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Sustainability of organic food production: challenges and innovations

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The greatest challenge for agriculture is to reduce the trade-offs between productivity and long-term sustainability. Therefore, it is interesting to analyse organic agriculture which is a given set of farm practices that emphasise ecological sustainability. Organic agriculture can be characterised as being less driven by off-farm inputs and being better embedded in ecosystem functions. The literature on public goods and non-commodity outputs of organic farms is overwhelming. Most publications address the positive effects of organic farming on soil fertility, biodiversity maintenance and protection of the natural resources of soil, water and air. As a consequence of focusing on public goods, organic agriculture is less productive. Meta-analyses show that organic agriculture yields range between 0·75 and 0·8 of conventional agriculture. Best practice examples from disadvantaged sites and climate conditions show equal or, in the case of subsistence farming in Sub-Saharan Africa, higher productivity of organic agriculture. Hence, organic agriculture is likely to be a good model for productive and sustainable food production. Underfunding in R&D addressing specific bottlenecks of organic agriculture are the main cause for both crop and livestock yield gaps. Therefore, the potential for improving the performance of organic agriculture through agricultural research is huge. Although organic farming is a niche in most countries, it is at the verge of becoming mainstream in leading European countries. Consumer demand has grown over the past two decades and does not seem to be a limiting factor for the future development of organic agriculture.

Organic agriculture: Strengths: Weaknesses: Sustainability

At present, agriculture faces the unprecedented challenge to secure food supplies for a rapidly growing human population while seeking to minimise the adverse impacts of agriculture on the environment and reduce the use of non-renewable resources and energy. A shift towards sustainable agricultural production entails the adoption of more system-oriented strategies, which include farm-derived inputs and productivity based on ecological processes and functions[1]. Sustainable agricultural systems also involve the traditional knowledge and entrepreneurial skills of farmers[2]. System-oriented sustainable practices include organic farming, Low External Input Sustainable Agriculture and agro-forestry. In addition, a few elements of agro-ecology such as integrated pest management, integrated production and conservation tillage, have been successfully adopted by conventional farms as well.

The concept of organic agriculture

Organic farming is most consistent in combining agro-ecological approaches with productivity. Because of the ban or restricted use of many direct control techniques such as pesticides, herbicides, synthetic soluble fertilisers and veterinary medicines, organic farmers rely heavily on preventive and system-oriented practices. Organic farm management aims to maximise the stability and homoeostasis of agro-ecosystems. It improves soil fertility through the incorporation of legumes and

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compost and by the recycling of local nutrients and organic matter. Preventive and direct measures found in nature are the repertoire of organic farmers to regulate pests and diseases in crops and livestock.

Less driven by off-farm inputs and better embedded in ecosystem functions, organic farms are supposed to produce more public goods than the conventional ones. In addition, organic producers claim to deliver premium quality and healthy foods, which leads to a continuously growing demand by consumers. While the organic food chains are well organised in developed markets, organic farming is still germinal in most developing countries. They often organise access to local markets as part of a Participatory Guarantee System (a system relying on mutual control within a farm community or group of farmers) or, as a second step, they can profit from high-value export markets when certified by accredited third-parties. So far, organic farming is a niche production, with 37 million hectares (ha) of certified land area globally, which represents 0·9 % of all agricultural land[3]. Nonetheless, the continuous growth of the organic markets, up to 51 billion € in 2012, has increasingly attracted the interest of traders and policy makers.

Multi-functionality : the most characteristic feature of organic agriculture

Organic agriculture produces both commodity and non-commodity outputs and addresses ethical concerns such as animal welfare and the livelihoods of farmers (fair trade)[4]. Hence, it is a predominantly multi-functional concept of agriculture. Public goods, or non-commodity outputs, as provided by organic farms have been comprehensively reviewed by several authors[5–9].

In the case of Switzerland, calculation with a comparative-static mathematical programming model showed that the state-supported schemes for organic farming (direct payments) are equally cost-effective at achieving environmental policy targets as the combination of different targeted and tailored agri-environmental measures[10]. It also reveals that the specific agri-environmental measures such as ecological compensation areas (e.g. hedgerows, field margins with wild flowers and extensive grassland) are more cost-effective when implemented on organic farms than on non-organic farms.

The most notable environmental advantages of organic agriculture are summarised in the next sections.

(Bio)diversity on organic farms

Diversity is an important driver for the stability of agro-ecosystems[11] and hence, for a continuously stable supply of food. At the farm level, organic farmers often practice diversification by producing several different commodities, both livestock and crops, and by processing and marketing them directly.

Comparative biodiversity assessments on organic and conventional farms reveal a 30 % higher species diversity and a 50 % greater abundance of flora and fauna in organic fields[12–14]. The higher biodiversity applies to different taxonomic groups, including micro-organisms, earthworms, weeds and wild flowers, insects, mammals and birds[13,15–22]. In regions where the number of organic farms increased, the diversity and abundance of bees grew considerably, which contributed to the pollination of crops and wild plants over larger areas[23]. Most of the studies indicate that the diversity of species on organic farms is predominantly the effect of the ban of pesticides, herbicides and fast-release fertilisers. Furthermore, diversified crop rotation or mechanical weeding have a positive effect on the species diversity of organic farms[13]. Sufficient semi-natural landscape elements such as hedgerows, fallow-ruderal habitats and wildflower strips are additional measures used by organic farmers to stabilise pest populations[24]. They belong to the toolset of organic farmers in order to make crop production more resilient.

The most recent hierarchical meta-analysis of 184 observations from ninety-four individual studies confirmed that the species richness was increased on organic fields by 34 %, on average, compared with the conventional fields[25]. This effect has been robust over the past 30 years. Quite obviously, the heterogeneity of these results is big. The positive effect of organic agriculture is greater in intensively farmed regions and in regions dominated by arable crops. Not all taxonomic and functional groups and crops profit from organic farming, but a significant majority do.

Lower negative environmental impacts

The high dependence of traditional farming on chemical fertilisers, herbicides and pesticides has caused considerable environmental damage. Owing to the ban of chemical fertilisers on organic farms, 35–65 % less nitrogen leaches from arable fields into soil zones where it could degrade the ground and drinking water quality[9,26]. Other nutrient elements such as potassium and phosphorous, are not found in excessive quantities in organically managed soils, which increases their efficient use[27]. Since synthetic herbicides and pesticides are not applied on organic farms, leaching and run-off effects are likely not to occur. The only pesticides used in organic agriculture that cause residues in soils are copper fungicides. They are used in horticultural crops such as potatoes, wine, hops and a few vegetables at annual rates of 3–4 kg copper/ha. The replacement of copper fungicides by breeding of disease resistant varieties and by easily degradable botanicals has a high priority in national and EU organic research.

Stable soils; less prone to erosion

Fertile soils with stable physical properties have become the top priority of sustainable agriculture. Thus, the essential conditions for fertile soils are the vast populations of bacteria, fungi, insects and earthworms, which build up stable soil aggregates. There is abundant evidence from long-running field studies that organic farms and organic soil management lead to good soil fertility. Compared with conventionally managed soils, organically managed ones show a higher organic matter content, higher biomass, higher enzyme activities of micro-organisms, better aggregate stability, improved water infiltration and retention capacities, and less susceptibility to water and wind erosion[27–34].

Carbon sequestration

Organic farmers use different techniques for building soil fertility. The most effective are fertilisation by animal manure, composted harvest residues and leguminous plants as main and intermediate crops. Introducing grass and clover leys as feedstuff for ruminants into the rotation and diversifying the crop sequences, as well as reducing ploughing depth and frequency, also augment soil fertility. All these techniques increase carbon sequestration rates on organic fields. The only references for quantifying this effect are long-running field experiments in different parts of the world. A scientific meta-analysis of the raw data of seventy-four long-term field trials (most of them in the temperate zones) reveal significant carbon gains in organically managed plots, whereas, in the conventional or integrated plots, soil organic matter is either stable or exposed to losses by mineralisation[35]. In this meta-analysis, which gathered the data from all existing long-term field trials, the average difference in the annual sequestration rate between organic and conventional management was 450 kg atmospheric C/ha per year. The mean difference of the carbon stocks of soils was 3·5 metric tonnes (t)/ha per year, and the average duration of these long-running field trials was 16 years. A further increase of carbon capture in organically managed fields can be measured by reducing the frequency of soil tillage. In an experiment in Switzerland, the sequestration rate was increased to 870 kg C/ha per year by not turning the soil upside down with a plough, but by preparing the seedbed by loosening the soil with a chisel plough instead[36]. In conclusion, the combination of organic agriculture and reduced soil tillage is likely to be among the best strategies for increasing carbon sequestration in arable crops. Unfortunately, this technique is not yet widely adopted by organic farmers as weeds become more difficult to manage.

More efficient use of nitrogen, less greenhouse gas emissions on organic farms

Crop productivity has increased substantially through the use of heavy inputs of soluble fertilisers, mainly nitrogen, and synthetic pesticides. However, according to a meta-analysis by Erisman *et al.*[37] in the USA, only 17 % of the 100 Mt industrial nitrogen annually applied on conventional farms is taken up by crops; hence, the remainder is lost to the environment. In a long-running field trial in Switzerland (lasting 36 years), the total nitrogen input into an organic arable crop rotation was 64 % of the integrated/conventional rotation; the total organic yields over the same period were 83 % of the conventional ones. Therefore, organic farms are likely to use nitrogen in a more efficient and less polluting way[27].

As a result of the limited availability of nitrogen in organic systems, a careful and efficient management of fertilisers is required[38]. On the other hand, high levels of reactive nitrogen (NH_4, NO_3) in soils may contribute to the emission of nitrous oxides, which are a major source of agricultural emissions. In a scientific meta-analysis based on twelve studies that cover annual measurements, it appeared with a high significance that area-scaled nitrous oxide emissions from organically managed soils were 492 (95% CI 160, 160) kg CO_2 equivalents/ha per year lower than that of non-organically managed soils[39].However, yield-scaled nitrous oxide emissions were higher by 41(95% CI 34,34) kg CO_2 equivalents/t DM under organic management (arable land use). To equalise this mean difference in yield-scaled nitrous oxide emissions between both farming systems, the yield gap has to be <17 %. This underlines the importance of addressing yield stability and productivity in organic agriculture especially in the context of greenhouse gas emissions where the negative externalities are global and closely linked to total food production.

Organic farms are well-adapted to climate change

As a result of climate change, agricultural production is expected to face less predictable weather conditions than those experienced during the past century. South Asia and Southern Africa, in particular, are expected to be worst affected by negative impacts on important crops, with possibly severe humanitarian, environmental and security implications[40].

Thus, the adaptive capacity of farmers, farms and production methods will become relevant to cope with climate change. As unpredictability in weather events increases, robust and resilient farm production will become more competitive, and farmers' local experiences will be invaluable for permanent adaptation. Organic agriculture stresses the need to use farmer and farmer–community knowledge, particularly about aspects such as farm organisation, crop design, manipulation of natural and semi-natural habitats on the farm, use or even selection of locally appropriate seeds and breeds, on-farm preparation of fertilisers, natural plant strengtheners and traditional drugs, and curing techniques for livestock, as well as innovative and low-budget techniques. Such knowledge was described by Tengo and Belfrages[41] as a 'reservoir of adaptations.'

Techniques for enhancing soil fertility help to maintain crop productivity in case of drought, irregular rainfall events with floods and rising temperature. Soils under organic management retain significantly more rainwater due to the 'sponge properties' of organic matter. Water infiltration capacity was 20–40 % higher in organically managed loess soils in the temperate climate of Switzerland when compared with conventional farming[27]. Pimentel *et al.*[31] estimated the amount of water held in the upper 15 cm of soil in the organic plots of the Rodale experiment in Pennsylvania/USA at 816 000 litres/ha. This water reservoir was most likely the reason for higher yields of corn and soyabean during dry years. The water capture in the organic plots was approximately 100 % higher than in the conventional ones during torrential rains[42]. This significantly reduced the risk of floods, an effect that could be relevant if organic agriculture were practiced over much larger areas. Improved physical properties of soils and therefore a better drought tolerance of crops, were also observed in on-farm experiments in Ethiopia, India and the Netherlands[28,43,44].

The diversification of farm activities as is typical for organic farms, greatly reduces weather-induced risks, as well. Landscapes rich in natural elements and habitats effectively buffer climate instability. New pests, weeds and diseases, the results of global warming, are likely to be less invasive in natural, semi-natural and agricultural habitats that contain a higher number of species and a greater abundance of individuals[24,45,46].

Yield gap

The fast-growing human population gives rise to the crucial question as to whether organic farming could feed the world. The indisputable advantages of organic farming in delivering public goods and services shrink if too much land is needed to produce food. Therefore, the lower yields of organic agriculture are often the main reason that the sustainability of this farming concept is questioned.

Two recently published scientific meta-analyses shed light on this important aspect: the overall yield gaps of organic crops are estimated to be 25 %[47] lower than conventional ones, based on 316 comparisons, and 20 % lower, based on 362 comparisons[48]. The yield difference is an average for all crops analysed. The categorical meta-analysis showed that organic crop rotations are likely to be nitrogen-limited, that phosphorous limits yields in strongly alkaline and acidic soils and that only the best management practices can result in yields comparable with those of conventional farms. Out of the 362 studies, 316 define the best practice as sufficient control of weeds, diseases and pests. Another meta-analysis that mainly gathered data from a case-study in Africa[49] indicated that organic farms are more resilient on water-restricted and drought-affected sites and therefore, likely to be more productive than conventional farms (number of farms in the study >1 million, yield increase when converted from conventional to organic farming +116%)[49]. Major factors that influenced the productivity of organic farms in a positive way were soil fertility building and improved on-farm and in-field biodiversity (better use of nature capital). In addition, there were many socioeconomic factors responsible for the result (improved human and social capital).

Research gaps

Globally, US$49 billion is annually spent on food and farming research[50]. The research spending for knowledge, techniques and tools that are highly specific to, and in compliance with, organic standards is probably far <1 % of private and public R&D budgets[5,7]. Innovation on organic farms is, therefore, still more strongly driven by farmers' own initiative and less by scientists and farm advisors.

However, the concept of organic agriculture offers ample scope to increase the productivity of farms, on the basis of both eco-functional intensification and the smart and selective use of modern techniques and technologies. The first priority for more research encompasses soil fertility building, improved crop rotations, crop mixtures with full integration of legumes and functional biodiversity in arable and horticultural crops. Emphasis must be given to crop breeding, which targets the specific environment of organic and low-input crop systems such as nutrient uptake from soils better synchronised to the mineralisation of organic manures. Other specific breeding goals are increased pest and disease tolerance or resistance, improved competitiveness against weeds and co-breeding of cereals and legumes as partners in mixtures. Well-adapted breeds are also important for livestock production, e.g. dairy cows with both longevity and the ability to produce high milk yields from roughage feed. A major research deficit can also be identified in the preventive and curative management of animal health. Relevant productivity gains can be expected from botanicals and bio-control organisms in both crop and livestock health. Good examples from ongoing research activities are the release of egg and larvae parasitoids in crops, the spraying of botanicals against diseases and the use of tannin-rich fodder herbs and legumes or nematophagous fungi as de-wormers against the endo-parasites of livestock[51].

Conclusions

Organic agriculture is mainly debated as a consumer trend to which farmers must react. It is still not perceived as a holistic strategy for truly sustainable farm productivity. Although it is still a niche of roughly 1 % of global agricultural production, it has the potential to become mainstreamed, as seen in European examples such as Austria, the Czech Republic, Denmark, Estonia, Germany and Switzerland. The productivity gap of organic agriculture relative to conventional agriculture is often overestimated, as meta-analyses show that organic yields are in the range of 0·75–0·8 of conventional ones. Best practice examples and innovation coming from recent public research schemes show that organic agriculture has a significant potential for further yield increases. Environmental benefits, as provided by organic farms, are absolute goods and cannot be relativised by the fact that yields are lower than in conventional agriculture. This is especially true for soil fertility building, biodiversity preservation and the reduced losses of nitrogen,

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phosphorous and pesticides through leaching, surface run-off erosion and drainage. The future strategy of research and innovation in organic agriculture must prioritise productivity gains that address the farms as a whole and major attention must be given to secure the positive ecological performance organic agriculture can provide.

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U. N. wrote the paper.

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