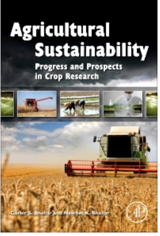

Chapter 2

Organic Agriculture—Driving Innovations in Crop Research

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1. INTRODUCTION

At present, agriculture faces the unprecedented challenge of securing food supplies for a rapidly growing human population, while seeking to minimize adverse impacts on the environment and to reduce the use of non-renewable resources and energy. A shift towards sustainable agricultural production entails the adoption of more system-oriented strategies that include farm-derived inputs and productivity based on ecological processes and functions (Garnett and Godfray, 2012). Sustainable agricultural systems involve the traditional knowledge and entrepreneurial skills of farmers (IAASTD, 2008). System-oriented sustainable practices include organic farming and low external input sustainable agriculture (LEISA). Elements of agroecology—such as integrated pest management, integrated production (IP), and conservation tillage—have been successfully adopted by conventional farms.

Organic farming offers the most consistent approach to agroecological progress. Because of the ban or restricted use of many direct control techniques such as pesticides, herbicides, synthetic soluble fertilizers, and veterinary medicines, organic farmers rely heavily on preventive and system-oriented practices. Organic farm management aims to maximize the stability and homeostasis of agroecosystems. It improves soil fertility through the incorporation of legumes and compost and by recycling local nutrients and organic matter. Organic practices rely on preventive measures found in nature to regulate pests and diseases in crops and livestock. Because organic farming systems are relatively free from the use of synthetic pesticides, and organic processors use only a few additives, organic agriculture offers consumers high-quality and healthy food. Organic farmers may profit from ready access to local markets as part of a participatory guarantee system (PGS) or from high-value export markets when certified by accredited third-parties.

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Organically farmed, third-party certified land—including in-conversion areas—comprises 37 million hectares or 0.9% of total global agricultural land area. Organic agriculture is the most advanced and widely practiced in Europe. In some countries, organic agriculture is becoming mainstream: e.g., in Austria where 20% of the agricultural land area is organically managed. In developing countries, permanent crops such as coffee, tea, cocoa, coco nuts, and olives are increasingly produced according to organic standards to satisfy fast-changing consumer habits. The global market for certified organic products has grown to 44.6 billion Euros (Willer and Kilcher, 2012).

In the past, the unsustainable production of food, feed, fiber, and fuel strongly degraded global ecosystems and the services those systems provided for human survival (Millennium Ecosystem Assessment, 2005). Such ecosystem services include the provision of pure water, the recycling of organic matter and nutrients, the adaptation to climate and weather events by fertile soils, the regulation of crop pests and diseases through biodiversity and natural enemies, and the pollination of crops by wild animals, to name a few. Such degradations have not been halted or reversed yet, despite the fact that sustainability has become the axiom of agricultural policy. Global loss of fertile soils caused by wind and water erosion is continuing at an annual rate of 10 million hectares because of unsustainable farming techniques (Pimentel et al., 1995).

While the benefits to consumers and the bounty of public or common goods of organic farming and food systems are well documented (Scialabba El Hage and Hattam, 2002; UNCTAD, 2006; Niggli, 2010; Schader et al., 2012), scientists and global food security experts linger on the insufficient productivity of organic farming systems. Two most recently published scientific meta-analyses shed light on this important aspect. The overall yield gaps of organic for all crops are estimated to be 25% (Seufert et al., 2012) based on 316 comparisons and at 20% based on 362 comparisons (De Ponti et al., 2012).

Nitrogen availability was identified as a major yield-limiting factor in organic systems (Seufert et al., 2012). Nitrogen fertilizers exemplify the trade-offs between productivity and soil fertility. Mulvaney et al. (2009) pointed out that synthetic nitrogen fertilizers deplete organically bound soil nitrogen as well as soil organic carbon, leading to stagnating yields in a wide variety of soils, geographic regions, and tillage practices. In Asia, yields of cereal production have even decreased as a consequence of these depletion phenomena (Mulvaney et al., 2009).

Mulvaney et al. (2009) suggested a "gradual transition from intensive synthetic N inputs to legume-based crop rotations" for sustainable cropping systems. This very recommendation qualifies the yield gap between organic and conventional systems because, in the latter, yields are based upon an unsustainably excessive use of synthetic nitrogen fertilizer.

Some of the data of the two yield meta-analyses published in 2012 are derived from long-term field experiments. De Ponti et al. (2012) reported a decrease of the yield gap of organic farming to 16% on farms and fields managed organically for over 5 years. For countries where organic agriculture has a long tradition and is technologically advanced, the yield gap is further reduced. In Switzerland, with 11% of all agricultural land transitioned to organic, and Austria, where 20% of all agricultural land has transitioned to organic, the yield gap is reduced further to about 12% (De Ponti et al., 2012). More importantly, 25% of all data from the 362 comparisons shows relative yields of organic farms to be 90–180% of conventional cropping. These cases are relevant when estimating the potentials of organic farming and also those of further research on eco-functional intensification (Niggli et al., 2008), as described in the last part of this chapter.

Individual long-term system comparison field trials further reveal that organic systems have relatively high yields with an excellent input–output efficiency. The DOK trial (referring to bio-**d**ynamic, bio-**o**rganic and conventional) in Switzerland compared the same 7-year crop sequence for organic and conventional management since 1978. The organic plots produced 80% of the conventional yields, but fertilizer use and energy use were reduced by 34% and 53%, respectively, and pesticide applications were reduced by 97% (Mäder et al., 2002). "Enhanced soil fertility and higher biodiversity found in organic plots may render these systems less dependent on external inputs" was the conclusion of the authors. The field experiment has continued for 34 years, and the efficient input–output ratio of the organic systems has remained stable.

2. SOIL FERTILITY AND ORGANIC FARMING IN THE TROPICS—CHALLENGES AND THE WAY FORWARD

One of the most important issues faced by organic farming and sustainable production systems is how to maintain and improve soil fertility. Soil fertility is a measure of the ability of soil to sustain crop growth in the long-term, and can be determined by physical, chemical, and biological processes intrinsically linked to soil organic matter content and quality (Bhupinderpal-Singh and Rengel, 2007; Diacono and Montemurro, 2010). Agricultural lands are being degraded through depletion of soil organic matter, nutrient loss and imbalance, accelerated soil erosion, waterlogging and salinity in irrigated areas, degradation of soil structure leading to crusting and compaction of the surface soils, and decline in soil water and nutrient retention capacities (Lal, 2009). Degraded lands account for about 65% of the arable land in Africa, 74% of the arable land in Central America, and 45% of the arable land in South America (Oldeman et al., 1991; Scherr, 1999). While nutrient loss is the main form of land degradation in Central and South America, salinization and nutrient loss accounted for about 36% of arable land degradation in Asia (Oldeman et al., 1991).

African soils are inherently low in fertility because they developed from poor parent material, are old, and lack volcanic rejuvenation. African soil types are highly weathered, with low organic matter, low capacity to retain and supply nutrients to plants, high nitrogen leaching and phosphate fixation potential, low to medium water-holding capacity, weak soil structure, and deficiency in minor nutrients (Deckers, 1993). Soil fertility depletion is a major constraint to food security and income generation for African smallholder farmers as tropical soils lose nutrients every year (Pinstrup-Andersen et al., 1999; Sanchez and Swaminathan, 2005; AFS, 2006; Henao and Baanante, 2006).

By contrast, South Asian countries have progressed from food-deficit status in the early 1970s. Almost all countries in the region have increased per capita food production. The Green Revolution is credited with solving South Asia's food crises from the 1970s by promoting widespread diffusion of fertilizer-responsive wheat and rice varieties in areas with access to inputs, credits, and irrigation. In 1998, the respective consumption of N, P, and K corresponded to 71, 23, and 8 kg ha^{-1} (Katyal and Reddy, 2012). Monoculture crop production, cereal dominated crops such as rice–wheat and rice–rice–wheat rotations, mechanization, and increased intensity of land and water use occurred simultaneously with reduced return of organic matter to the soil, to cause deterioration and compaction in most of the soil structure in South Asia (Gill, 1995). Long-term problems resulting from irrigation have caused lands to retire from use in places where Green Revolution technologies have been widely adopted (Paarlberg, 1993). Soil acidity and aluminum toxicity are growing problems in hilly areas, and as this builds up, farmers find it increasingly difficult to realize an acceptable return to their labor and inputs (Gill, 1995).

Attempts to improve African crop production during the Green Revolution often neglected impacts on soil fertility. Traditional agricultural systems maintained soil fertility through long-term bush fallows of 10 or more years (Schlecht et al., 2006), but this has given way to continuous cropping and intensive use of land under an external inputs system. External inputs—mineral fertilizers, lime, irrigation water, and improved cereal germplasm—were promoted in the 1960s to overcome constraints on crop production. Unlike in Asia and Latin America, where these technologies boosted agriculture production, African production did not respond favourably, because of the diversity of the agroecologies and cropping systems, variability in soil fertility, weak institutional arrangements, and unfavorable policies (Bationo et al., 2012). Instead, continuous cultivation of the land caused a significant decline in soil organic matter content and nutrients (Abdullah and Lombin, 1978; FAO-RAF, 2000). Long-term field experiments in west African agroecosystems showed that the use of mineral fertilizers without recycling of organic materials resulted in high yields, but severe loss of soil organic matter: 5% and 2% per annum on sandy soils and more textured soils, respectively (Bationo et al., 2012). The use of synthetic fertilizer in Africa is also limited by inherent low conversion efficiency, high cost, lack of capital, inefficient distribution systems, unfavorable policies, and other socio-economic factors (Kherallah et al., 2002; Omotayo and Chukwuka, 2009). The global phosphorus scarcity is likely to threaten global food security. Nitrogen and phosphorus fertilizers will become more expensive in the future, putting upward pressure on fertilizer and food prices, and geopolitical source concentrations may lead to high price fluctuations and supply and accessibility risks. Making the most efficient use of limited nitrogen and phosphorus inputs will become a key driver for agricultural systems in the future.

Organic agriculture is one of the valid alternative approaches having the potential to meet the above-mentioned challenges. Organic agriculture is a holistic production system aiming to sustain the health of soils, ecosystems, and people (FAO/WHO, 1999; IFOAM, 2007; Ramesh et al., 2010). Organic agriculture fuels nutrient cycling in food production, based on organic fertilizers such as green manure, compost or animal manure.

Four fertility management practices typically used in organic farming systems are: (i) application of organic residues as soil amendments or nutrient source; (ii) use of biological nitrogen (N)-fixation; (iii) rotations that include cover crops, intercrops, and alley cropping; and (iv) diversification of plant species in space and time to fulfill a variety of ecosystem services. Integration of cover crops such as Mucuna in cereal–Mucuna relay intercropping improved physical, chemical, and biological soil properties as compared with sole maize monocropping or legumes—e.g., beans—intercropped with maize (Azontonde, 1993; Tian et al., 2001; Bationo et al., 2011). Soil erosion was reduced to about 10 times in maize–Mucuna relay intercropped as compared with sole maize cropping in southern Benin (Azontonde, 1993). Mucuna and Pueraria increased soil organic matter, available phosphorus, and total potassium on degraded land (Wiafe, 2010). Pueraria cover crops grown in association with food crops stimulated biological activity, improved soil nutrient availability, and N accumulation in P- and K-poor soils (Tian et al., 2001). Combined use of crop residues, manure, and inorganic P supplied increased yields of cowpea and associated cereals (Bationo et al., 2011).

Timely applications of organic materials with low carbon-to-nitrogen (C:N) ratios, such as green manure and compost, can synchronize nutrient release with plant demand (Omotayo and Chukwuka, 2009). Organically managed farms in India recorded lower productivity and yield losses but gave higher net profit to farmers and improvement in soil quality parameters (Ramesh et al., 2010), indicating better soil health. According to Ramesh et al. (2010), there is less bulk density, a slight increase in soil pH and electrical conductivity, increase in organic carbon, increase in availability of both macronutrients (N, P, K) and micronutrients (Zn, Cu, Fe, Mn) under organic farms as compared with conventional farms. When compared with conventional farms, organically managed soils had higher levels of dehydrogenase (by 52.35%), alkaline phosphatase (28.4%), and microbial biomass carbon (33.4%). This indicates higher microbial activity in organically amended soils, which is essential for nutrient transformations and increased availability of nutrients to plants.

Some constraints on organic-based soil management systems include: requirement for a large labor force to collect, process, and transport bulky organic materials; need for large quantities of organic materials to supply adequate nutrients to the soil to meet crops' nutritional demands; and need for nutrients from low-quality and slowly decomposing organic materials to be managed to fulfill crop requirements (Meertens, 2003; Danso et al., 2006; Omotayo and Chukwuka, 2009; Bationo et al., 2011). Other major challenges are competing use of organic matter in local farmland systems other than for soil fertility improvement, such as the demand for fodder crops, construction material and energy use, and lack of supportive institutions (Lele, 1994; Bumb and Baanante, 1996; Meertens, 2003; Chianu and Tsujii, 2005; Thierfelder and Wall, 2011).

While the improvement of soil fertility under organic farming is well documented in temperate systems (Mäder et al., 2002, 2006; Hepperly et al., 2006; Fliessbach et al., 2007; Teasdale et al., 2007; Birkhofer et al., 2008; Niggli et al., 2009; Gattinger et al., 2011), few scientifically sound studies are available demonstrating the long-term effect of organic farming in the tropical and subtropical regions on soil fertility. Therefore, the Research Institute of Organic Agriculture (FiBL) has implemented long-term farming system comparison trials in Kenya, India, and Bolivia in 2007. The experiments are expected to provide solid agronomic soil fertility, and socio-economic data of the predominant organic and conventional agriculture production systems representative for smallholder farms in the respective geographic regions.

Organic farming is an alternative and holistic approach that uses practices to improve soil physical, biological, and chemical properties, and can deliver agronomic and environmental benefits, particularly long-term improvement of soil fertility and quality. Organic agriculture aims for resilience, or the capacity to resist shocks and stresses, and persistence, or the capacity to continue over long periods. Soil fertility is knowledge and management intensive. Farmers' knowledge of soil fertility evaluation needs to be understood (Mowo et al., 2006) in addition to their social and economic realities to improve their sustainable organic farming practices.

3. PLANT BREEDING STRATEGIES FOR ORGANIC AND LOW EXTERNAL INPUT FARMING

Domestication and selection of plants is linked to human settlement and our cultural heritage. Nearly 10,000 years of domestication has resulted in more than 7,000 different crop plants selected for different purposes and ecological niches (FAO, 1996). However, only 30 crop species—comprising less than 0.1% of all edible plants—account for 95% of the global calorie intake, with rice, maize, and wheat accounting for more than 50% (FAO, 1996). Enormous efforts have been made to increase food production to feed a growing world population. Production of the main staple crops has increased by 145% since 1960.

Breeding and agronomic improvements are partly responsible, but so are increased inputs. Over the same period, agricultural land increased by 11%, the amount of irrigated land doubled, and fertilizer and pesticide use increased four-fold, all causing negative side effects (Pretty, 2008).

Sustainable plant breeding and seed networks are essential for food sovereignty and adaptation to climate change (Sthapit et al., 2008; FAO, 2010). Plant breeding has selected for increase of gross yield of crops that rely on unsustainably high inputs grown as monocultures of homogeneous cultivars (Vanloqueren and Baret, 2008). In recent decades plant breeding has moved from family owned or public breeding programs to large-scale multinational breeding companies, and seed propagation has shifted from mainly farm-saved seed to F1 hybrid seed that need to be purchased each year (Vernooy, 2003; da Silva Dias, 2010). Genetic diversity has been lost as companies concentrated on breeding the most profitable crop species (Haussmann and Parzies, 2009; da Silva Dias, 2010; FAO, 2010). Numerous local varieties and landraces have disappeared, causing genetic erosion within species (Haussmann and Parzies, 2009).

The transformation of the seed sector was accompanied over the same period by a rapid consolidation of seed companies closely interlinked with the agrochemical sector (Howard, 2009). The three largest seed companies—Monsanto, DuPont, and Syngenta—control over 50% of the global seed market (ETC Group, 2011). These companies seek patents that restrict breeders' rights to use a released cultivar for further breeding purposes. Access to plant genetic resources is also limited by laws (Engels et al., 2011; Chable et al., 2012).

Loss of species and varieties cultivated, and narrow control of the seed sector, limit options for smallholder producers. Most of the underutilized crops are strongly linked to tradition and cultural knowledge and are adapted to specific niches, with short supply and sparse documentation (Hoeschle-Zeledon and Jaenicke, 2007). Diversification of crop species—especially with legumes and vegetables—reduces risk and prevents malnutrition (Hoeschle-Zeledon and Jaenicke, 2007; Ogoke et al., 2009; Keatinge et al., 2011, Mayes et al., 2012).

Farmers' crop choices depend on several criteria, including available inputs, relative prices, government policy, and various environmental factors (FAO, 2010). Poor supply of reasonably priced high-quality seed is a major constraint on production of vegetable crops in Africa (Keatinge et al., 2011). To counteract this trend, nutritious local crop species were successfully re-introduced in the scope of the project "Indigenous African leafy vegetables for enhancing livelihood security of smallholder farmers in Kenya" (Mwangi and Kimathi, 2006; Gotor and Irungu, 2010).

Resource-poor farmers in marginal, complex agricultural environments have been slow to adopt modern varieties. Such farmers lack access to external inputs, and the new cultivars seldom meet farmers' socio-economic and cultural priorities and needs (Keneni and Imtiaz, 2010; Temudo, 2011). High-input varieties are generally selected under uniform and highly controlled conditions where soluble fertilizer, seed treatment, herbicides, and other pesticides are applied. Such conditions do not reflect the situation on organic and low external input farms that operate primarily on closed nutrient cycles with minimal external inputs (Ceccarelli et al., 2007). Nutrient release from soil organic matter depends on complex biological, chemical, and physical factors (Messmer et al., 2012). High-yielding varieties selected for high input may suffer from temporarily insufficient nutrient supply, causing considerable yield reduction under organic and low external input systems (Dawson et al., 2008a). Cultivars are needed that show high nutrient use efficiency, optimized root morphology, and the capacity to establish beneficial plant microbial interactions that play important roles in nutrient uptake efficiency and disease suppression (Lynch., 2007; Fageria et al., 2008; Hartmann et al., 2009; Wissuwa et al., 2009). Such traits might become more important in future as, for example, soil-borne diseases may increase with climate change (Jaggard et al., 2010).

Breeders need to develop cultivars that perform well in very different environments. Genotype × environment × management interactions need to be considered for the most-promising breeding strategies. Breeding for low nitrogen (N) input conditions has been shown to be more efficient under severe N stress than under high-input conditions for wheat (Brancourt-Hulmel et al., 2005), barley (Ceccarelli, 1996; Sinebo et al., 2002; Ryan, 2008), oat (Atlin and Frey, 1989), maize (Presterl et al., 2003), and rice (Mandal et al., 2010).

Crops bred for specific farming practices are key to sustainable management of resources and eco-functional intensification of organic farming (Schmid et al., 2009; Lammerts van Bueren et al., 2011; Lammerts van Bueren and Myers, 2012). However, few studies have examined differences between direct and indirect selection for organic farming. One study comparing wheat selection under organic and conventional conditions concluded that indirect selection of varieties bred under conventional conditions would not result in the best lines for organic farming, and that varieties selected under organic conditions would perform better on organic farms (Reid et al., 2009). Similar results were found with the direct and indirect selection of maize for organic farming (Messmer et al., 2009).

Another reason why international breeding research in developing countries has had limited impact is that culture, quality, and flavor are seldom considered by such programs. Breeding often follows a top-down approach (Figure 2.1) where breeders are disconnected from farmers (McGuire, 2008; Temudo, 2011). The seed replacement rate is especially low in unfavorable growing conditions (Aw-Hassan et al., 2008; McGuire, 2008). Smallholder farmers in stressful environments rely mainly on diverse cultivars to slow the spread of pests and diseases, and to adapt to unforeseen climatic changes (Jarvis et al., 2011; Mulumba et al., 2012). Yield stability is more important than yield potential to smallholders (Sthapit et al., 2008).

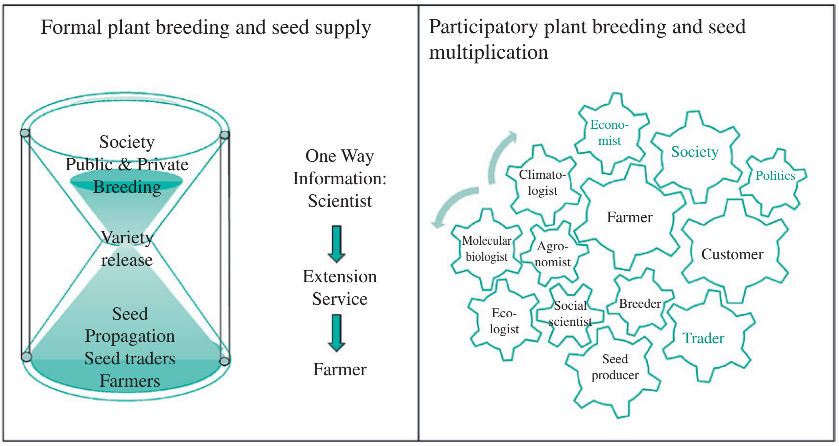

FIGURE 2.1 Formal and participatory plant breeding and seed supply.

Participatory cultivar selection (PCS) and participatory plant breeding (PPB) offer opportunities to involve farmers in cultivar selection and breeding (Ceccarelli et al., 2007; Dawson et al., 2008b; Desclaux et al., 2012). These approaches fully integrate the farmers' knowledge and skills, and resulting cultivars are more likely to be adopted in a short time (Vernooy, 2003). Large groups are able to deal with a wide range of different crops that need to be improved for different agroecological niches and cropping systems, resulting in greater biodiversity.

Genetic and agronomic improvement can be developed in parallel through PCS and PBB (Mayes et al., 2012). PPB is a transdisciplinary approach where different actors work together in a very dynamic and demand-driven process. This trans- and interdisciplinary approach requires new tools of group learning, innovation diffusion, and institutional changes (McGuire, 2008; Joshi et al., 2012).

Women involved in most field activities and cooking can contribute to breeding goals. Integrating women in the process will not only empower them in plant breeding and seed conservation but also improves their social status (Ceccarelli and Grando, 2007; Paris et al., 2008). In addition, they are very good multipliers not only of seed but also of information (McElhinny et al., 2007; Ashby 2009).

Murphy et al. (2005) combined PPB with evolutionary breeding based on natural selection for local adaptation, first proposed by Suneson (1956). Such integrated breeding approaches are known as evolutionary participatory breeding (EPB) and use the skills and knowledge of both breeders and farmers to develop heterogeneous landrace populations. EPB was shown to be an effective breeding method for both modern and traditional farmers (Murphy et al., 2005, Ceccarelli et al., 2010).

Farmers satisfied with new cultivars will multiply and distribute seeds among their social networks (Vernooy, 2003). Capacity building and training in seed multiplication, seed processing, seed testing and storage, as well as in the management of the startup of seed enterprises, will enable farmers to develop a local seed supply chain and become independent from global seed companies and volatile prices of hybrid seed (Aw-Hassan et al., 2008). Pautasso et al. (2012) highlighted the role of seed exchange networks in conservation of agrobiodiversity and their importance for local food security. Farm-saved seeds and local seed markets and seed fairs can all maintain and strengthen the formal and informal seed chain and thus improve smallholder farmers' access to seed (Sperling et al., 2008; Sthapit et al., 2008; da Silva Dias, 2010; Joshi et al., 2012).

Political dialog and public intervention in agricultural research are needed to enforce such farmer-driven seed initiatives (Vanloqueren and Baret, 2008, 2009). Collaborative participatory plant breeding and seed multiplication will improve biodiversity, resilience against environmental, economic, and food crises in the long term, and contribute to food security and sovereignty (Pretty, 2008; Mayes et al., 2012).

4. FUNCTIONAL BIODIVERSITY AND PEST MANAGEMENT IN ORGANIC FARMING

Traditional agricultural landscapes offered diverse habitats and succession stages; centuries of land-use have enabled a large number of species to survive in the agricultural landscape and to sustain pest control function (Winqvist et al., 2012). Modern agriculture is characterized by simplified landscapes, dominated by large-scale monocultures highly dependent on external inputs (Altieri, 1999). Agricultural intensification has resulted in less biodiversity (Postma-Blaauw et al., 2012). Intensification entails increased application of herbicides, insecticides, fungicides, and chemical fertilizer on local fields, to loss of natural and semi-natural habitats, and decreased habitat heterogeneity at the farm and landscape levels. The density and uniformity of crop cultivars offer locally concentrated food supplies for many pests and diseases to flourish, while depressing natural enemies' populations due to lack of food resources or shelter. Beneficial plants and insects might also be unintentionally harmed by the application of broad-spectrum pesticides. Diminished natural-enemy populations often result in pest outbreaks, which adversely affect crop yields (Geiger et al., 2010; Tscharntke et al., 2012). A key strategy in sustainable agriculture is to restore functional biodiversity of agroecosystems on crop, farm and landscape level and link agroecological intensification with biodiversity conservation (Brussaard et al., 2010; Tscharntke et al., 2012).

Functional biodiversity is defined by Moonen and Bàrberi (2008) as "that part of global diversity composed of clusters of elements (at the gene, species or habitat level) providing the same (agro)ecosystem service, that is driven by within-cluster diversity". The agroecosystem comprises managed fields, surrounding semi-natural or natural habitats, and human settlement and infrastructure. Production of food and other agricultural products is only one ecosystem service. Other ecosystem services include soil-related processes, soil food webs, and gene flow (Moonen and Bàrberi, 2008). Maximizing biodiversity *per se* does not necessarily increase the ecosystem functions, as often a few dominant species perform specific functions, while the remaining species are redundant for these functions (Moonen and Bàrberi, 2008; Postma-Blaauw et al., 2012). However, in high-input agricultural systems with low biodiversity on all levels, an increase in biodiversity is most likely adding complementary ecosystem services. More diverse communities have been shown to have higher and more stable ecosystem functioning, suggesting they should also have a consistently higher level of functioning over time. Diverse communities could maintain consistently high function because the species are driving function change over time (functional turnover) or because they are more likely to contain key species with temporally stable functioning. Agroecosystems should be redesigned in such a way that the system can develop mechanisms to recover disturbances autonomously in tune with the locally available biodiversity and with the existing environmental and socio-economic conditions (Altieri, 1999; Pfiffner and Wyss, 2004; Moonen and Bàrberi, 2008, Perfecto and Vandermeer, 2010).

Organic agriculture developed several strategies to improve crop production and other ecosystem services. Crop protection in organic agriculture is based on a multi-level approach (Figure 2.2) with a focus on indirect preventive plant protection measures (Step 1 to 3) followed by more-direct and curative measures (Step 4 and 5) only when needed at later stages (Wyss et al., 2005; Zehnder et al., 2007).

This multilevel strategy combines various tactics in farm management and cropping design in a holistic approach to limit pest populations below

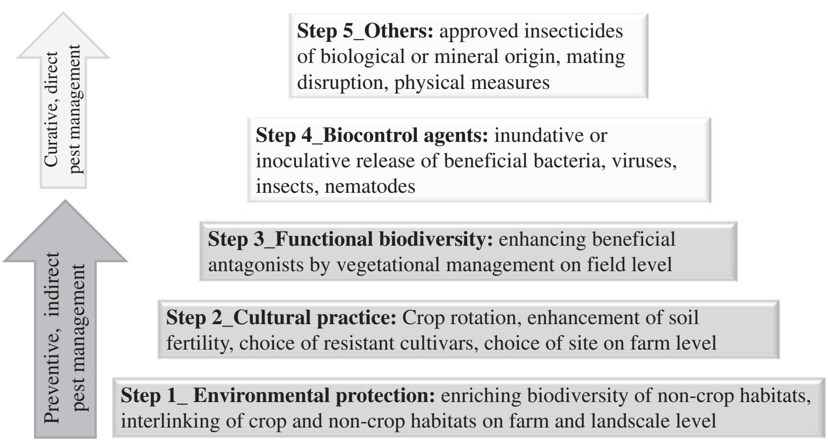

FIGURE 2.2 A five-step approach of arthropod pest management in organic agriculture based on the concept of Wyss et al. (2005) and Zehnder et al. (2007) modified by Hernyk Luka, FiBL 2012

damaging levels, thus minimizing the need for direct intervention (Pfiffner et al., 2005; Zehnder et al., 2007). Habitat management through farm site selection, crop isolation, and interlinking of natural and semi-natural ecosystems offers the first step. Non-crop habitats are known to play an essential role for reproduction and survival of natural enemies, offering food resources, overwintering sites, and refuges (Pfiffner and Luka, 2000). The second step involves adaptation of optimal cultural practices such as diverse crop rotation, selection of resistant or tolerant cultivars, and improved soil fertility through cover crops or soil amendments. On the individual field level, vegetational management in the form of hedgerows and flower strips enhances beneficial organism populations (step 3). Repellent or trap plants can be planted to divert the pest from the crop. Successful examples of preventive pest control include bio-fumigation effects of *Brassicaceae* crops on soil-borne pests and diseases, reduced preference of Colorado potato beetle for potato plants in manure-amended soils meeting optimal nutrients requirements, or reduced stem borer infestation through combined push-pull trap cropping in maize (for review see Zehnder et al., 2007, Cook et al., 2007).

Organic farming generally improved species richness and abundance compared with intensive conventional farming with higher inputs of energy, fertilizer, and pesticides; however, the surrounding landscape can either enhance or reduce its positive effects on functional biodiversity (Winqvist et al., 2012). Enriched non-production areas with diverse natural or semi-natural habitats are crucial for functioning pollination service and pest control, but these effects are less pronounced for soil biota (Smukler et al., 2010). Similar results were found by Batáry et al. (2012) for the response of plants, insects, and spiders to management intensity in cereals and grassland. Organic management promoted species richness of non-carnivore carabids and hunting spiders, while grasshoppers benefited from reduced management intensity. In general, reduction in field size by enlarging the edge area enhances functional biodiversity under organic and conventional farming. Functional groups that are not yet enhanced by organic farming need further improved management practices and strategies (Batáry et al., 2012).

Functional biodiversity specifically augments beneficial species relative to pest species by adding resources that selectively enhance only beneficials. The beauty of the functional biodiversity approach is that it starts a feedback loop: increased beneficial populations lead to decreased pest populations, which allows for reduced pesticide application, which in turn benefits natural enemies. Ratnadass et al. (2012) reviewed the effect of plant species diversity on a broad range of pathogens and pests across different cropping systems based on different mechanisms. They concluded that diverse vegetation does not necessarily reduce incidence of pests and diseases. Most pests and pathogens have several alternative hosts or reservoirs. To be successful, tailor-made functional biodiversity concepts are needed for each crop in each landscape (Pfiffner et al., 2005).

The Research Institute of Organic Agriculture (FiBL) in Frick, Switzerland, is currently investigating the efficiency of a functional biodiversity approach to control lepidopteran pests in cabbage. White cabbage (*Brassica oleracea* (L.), var. *capitata*) in central Europe is mainly attacked by the cabbage moth (*Mamestra brassicae*), the diamond-back moth (*Plutella xylostella*), and the small white cabbage moth (*Pieris rapae*), which all have specialized larval parasitoids. Because the endoparasitic wasp *Microplitis mediator* has different food requirements than its hosts, some plants benefit only the parasitoid and not any of the pests. Géneau et al. (2012) identified that cornflower (*Centaurea cyanus* L.), buckwheat (*Fagopyrum esculentum* Moench), and common vetch (*Vicia sativum* L.) improved the endoparasitic wasp's longevity and rate of cabbage moths parasitized, but had no effect on the longevity and fecundity of the cabbage moth. Behavioral assays showed that all plant species tested were attractive to *M. mediator* but cornflower was significantly more attractive than buckwheat (Belz et al., 2012).

Recent scientific studies on the complex interactions of crop, pest, and environment open new doors for preventive pest control by habitat management and functional biodiversity (Bàrberi et al., 2010; Petit et al., 2011; Farwig and Berens, 2012; Parolin et al., 2012). Many secondary metabolites and proteins were identified to be involved in plant defense as they are toxic or deterrent to herbivores or to other plants through allelopathy, whereas plant volatiles are released by the plant after attack, to attract natural enemies (Khan et al., 2010).

As the numerous combinations of species, environments, and practices are beyond the traditional factorial experimental approaches, a systems approach and dynamic modeling tools are required to test and verify the potential and limits of the management of functional biodiversity on plot as well as on landscape level (Ould-Sidi and Lescourret, 2011; Ratnadass et al., 2012). More complex cropping systems like permaculture or agroforestry need to be considered for more diversified agroecosystems (Malézieux et al., 2009; Tscharntke et al., 2011). Organic agriculture offers ideal conditions to integrate such a whole-system approach of functional biodiversity into innovative agroecosystems, that best benefits but also fosters biodiversity, thus minimizing the trade-off between production aims and biodiversity conservation (Simon, 2010).

5. AGRICULTURAL INNOVATION—THE NEED FOR TRANSDISCIPLINARY RESEARCH AND DEVELOPMENT

During the 20th century, the relation between science and society was based on an implicit agreement which stated that science was responsible for making discoveries and subsequently making them available to society (Gibbons, 1999). Disciplinary research in agriculture successfully developed and produced a multitude of innovations that increased productivity and contributed to food security. However, these knowledge-based solutions were usually communicated in a top-down approach. According to Pretty (1995), a one-way transfer of technology approach was used during the so-called production stage (1950–1975). Crop and animal breeding and genetics were predominant disciplines, while the farmers simply received the technology. In the following years (1975–1985) economists and agronomists gained importance and practiced a two-way communication approach. Farmers were included as informants and started to contribute to the design of new technologies. During the ecological stage (1985–1995) agroecologists, geographers, and anthropologists influenced agricultural research and development. The farmer was seen as cause and victim for unsustainable development. From 1995 onwards, a new understanding for institutional development emerged where psychologists, sociologists, political scientists, training specialists, and educators were involved. Society was calling for a revolution in science to enable itself to tackle the problems caused by the global industrial system of which science itself forms the basis.

A more systemic and holistic approach should replace the reductionist, disciplinary worldview (Funtowicz and Ravetz, 1993). Transdisciplinary research gained attention as it was seen as a conceptual approach oriented to solve problems of the life-world and comprising phases of problem identification, structuring, investigation, and bringing results to fruition (Hirsch Hadorn et al., 2008). Boundaries between scientific disciplines—and between science and society—are crossed in a recursive process, in which problems are not pre-determined, but jointly identified (Wiesmann et al., 2008). Disciplinary approaches are not excluded, but rather needed as the basic level of understanding. The two conceptual approaches are essentially complementary (Max-Neef, 2005). Additional knowledge and mutual understanding of each other's problems significantly improve the quality, acceptance, and sustainability of solutions developed for a particular problem. Thus, participation and integration are key elements of transdisciplinary research (Elzinga, 2008).

Despite the continuous development of new concepts in agricultural research and technology transfer, a broad movement into these new approaches is not visible. Participation in research and extension is still predominantly consultative, and farmers have little influence on the decision-making. Many research projects in food and agriculture are now positioned in distinct disciplines, and further narrowed down to particular segments of these (Francis et al., 2008). Specialization within disciplines even seems to pay off better than inter- and transdisciplinary research. Vanloqueren (Vanloqueren and Baret, 2009) compared two technological paradigms: genetic engineering—representative of specialization within disciplines—and agroecology—representative of inter- and transdisciplinary research. They identified the following determinants, which in combination lead to imbalances between both paradigms.

- *Complexity and framing of agricultural research*. While complexity in molecular biology and genetic engineering is applied to cell or gene level, complexity in agroecological engineering is referred to the ecosystems level.

The recent technology advances have helped to deal with the complexity at cell or gene level and led to the development of highly specialist research. In contrast, the agroecological system cannot be effectively addressed by a reductionist approach and requires a holistic view.

- *Performance of agricultural innovations*. Direct, local, and short-term benefits are favored through reductionist approaches leading in current sciences. Conversely, indirect, long-term or holistic benefits for agriculture are underestimated. Research focuses on simple quantifiable variables such as gross yield, while complex ones such as sustainability or externalities are left out.
- *Publication pressure*. Publications share scientific knowledge, and acceptance for publication should not be guided by market incentives. Nonetheless, large differences between the two paradigms with respect to appearance in high-ranking journals can be observed. Also the impact factor of journals representative of genetic engineering is far higher than that of journals for agroecological engineering.
- *Specialized research*. Molecular biology and genetic engineering profit from the growing specialization of science. Interdisciplinary research between medicine, animal, and plant sciences is gaining importance in biotechnology. However, in agroecological engineering, an interdisciplinary approach includes sciences such as agronomy, ecology, sociology, and economics. Interdisciplinarity in agroecology thus requires the crossing of boundaries between very distinctive disciplines.
- *Technology transfer*. Public sector research establishments aim to transfer scientific knowledge to the private sector. Thereby, spin-off companies with patented research results play a crucial role. As private sector investments into public universities increase, the number of patents and spin-off companies will likely grow as well. Extension and technology transfer to farmers may emphasize those technologies that farmers can use directly. Besides the private sector, genetically modified crops are more favorable for public sector research establishments than are agroecological innovations that require fundamental changes in cropping systems.

Under the current scientific paradigm, disciplinary, specialist approaches seem to have a clear advantage over inter- and transdisciplinary ones. Changing this trajectory leads to high transaction costs (Geels, 2004). Scientists are educated to develop specific competencies and to specialize. Crossing boundaries between scientific disciplines and between science and society implies, however, compromise on acquired specialization and the research environment and breaking out to new fields of research with considerable uncertainty (Vanloqueren and Baret, 2009). Thus, the question is how to move from the present unilateral reductionist system to a more holistic one that favors new inter- and transdisciplinary approaches?

Building up inter- and transdisciplinary agricultural innovation systems requires complementary institutions developed in parallel to the existing ones in basic and applied research. These institutions should be designed to undertake research and education in a problem-oriented way, where disciplinary, inter- and transdisciplinary forms of education are equally supported (Max-Neef, 2005; Hadorn et al., 2006; Francis et al., 2008). The mutual recognition of different disciplines and the willingness to integrate disciplinary and interdisciplinary knowledge in a transdisciplinary framework is an important first step (Giri, 2002). Creation of a mutual learning environment is key to integration of transdisciplinary processes (Wiesmann et al., 2008).

Agricultural sustainability is probably best achieved through agroecosystem research and development. While Gliessman (1998) defines agroecology as the application of ecological concepts and principles to the design and management of sustainable agroecosystems, Francis et al. (2003) goes a step further and sees agroecology as the integrative study of the ecology of the entire food system, including ecological, economic, and social dimensions. Whether agroecology is restricted to the ecology of the food system only, shall not be debated at this point. However, agroecology encompasses with certainty environmental (ecological), economic and social aspects—the three dimensions of sustainability. Agroecology is an inherently transdisciplinary process, as it links structure and functioning of agroecosystems and closes the gaps between different disciplines as well as between theory and practice (Caporali, 2011). Agroecosystems research and development create the mutual learning environment to develop appropriate solutions for future challenges associated with deterioration of natural resources and climate change.

Many farming systems claim to be sustainable. If agricultural sustainability can be ensured by the production system that makes best use of environmental goods and services while reducing and avoiding adverse system effects with regard to natural, social, and human capital, then organic agriculture can be considered to be truly sustainable (UNEP-UNCTAD, 2008). Organic agriculture is the most important example of policy-regulated agriculture which explicitly integrates biophysical and socio-economic aspects of sustainability (Caporali, 2011). Driven by the aim to contribute to more holistic agriculture, the Research Institute of Organic Agriculture (FiBL) was an early adopter of participatory research processes. Agricultural research and extension became united under the single roof of FiBL, and henceforth allowed fruitful exchange between farmers and scientists. Research results were quickly transferred to practice and contributed significantly to the shaping of organic agriculture in Switzerland (Niggli, 2007). Meanwhile, FiBL is building on its experience in Europe and partners in multinational research and development projects in Asia, Africa, and Latin America. All of these projects have a common feature—they aim to make substantial contributions to agroecology by inter- and transdisciplinary research and development.

In conclusion, if agricultural research is to provide sustainable solutions, inter- and transdisciplinary research is indispensable. Reductionist methodologies need to be complemented by more holistic approaches. New institutions and education programs need to be introduced to foster a continuous dialogue leading to a change in perception of values in society. Students, scientists, and advisors need to be trained in a systems approach to address multi-dimensional problems of agroecosystems. Organic agriculture can be the point of departure to develop and advance inter- and transdisciplinary research and a driving force for a renewal of agriculture in the future (Kotschi, 2011).

6. OUTLOOK

Organic agriculture not only conserves resources and nature; it is also conservative as a farming system. Rooted in the traditional knowledge of farmers, driven by consumer expectations like "nature knows best", and guided by a precautionary approach, organic farming is skeptical of novel technologies.

The dos and don'ts of organic farming give direction for scientific innovation to benefit both the environment and society. However, organic farmers are confronted with real production problems that are already solved in conventional farming systems. The challenges can be found everywhere: in the insufficient control of weeds, plant diseases, and pests; in the management of soil and plant nutrients up to the optimal development of crops; in the availability of germplasm for low-fertilizer and low-pesticide input conditions, to name a few.

Consumers are often seen as the limiting factor in the transition to organic. Studies show that consumers are well informed about organic agriculture in most countries and a majority of them appreciate it as being the best option for agriculture and foods (Aertsens et al., 2009). In contrast with this positive marketing profile, organic food consumption is below 10% even in countries with developed organic markets.

Therefore, the bottleneck to bring organic agriculture into the mainstream is not consumption but agricultural production. Technical problems lead to high costs, to insufficient market supply, and to reluctance by farmers to accept high risks and greater labor requirements.

Organic food and farming systems might be very attractive fields for scientists to search for system-oriented solutions. On the other hand, systems research is not always rewarding in the short term, as results take longer to produce, and inter- and transdisciplinary research tends to overextend scientists. Investment in organic farming research promises an efficient return in contrast to conventional farming, as the marginal utility of organic research is still high. Research funding in organic agriculture is insufficient in most regions of the world, and a critical mass of research teams is needed to address the problems faced by organic farmers.

How do we tackle these constraints and opportunities? First of all, organic food and farming research should become viewed as excellent, effective, and targeted to the big challenges of the forthcoming decades. The development of organic agriculture needs to be driven more by science than by tradition. Scientists able to handle complexity, societal responsibility, and farm community knowledge need to drive the research agenda. Finally, organic agriculture should become more open towards innovation. The concept of eco-functional intensification (Niggli et al., 2008) includes the smart use of novel technologies. Well-selected elements of precision farming, ICT, nanotechnology, and molecular-based breeding might one day offer tools consistent with the principles of organic agriculture. These principles promote greater diversity on landscape, farm, field, and germplasm level. They care about ecosystems and their functioning, and they produce food and fiber with minimum waste, energy, and environmental impact. And most importantly, the principles of organic agriculture respect human and animal well-being.

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