An agronomic approach to yield comparisons between conventional and organic cropping systems

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Abstract

This paper discusses relevant agronomic aspects related to the comparison of the productivity of organic and conventional cropping systems. In a first step some key requirements are being delineated, which ensure the validity of comparisons. These include the need to consider complete rotation yields and the use of representative amounts of organic inputs. A main chapter is dedicated to the potential of biological nitrogen fixation (BNF) to substitute mineral nitrogen, which currently covers an estimated third (83 Tg) of the total nitrogen input to agricultural fields with a growing trend. Replacing this input by BNF would result in a strong decrease of global cereal production. In regions with sufficient farm land increased legume growing has a considerable potential to substitute N-fertilizers, provided that P-deficiency and pathogens can be managed. In areas with high population density and limited availability of agricultural land, e.g. Bangladesh, differences in output between conventional and organic systems are expected to be high. To bring forward Organic Agriculture (OA) as a sustainable method of global food production with high process quality, it is suggested to focus rather on a large scale organic vegetable and fruit production than on global supply of carbohydrates and proteins.

Introduction

The question whether OA-systems are able to supply the current and future global demand for food and feed is a controversial and topical issue in public and political discussions. A sober analysis needs to distinguish between political, economic and agronomic aspects of world nutrition before integrating them into complex strategies. Political and economic aspects of world nutrition include armed conflicts, rural poverty, access to land as well as availability and affordability of food. These factors are more or less independent of the production system. In contrast the absolute amount of carbohydrates and proteins needed for human nutrition is mainly an agronomic issue, which depends of the productivity, i.e. the yield level and stability of the production systems, and of consuming patterns.

A recent meta-analysis compared conventional and organic yield data of 362 data sets. Crop yields in organic systems were on average 80% of those obtained in conventional systems (de Ponti et al. 2012). Yield differences (conventional = 100% versus organic) showed a wide range, e.g. 40-145% for rice and 21-140% for vegetables. A further meta-analysis partly confirmed these estimations. On average of 316 comparisons organic yields were 25% lower than conventional yields (Seufert et al. 2012). Interestingly, yield differences (67 data sets) were much higher in developing (less 43%) than in developed countries.

This paper critically discusses some key issues of yield comparisons between conventional and organic systems focussing on the agronomic context.

Methodical problems of yield comparisons

The two main problems related to the validity of yield comparisons between different systems are adequate scaling, i.e. the necessity to consider the output of complete rotations, and the selection of representative production techniques. Paired comparisons of individual crop yields are generally only of limited validity since yield over time, i.e. the whole production system is not adequately considered (Connor 2013). Intensive, often unsustainable rice production systems for example in Bangladesh with up to three seasons per year produce high amounts of caloric energy in a short period of time and cannot be run organically without significant yield reductions. These practices however also require convincing solutions for decreasing soil fertility, in particular with respect to soil carbon balance. Organic systems in contrast require the time to grow fertility building crops and are best suited for areas where cropland availability is high and population density is low. Using scarce farmland for fodder crops in contrast is an unrealistic option for cash crop regions.

The validity of a study is also reduced if the empirical data has been generated using non-representative amounts of manure, an occasional practice in OA, e.g. in the Republic of Korea. The approach of applying

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high amounts of manure (substitution method) is also a common practice on some research stations and counteracts the generalisation of yield comparisons. Likewise it is important to distinguish between actual and attainable yields. Under conditions of low input agriculture with missing access to agricultural inputs, conversion to OA may lead to higher actual yields compared with conventional production. A proper comparison however also needs to include the attainable yield, which could be obtained if key constraints were resolved.

Agronomics constraints in OA

Nitrogen supply

A key difference between conventional and organic systems is the availability of nitrogen input sources. Since the end of the Second World War the global use of mineral nitrogen fertilizers has steadily increased. Together with animal manure they constitute the major input of nitrogen in conventional arable land (Bouwman et al. 2009). Soil fertility in OA in contrast is mainly maintained by growing leguminous crops and applying manure. The only relevant factor for net nitrogen input to the soil however is biological nitrogen fixation (BNF) via legumes, since manure is just a by-product. Absolute nitrogen input in fields via BNF is mainly a function of legume share in the rotation, legume total dry matter production and the percentage of nitrogen derived from the air. Net contribution to the soil nitrogen balance further depends on legume use either as green manure, fodder for livestock or cash crop and may vary considerably. A recently published summary of global estimates of N_2 fixed by BNF indicated global averages of 110 - 227 kg N ha^{-1} a^{-1} for fodder legumes and ~ 115 kg N ha^{-1} a^{-1} for grain legumes. The authors estimated that ~ 77% of the N_2 fixed by legumes resulted from soybean production (Herridge et al. 2008). Under temperate climate the N_2 fixing potential in particular of red clover or alfalfa grown in pure stands may be much higher attaining values of ~ 300 - 400 kg N ha^{-1} a^{-1}. Under most practical conditions however, BNF via fodder legumes is much lower, mainly because fodder legumes are preferably grown in mixtures with grasses. The use of fodder crops for animal nutrition further leads to inevitable NH_3 volatilization losses during storage and broadcasting of manure or slurry. The strong dependence of soil nitrogen mineralization of environmental conditions, in particular temperature and humidity may further limit the productivity of organic cereal growing, if crop nitrogen demand is not adequately matched. Under temperate climatic conditions in North Western Europe calculative net nitrogen amounts available in a standard organic crop rotation may attain 50 - 100 kg N per crop and year. In contrast mineral nitrogen input in intensive conventional cereal production systems ranges between 140 - 240 kg N ha^{-1} and may additionally include manure.

According to recent calculations from Bouwman et al. 2009 the total global nitrogen input in agricultural soils (cropland and grassland) amounted ~ 249 Tg in 2000. Mineral nitrogen covered one third of the input (83 Tg), while the contribution of BNF was only 30 Tg. Fixing 83 Tg with fodder legumes with an estimated annual fixation of 165 kg N ha^{-1} would require at a rough estimate ~ 500 Million hectares, which is one third of the estimated arable land world-wide. In any case the partial substitution of cereals by legumes will have consequences on the global cereal supply and would imply a strong change in human food consumption patterns. In countries with high population density and low availability of arable land, e.g. Bangladesh or Japan, this scenario seems not to be very probable. Likewise the lower output of exclusively legume driven rotations often goes along with lower yield stability, since many legume species are known to be self-incompatible. Soil P-deficiency, e.g. in East Africa and the Sahel (Sanchez 2002) and various diseases such as stem rot of clover and alfalfa (*Sclerotinia trifoliorum*) may further decrease the efficiency of BNF.

Biotic constraints for crop productivity

Biotic factors include a wide range of animal pests, pathogens and weeds, which may lead to significant reductions in crop performance. Actual yield losses of major food crops in 19 world regions in the period 2001-2003 were estimated to amount 28.2% for wheat, 31.2% for maize, 37.4% for rice and 40.3% for potatoes (Oerke 2006). *Nota bene* that actual yields are those obtained with the current status of crop protection, which already includes physical, biological and chemical control. Potential losses without any crop protection were estimated to be much higher amounting 67% on average of the four crops, mainly as a result of weed competition. Actual yield losses of different crops in contrast were mainly affected by other factors (insects, pathogens) indicating the use of herbicides in many systems (Oerke 2006).

Weeds in OA, although a serious problem, can be managed by site specific combinations of indirect methods such as crop competitiveness (Drews et al. 2009) and direct methods such as mechanical control. In general, the success of weeding mainly depends on the level of intensity. In contrast, pest and diseases may cause significant yield losses impossible to control via reduced interception of radiation, through early canopy senescence, reduced rates of photosynthesis or reduced partitioning of assimilates from infected leaves (Hay and Porter 2006). For example, diseases such as late blight of potato (*Phytophthora infestans*) may have devastating effects on tuber yield and are still without serious biological control options. Pests and diseases both also affect yield stability, which is of equal importance to absolute yields.

Discussion

Maintaining or increasing crop productivity by mineral nitrogen application is not sustainable as long as nitrogen is synthesized using non-renewable energy sources. Nevertheless, on a global scale energy use for mineral nitrogen production is negligible and ecological problems of nitrogen use such as water pollution are much more relevant. Organic farming systems in contrast have to stick to demanding principles, which include the necessity for sustainable production and the limited intensity of soil use. To fulfil these requirements OA-systems need to have a balance for soil carbon and nitrogen, which includes an adequate proportion of fertility building crops in the rotation. Without them soil N and C soil reserves would be depleted in the medium term with disastrous effects on crop yields. Feeding ruminants on valuable arable land with fodder legumes is only an option for countries with sufficient land resources. Regions with intensive rice production, e.g. in South East Asia with high population densities are currently heavily dependent on nitrogen fertilizers to maintain the production level.

From an ecological and agronomic point of view the greater use of BNF via inclusion of legumes in conventional crop rotations would be beneficial for soil fertility. The extent to which it is possible to replace mineral nitrogen however will mainly depend on the economically feasible proportion of fodder legumes in the crop rotations and the development of global consuming patterns. Another important issue related to conversion scenarios is the effect on production and consumer prices, which is currently not clear, although increases of both seem to be probable. Increases of food prices however are controversial, since they would mainly affect food security of the poor.

Conclusions

Discussions on the world nutrition situation need to distinguish between system immanent and system independent aspects in particular economy and policy. Currently the contribution of OA to global food supply is low (< 1%) and there are no clear indications that OA in the pure form can play a relevant role for global food supply in a larger scale. However, many approaches currently practised in OA may help to increase the sustainability of conventional production systems, e.g. manuring and enhanced growing of legumes. The level of agricultural intensity needed to meet the increasing demand for carbohydrates and proteins still needs to be determined.

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