cropping strategies follows.

Rotation. Crop rotation is an ancient and essential agricultural practice to restore soil fertility (e.g., rotations with legumes such as alfalfa or fava beans), and it also contributes to weed and pest control (by breaking the life cycles of the organisms), thereby increasing yields (Francis, 1989; Bennett et al., 2012; Gliessman, 2014; Wezel et al., 2014; Brankatschk and Finkbeiner, 2015). Conventional agriculture, heavily reliant on agrochemicals (and also due to the novel characteristics of the food system), greatly simplifies the rotation pattern, often reducing it to two crops (i.e., maize, soybean) or even carrying on with monoculture for many years in a row (i.e., soybean in Latin America). This greatly affects soil health and crop yields. For example, for the case of a continuous cultivation of wheat (*Triticum aestivum*), it is well known that the second crop yields about 10% less than the first crop, and third crop yields can be 10%–15% lower than the second (Bennett et al., 2012). Yield decline due to short rotations can range from 10%–20% for maize and wheat (but higher losses have been reported) to 20%–40% for rice, and up to 50% for sweet potatoes and sugar cane (Bennett et al., 2012). Agroecological practices adopt long-term rotation to avoid the accumulation of pests and weeds and soil overexploitation and degradation. Furthermore, sound rotation may increase crop yields and/or reduce the amount of inputs (i.e., N-based fertilizers). For example, maize yield increases when maize is rotated with a legume crop, compared with a continuous maize monoculture system, or a rotation with other cereals (Gentry et al., 2013). Nevertheless, rotations have to be carefully planned to ensure that crop features are appropriate for the rotation cycle, taking advantage of synergistic effects (Wezel et al., 2014).

Multicropping (multiple cropping). Multicropping refers to growing two or more crops on the same field in the same growing seasons. Crops may be planted one after another, in temporal succession, or in different plots within the same field, or intercropped.

Intercropping. Intercropping is the practice of growing two or more crops or genotypes together for part of or the whole growing season (Fig. 2.5).

For intercropping to be successful, the majority of interactions that occur among crop species (i.e., the effect on soil, light, water, nutrients, pests) should be beneficial and/or complementary (i.e., facilitative interactions – Brooker et al., 2016, p. 99, define "*facilitative plant–plant interactions are 'positive, non-trophic interactions that occur between physiologically independent plants and that are mediated through changes in the abiotic environment or through other organisms*") (Francis, 1989; Hainzelin, 2013; Li et al., 2013; Gliessman, 2014; Wezel et al., 2014; Brooker et al., 2016; Wojtkowski, 2016; Altieri, 2018).

Intercropping presents also some drawbacks: it may limit mechanization of production, it may require more labor, the use of herbicides may be constrained, or when not properly chosen, a secondary crop may compete with the main crop reducing its yield and economic performance (Gliessman, 2014).

Some traditional intercropping systems include maize/bean, sorghum/pigeon pea, banana/coffee, and maize/cassava, and involve intercrops of plants with dissimilar size

Figure 2.5 Intercropping of vegetables and potatoes (on the right) in a plot of an organic farm in Padova, Northeast Italy. Note the massive hedgerow that surrounds the farm, and the grass strip at the bottom.
Source: Photo T. Gomiero.

and growth cycle in the field, so as to also have better vertical distribution of leaves in the total canopy (Francis, 1989; Hainzelin, 2013; Gliessman, 2014; Altieri, 2018).

The *milpa* system, the maize–beans–squash intercrop, is a very old and well-known traditional practice in Mesoamerica. In the *milpa* system, beans fix nitrogen, which is then made available to maize through mycorrhizal fungal connections between root systems. The squash, providing shadow to the soil, helps control weeds. Tests carried out in Mexico reported maize yields in the *milpa* system could achieve yields as high as 50% above monoculture yields (planting on land that had only been managed using local traditional practices, and making use of these practices) (Altieri, 1987, 2018; Altieri and Nicholls, 2004; Gliessman, 2014).

Traditional, multiple-cropping systems may provide about 15% to 20% of the world's food supplies. In Latin America, farmers grow 70% to 90% of their beans in combination with maize, potatoes, and other crops. Sixty percent of maize grown in this region is intercropped (Altieri and Nicholls, 2004). Traditional cropping systems are also genetically diverse, containing numerous varieties of domesticated crop species as well as their wild relatives. In the Andes, farmers cultivate as many as 50 potato varieties in their fields (Altieri and Nicholls, 2004; Altieri, 2018), and up to 80 landraces in some Andean valleys of Peru and Bolivia (Brookfield, 2001). Genetic diversity confers at least partial resistance to diseases that are specific to particular crop strains and allows farmers to exploit different soil types and microclimates for a variety of nutritional and other uses (Brookfield, 2001; Altieri and Nicholls, 2004; Brookfield and Padoch, 2007; Jarvis et al., 2007; Altieri, 2018).

Traditional agroforestry systems throughout the tropics commonly contain well over 100 annual and perennial plant species per field, species used for construction materials, firewood, tools, medicine, livestock feed, and human food (Altieri and Nicholls, 2004; Atangana et al., 2014; Farrell and Altieri, 2018).

Combining two or more crops within a mixture can sometimes increase total crop productivity because facilitative interactions among the crop species result in greater total resource utilization compared with growing the component crops as monocultures (Francis, 1989; Li et al., 2004; Gliessman, 2014; Li et al., 2013; Brooker et al., 2016; Gurr et al., 2016; Martin-Guaya et al., 2018; Reiss and Drinkwater, 2018). In some crops, yield increases have been reported to reach 90%, by reducing limitations to crop growth imposed by nitrogen/phosphorus availability and/or the presence of disease (Li et al., 2007). Intercropping has been practiced by farmers in China for more than 2000 years (Li et al., 2007). Knörzer et al. (2009) reported that in China's northeast 300,000 ha of maize fields have been converted to intercropping with sweet clover (*Melilotus officinalis*), resulting in maize yields about the same as those from monoculture, but in an additional 15 t/ha of sweet clover, which can be used to feed three cows a year. Li et al. (2007) reported increased yield for maize and wheat when intercropped with a legume like soybean or faba bean, due to complementary N use (i.e., wheat is much better at extracting soil-available N than legumes are, and thus legumes are forced to get nitrogen from atmospheric N fixation). Intercropping is known to be more efficient in poorer soil and poorer environmental conditions, because of higher nutrient uptake, improved resource utilization, and low-input cultivation, but it loses this advantage if combined with high-input cultivation (Knörzer et al., 2009).

Nevertheless, in some cases intercropping can decrease yields by interspecific competition (Li et al., 2007).

A key indicator to assess the performance of intercropping is the land equivalent ratio (LER), a measure of the yield advantage obtained by growing two or more crops as an intercrop compared with growing the same crops as a collection of separate monocultures (Vandeermer, 2011; Gliessman, 2014; Wojtkowski, 2016). For example, crops A and B are intercropped. The yield of crop A in the intercropped system is 10 t/ha and in monoculture is 8 t/ha. The yield of crop B in the intercropped system is 5 t/ha and in monoculture is 3 t/ha. The LER is calculated as $8/10 + 3/5 = 1.4$, a figure indicating that to achieve the same yield from the crops A and B under monoculture we would require 40% more land than as having A and B intercropped. LER is, therefore, an indicator of the intensification achieved by the intercrop system.

Recent meta-analyses of intercropped systems reported LERs of 1.28 (Martin-Guaya et al., 2018) and 1.17 (Yu et al., 2015). The authors noted that intercropping could potentially be a sound means to supply more food to feed people in the future. Nevertheless, it has to be stressed that LER does not provide an economic assessment of production, while being an important indicator in assessing the overall sustainability of an enterprise. Therefore, in some cases farmers may require some economic incentives for adopting this more complex practice (Martin-Guaya et al., 2018). Intercropping systems are usually less affected by pests, but the effect depends on the choice of the crops intercropped, as in some cases crop mixtures may, for example, change the microclimate, increasing humidity and favoring the presence of some pests (Francis, 1989; Gliessman, 2014; Wezel et al., 2014). Intercropping can also reduce weeds. Intercropping maize with legumes has shown to reduce weeds and increase yields by 37% (Verret et al., 2017). Therefore, intercropping can increase outputs while decreasing management costs (Fig. 2.6).

The integration of crops and small livestock, complex crop associations and rotations, agroforestry, and remarkable tropical home garden systems characterize traditional agriculture, which has fed people well for a very long time (Altieri, 1987; Gliessman, 2014). Nevertheless, it has to be highlighted that adoption of agroecological practices may be more labor intensive. Therefore, in societies where the cost of labor is high (i.e., Europe, United States), farmers may have limited interest in such practices. Such an issue directly concerns how a society accounts for externalities. If the cost of externalities caused by unsustainable agricultural practices were to be internalized, adopting agroecological practices may prove much more cost effective (Gomiero, 2016; Wojtkowski, 2016).

Agroforestry. Agroforestry refers to land-use systems and technologies where woody perennials (trees, shrubs, etc.) are grown on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. Agroforestry allows to diversify production, protect soil, reduce pest pressure, and increase social, economic, and environmental benefits for farmers

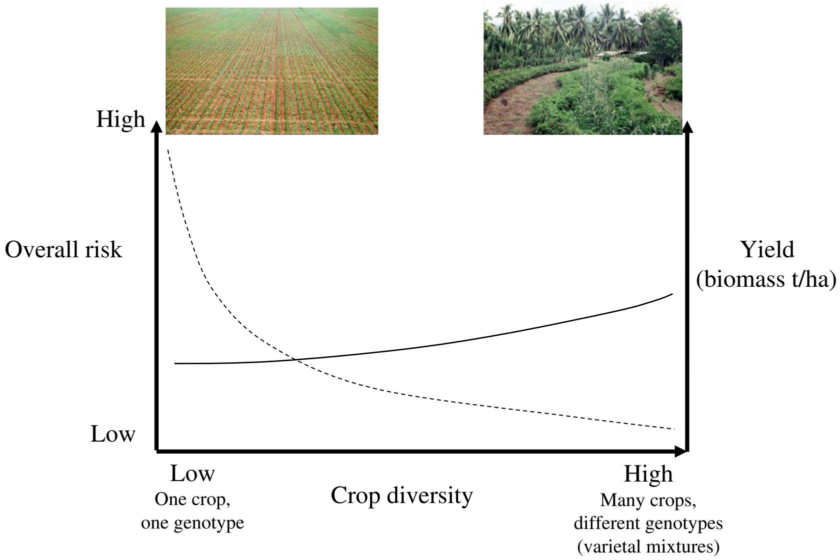

Figure 2.6 Increasing crop biodiversity (both as number of species and varieties) greatly reduces risks and enhances total yield per hectare.
Source: Photo on the left (maize monoculture) from FAO (http://www.fao.org/docrep/006/x8234e/x8234e08.htm); photo on the right (complex cropping system) from FAO (http://ref.data.fao.org/photo?entryId = 3f405bf8−54e2−4be1−834b-bc7ba2c3636a).

and for society at large (Altieri and Nicholls, 2004; Perfecto et al., 2009; Gliessman, 2014; Atangana et al., 2014; Wezel et al., 2014; Wojtkowski, 2016; Farrell and Altieri, 2018; FAO, 2018b). Agroforestry is a key feature of tropical home gardens, where tens of different species can be cultivated on the same plots, on three to four different layers (Atangana et al., 2014; Farrell and Altieri, 2018; FAO, 2018b). Complex tropical agroforest systems can achieve high agricultural yields, make systems more resilient and preserve high levels of biodiversity, both agricultural and wild (Perfecto et al., 2009; Clough et al., 2011; Atangana et al., 2014; Farrell and Altieri, 2018). Agroforestry is spreading also within Europe, especially in the southern part, as a way to diversify cultures, promote soil and environmental conservation, increase the carbon sink, reduce the use of agrochemicals, and as a means to respond to the effects of climate change (Wezel et al., 2014; Torralba et al., 2016; Mosquera-Losada et al., 2018).

2.5.2.3 The importance of adopting agroecological management at the landscape level

Agricultural intensification results in a dramatic simplification of landscape composition and in a sharp decline of biodiversity, which affects the functioning of natural pest control, as natural habitats provide shelter for a broad spectrum of natural species that operate as pest control for all crops. Research demonstrates that pesticides disrupt the communities of pests' natural enemies, in turn leading to increased pest damage in crops (van den Bosh, 1989; Winston, 1997; Crowder et al., 2010; Bommarco et al., 2011; Hamilton et al., 2015; Gurr et al., 2016). Hoy (1998) pointed out that effective resistance mitigation requires a holistic approach to pest management.

Landscape heterogeneity is a key factor in promoting biodiversity in the agricultural landscape. A mosaic landscape may support a larger number of species in a given area, simply because the landscape contains a larger number of habitats. Properly preserving a healthy agroecological landscape and landscape-ecological structures (i.e., hedgerows, herbaceous strips, and woodlot) helps protect crops by relying on helpful organisms that predate on pests (e.g., ladybird beetles, aphids, parasitoid wasps, aphids, and caterpillars) (Thies and Tscharntke, 1999; Bianchi et al., 2003; Altieri and Nicholls, 2004; Perfecto et al., 2009; Macfadyen et al., 2009; Crowder et al., 2010; Hobbs et al., 2014; Gurr et al., 2016; Wezel et al., 2014; Hamilton et al., 2015; Gomiero, 2015b; Wojtkowski, 2016). Mols and Visser (2007), for example, found that the great tit (*Parus major* L.), a European cavity-nesting bird, reduces the abundance of harmful caterpillars in apple orchards by as much as 50%–99%. In the Netherlands, the foraging of *P. major* increased apple yields by 4.7–7.8 kg per tree. Bianchi and Van Der Werf (2003), found that landscapes with 9%–16% noncrop habitat provided enough resources for local populations of ladybird beetles to control aphid outbreaks. On the contrary, reducing ecological structures and causing habitat fragmentation results in a significant reduction in local biodiversity and this may impact on the biological control of pests (Thies and Tscharntke, 1999; Altieri and Nicholls, 2004; Bianchi et al., 2006; Gardiner et al., 2009; Wezel et al., 2014; Hamilton et al., 2015). It has also been suggested that biodiversity conservation, by retaining local food web complexity, can also represent an effective management strategy against the spread of invasive species that often act as pests in new environments (Kennedy et al., 2002). This may help avoid the downside of using exotic natural enemies to fight novel invasive species, as species introduced for biocontrol can act as invasive species in their own right (Thomas and Reid, 2007). Perfecto et al. (2009) studied the effect of trees in shadow coffees in Mexico, and found that biodiversity harbored by trees allows for the existence of a complex web of relations among ants, ladybird beetles, birds, spiders, and parasitic wasps contributing to effectively control about a hundred potential coffee pests. Castelan et al. (2018) carried out a test in Brazil to assess the role of natural forests on banana plantations. The authors demonstrated that preserving natural ecosystems near plantations reduced pest attack on banana plants (increasing yields) and improved the nutritional quality of produce. A multi-site field studies carried out in Asia, on rice fields, by Gurr et al., (2016), seems confirming that increasing biodiversity promotes ecological intensification of agriculture. The authors report that inexpensive intervention aiming at increasing nectar-producing plants around rice fields, significantly reduced populations of two key pests, reduced insecticide applications by 70%, increased grain yields by 5% and delivered an economic advantage of 7.5%.

2.6 Cropping biodiversity to reduce losses and increase yields

2.6.1 The potential benefits of varietal mixture to cope with pest and increase yields

Before the green revolution, farmers selected local crop varieties (landraces) aiming at obtaining crops resistant to local pests and local environmental conditions (which is also what many small subsistence farmers do today). Since the process of industrialization of agriculture started and agrochemicals became available, crops have been selected mainly with the aim to increase yields and to fit in with extensive monotypic monoculture. This has led to selection of genetically uniform HYV that have become increasingly vulnerable to pests and dependent on human management. In the process, thousands of landraces have been lost all over the world (Marshall, 1977; Wolfe,1985; Brookfield, 2001; Heal et al., 2004; Fowler and Hodgkin, 2005; Jarvis et al., 2007, 2008, 2011; Frison et al., 2011; Hainzelin, 2013; Wojtkowski, 2016).

The risks arising from reduced crop genetic diversity have been discussed by scholars since the 1950s, when such new genetically homogeneous varieties began to enter the market (Marshall, 1977; Heal et al., 2004). Scholars have argued that the impoverished germplasm of HYV would have weakened the resistance of crops in front of pest attack. Browning (in: Heal et al., 2004) pointed out that diversity was the only defense against the unknown (such as the presence of novel pests or environmental conditions).

The continuous and ever-increasing use of pesticides required to protect new varieties eventually caused major environmental pollution, while pesticide residues became common on food. Furthermore, pesticides did not solve the problems faced by crops, as pests quickly became resistant to them. This led to a process known as the "pesticide treadmill" (Flint and van den Bosch, 1981; van den Bosh, 1989; Vandeermer, 2011), whereby an increasing quantity and expanding range of chemicals have to be used (Flint and van den Bosch, 1981; Hoy, 1998; Altieri and Nicholls, 2004; Vandeermer, 2011).

A promising strategy to control pests and hinder pathogen adaptation to varietal resistance is the use of mixtures of varieties such that the mix will form a heterogeneous environment for the parasite (Marshall, 1977; Wolfe,1985; Zhu et al., 2000, 2007; McDonald and Linde, 2002; Brookfield, 2001; Brookfield et al., 2002; Altieri and Nicholls, 2004; Brookfield and Padoch, 2007; Hainzelin, 2013; Han et al., 2016). The main purpose of genetic mixtures (crop variety mixtures) for pest and disease management is to slow down pest and pathogen spread. In variety mixtures (also mixture of landraces), two or more component varieties are grown concurrently within the same field, introducing diversity to the crop stand. Cultivation of variety mixtures is a characteristic trait of subsistence agriculture, nevertheless, due to the benefits provided, this strategy is also gaining increasing attention in industrialized countries (Brookfield, 2001; Altieri and Nicholls, 2004; Jarvis et al., 2007; Kiær et al., 2009; Newton et al., 2010; Frison et al., 2011; Hainzelin, 2013; Brooker et al., 2016; Dwivedi at al., 2016; Wojtkowski, 2016). Dwivedi et al. (2016) stressed that landraces, given their more than millennial evolutionary history and adaptation to stressful environments, can represent an ideal resource to explore novel genetic variation that overcomes challenges to crop production, enhancing the yield (through, for example, a process of facilitation), and stability of staple crops in vulnerable environments.

It has been reported that cropping varietal mixtures allows for better pest management, provides buffering against variation in environmental factors, and guarantees more stable and potentially increased crop yields (Zhu et al., 2000; Kiær et al., 2009; Newton et al., 2010; Mulumba et al., 2012; Hainzelin, 2013; Li et al., 2013; Zhang et al., 2013; Yu et al., 2016; Wojtkowski, 2016). Döringa et al. (2015) reported that increasing plant diversity in the field raised wheat yields by 2%–4% over monocultures. A metaanalysis conducted by Kiær et al. (2009) confirms the potentials of seed mixtures of wheat and barley to provide increased grain yields and improve its stability over time. Although the overall yield increase found for cultivar mixtures compared with the expected yield from their component monocultures was just 2.2%, this increase is comparable to the average annual rate of yield gain due to plant breeding improvements (between 1% and 3%) (Reiss and Drinkwater, 2018). In China, Zhu et al. (2000, 2007) conducted a series of tests on rice, in areas heavily affected by the rice blast fungus (*Pyricularia oryzae*, one of the mayor epidemic diseases limiting rice production in southwest China), and on wheat fields (intercropped with broad bean, *Vicia faba*) affected by wheat rust. In both cases, a number of varietal mixtures were interplanted. The authors claim that results were impressive. In the case of rice, pests were reduced by 94%, yields were 85% higher than usual monoculture, and farmers' average income increased by US \$150 ha^{-1}. In the case of wheat, wheat rust was reduced by 25%, wheat yield remained the same, while the yield of broad beans increased. Positive effects induced by the adoption of varietal mixtures are also reported for other crops in Asia (Zhu et al., 2000; Li et al., 2013; Reiss and Drinkwater, 2018). Further to that, such an approach helps foster conservation of agrobiodiversity, crop varieties, and landraces in situ, reducing the risk of further biodiversity losses (Zhu et al., 2003).

Nevertheless, issues associated with this agricultural practice have also been documented. Reiss and Drinkwater (2018) argued that, in specific cases, negative mixing effects have been observed, and at times both positive and negative mixing effects are observed in the same trial. The authors highlighted that the mixing effect of a specific variety mixture may be difficult to predict, therefore results of individual trials may not apply to other mixtures and other growing conditions. For example, tests carried out by Han et al. (2016) proved that only some rice combinations grown in a mixture showed effective control of rice blast, while using other varietal mixtures did not achieve the same results. Developing pest-resistant varieties (landraces) has been indicated as a possible solution to cope with pests and reduce the use of agrochemicals. Nevertheless, if crops are not properly managed, pests can eventually overcome crops' resistance.

2.6.2 Cropping perennial crops

Since the 1980s, in the United States, due to the dramatic consequences of ploughing on soil conservation (such as the "dust bowl," Worster, 2004; Montgomery, 2007a), some authors began to suggest moving 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 (Jackson, 1980, 2002; Soule and Piper, 1991).

Although conservation tillage and the adoption of cover crops can improve SOM, in general, they cannot accumulate as much SOM stock as in grasslands, forests, or the native ecosystems that agriculture replaces. Developing perennial grain agroecosystems may greatly benefit agriculture and help accumulate SOM in fields and reduce nitrogen loss. Field tests carried out in the central USA by Glover et al. (2010a) reported better performance of perennial grassland (mixtures of about 30 species) compared with wheat fields for all agronomic (i.e., biomass harvested, use of inputs, management costs) and environmental performance parameters (i.e., soil structure, biodiversity). Management costs are reduced because perennial crops do not need to be replanted every year, so they also require fewer passes of farm machinery and fewer inputs of pesticides and fertilizers, which reduces fossil fuel use. Glover et al. (2007) reported that herbicide costs for annual crop production may be 4–8.5 times the herbicide costs for perennial crop production, so fewer inputs in perennial systems mean lower cash expenditures for farmers.

Perennial crops, with their roots exceeding depths of two meters, can improve ecosystem functions such as water conservation, nitrogen cycling, and carbon sequestration by more than 50% when compared with conventional crops. Perennial crops are reported to be 50 times more effective than annual crops in maintaining topsoil, to reduce N losses 30- to 50-fold, and to store around 300–1100 kg carbon/ha per year compared with the 0–400 kg carbon/ha per year of annual crops (Cox et al., 2006; Glover et al., 2007, 2010b; Crews and Rumsey, 2017). Due to their effect on soil carbon and their lower inputs requirements, some authors claim that perennials could help slow down climate change (Cassman et al., 2003; Cox et al., 2006, 2010; Glover et al., 2007, 2010a,b; Powlson et al., 2011; Crews and Rumsey, 2017; Baker, 2017). Perennial crops are predicted to better adapt to temperature increases of the magnitude predicted by most climate-change models. Cassman et al. (2003) reported that increase of 3°C–8°C are predicted to increase yields of switchgrass (*Panicum virgatum*), a perennial forage and energy crop, by 5000 kg/ha, whereas annual species yields are predicted to decline (e.g., maize, −1500 kg per ha; soybean, −800 kg per ha; sorghum, −1000 kg/ha). Perennial cereals can also be intercropped with legume forages, which offers some important benefits, such as providing nitrogen to the grain crops, facilitating the accrual of SOM, increasing forage quality, and helping support pollinators (Hayes et al., 2016; Ryan et al., 2018).

In recent years, there has been an increasing focus on perennial breeding programs in all continents (Cox et al., 2010; Glover et al., 2012; Pimentel et al., 2012; Baker, 2017). Glover et al. (2012) reported the increasing adoption of perennial species in Africa, as such species are better suited to the poor African soils and can gain access to more of the soil's nutrients and water, and for a longer time, compared with annual crops. In 2014, an international workshop on the topic was held in Rome, Italy, at the FAO headquarters (FAO, 2014b).

Novel perennial crops have been developed both by hybridizing high-performing domestic annual species with closely related wild perennials (wheat, rye, sorghum, rice), and by the domestication of wild perennial plant species with the potential to serve as new grain crops (e.g., *Helianthus maximiliani* and *Silphium integrifolium*, which are related to common sunflower *Helianthus annuus*) (Cox et al., 2010; Baker, 2017; Ryan et al., 2018). Some authors reported that intermediate wheatgrass (*Thinopyrum intermedium*) is perhaps the most advanced example of a recently domesticated perennial grain crop, and that grain from improved lines of this crop is marketed as Kernza and is now being used in restaurants, bakeries, and commercial products (Baker, 2017; Ryan et al., 2018).

However, perennial crops also present some problems. Even if perennials yield more aboveground biomass, edible yield of perennial species is lower than conventional species (species that went thought long-term domestication). Nevertheless, it is believed that artificial selection in a properly managed agricultural environment could increase seed yield while maintaining perenniality

(Cox et al., 2006; Glover et al., 2010b; Crews and Rumsey, 2017; Baker, 2017; Ryan et al., 2018). Perennials' longevity may lead plants to allocate resources to belowground biomass, reducing seed productivity. Experts claim that this might not preclude selection of perennials that are high-yielding and economically viable (Glover et al., 2010b; Ryan et al., 2018). Perennial crops may be slow growing but then stay in the ground for multiple years. Such characteristics made fields cropped with perennial crops more susceptible to weed invasion than those cropped with annual crops, being thus at risk of poor establishment and crop failure (Pimentel et al., 2012). It has been argued that in some cases (i.e., perennial wild rice in the United States) perennial crops may become invasive (Pimentel et al., 2012).

Farmers should be aware of such potential problems and preempt them. For example, interplanting perennial grain crops with legume crops can reduce potential weed problems (Pimentel et al., 2005; Hayes et al., 2016; Ryan et al., 2018). The authors claimed that investing in proper breeding programs may overcome the present problems, focusing in particular on:

1. producing perennials with reliable regrowth and high grain yield and quality over multiple years,
2. making them adapted to abiotic stresses (i.e., water and nutrient deficiencies),
3. making them more resistant to pests and diseases (Glover et al., 2010b).

Profitability is a crucial factor in farmers' decision-making. Some authors (Baker, 2017; Ryan et al., 2018) argued that perennials help save on annual sowing and production costs (e.g., fuel, fertilizers, pesticides) compared with annual grain crop production, and that cost reduction, along with price premium for grain quality, may make perennials interesting for farmers. Ryan et al. (2018) claimed that the value of ecosystem services provided by perennial grain crops should be recognized if we want to develop a true multifunctional agriculture, and that information about this agricultural practice should be made known to farmers.

2.7 Technological approaches

In this section, I will briefly review the potential role of technology in enhancing the performance and sustainability of agricultural practices, namely the use of precision farming and transgenic crops.

2.7.1 Precision agriculture

Precision agriculture (PA) (also known as "precision farming," "site-specific crop management," "prescription farming," and "variable rate technology") has been developing since the 1990s, and refers to agricultural management systems carefully tailoring soil and crop management to fit the different conditions found in each field. PA 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 soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment (Bongiovanni and Lowenberg-Deboer, 2004; NRC, 1997; Gebbers and Adamchuk, 2010; Schrijver, 2016). PA is believed to be able to reduce the amount of inputs required, and better protect crops and soil.

Performances of PA are still debated, as comprehensive research is lacking (Yost et al., 2017). Paustian and Theuvsen (2017) noted that the advantages of PA adoption by farmers have been demonstrated by numerous expost studies, but most existing studies concentrate on only a few aspects of PA adoption. Paustian and Theuvsen (2017) noted that, in Germany, farming a large amount of arable land has a significant effect on PA adoption by farmers. However, the authors do not provide information about any changes in performance since PA adoption. Yost et al. (2017) analyzed a long-term dataset from Missouri on wheat, maize, and soybean cultivation, comparing yields before and after adoption of PA practices. The authors concluded that the greatest production advantage of a decade of PA lay in reducing temporal yield variation but did not concern yields. Nevertheless, they claimed that reducing yield variation was a positive outcome, as it leads to greater yield stability and resilience to a changing climate. Unfortunately, the work does not deal with the economic issues, and the economic sustainability of the enterprise is unclear. Robertson et al. (2009) analyzed the economic performance of six large Australian farms (1250−5800 ha cropping program) and found a benefit of PA adoption ranging from \$1 to \$22 ha^{-1} across the six farms, with the initial capital outlay recovered within 2−5 years. Due to the characteristics of PA, where data concerning farm and management practices are stored in databases, it has been highlighted that an issue might be posed by the future ownership of data (Schrijver, 2016).

2.7.2 Genetically modified crops

Adoption of herbicide-resistant GM crops (Roundup/glyphosate, or gluphosinate) allowed the adoption of no-till practices. Nevertheless, due to agricultural policies (e.g., heavy subsidies on maize in the United States) and global markets (e.g., increasing demand for soybean in Asia), herbicide-resistant crops have been eventually cropped continuously (maize after maize, or soybean after soybean), or, at best, in a very simple rotation (such as maize alternated to soybean in the United States), without adoption of long rotations, as recommended by the CA. Such practices led to weeds becoming resistant to herbicides (to date, about 220 weed species have evolved resistance to one or more herbicides, Heap, 2014; Bonny, 2016). Herbicides were thus used in higher amounts, dramatically increasing environmental pollution and causing human health concerns (Binimelis et al., 2009; Powles and Yu, 2010; Cerdeira et al., 2011; Benbrook, 2016; Bonny, 2016). Producers of GM crops are counteracting the issue by making HR crops resistant to other herbicides such as Dicamba and 2,4-D, which will further increase herbicide use and contamination, and are already causing dramatic conflicts among farmers. Dicamba, for example, is highly volatile and can drift away for many kilometers, affecting non-HT crops in the surrounding area and causing enormous economic damage. Damage for which, it seems, nobody is held accountable. Some farmers' associations sued Monsanto over the release of drifting herbicides (Charlier, 2017; Hall and Lokai-Minnich, 2018; Beck, 2018), and claimed that use of such compounds may be part of a strategy to force all farmers to plant HT crops, which, at present, are produced in a regime of near-monopoly. It is difficult to find any rationale in this approach to weed control, as it is clearly going to fail (and cause increased toxic compound accumulation in GM crops). Actually, in the United States, resistance to Dicamba in noxious weeds such as Burning bush (*Kochia scoparia*) and Pigweed (*Amaranthus* spp.) have been reported since the early 1990s (Cranston et al., 2001; Harwood et al., 2001; Steckel, 2017; LeClere et al., 2018). Therefore, widespread use of said herbicide on GM crops would quickly increase the problem.

GM crops engineered to produce Bt toxins went through a similar path, requiring agrochemical companies to increase the number of Bt toxins produced by plants (Tabashnik et al., 2013; Gassmann et al., 2014; Bøhn and Lövei, 2017), as well as to adopt other techniques of pest control at the same time (e.g., fungicides, hormonal traps).

It has been claimed that GM crops helped reduce the use of agrochemicals and increase farmers' profits, due to the lower amount of inputs and labor required by GM crops [for a later review see Klümper and Qaim (2014), although the choice of literature, including many references, may not meet rigorous scientific standards]. Positive outcomes may have been achieved in the early years following introduction of GM crops. However, as soon as weeds and pests developed resistance to glyphosate and Bt, use of agrochemicals skyrocketed. Further to that, along with the increasing cost of GM seeds (in the last decade, in the United States, the price of GM seeds increased by 300%–400%), farmers' profits were quickly eroded, and, as a matter of fact, many farmers, to save money, have been reported to be turning to conventional seeds (Bunge, 2016a,b; Hakim, 2016).

Adoption of GM crops has raised a number of concerns. Genetic contamination of wild plants and weeds are widely reported (Andersson and de Vicente, 2010; Bauer-Panskus et al., 2013). In the mid-2000s, nontransgenic canola fields were reported to have become contaminated with glyphosate-resistant canola (Cerdeira and Duke, 2006). Although herbicide-resistant GM crops are not affected by the herbicide, they do accumulate the herbicide in the plant, including the edible parts (Bøhn et al., 2014). That means that animals and humans are exposed to the compounds present in the herbicides: active principles, adjuvants (which may be much more toxic than the active principles, Mesnage et al., 2014), and their degradation products (which may be highly toxic too). Due to pest resistance to the first Bt toxins, GM crops are being engineered to produce many different Bt toxins (Bt maize producing 4–5 different toxins are on the market). Although Bt is considered unable to affect human health, and producers claim that GM Bt crops are safe (Koch et al., 2015), the increasing quantity of Bt toxins (of different types) present in GM crops, and the possible interactions between Bt toxins and pesticide residues and other compounds present in plants should be a matter of concern (Then, 2010; Mesnage et al., 2013; Then and Bauer-Panskus, 2017).

Introduction of GM crops did not result in increased crop yields. Although in the last few decades the yield of soybean, maize, and other crops has risen substantially, that was due to the improvement of varieties (achieved by traditional breeding) or improvement of agricultural practices (Grassini et al., 2013). NAS (2016, p. 7) states that "…there is no evidence from USDA data that they have substantially increased the rate at which of US agriculture is increasing yield." Recently, Nilsen (2017) reported that the rate of yield increase of US maize has been the same for the last 50 years, and that introduction of GM maize has not resulted in a noticeably increased yield growth trend.

It has been claimed that adoption of GM crops may help African countries to better feed themselves. Some experts highlight that very low amounts of inputs are used in Africa, therefore higher yields can be achieved by simply helping farmers buy fertilizers, or adopt more suitable crop varieties and agricultural practices (Sanchez, 2010). The IAASTD report[2] (IAASTD, 2009) on GM crops, which involved more than 400 experts, concluded that they may not represent a suitable tool for reducing hunger and poverty, improving nutrition, providing health and rural livelihoods, and facilitating social and environmental sustainability.

2.8 Conclusion

A number of issues are of major concern for the sustainability of our food system. A larger population has to be fed, and economic development is driving hundreds of millions of people to shift from a diet based mostly on vegetables to one rich in animal products. This is leading to an increasing cost of food production, both in terms of resource use and environmental impact of agriculture. In many regions of the globe, especially in those more densely populated, we are already experiencing dramatic problems concerning soil degradation, water shortages, energy supply, and environmental contamination by agrochemicals. Intensive and inappropriate agricultural practices, while boosting yield and profits in the short term, may put long-term productivity and food security at risk. Therefore, adoption of sound agricultural practices is of primary importance to preserve soil health, reduce the environmental impact of agriculture, and reduce yield loss.

In this chapter, a number of agricultural practices proposed as sustainable alternatives to conventional agriculture have been reviewed and assessed. Such practices have different goals. Some of them (i.e., CA), aim at improving soil conservation, in particular at reducing soil erosion. Others (i.e., those proposed by the agroecology movement) are more concerned with an ecological management of crops, integrated with the local landscape, that can protect soil, prevent the insurgence of pests, and reduce the use of agrochemicals.

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[2] IAASTD was a 3-year project promoted by the United Nations, the World Bank and the World Health Organization, aiming at assessing agricultural knowledge and science and technology in relation to reducing hunger and poverty, improving nutrition, providing health and rural livelihoods, and facilitating social and environmental sustainability.

Upon reviewing the above, it appears that CA, while offering important benefits in view of soil protection, may nevertheless present some important drawbacks. Therefore, the impact of its adoption has been carefully monitored, and depending on the specific case, it may be useful to favor minimum tillage in place of continuous no-till. It has to be stressed that CA relies on the use of herbicides, which are required for weed control. In the long term, such practice leads to soil and water contamination by chemicals, and when badly implemented (as it is often the case, especially since GM crops were widely cropped), causes weeds to become resistant to herbicides, forcing farmers to apply more and more herbicides. The latter issue is of great concern, with particular reference to the sustainability of GM crops (another highly relevant issue concerns the fact that GM crops also accumulate herbicides in the edible parts). Agroecology offers a range of practices that seem able to provide multiple benefits: preventing yield loss, protecting the soil, reducing the use of inputs, preserving crop genetic biodiversity, and preserving the agroecological landscape. Also, in this case, monitoring is required to assess how well a practice may fit into the specific features of the local agroecological and socioeconomic systems, and pros and cons have to be carefully weighed.

Further research is needed to explore the potential of low-impact agroecological practices, to further improve them and make them available to an ever-greater number of farmers.

In parallel, sound agricultural policies have to be developed (fostering collaboration among the different actors of the food system) to facilitate adoption of those practices by farmers. Eventually, functioning of the whole food system should be addressed, including critical issues such as postharvest food waste, the overall impact of food choices, the alternative use of food such as the production of biofuels, power relations along the food chain, and the impact of the globalization process.

The rapid changes we are experiencing both socially (e.g., population growth) and environmentally (e.g., the potential impact of climate change) provide an urgent warning signal to policy makers, researchers, and society as a whole to address such issues promptly to better cope with the major challenges waiting ahead.

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