Chapter 3

Can Organic Crop Production Feed the World?

Holger Kirchmann[1], Lars Bergström[1], Thomas Kätterer[1], Olof Andrén[1] and Rune Andersson[2]

[1] Department of Soil and Environment, Swedish University of Agricultural Sciences, P.O. Box 7014, SE-75007 Uppsala, Sweden
[2] Department of Food Science, Swedish University of Agricultural Sciences, P.O. Box 7051, SE-75007 Uppsala, Sweden

E-mail of corresponding author: holger.kirchmann@mark.slu.se

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Abstract Agriculture provides the most essential service to mankind, as production of crops in sufficient amounts is necessary for food security and livelihood. This chapter examines the question of whether organic agriculture can produce enough food to meet future demand. This question relates to a moral imperative and any evaluation must therefore be based on objective scientific facts excluding ideological bias, political correctness, economic incentives or environmental opinions. The chapter begins by defining the conditions necessary for a stringent evaluation of crop yields and explains potential pitfalls. Yield data from national statistics, organic and conventional long-term experiments and comparative studies are then compiled and evaluated, followed by a discussion of the main factors behind low-yielding production. In a global perspective, the scientific literature shows that organic yields are between 25 and 50% lower than conventional yields, depending on whether the organic system has access to animal manure. The amount of manure available on organic farms is usually not sufficient to produce similar crop yields as in conventional systems and therefore green manures are commonly used. However, organic crop yields reported for rotations with green manure require correction for years without crop export from the field, which reduces average yield over the crop rotation. When organic yields are similar to those in conventional production, nutrient input through manure is usually higher than nutrient addition in conventional agriculture, but such high inputs are usually only possible through transfer of large amounts of manure from conventional to organic production. The main factors limiting organic yields are lower nutrient availability, poorer weed control and limited possibilities to improve the nutrient status of infertile soils. It is thus very likely that the rules that actually define organic agriculture, i.e. exclusive use of manures and untreated minerals, greatly limit the potential to increase yields. Our analysis of some yield-related statements repeatedly used by advocates of organic agriculture reached the following conclusions: Organic manure is a severely limited resource, unavailable in quantities sufficient for sustaining high crop yields; legumes are not a free and environmentally sound N source that can replace inorganic fertilisers throughout; and low native soil fertility cannot be overcome with local inputs and untreated minerals alone.

Agricultural methods severely limiting crop yields are counter-productive. Lower organic yields require compensation through expansion of cropland – the alternative is famine. Combining expected population growth and projected land demand reveals that low-yielding agriculture is an unrealistic option for production of sufficient crops in the future. In addition, accelerated conversion of natural ecosystems into cropland would cause significant loss of natural habitats. Further improvement of conventional agriculture based on innovations, enhanced efficiency and improved agronomic practices seems to be the only way to produce sufficient food supply for a growing world population while minimising the negative environmental impact.

Keywords Area demand · Conventional yields · Cropland expansion · Habitat loss · Nutrient input · Organic yields · Population growth · Weeds

1. INTRODUCTION

Providing healthy food for everyone is probably the most important survival issue for mankind in the future. We are currently producing a slight excess of food in relation to consumption (Alexandratos, 1999; Dyson, 1999). However, the demand for food, feed and fibres will greatly increase during coming decades (Evans, 1998; FAO, 2007) driven by a growing population, which is getting wealthier (Bruinsma, 2003; GeoHive, 2007). The global human population has doubled over the last 40 years, to around 6.5 billion people in 2006, and food plus feed production has tripled during the same period (FAO, 2007). By 2030, the global population may reach 8-9 billion, of which 6.8 billion may live in developing countries (Bruinsma, 2003; GeoHive, 2007). As the projected increase will mainly take place in developing countries, Africa would need to increase food production by 300%, Latin America by 80%, Asia by 70%, but even North America by 30%. Assuming that the additional population consumes only vegetarian food, a minimum of 50% more crops will need to be produced by 2030 to ensure sufficient food supply. As a satisfactory diet has been defined to consist of 40 g animal protein per person and day (Gilland, 2002) and taking into account that diets throughout the world are changing with the rise in income towards more meat and dairy products irrespective of culture, there will be a need to actually increase food plus feed production by 60 to 70%. For example, in developing countries, meat consumption amounted to 71 g per person and day in 1997-99 and is projected to further increase to 100 g per person and day in 2030 (Bruinsma, 2003). In developed countries, meat consumption of 180 g per person and day is projected for 2030. Since the largest proportion of the projected increase is expected to come from pork, poultry and aquaculture, meeting future demand will depend on achievable increases in cereal yields (Bradford, 1999). A doubling of cereal yields may be necessary by 2030.

Global food production increased by 70% from 1970 to 1995, largely due to the application of modern technologies in developing countries, where food production increased by 90%. However, global food production must grow to the same extent in the coming three decades, as pointed out above, to meet human demand (Bruinsma, 2003; Cassman et al., 2003; Eickhout et al., 2006). Two principal possibilities for achieving this increase have been identified: intensifying agricultural production on existing cropland or ploughing up natural land into cropland, i.e. clearing pastures and rangelands, cutting forests and woodland areas, etc. Some experts have a positive view that food production can be greatly increased if high-yielding production is widely applied (Bruinsma, 2003), and the expansion of arable land in the world is expected to only slightly increase from 1400 Mha in 2006 (FAO, 2007) to 1600 Mha in 2030 (Bouwman et al., 2005). In 2025, the world's farmers will be expected to produce an average world cereal yield of about 4 metric tons per hectare (Dyson, 1999) if conditions are optimised.

There are recent claims that sufficient food can be produced by organic agriculture, expressed in terms such as 'organic agriculture can feed the world' (e.g. Woodward, 1995; Vasilikiotis, 2000; Leu, 2004; Tudge, 2005; Badgley and Perfecto, 2007). The following three arguments have been put forward: (i) Lower production of most crops can be compensated for by increased production of legumes, in particular of grain legumes, while a change to a diet based mainly on vegetables and legumes will provide enough food for all (Woodward, 1995). (ii) Realities in developing countries must be taken into account: *'Increased food supply does not automatically mean increased food security for all. Poor and hungry people need low-cost and readily available technologies and practices to increase food production'* (Pretty et al., 2003). (iii) *'Organic agriculture can get the food to the people who need it and is therefore the quickest, most efficient, most cost-effective and fairest way to feed the world'* (Leu, 2004). These arguments confuse the original scientific question with other realities interacting with food sufficiency, such as change in dietary composition, poverty, finance, markets, distribution system, etc. However, the basic scientific question remains and requires a stringent review and evaluation of the production potential of organic and conventional systems.

A fundamental question is whether organic yields can be increased radically or whether more natural ecosystems have to be converted into cropland. The following four observations indicate that intensification rather than area expansion is necessary: (1) Agricultural land is steadily decreasing as it is being taken over for urban or industrial use (Blum et al., 2004); (2) global warming may reduce the potential for higher yields in large parts of the world (Parry et al., 2005); (3) significant areas of farmland may be used for fuel production, competing with food production (Nonhebel, 2005); and (4) cropland simply cannot be expanded, due to shortage of suitable land. On the other hand, current yield increases appear to be falling below the projected rate of increase in demand for cereals (Cassman et al., 2002), challenging scientists to do their best to increase crop productivity per unit area (Evans, 1998).

Food production is coupled to a moral imperative, as sufficient food supply is a cornerstone of human welfare. Development of agricultural practices ensuring food sufficiency is a basic human requirement, a prerequisite for satisfactory social conditions and a necessity for civilisations to flourish. Lack of food, on the other hand, is a tragedy leading not only to suffering and loss of life but also to inhuman behaviour, political instability and war (Borlaug, 1970). In fact, eradication of famine and malnutrition has been identified as the most important task on Earth (UN Millennium Project, 2005). Thus, when discussing different forms of crop production, it is of the utmost importance to examine without prejudice the forms of agriculture that can contribute to food sufficiency and security, at present and in the future. Separation of facts and wishful thinking is absolutely necessary and only an unbiased review of the scientific literature can provide objective answers to the questions put forward below. A strong belief and enthusiasm for certain solutions cannot be allowed to hamper the search for objectivity.

The overall aim of this chapter was to examine a morally important aspect of organic agriculture. This was achieved by examining the following questions:

- Can sufficient crop production be obtained through conversion to and/or introduction of organic production?
- Can future food demand be covered by organic agriculture?
- Is it possible to significantly increase organic yields in the future?

2. DEFINING CONDITIONS NECESSARY FOR A STRINGENT COMPARISON OF CROP YIELDS FROM ORGANIC AND CONVENTIONAL SYSTEMS

Evaluating crop yields from organic and conventional production seems straight-forward but there are restrictions and difficulties to be considered. The conditions outlined below are necessary for stringent scientific comparisons based on robust quantitative thinking.

2.1. Evaluate comparable systems

Yield examinations require that only systems of the same type are compared. Comparing yields from pure crop production systems with those from mixed crop-animal systems, or biofuel-crop systems, is incorrect. The main reason is that each system is characterised by specific crops and a level of production typical for these crops that is not necessarily related to organic/conventional methods. For example, systems with forage and milk production have a higher production level (tonnes of dry plant matter per hectare) than cereal production without animals and manure application. Furthermore, to avoid misinterpretation of yields, crops grown within the same type of system should also be similar.

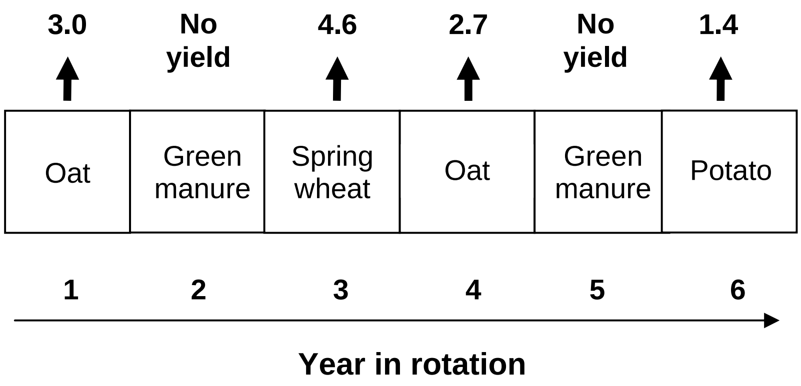
2.2. Choose long-term studies

A critical aspect of a relevant comparison of crop yields from organic and conventional systems is the time span of the comparison. Short-term comparative studies can lead to biased conclusions for several reasons. If a conventional system is converted into an organic system, previous soil management practices will affect crop growth in the organic system. A reduced weed population (including seed bank), elevated soil P and K fertility levels, a high organic matter content and amount of recent plant residues, etc. may initially result in higher yields in the organic system than those found after a decade. In other words, only long-term studies with minimal residual effects are really useful.

Using yield data from a single harvest is not valid for a proper evaluation. As yield data vary between years due to weather conditions, fertility management during the previous year, damage through pests, weeds, etc., a single harvest estimate is not representative. More importantly, yields of actual crops may not be a complete measure of the total productivity of a system. When non-food crops (green manure) form part of the rotation or when land lies fallow for a year or so, the year without harvest means a loss of production. Tables of single crop yields may not include these 'lost' years. In other words, total crop output over a whole crop rotation period of several years is the most relevant variable when comparing or discussing crop production in different systems. This has to be taken into account in a scientific comparison of production capacity (Fig. 1).

2.3. Exclude yield data from organic systems with high applications of manure

A common hidden assumption is that organic manures, composts, etc. are not limited by any means, and that sufficient organic manure is accessible to all farms and can be applied freely. In other words, data from experiments using large quantities of manure are used as proof that it is possible to produce high yields through organic management. However, the amount of nutrients that can be applied through organic manures is actually quite low. For example, only 58 kg N ha^{-1} yr^{-1} (Kirchmann et al., 2005) would potentially be available in Sweden if manure were to be equally distributed on all arable land in the country. Only 50-70% of this amount is available when losses



Mean yield per harvested crop: 2.9 Mg ha^{-1} yr^{-1}

Yield reduction by green manure years: 33%
Mean yield over the rotation: 1.9 Mg ha^{-1} yr^{-1}

Figure 1. Note the difference between crop yield each year and average yield per 6-yr rotation period. Years with non-food crops, e.g. green manure or fallow, reduce mean yield by an equivalent percentage. Data were taken from Torstensson et al. (2006).

through ammonia volatilisation during storage and handling are considered (Kirchmann and Lundvall, 1998). This quantity is far less than the amount of N applied in the organic studies examined in this review.

Thus, high crop yields are not proof of the productivity of an organic system as long as it uses large amounts of manure transferred from other systems and not produced by the farming system itself. The high yields are actually only proof of the well-known fact that manure can be used as a fertiliser to increase yields. A realistic assessment of the production capacity of organic systems is only possible if any major nutrient transfer from conventional systems is excluded, see Chapter 5 of this book (Kirchmann et al., 2008). If all farming systems were to be organic, it would be impossible to rely on nutrient transfer from conventional production and the amounts of manure applied would be equivalent to the production level of the system. For example, Chen and Wan (2005) showed that the amount of nutrients supplied through organic manures in China is far below the amount required to produce sufficient food for its people.

2.4. Consider whether differences in the management of systems other than those originating from organic regulations is a cause of bias

A number of management options are not regulated by organic farming regulations, such as use of crop residues, soil tillage, use of catch crops, etc. Differences in management can have a great impact on yields, but these practices are not dependent on an organic/conventional approach and can be managed in the same way in both systems. For example, incorporation of crop residues in organic systems but their removal and sale in conventional systems can affect soil organic matter levels, and ultimately also yields. Using catch crops in one system but not in another can also have a considerable impact on yields (Torstensson et al., 2006).

On the other hand, differences in manure handling can greatly affect the amount of N available for spreading and the release of N in soil. For example, composting of manure, which is a prerequisite in biodynamic agriculture, results in high ammonia losses (e.g. Kirchmann, 1985), while anaerobic storage of slurry limits N losses (Kirchmann and Lundvall, 1998). Thus, systems applying liquid manure (slurry) return more N than those using composted manure. Consequently, slurry with its higher content of plant-available N results in higher yields than composted manure (e.g. Hadas et al., 1996; Svensson et al., 2004).

If differences in management between systems are due to reasons other than organic farming regulations, a bias is added to the comparison. The consequences of any such differences need at least to be discussed and considered before any conclusions are drawn.

3. COMPARING ORGANIC AND CONVENTIONAL CROP YIELDS

3.1. National crop yield statistics

A search in agricultural statistical databases of EU countries, the USA, Canada and Australia revealed that information on organic crop yields is very scarce. No crop yield data were found, but information on the number of organic farms, the extent of farmland under organic cultivation and, in a few countries, data on milk production are available. We found that during 2007, only Sweden and Finland provided statistics on organic crop yields, which were significantly lower than conventional yields.

Official Swedish statistics (SCB, 2006) reveal that yields of organically grown crops are 20 to 60% lower than those of conventionally grown crops. Yields of organically grown legumes (peas and beans) and grass/clover leys are, on average, 20% lower (Fig. 2), whereas yields of cereals are 46% lower and yields of potatoes as much as 60% lower than in conventional production. National statistics for Finland (Statistics Finland, 2007; Finnish Food Safety Authority, 2006) show a similar picture. Yields of organically produced cereals are 41% lower and yields of potatoes 55% lower (Fig. 2). The statistical data represent average figures combining pure cropping systems without animal husbandry and mixed crop-animal systems using animal manure. This means that yields of organic farms using animal manure are probably somewhat underestimated, while the converse is true for organic farms without animals, which have even lower yields. In line with the discussion above, it should be borne in mind that statistical yield data represent single crops in a rotation and do not consider years in the rotation when non-food crops (green manure) are grown or when the fields are under fallow. Thus, total crop output per time unit cannot easily be derived from national statistics.

3.2. Cropping system studies in the USA

During the compilation of comparative long-term field studies, we found that some experiments from the USA showed similar yields for organic and conventional systems (Table 1). This motivated a separate examination of these studies. For example, there were no differences in yields of soybean in several studies (Sanchez et al., 2004; Pimentel et al., 2005; Smith et al., 2007). Furthermore, some organic maize and oat yields (Porter et al., 2003; Pimentel et al., 2005) were also reported to be similar to those in conventional systems (see Table 1). In general, even

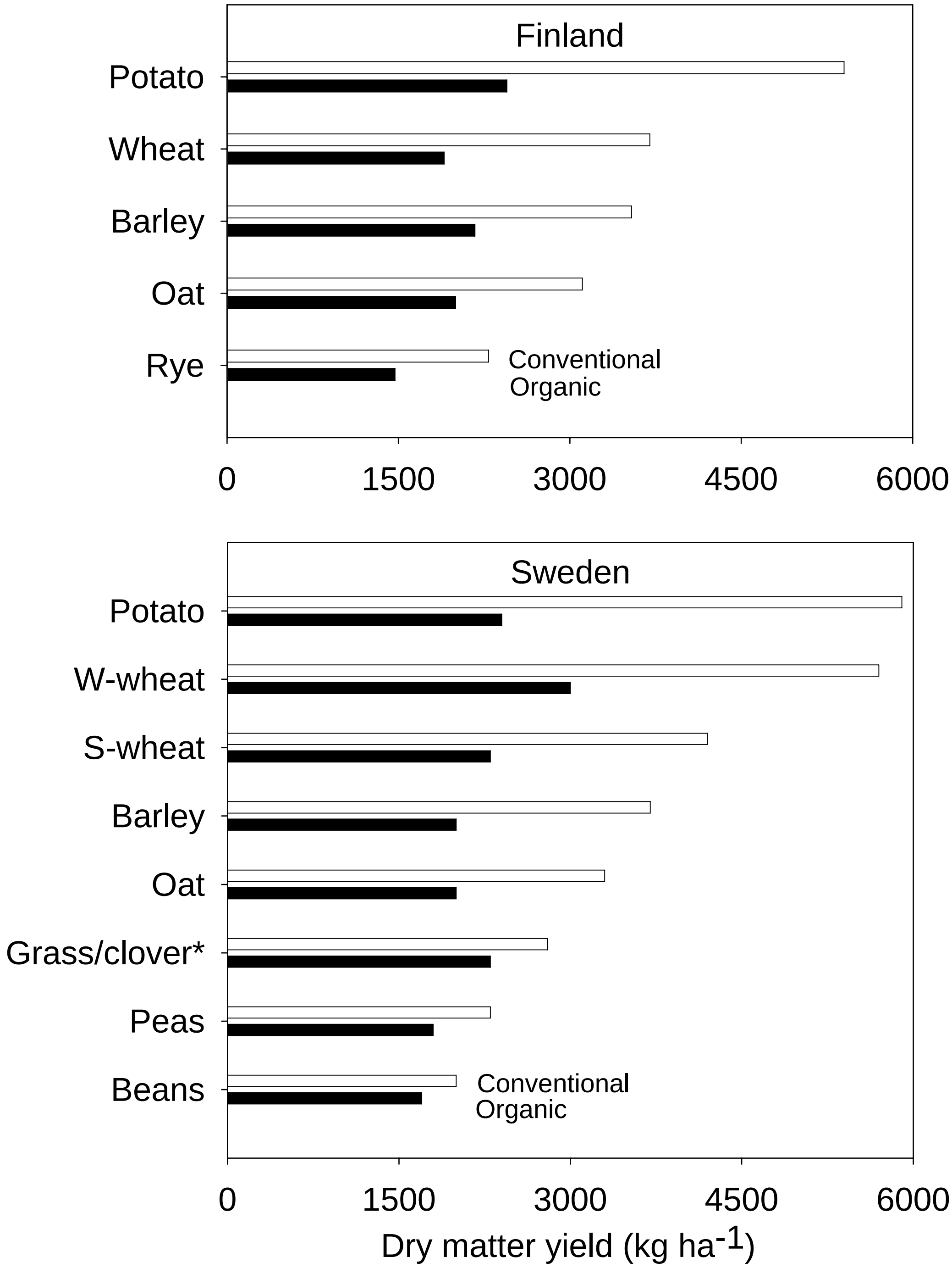


Figure 2. Official national yield data for organically and conventionally grown crops in Finland and Sweden in the year 2005. Figures were derived from Statistics Finland (2007), Finnish Food Safety Authority (2006) and SCB (2006). *Only the first of two or three cuts is represented by the data.

Table 1. Comparison of yields and N inputs in organic and conventional cropping systems in the USA

Farming system, experiment and crop	Mean yield (Mg ha^{-1})		Yield difference (%)	N input[a] (kg ha^{-1} yr^{-1})		Yield/N input (kg kg^{-1} N)		References
	Con.	Org.		Con.	Org.	Con.	Org.	
Cropping systems with animal manure or compost								
California: Davis, LTRAS (9 yr)								Denison et al. (2004)
Maize	11.5	7.6	-66	235	373	49	20	
Tomato	59[b]	66[b]	11	160	214	369[b]	308[b]	
Maryland: Beltsville, SADP (9 yr)								Teasdale et al. (2000; 2007)
Corn	5.5	4.9	-11	159	120	46	41	
Wheat	3.8	2.9	-24	100	130	38	22	
Michigan: Kellogg Biological Station, LFL (8 yr)								Sanchez et al. (2004)
Corn	8.6	7.4	-14	140	104	61	71	
Soybean	2.3	2.4	4	0	0	-[c]	-[c]	
Wheat	3.2	2.7	-15	65	104	49	26	
Minnesota: Lamberton site (7 yr)								Porter et al. (2003)
Corn	8.7	7.9	-10	62	185	140	43	
Soybean	2.9	2.3	-20	1	31	-[c]	-[c]	
Oat	1.9	1.8	-5	49	92	38	19	
Pennsylvania: Kutztown, Rodale Institute (FST) (22 yr)								Pimentel et al. (2005)
Corn	6.5	6.4	-2	87	198	74	32	
Soybean	2.5	2.5	0	0	0	-[c]	-[c]	
Mean value			*-13*	*88*	*120*	*62*	*34*	
Legume-based cropping systems								
California: Davis, LTRAS (9 yr)								Denison et al. (2004)
Rain-fed wheat	4.8	4.1	-15	110	0	-[c]	-[c]	
Irrigated wheat	5.6	4.5	-20	165	0	-[c]	-[c]	
Michigan: Kellogg Biological Station, LTER (12 yr)								Smith et al. (2007)
Corn	4.5	4.2	-10	123	0	-[c]	-[c]	
Soybean	2.2	2.2	0	0	0	-[c]	-[c]	
Wheat	3.6	2.1	-42	56	0	-[c]	-[c]	
Pennsylvania: Kutztown, Rodale Institute (FST) (22 yr)								Drinkwater et al. (1998)
Corn	6.5	6.4[d](5.1)	-2[d] (20)	87	140	75	46	Pimentel et al. (2005)
Soybean	2.5	2.2[d](1.8)	-12[d] (30)	0	0	-[c]	-[c]	
Mean value			*-20*	*77*	-[c]	-[c]	-[c]	

[a] N input refers to N sources applied (inorganic fertiliser, manures, compost) excluding N fixation.
[b] Figures refer to fresh weight yield and were excluded from the calculation of mean N yield/N input.
[c] Figures were excluded from the calculation as the input of N through fixation is unknown.
[d] Yield figures refer to crops in single years and do not take into account that during one out of the five years in rotation, non-harvested red-clover-alfalfa hay or hairy vetch was grown and used as green manure. Total crop output over the rotation is therefore 20% lower and corrected figures are given in brackets (for explanation see Fig. 1).

average yields were reported to be little affected by organic and conventional management, being 13% lower for organic systems that combine crops with animals and 20% for organic systems without animals.

A more thorough examination of the organic systems in the USA revealed that the total amount of nutrients applied was as high as or even higher than that in comparative conventional systems (Teasdale et al., 2000; 2007; Porter et al., 2003; Denison et al., 2004; Sanchez et al., 2004; Pimentel et al., 2005). Similar nutrient application rates have also been reported in other publications dealing with organic cropping systems in the USA (Lockeretz et al. 1980; Liebhardt et al., 1989; Clark et al., 1999). Instead of the inorganic fertilisers that are used in conventional systems, organic farmers in the USA purchase manure, compost, food waste, etc., to satisfy crop nutrient demand and improve soil fertility. However, the critical point is where this manure and compost originate from, i.e. whether the amount of manure or compost applied is sustained by the organic systems or whether it mainly originates from off-farm, non-organic production. In the case of the USA studies, supply of nutrients to organic production was higher than removal, showing that nutrients were purchased, to a large extent from conventional systems as pointed out above. One can therefore conclude that high organic yields can only be achieved if there is an excess of manure/compost, or if other products can be transferred from conventional to organic production. As long as conventional production is the dominant form, this is possible. However, the results are not representative of conditions where modern conventional agriculture is scarce, such as in Africa or in areas completely converted to organic farming.

3.3. Cropping system studies in Europe and Australia

Compilation of a number of long-term field experiments in Europe and Australia (Table 2) revealed that yield differences between organic and conventional systems were much larger than those reported from the USA. On average, organic systems in Europe and Australia that combine crops with animals had 25% lower yields and organic systems without animal husbandry had 47% lower yields than equivalent conventional systems. Studies of farms under long-term organic management in Australia (Table 2) also showed yields of individual crops to be substantially lower than those on conventional neighbouring farms (Kitchen et al., 2003; Ryan et al., 2004). In addition, Australian organic wheat crops reported by Ryan et al. (2004) were preceded by an average of 4.7 years of pasture, compared with 3.3 years for the conventional crops. The general reason for the large deviation between organic and conventional yields in these studies compared with those in the USA seems to be the limited purchase of manures/compost by organic farms in Europe and Australia.

Nutrient flows to fields and farm-gate balances between organic and conventional farms have been examined to determine whether nutrient inputs in European organic systems are lower throughout (Kaffka and Koepf, 1989; Fowler et al., 1993; Nolte and Werner, 1994; Granstedt, 1995; Halberg et al., 1995; Nguyen et al., 1995; Fagerberg et al., 1996; Wieser et al., 1996). These studies clearly show that the mean input of N, a major yield-determining nutrient, was lower throughout in organic systems over a crop rotation period than in conventional systems. This may explain why there is a greater deviation between organic and conventional yields in Europe. The low nutrient inputs to organic systems can be explained by the European approach of viewing organic crop-animal farms as a self-sustaining unit. The general aims for organic agriculture are to mainly rely on recycling of nutrients from within the system and to enhance the biological activity in soil in order to increase

Table 2. Comparison of yields and N inputs in organic and conventional cropping systems from Europe and Australia

Farming system, experiment and crop	Yield ($Mg\ ha^{-1}$)		Yield difference (%)	N input ($kg\ ha^{-1}\ yr^{-1}$)		Yield/ N input ($kg\ kg^{-1}$ N)		References
	Con.	Org.		Con.	Org.	Con.	Org.	
Mixed crop-animal systems								
Norway: Apelsvoll site (8 yr)								Korsaeth & Eltun (2000); Eltun et al. (2002)
Barley, wheat	5.0	3.7	-26	100	-[a]	50	-[a]	
Forage	10.7	8.3	-22	210	143	51	58	
Fodder beet	9.0	9.3	+3	140	-[a]	64	-[a]	
Switzerland: DOK trials (24 yr)				138[b]	105[b]			Spiess et al. (1993); Besson et al. (1999); Mäder et al. (2002)
Winter wheat	4.5	4.1	-10	-[b]	-[b]	-[b]	-[b]	
Forage	14.0	11.5	-18	-[b]	-[b]	-[b]	-[b]	
Potato	48.0	30.0	-38	-[b]	-[b]	-[b]	-[b]	
Sweden: Bjärröd trial (18 yr)								Kirchmann et al. (2007)
Winter wheat	6.1	4.2	-31	120	116	51	36	
Barley	3.7	2.1	-43	80	60	46	35	
Forage	7.5	6.1	-19	a	-[a]	-[a]	-[a]	
Australia: New South Wales (30 yr)								Ryan et al. (2004)
Wheat	5.5	2.9	-48	17	0	-[a]	-[a]	
Mean value			*-25*	*115*	*102*	*52*	*43*	
Pure cropping systems								
Sweden: Mellby trial (6 yr)								Torstensson et al. (2006)
Oats	5.8	2.8[c] (1.9)	-52[c] (67)	97	71	60	27	
Sweden: Lanna trial (6 yr)								Aronsson et al. (2007)
Winter wheat	5.9	3.4[c] (2.3)	-42[c] (61)	134	84	44	27	
Mean value			*-47[c] (64)*	*115*	*77*	*52*	*27*	

[a] Figures were excluded from the calculation as the N input by a specific crop is lacking. Furthermore, the amount of N added through a previous N fixing crop is not given.
[b] Only mean N application for the whole rotation.
[c] Yield figures refer to crops in single years and do not take into account that during 2 out of the 6 years in the rotation, non-harvested green manure crops were grown. Total crop output over the rotation is therefore 33% lower and corrected figures are given in brackets (for explanation see Fig. 1).

mineral weathering and biological N_2-fixation (Watson et al., 2002; International Federation of Organic Agricultural Movements, 2006). Furthermore, according to the European founders of organic agriculture, high yields caused by easily available nutrients are regarded as being detrimental to crop quality (Steiner, 1924; Balfour, 1944; Rusch, 1978). Thus, the application of nutrients of off-farm origin is often kept to a minimum and this view is reflected in the design of European organic long-term experiments (Table 2).

One of the comparative studies cited in Table 2 was run on a nutrient-depleted soil that had not received any inorganic fertilisers for 40 years prior to the start of the experiment (Kirchmann et al., 2007). Organic yields amounted to only 50% of those achieved in a comparable conventional cropping system over 18 years, despite use of animal manure at amounts larger than those obtained from on-farm production and large additions of rock phosphate and potassium sources approved by the organic farming organisations. This study underlines the importance of the initial soil fertility status at a site used for a comparative study. Very often, the residual soil fertility effect from previous applications of conventional, inorganic P and K fertilisers before the start of the experiment is overlooked. The continuous decline in organic yields at certain sites can in most cases be explained by further depletion of this soil fertility.

In two organic systems without animals (Table 2), green manure crops were grown during two of the six years and no food/feed crops were produced (Torstensson et al., 2006; Aronsson et al., 2007). This means that over the whole crop rotation, organic yields are reduced by a further 33% in accordance with the reasoning in Fig. 1. This correction of yield levels by considering years with non-food crops resulted in an overall yield reduction of 64% in the organic system compared with conventional yields.

It is doubtful whether there will be an increased nutrient input through transfer of organic manures or composts from conventional to organic farms in Europe, as this would be against the principle of basing organic farming on 'living ecological cycles' relying on on-farm N input and recycling (International Federation of Organic Agricultural Movements, 2006). Although in certain years N input in organic systems can amount to several hundred kilos per hectare from N_2-fixing crops, the total input over a rotation period is still lower than in conventional as years in the rotation without legumes mean little or no N input. On the other hand, organic forage-ruminant systems, i.e. systems with a large proportion of N_2-fixing forage crops in the rotation, seem to be capable of providing a high continuous input of N to soil (Eltun et al., 2002; Posner et al., 2008) similar to that in conventional systems. These results are in agreement with knowledge from the Norfolk rotation, long before organic agriculture became fashionable.

3.4. Organic yields higher than conventional?

A review by Badgley et al. (2007) points out that organic agriculture is misjudged concerning crop production and its potential to supply sufficient food. According to their review, only small yield reductions occur through organic agriculture in developed countries, but organic yields are higher than conventional yields in developing countries. This conclusion is supported by a large number of other papers, which may be taken as evidence of its scientific reliability. We re-examined the papers cited by Badgley et al. (2007) to determine whether their conclusions are based on valid assessments.

A number of the studies cited from developed countries are summarised in Table 3. However, due to their limited accessibility and often lower scientific credibility, non-peer-reviewed conference papers, institution reports and magazine articles were not considered. The re-examination of papers reporting high organic yields showed that the data were used in a biased way, rendering the conclusions flawed. Firstly, none of the organic studies cited reported higher crop output from organic production than from conventional over a whole rotation, but only for

Table 3. Studies showing higher yields in organic systems than in conventional and the reasons for this

Type of study and year	Yield (Mg ha^{-1}) Con.	Yield (Mg ha^{-1}) Organic	Organic yield increase (%)	Remarks	References
Scientifically non-valid comparisons					
Germany: Talhof, (conventional 1922-1929 vs biodynamic performance 1930-1937)					Koepf et al. (1976)
Winter wheat	1.9	2.4	21	Comparing different periods, neglecting general yield improvement over time	
USA: Western corn belt, survey of 363 farms (1974-1978)					Lockeretz et al. (1981)
Corn			(-30)[b]	[b]Only very few organic corn yields out of 81 measurements were higher than conventional. On average, organic corn yields were 30% lower	
Ohio: Spray Brothers Farm (1981-1985)					National Research Council (1989)
Corn	-	-	25	Farm yields were compared with mean yields from the county	
Soybean	-	-	40		
Amount of nutrients added not supported by the organic systems					
California: Davis, SAFS project (1994-1998)				Higher applications of N, P and K through compost to the organic system showing higher in 2 years out of 4.	Poudel et al. (2002)
Corn			20		
Tomato			10		
Iowa: Neely-Kinyon LTAR (1998-2001)				Higher N, P and K additions through compost to the organic systems resulted in higher yields after 3 yrs. Only N fertiliser to the conventional system.	Delate and Cambardella (2004)
Corn	7.1	8.1	15		
Soybean	2.7	3.1	15		
Canada: Nova Scotia, field plot (1990-1992)				Nutrient additions through compost to the organic plots were twice as high as through NPK fertiliser.	Warman and Havard (1997)
Cabbage	45.3	46	2		
Carrot	26.2	27.9	6		
Yield reduction by non-food (green manure) years in rotation not considered					
South Dakota: field plots (1986-1992)				The set-aside land for green manure years was 25%, which means that a 9% higher single crop yield was -18% over a whole crop rotation	Smolik et al. (1993;1995)
Spring wheat	-	-	9[a] (-18)		

single years. Secondly, when yields were higher during a single year in organic production, this was coupled to one or both of the following conditions: (1) The amount of nutrients applied to the organic system through manure and compost was equal to or even higher than that applied to the conventional system through inorganic fertilisers; (2) non-food crops (legumes) were grown and incorporated in the preceding year to provide the soil with N. Thirdly, on-farm data were compared with mean yield data within a region. Such comparisons have no validity, since the possible factors behind the differences are not given. In summary, the yield data reported were misinterpreted and any calculations based on these data are likely to be erroneous.

The paper by Badgley et al. (2007) also presents comprehensive yield figures from developing countries. However, of the 137 yield figures reported, 69 originate from the same paper (Pretty and Hine, 2001). A closer inspection revealed that crop yields were based on surveys and there was no possibility to check crop performance variables and the science behind the data. In fact, only six of the papers for developing countries cited by Badgley et al. (2007) were derived from peer-reviewed journals. In four papers, rice yields in conventional systems were compared with so-called intensified rice production. However, intensified rice production uses mineral fertilisers, although at lower rates, and is not an organic form of agriculture by European standards (e.g. Sheehy et al., 2004; Latif et al., 2005). Our conclusion is therefore that the argument that organic agriculture can produce similar or even higher yields than conventional does not hold given the boundary conditions outlined above.

3.5. Trends in organic crop yields

Yield trends over time were analysed in four Swedish comparative studies to determine the potential to increase production through organic and conventional management. The underlying question is whether yields are following the same trends in organic agriculture as in conventional.

In the study by Kirchmann et al. (2007) (Fig. 3), the initial 10-year period was characterised by a relatively constant yield difference between the organic and conventional system. Thereafter, yields increased in both systems but the increase was larger in the conventional system than in the organic, despite higher additions of animal manure to the organic system. In two other studies without animal manure (Torstensson et al., 2006; Aronsson et al., 2007), which used green manure for organic production and fertiliser for conventional, the relative yield differences between systems were much larger (see Fig. 3). Furthermore, no yield increase was observed in the organic system over the 5-6-year experimental period, whereas conventional yields increased in one experiment and remained constant in the other. In studies without animal manure, there is good reason to assume that organic yields barely increase over the longer term, as residual soil nutrients are depleted at faster rates than in studies with manure application. For instance, in relatively fertile soils, a decade or more may be needed before residual soil nutrients are sufficiently exhausted for a yield reduction to become apparent (Denison et al., 2004).

In another experiment run for 12 years at a fertile site, each crop in the rotation was grown every year and animal manure was applied in relation to the level of nutrient removal by harvested crops (Ivarson and Gunnarsson, 2001) (Fig. 4). Differences between organic and conventional yields were smaller at this site, in particular for forage crops. However, there were no indications that organic yields would increase more or decrease less over time than conventional yields.

Based on the four experiments presented above, we conclude that there is no evidence that yields increase more in organic agriculture than in conventional. However, there is evidence that conventional agriculture has a greater capacity for increased yields than organic agriculture.

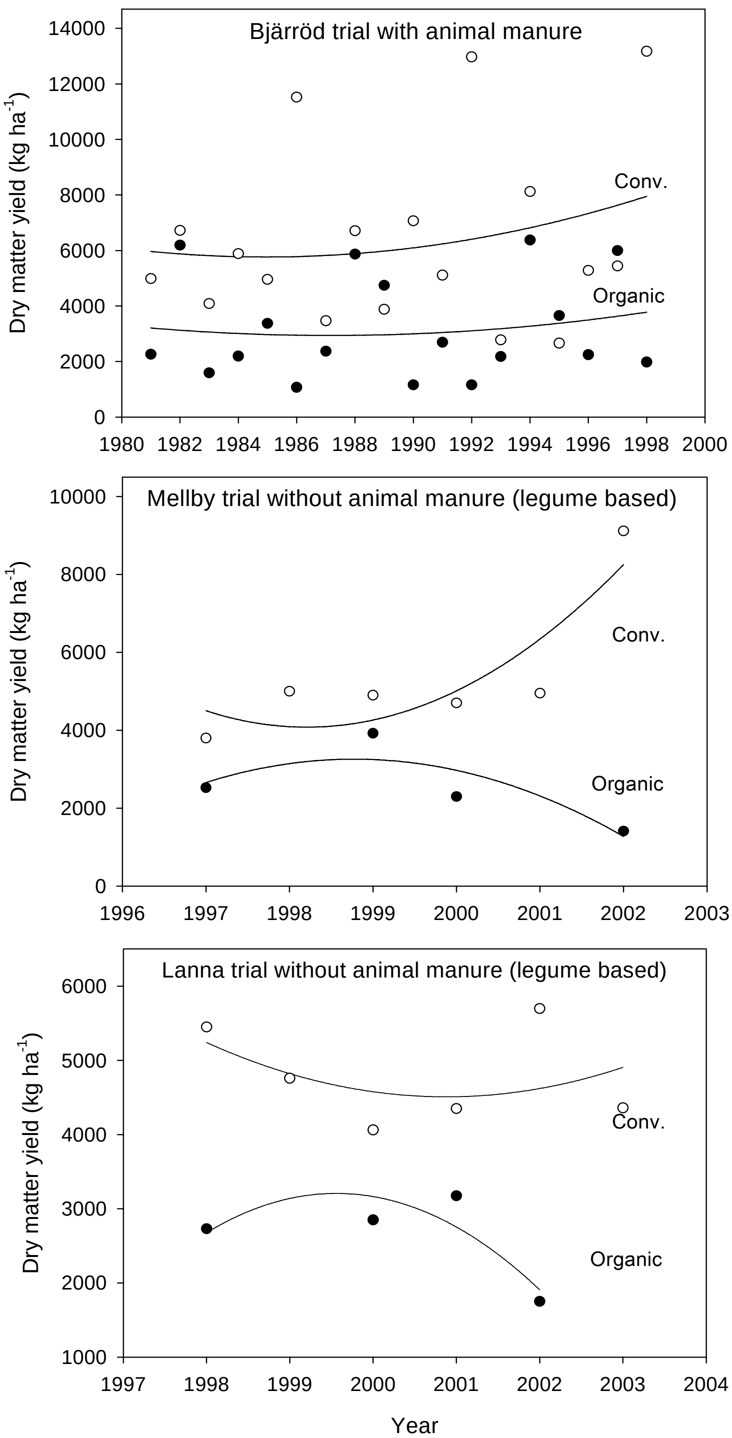


Figure 3. Trends in crop yield in three Swedish long-term studies. Data for the Bjärröd study are from Kirchmann et al. (2007), for the Mellby study from Torstensson et al. (2006) and for the Lanna study from Aronsson et al. (2007). Absent yield data for 1998 and 2001 in the Mellby study and for 2003 in the Lanna study are due to years with green manure crops not being harvested. (Open circles = conventional, filled dots = organic).

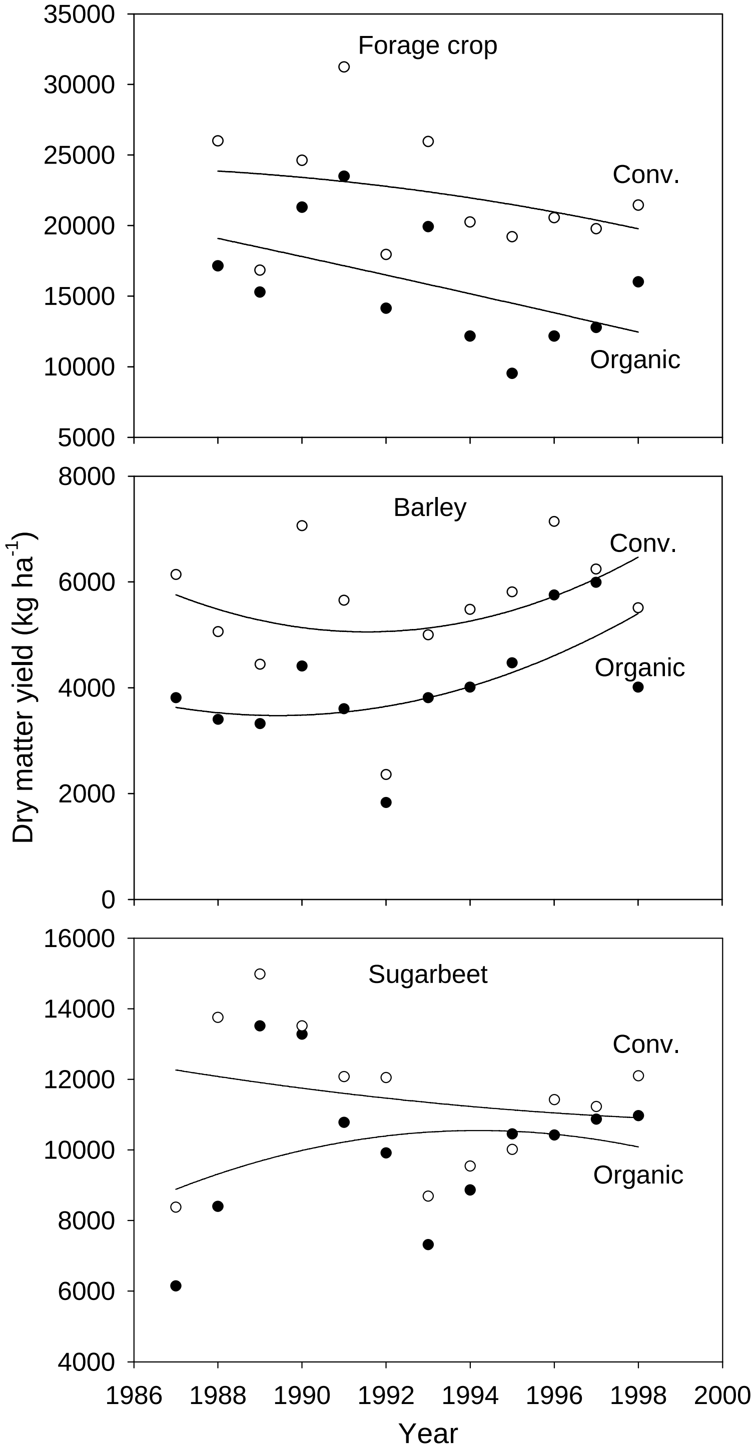


Figure 4. Trends in yield during two 6-year rotations on a fertile site in southern Sweden (Bollerup) of organically and conventionally grown crops to which animal manure was applied in relation to the level of harvested crops. Data from Ivarson and Gunnarsson (2001). (Open circles = conventional, filled dots = organic).

3.6. Food production at the global scale

In summary, this review shows that the reduction in crop yields through large-scale conversion to organic agriculture would, on average, amount to 40%, with a range of variation of 25-50%. A 40% reduction in yield on a global scale is equivalent to the amount of crops required by 2.5 billion people. This estimate is in fact identical to that calculated by Smil (2001), who assessed the role of industrial nitrogen fixation for global food supply. Smil (2001; 2002) concluded that the Haber-Bosch process for industrial fixation of atmospheric nitrogen provides the very means of survival for 40% of humanity and that only half of the current world population could be supported by pre-fertiliser farming, even with a mainly vegetarian diet. The similarity of these estimates confirms the strategic role of fertilisers as a keystone for the well-being and development of mankind.

It is obvious that world-wide adoption of organic agriculture would lead to massive famine and human death. This is something that advocates of organic agriculture are silent about, perhaps because of the severe moral dilemma it poses.

4. FACTORS LIMITING YIELDS IN ORGANIC SYSTEMS

Yield data presented above lead to the fundamental question of what causes lower yields in organic systems than in conventional. According to conventional agronomic understanding, the following factors can be suggested: (i) Low nutrient input; (ii) low nutrient use efficiency; (iii) high weed abundance; (iv) limited possibilities to improve low native soil fertility in resource-poor areas; and (v) poor control of pests and diseases. Reports detailing the causes of low organic yields are scarce, but in the following section we discuss some of the potential factors.

4.1. Low nutrient input and lower efficiency

A low N input has been identified as one yield-limiting factor for organic systems (Clark et al., 1999; Kirchmann et al., 2007), since organic manures cannot be produced by organic systems themselves in sufficient quantities to deliver enough N for high yields. On the other hand, numerous studies of N_2-fixing crops reveal that grain legumes, green manures and tree legumes have the capacity to fix several hundred kilograms of N during one year (Giller, 2001). So why is the potential of N_2-fixing crops to replace inorganic N fertilisers not fully used? Legumes can indeed improve yields of subsequent crops (e.g. Giller and Cadish, 1995; Sanchez, 2002), improve soil fertility and break pest and disease cycles in a crop rotation, but the total amount of N available to other crops over a whole rotation must be sufficiently high, which means that legumes must be grown every second year at a minimum. There are other limitations associated with the use of legumes. Legume N is not a free source of N. As pointed out earlier, growth of green manure legumes for N supply and soil fertility improvement is often only possible at the expense of not using the land for export of food from the field (Fig. 1).

In addition, biologically fixed N and other forms of organic N are not necessarily released in synchrony with the demand of the following crop. The overall lower agronomic effect of N in the organic systems (Tables 1 and 2) is a clear indication that the N use efficiency of organic inputs (animal manure, green manure, compost, etc.) is lower. The main reason for this is that N from legume residues and animal manures is released even at times when there is no crop growth (Marstorp and Kirchmann, 1991; Dahlin et al., 2005), which carries a risk of significant leaching losses (Bergström and Kirchmann, 1999; 2004) and thus lower N use efficiency.

Using legumes as cash crops in a rotation does not necessarily mean that the amount of N fixed increases the soil N pool. Harvesting grain legumes can remove more N than is fixed. As pointed out by Giller (1998), legumes are not necessarily N providers but can be plunderers. For example, soybeans can remove more N than they add (Toomsan et al., 1995), while peas do not necessarily contribute a net supply of N to soil (Jensen, 1987; 1996). As pointed out earlier, only organic grassland-ruminant systems, i.e. systems with mainly N_2-fixing forage crops in rotation, have the capacity to provide continuous inputs of N to soil similar to those in conventional systems.

Phosphorus has also been suggested to be a limiting nutrient in certain cropping systems. On grazed organic systems in southern Australia, where legume-based annual pastures are rotated with crops, P can become the yield-limiting element (Ryan et al., 2004). Similarly, permanent clover-based pastures of biodynamic farms in Australia show lower production than conventional, which is also ascribed to lower inputs of nutrients, particularly of P (Burkitt et al., 2007a;b). A correct view on this is that over the long-term, less can be taken out of a system if less is put in (Goulding, 2007). However, crop yield also depends on the availability of the nutrients and not only on the quantity added. The same amount of nutrients can be added to organic production as would be supplied by inorganic fertilisers, but in the form of untreated minerals. This was actually done with P and K in the organic treatments in the Swedish long-term study discussed above (Kirchmann et al., 2007) but that study showed that despite very large applications of untreated minerals, the availability of N remained the yield-limiting factor. The same conclusion was drawn by Pang and Letey (2000) and Berry et al. (2002), who found that inadequate N availability and not necessarily nutrient addition was the bottleneck for organic production and stressed that the amount of N available during the period of rapid growth restricts crop productivity in organic systems.

4.2. Poor weed control

Weed control is a primary concern in all types of agriculture. Weeds compete with the main crops for water, nutrients and light and can thereby significantly reduce yields. However, weeds can also contribute carbon to soil.

As organic agriculture is limited by two options for weed control, physical-mechanical treatment and choice of crop rotation, weed populations are larger in most organically grown crops. For example, Kirchmann et al. (2007) compared weed biomass production over 18 years in an organic and a conventional cropping system and found a slightly increasing trend in the organic system with irregular fluctuations between years. On average, about 1 Mg dry weed biomass per hectare was produced over the 18-year period, with peak values of around 3 Mg dry matter (Fig. 5), which was 25 times more than in the conventional system in which pesticides were used. Other comparative studies of organic and conventional production also report an overall higher weed biomass under organic management (Barberi et al., 1998; Poudel et al., 2002; Smith and Gross, 2006). The yield decreasing effect of weeds alone in organic systems can amount to 20-30% according to Posner et al. (2008), who compared effective weed control with ineffective treatment.

Weed management can be improved through a diverse and long rotation period (Taesdale et al., 2004) and especially through growth of perennial forage crops (Sjursen, 2001). Otherwise, the potential for a reduction in the weed seed bank through organic practices is small (e.g. Clark et al., 1999; Porter et al., 2003). Teasdale et al. (2007) showed that weed control in organic no-till systems is barely possible. Weeds with deep root systems cannot be fully disrupted and their biomass can even increase. Peigné et al. (2007) stressed that pressure from weed grasses is

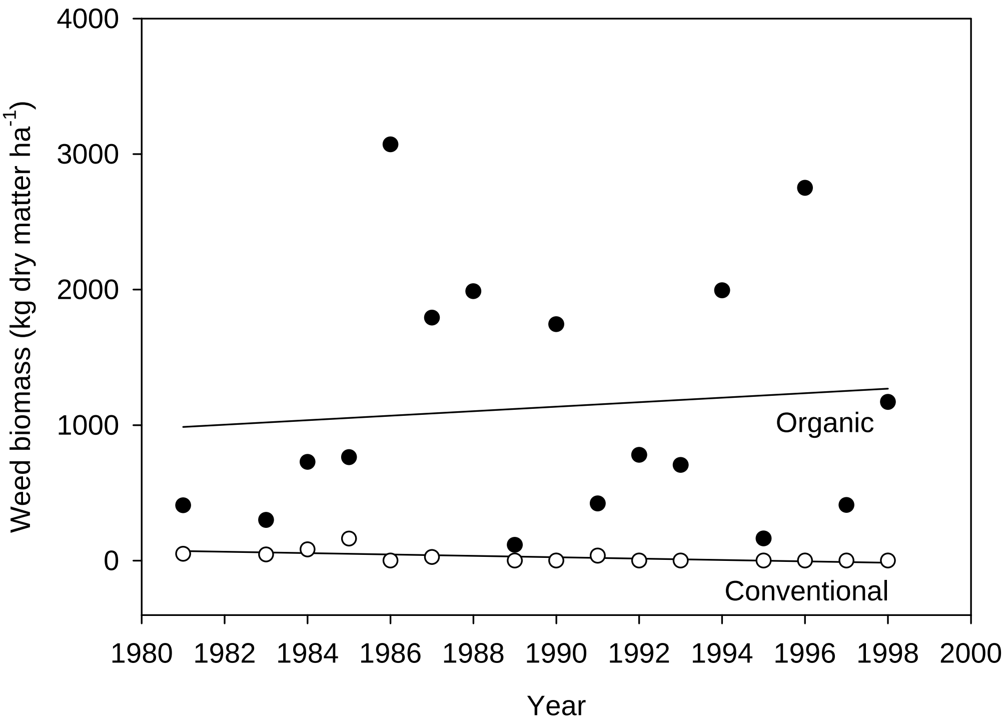


Figure 5. Trends and fluctuations in weed biomass in an organic and conventional cropping system over an 18-year period (data from Kirchmann et al., 2007). Weed data are lacking for 1982, 1988 and 1994 when grass/clover forage was grown. (Open circles = conventional, filled dots = organic).

much greater in organic conservation tillage than in conventional. Thus overall, we can conclude that effective weed control in organic agriculture is rather limited.

4.3. Low native soil fertility – the example of sub-Saharan Africa

The central question put forward in this section is whether introduction of organic practices in developing countries can increase yields and thereby ensure food supply. Smallholder farmers in developing countries have practised organic methods for thousands of years, as these methods have been the only approach available to manage soil fertility in such systems. The principal question is whether these smallholder farmers can significantly improve food production with locally available resources and improved low cost technologies. In other words, are organic or near-organic practices the way forward? Supporters of organic agriculture point out that the only solution for poor people living under difficult conditions is to apply existing organic methods and improve these practices.

Three of the authors of this chapter have been involved for decades in soil fertility projects in developing countries with the aim of improving agricultural production using local resources and simple technologies. Moreover, all of us have a reasonable understanding of the malnutrition, poverty, lack of infrastructure and other socio-economic weaknesses that are realities in many developing countries. Furthermore, our research work fully supports existing agricultural methods such as erosion control, use of legumes in rotation, application of animal manure, recycling of organic waste, double dig for gardening, etc. However, our experience has forced us to question whether the proposed exclusive use of organic inputs and natural resources to increase crop production makes sense in resource-poor areas. In fact, it is the limited amount of nutrient resources available and/or their inappropriate quality (e.g. Campbell et al., 1998; Palm et al., 2001) that constrain agricultural production in many developing countries. In addition, many soils in these countries are natively poor in plant nutrients and soil depletion is continuing in sub-Saharan Africa (e.g. Smaling and Braun, 1996; Smaling et al., 1997; Mugwira and Nyamangara, 1998). Applications of nutrients to soil through transfer from adjacent areas to agricultural fields by cut-and-carry of organic matter are insufficient, as even these systems are poor in nutrients. The transfer may help to increase the fertility status at a very small scale, for example in domestic gardens (Prudencio, 1993), but at the larger scale the fertility of arable soils cannot be restored by such practices. Crops cannot be supplied with sufficient nutrients through the removal of vegetation from nutrient-depleted, adjacent ecosystems (e.g. Vanlauwe and Giller, 2006).

Here is an example of how crop yields from remote and resource-poor areas employing organic practices can be presented: '*Maize yields increased four to nine times. The organically grown crops produced yields that were 60% higher than crops grown with expensive chemical fertilizers'* (Leu, 2004). A yield increase of between 400 and 900% is dramatic but such an enormous increase shows that initial yield levels must have been extremely low, indicating the very difficult conditions for crop production in general. Enhanced production from 250 kg to 1000-2000 kg maize per hectare could represent the actual figures behind the quote. Furthermore, the reader is mistakenly led to believe that chemical fertilisers produce lower yields than organic materials. Higher organic yields than conventional are not proof of the superiority of organic practices. The application of organic material means addition of micronutrients, which are often also lacking in infertile soils. To make the comparison unbiased, the same micronutrients need to be applied with conventional fertilisers. Again, there is no information about the amount of manure applied or what is available for agricultural crops in the region as a whole. It is unclear whether the production increase would be possible for a larger region or just a single field. Viewed over a period of several years, the improvement may not last due to shortage of high-quality organic material. Furthermore, no information is provided on the potential yields from organic resources combined with inorganic fertilisers. A combination of organic material and inorganic nutrient sources has been shown to result in much higher yields than with organic inputs alone (e.g. Murwira and Kirchmann, 1993; Bekunda et al., 1997). In reality, a combination of organic and inorganic nutrient sources is the most successful approach to increase crop yields in resource-poor areas with low fertility soils (Palm et al., 1997; Vanlauwe et al., 2001; TSBF, 2006). The approach of applying exclusively organic products is based on misinformation about the effects of inorganic fertilisers on soils (Vanlauwe and Giller, 2006) and misunderstanding of their environmental impact.

On the other hand, the exclusive use of inorganic fertilisers without applying animal manures and without returning crop residues or other organic materials to the soil can result in a decline in crop yields over time, as shown in a number of long-term field experiments from sub-Saharan Africa (Singh and Balasubramanian, 1979; Swift et al., 1994; Laryea et al., 1995; Pieri, 1995). Advocates of organic agriculture use this type of result to claim that artificial fertilisers damage the soil and decrease soil fertility. A wide-spread view within organic agriculture is that '*more and more synthetic fertilizers are needed to maintain yields. The system error of conventional farming is the independence of natural regulating processes and local resources. The main cause for lower production is found in unutilized or inefficient use of natural resources'* (Rundgren, 2002). This is incorrect. As pointed out above, limited supply of natural resources and their poor quality is the main reason for low yields in areas with low soil fertility, not inefficient use of nutrients. The major reason why yields sometimes decline when inorganic fertilisers are used on highly depleted soil is the lack of other essential nutrients not applied with NPK fertilisers. Organic manures and composts usually contain other essential plant nutrients (Ca, Mg, S, Cu, Zn, etc.) in addition to N, P and K. Comparing organic practices with fertiliser application on highly depleted soils is only possible when the fertiliser treatment is not deficient in any other way. In fact, the experiments cited above showed that combining animal manure with inorganic fertilisers led to steadily increasing yields. However, long-term use of artificial N fertilisers such as ammonium sulphate or urea can reduce yields over time due to acidification (Kirchmann et al., 1994). On the other hand, this only occurs if the standard agronomic practice of liming is neglected.

As mentioned above, all efforts to increase yields with locally available resources are positive and the knowledge on how best to use organic and local resources is of the utmost importance. However, there is no scientific reason why conditions cannot be improved through the development of practicable and sustainable management practices utilising the benefits of combined application of organic resources and fertilisers (Palm et al., 1997; Vanlauwe et al., 2001; TSBF, 2006).

Occasionally, erroneous conclusions are drawn based on the fact that hungry and poor people cannot afford to buy food. Therefore, the only option proposed for poor farmers is low-cost organic management (e.g. Vandermeer and Perfecto, 2007). Most hungry and poor people are rural and agriculture is their mainstay. They are hungry because they are not able to produce sufficient food and they are poor because they have nothing to sell. Such disastrous conditions are often caused by a number of factors, such as poor economic and agricultural policy; inadequate investment in infrastructure and rural education; insufficient agricultural services such as research, extension, credit, input supply and marketing; and low investment in rural healthcare. However, the bottom line is that lack of nutrients, poor soil fertility, limited amounts of organic manures, etc. are causing low yields and these causes cannot be overcome by organic methods – the critical shortages will remain. Only introduction of higher yielding technologies producing more food per capita, together with other necessary actions, will improve food security and income for the poor (UN, 2005).

5. PLACING ORGANIC YIELDS IN PERSPECTIVE

Yield decreases – not of a few percent but of 25-50% – demand attention. Such drastic yield reductions highlight the fact that sufficient food through organic production cannot be taken for granted. Moreover, foreseeable environmental consequences must be outlined. What would actually happen if organic agriculture were to be introduced all over Western Europe?

5.1. Low-yielding agriculture demands additional cropland area

Data in the literature clearly show that organic yields are significantly lower, as is discussed in detail above. In order to produce the same amount of organically grown crops, countries would be forced to convert more land into cropland. Based on yield data from European long-term experiments (Table 3) and excluding any major nutrient transfer from conventional agriculture, we assessed the additional cropland required if organic practices were to be introduced (see Fig. 6). Conversion to organic cropping systems without animals would require 100% more cropland, since

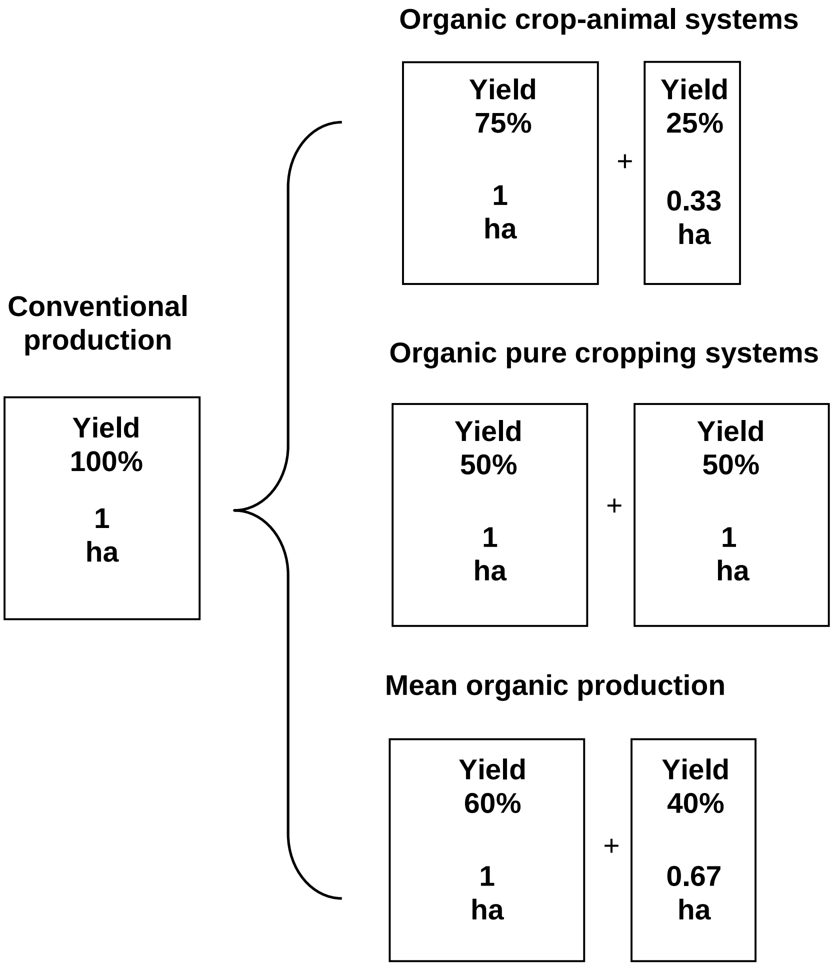


Figure 6. Additional demand for cropland to produce the same amount of crops through organic agriculture as in conventional agriculture. Data for crop-animal and pure cropping systems were taken from Table 2 and mean values for both systems from national statistics (Fig. 2).

yields of such systems amount to roughly 50% of conventional yields, while organic crop-animal systems would require 33% more land as yields from these amount to about 75% of those in conventional systems. Mean estimates of relative yields for organic cropping and mixed crop-animal systems (derived from Swedish National Statistics; Fig. 1) indicate the need to expand agricultural land by approx. 67%. As the additional cropland would be used less efficiently than in conventional agriculture, the land area needed would be correspondingly larger than the percentage yield decrease.

Calculated values for additional land demand due to conversion to organic agriculture reported by Halberg and Kristensen (1997) for Danish dairy farming show that organic production would require the area used for farming to be extended by 47% in order to maintain yields.

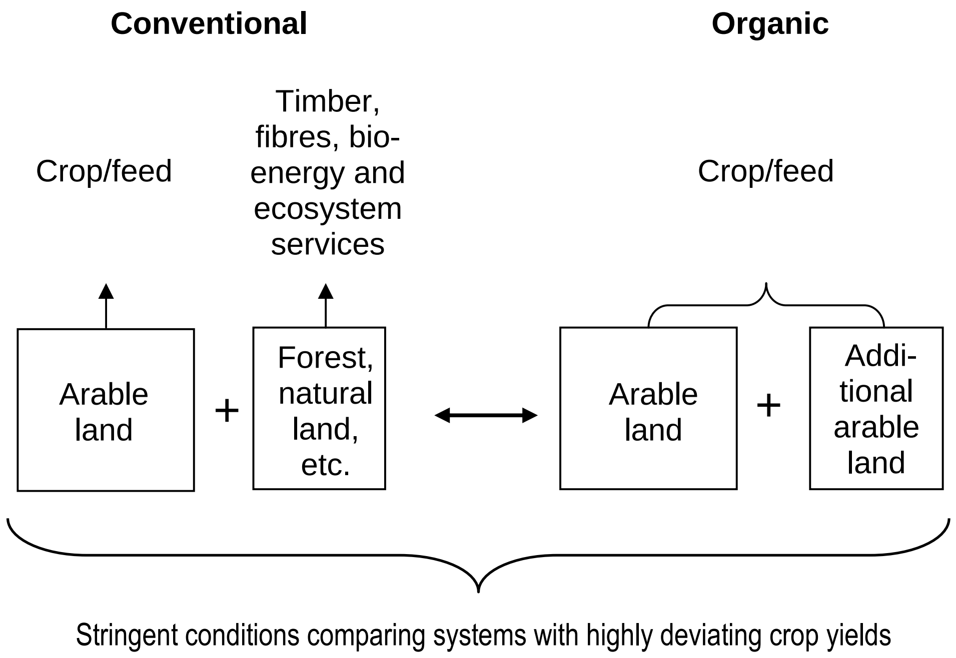


Figure 7. Land demand to produce the same amount of crops must be considered in a scientifically meaningful comparison between different types of agriculture. The additional area required for low-yielding agriculture competes with other land uses, e.g. forests, grazing land, bio-fuel cropping, etc.

Conversely, impressive savings in land area have been achieved through the introduction of modern agricultural practices and the associated increase in yields. Had yields in China and India remained at the level of the 1960s, land area would have needed to be increased two- and threefold, respectively (Quinones et al., 1997). Moreover, in many areas of the world, there is no additional land available for agriculture. For example, China has 7% of the world arable land area and 20-25% of the world population and there is no more agricultural land available (Chen and Wan, 2005).

The need for more farmland to produce the same amount of crops through low-yielding systems instead of high-yielding adds an important boundary condition to the comparison of these systems, as illustrated in Fig. 7. Conversion of other ecosystems into cropland means lost production of other raw materials (wood, timber, bio-energy, etc.) from this area and a decline in specific functions and ecosystem services such as biodiversity. These conditions must be considered and must be part of a stringent comparison of agricultural systems. The slogan '*Growing less food per acre leaving less land for nature'* (Borlaug and Dowswell, 1994), must find its way into the conceptual framework for comparing land use, analysis of ecosystem services and computer modelling.

As more cropland is required for low-yielding agriculture, the question arises as to what type of land could be used as cropland to produce sufficient food. Furthermore, population growth and the need for improved human nutrition indicate that more food must be produced in the future. How can we cope with this demand through low-yielding agriculture? Is introduction of low-yielding agriculture a realistic option to meet future needs?

Combining expected population growth and projected land demand indicates that it seems unrealistic to introduce low-yielding agriculture as an option to produce sufficient food in the future. Population growth paired with introduction of low-yielding agriculture would roughly require at least a doubling of global arable land, from 1400 to 2500-3000 Mha. However, land suitable for agriculture is a limited resource and both the best and the second-best land is already in agricultural production. What remains is often only less suitable land, which is characterised by lower soil fertility, the presence of stones and gravel, or high risks for erosion or other rapid degradation when cropped. In most cases, only forests are at hand for conversion, as pointed out by Gregory et al. (2002). Thus, intensification on existing cropland seems to be the main path forward.

One major consequence of a great expansion in cropland would be further loss of natural habitats, as pointed out by e.g. Green et al. (2005), Hole et al. (2005) and Trewavas (2001). Advocates of organic agriculture are silent about how to cope with increasing demand for crops and pay little attention to the necessity for expanding cropland. The consequence of converting natural ecosystems into low-yielding production systems means loss of biodiversity, whereas comparisons of biodiversity in organic and conventional agricultural systems do not include the boundary conditions outlined in Fig. 7 (e.g. Mäder et al., 2002; Bengtsson et al., 2005; Gabriel et al., 2006).

6. CONCLUSIONS

The evaluation of organic yield data by advocates of organic agriculture is flawed in many ways, and different viewpoints are discussed in this chapter. The important points can be summarised as follows:

- Yields of organically grown crops in Europe are in most cases significantly lower than those of conventional crops.
- High organic yields, as reported in certain studies in the USA, are not relevant for comparisons with conventional yields, since they rely on the purchase of large amounts of animal manure.
- Average organic yields from rotations based on green manure are misleading unless years with crops not yielding exportable products are included in the calculations.
- Organic yields are limited by both nutrient shortages and high weed populations, and they are more difficult to increase through on-farm manures and exclusive use of untreated minerals than if the whole toolbox of modern production were allowed.
- Organic agriculture uses cropland less efficiently and requires more cropland to produce the same crop yields. There is good reason to believe that a large-scale conversion to organic agriculture would lead to severe food shortages.
- In order to secure a sufficient food supply in the future, emphasis should be placed on further development of modern but locally adapted forms of production without an ideological bias that *a priori* excludes potential solutions.

7. REFERENCES

Alexandratos, N., 1999, World food and agriculture: Outlook for the medium and longer term, *Proc. Natl., Acad. Sci. USA* 96: 5908-5914.

Aronsson, H., Torstensson, G., and Bergström, L., 2007, Leaching and crop uptake of N, P and K from organic and conventional cropping systems on a clay soil, *Soil Use Manage.* 23: 71-81.
Badgley, C. and Perfecto, I., 2007, Can organic agriculture feed the world? *Renew. Agric. Food Syst.* 22: 80-82.
Badgley, C., Moghtader, J., Quintero, E., Zakern, E., Chappell, J., Avilés-Vázquez, K., Samulon, A., and Perfecto, I., 2007, Organic agriculture and the global food supply, *Renew. Agric. Food Syst.* 22: 86-108.
Balfour, E.A., 1943, *The Living Soil*. Faber & Faber Ltd., London, UK, 276 p.
Barberi, P., Cozzani, A., Macchia, M., and Bonari, E., 1998, Size and composition of the weed seedbank under different management systems for continuous maize cropping. *Weed Res.* 38: 319-334.
Bekunda, M.A., Bationo, A., and Ssali, H., 1997, Soil fertility management in Africa: A review of selected research trials, in: *Replenishing Soil Fertility in Africa*, R.J. Buresh, P.A. Sanchez, and F. Calhourn, eds. SSSA Special Publications No. 51, Madison, WI, USA, pp. 63-79.
Bengtsson, J., Ahnström, J., and Weibull, A-C., 2005, The effect of organic agriculture on biodiversity and abundance: a meta-analysis, *J. Appl. Ecol.* 42: 261-269.
Bergström, L. and Kirchmann, H., 1999, Leaching of total nitrogen from nitrogen-15-labeled poultry manure and inorganic nitrogen fertilizer, *J. Environ. Qual.* 28: 1283-1290.
Bergström, L. and Kirchmann, H., 2004, Leaching and crop uptake of nitrogen from nitrogen-15-labeled green manures and ammonium nitrate, *J. Environ. Qual.* 33: 1786-1792.
Berry, P.M., Sylvester-Bradley, R., Philipps, L., Hatch, D.J., Cuttle, S.P., Rayns, F.W., and Gosling, P., 2002, Is the productivity of organic farms restricted by the supply of available nitrogen? *Soil Use Manage.* 18: 248-255.
Besson, J., Myre, K., and Niggli, U., 1999, DOK-Versuch: Vergleichende Langzeituntersuchungen in den drei Anbausystemen biologisch dynamisch, organisch-biologisch und konventionell. II. Ertrag der Kulturen: Kartoffeln, 1. und 2. Fruchtfolgeperiode, *Schweiz. Landw. Forsch.* 31: 127-155. (In German).
Blum, W.E.H., Buesing, J., and Montanella, L., 2004, Research needs in support of the European thematic strategy for soil protection, *Trends Anal. Chem.* 23: 680-685.
Borlaug, N.E., 1970, *The Green Revolution, Peace and Humanity* - Nobel Lecture, December 11, 1970, www.agbioworld.org/biotech-info/topics/borlaug/nobel-speech.html, Agbioworld, Tuskegee Institute, AL 36087-0085, USA. Assessed 24 November 2007.
Borlaug, N.E., and Dowswell, C.R., 1994, *Feeding a Human Population that Increasingly Crowds a Fragile Planet*, 15th World Congress of Soil Science, Keynote lecture, Supplement to Transactions, Acapulco, Mexico July 10-16, 1994.
Bouwman, A.F., van der Hoek, K.W., Eickhout, B., and Soenario, I., 2005, Exploring changes in world ruminant production systems, *Agric. Sys.* 84: 121-153.
Bradford, G.E., 1999, Contributions of animal agriculture to meeting global human food demand, *Livestock Prod. Sci.* 59: 95-112.
Bruinsma, J., 2003, *World Agriculture towards 2015/2030—An FAO Perspective*. Earthscan, London, UK, 432 p.
Burkitt, L.L., Small, D.R., McDonald, J.W., Wales, W.J., and Jenkin, M.L., 2007a, Comparing irrigated biodynamic and conventionally managed dairy farms. 1. Soil and pasture properties, *Aust. J. Exp. Agric*. 47: 479-488.
Burkitt, L.L., Wales, W.J., McDonald, J.W., Small, D.R., and Jenkin, M.L, 2007b, Comparing irrigated biodynamic and conventionally managed dairy farms. 2. Milk production and composition and animal health, *Aust. J. Exp. Agric.* 47: 489-494.

Campbell, B., Frost, P., Kirchmann, H., and Swift, M., 1998, A survey of soil fertility management in small-scale farming systems in North Eastern Zimbabwe, *J. Sustain. Agric.* 11: 19-39.
Cassman, K.G., Döbermann, A.D., and Walters, D.T., 2002, Agroecosystems, N-use efficiency and N management, *Ambio* 31: 132-140.
Cassman, K.G., Döbermann, A.D., Walters, D.T, and Yang, H, 2003, Meeting cereal demand while protecting natural resources and improving environmental quality. *Ann. Rev. Environ. Resour*. 28: 10.1-10.44.
Chen, F. and Wan, K., 2005, The impact of organic agriculture on food quantity, food quality and the environment: a Chinese perspective, *Soil Use Manage*. 21: 73-74.
Clark, M.S., Horwarth, W.R., Shennan, C., Scow, K.M., Lantni, W.T., and Ferris, H., 1999, Nitrogen, weeds, and water as yield-limiting factors in conventional, low-input and organic tomato systems, *Agric. Ecosys. Environ.* 73: 257-270.
Dahlin, S., Kirchmann, H., Kätterer, T., Gunnarsson, S., and Bergström, L., 2005, Possibilities for improving nitrogen use from organic materials in agricultural cropping systems, *Ambio* 34: 288-295.
Delate, K. and Cambardella, C.A., 2004, Agroecosystem performance during transition to certified organic grain production, *Agron. J.* 96: 1288-1298.
Denison, R.F, Bryant, D.C., and Kearney, T.E., 2004, Crop yields over the first nine years of LTRAS, a long-term comparison of field crop systems in a Mediterranean climate, *Field Crops Res.* 86: 267-277.
Drinkwater, L.E., Wagoner, P., and Sarrantonio, M., 1998, Legume based cropping systems have reduced carbon, nitrogen losses, *Nature* 396: 262-265.
Dyson, T., 1999, World food trends and prospects to 2025, *Proc. Natl., Acad. Sci. USA* 96: 5929-5936.
Eickhout, B., Bouwman, A.F., and van Zeijts, H., 2006, The role of nitrogen in world food production and environmental sustainability, *Agric. Ecosys. Environ*. 116: 4-14.
Eltun, R., Korsaeth, A., and Nordheim, O., 2002, A comparison of environmental, soil fertility, yield, and economical effects in six cropping systems based on an 8-year experiment in Norway, *Agric. Ecosys. Environ*. 90: 155-168.
Evans, L.T., 1998, *Feeding the Ten Billions – Plants and Population Growth*, Cambridge University Press, Cambridge, UK, 247 p.
Fagerberg, B., Salomon, E., and Jonsson, S., 1996, Comparisons between conventional and ecological farming systems at Öjebyn, *Swedish J. Agric. Res.* 26: 169-180.
FAO, 2007, Food and Agriculture Organization of the United Nations, Statistical Yearbook 2005/06, Rome, www.fao.org/statistics/yearbook/vol_1_1/site_en.asp?page=resources. Assessed 28 April 2007.
Finnish Food Safety Authority (EVIRA), 2006, Organic farming 2005 – Statistics, http://www.evira.fi/portal/se/vaxtproduktion_och_foder/ekoproduktion/aktuellt_inom_ekovervakningen/ Loimaa, Plant Production Inspection Centre, Finland. Assessed 20 December 2007.
Fowler, S,M, Watson, C.A., and Wilman, D., 1993, N, P and K on organic farms: herbage and cereal production, purchases and sales, *J. Agric. Sci.* 120: 353-360.
Gabriel, D., Roschewitz, I., Tscharntke, T., and Thies, C., 2006, Beta diversity at different spatial scales: plant communities in organic and conventional agriculture, *Ecol. Appl.* 16: 2011-2021.
GeoHive, 2007, Global Statistics, World Population Prospects, www.geohive.com/earth/pop_prospects2.aspx. Assessed 27 March 2007.
Gilland, B., 2002, World population and food supply. Can food production keep pace with population growth in the next half-century? *Food Policy* 27: 47-63.

Giller, K.E. and Cadish, G., 1995, Future benefits from biological nitrogen fixation: an ecological approach to agriculture, *Pl. Soil* 174: 255-277.

Giller, K.E., 1998, Tropical legumes: Providers and plunderers of nitrogen, in: *Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems,* L. Bergström and H. Kirchmann, eds., CAB International, Wallingford, UK, pp. 33-45.

Giller, K.E., 2001, *Nitrogen Fixation in Tropical Cropping Systems, 2nd edition,* CAB International, Wallingford, UK, 423 p.

Goulding, K., 2007, Nutrient management on farms, or 'You get out what you put in', *J. Sci. Food Agric.* 87: 177-180.

Granstedt, A., 1995, Studies of the flow, supply and losses of nitrogen and other plant nutrients in conventional and ecological agricultural systems in Sweden, *Biol. Agric. Hort.* 11: 51-67.

Gregory, P.J., Ingram, J.S.I., Andersson, R., Betts, R.A., Brovkin, V., Chase, T.N., Grace, P.R., Gray, A.J., Hamilton, N., Hardy, T.B., Howden, S.M., Jenkins, A., Meybeck, M., Olsson, M., Ortiz-Monasterio, I., Palm, C.A., Payn, T.W., Rummukainen, M., Schulze, R.E., Thiem, M., Valentin, C., and Wilkinson, M.J., 2002, Environmental consequences of alternative practices for intensifying crop production, *Agric. Ecosys. Environ.* 88: 279-290.

Green, R.E., S.J. Cornell, J.P.W. Scharleman, and Balemford A., 2005, Farming and the fate of wild nature, *Science* 307: 550-555.

Hadas, A., Kautsky, L., and Portnoy, R., 1996, Mineralization of composted manure and microbial dynamics in soil as affected by long-term nitrogen management, *Soil Biol. Biochem.* 28: 733-738.

Halberg, N., Kristensen, E.S., and Kristensen, I.S., 1995, Nitrogen turnover on organic and conventional mixed farms, *J. Agric. Environ. Ethics* 8: 30-51.

Halberg, N. and Kristensen, I.S., 1997, Expected crop yield loss when converting to organic dairy farming in Denmark, *Biol. Agric. Hort.* 14: 25-41.

Hole, D.G., Perkins, A.J., Wilson, J.O., Alexander, I.H., Grice, P.V., and Evans, A.D, 2005, Does organic farming benefit biodiversity? *Biol. Cons.* 122: 113-130.

International Federation of Organic Agricultural Movements, 2006, The four principles of organic farming, Bonn, Germany, www.IFOAM.org. Assessed 19 March 2007.

Ivarson, J. and Gunnarsson, A., 2001, Försök med konventionella och ekologiska odlingsformer 1987-1998, Meddelande från Södra Jordbruksförsöksdistriktet Nr 53, Swedish University of Agricultural Sciences, Uppsala, Sweden, 165 p. (In Swedish).

Jensen, E.S., 1987, Seasonal patterns of growth and nitrogen fixation in field-grown pea, *Pl. Soil* 101: 29-37.

Jensen, E.S., 1996, Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops, *Pl. Soil* 182: 25-38.

Kaffka, S. and Koepf, H., 1989, A case study on the nutrient regime in sustainable farming, *Biol. Agric. Hort.* 6: 89-106.

Kirchmann, H., 1985, Losses, plant uptake and utilisation of manure nitrogen during a production cycle, *Acta Agric. Scand.,* Supplementum 24, 77 p.

Kirchmann, H. and Lundvall, A., 1998, Treatment of solid animal manures: identification of low NH_3 emission practices, *Nutr. Cycl. Agroecosyst.* 51: 65-71.

Kirchmann, H., Nyamangara, J., and Cohen, Y., 2005, Recycling municipal wastes in the future: from organic to inorganic forms? *Soil Use Manage.* 21: 152-159.

Kirchmann, H., Persson, J., and Carlgren, K., 1994, The Ultuna long-term soil organic matter experiment, 1956-1991, Swedish University of Agricultural Sciences, Department of Soil Sciences, Report 17, Uppsala, Sweden, 55 p.

Kirchmann, H., Bergström, L., Kätterer, T., Mattsson, L., and Gesslein, S., 2007, Comparison of long-term organic and conventional crop-livestock systems in a previously nutrient- depleted soil in Sweden, *Agron. J.* 99: 960-972.
Kirchmann, H., Kätterer, T., and Bergström, L., 2008, Nutrient supply in organic agriculture – plant availability, sources and recycling, in: *Organic Crop Production – Ambitions and Limitations,* H. Kirchmann and L. Bergström, eds., Springer, Doordrecht, The Netherlands.
Kitchen. J.L., McDonald. G.K., Shepherd, K.W., Lorimer, M.F., and Graham, R.D., 2003, Comparing wheat grown in South Australian organic and conventional farming systems, I. Growth and grain yield, *Aust. J. Agric. Res.* 54: 889-901.
Koepf, H.H., Pettersson, B.D., and Schaumann, W., 1976, *Biologische Landwirtschaft*, Verlag Eugen Ulmer, Stuttgart, Germany, 303 p. (In German).
Korsaeth, A. and Eltun, R., 2000, Nitrogen mass balances in conventional, integrated and ecological cropping systems and the relationship between balance calculations and nitrogen runoff in an 8-year field experiment in Norway, *Agric. Ecosys. Environ*. 79: 199-214.
Laryea, K.B., Anders, M.M., and Pathak, P., 1995, Long-term experiments on Alfisols and Vertisols in the semiarid tropics, in: R. Lal and B.A. Stewart, eds., *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, CRC Press, Boca Raton, FL, pp. 267-292.
Latif, M.A., Islam, M.R., Ali, M.Y., and Saleque, M.A., 2005, Validation of the system of rice intensification (SRI) in Bangladesh, *Field Crops Res.* 93: 281-292.
Leu, A., 2004, Organic agriculture can feed the world, *Acres - a Voice for Eco-Agriculture* 34(1): 1-4.
Liebhardt, W.C., Andrews, R.W., Culik, M.N., Harwood, R.R., Janke, R.R., Radke, J.K., and Rieger-Schwartz, S.L., 1989, Crop production during conversion from conventional to low-input methods, *Agron. J.* 81: 150-159.
Lockeretz, W., Shearer, G., and Kohl, D.H., 1981, Organic farming in the corn belt, *Science* 211: 540-547.
Lockeretz, W., Shearer, G., Sweeney, S., Kuepper, G., Wanner, D., and Kohl, D.H., 1980, Maize yields and soil nutrient levels with and without pesticides and standard commercial fertilisers, *Agron. J.* 72: 65-72.
Marstorp, H. and Kirchmann, H., 1991, Carbon and nitrogen mineralization and crop uptake of nitrogen from six green manure legumes decomposing in soil, *Acta Agric. Scand.* 41: 243-252.
Mäder, P., Fliesbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U., 2002, Soil fertility and biodiversity in organic farming, *Science* 296: 1694-1697.
Mugwira, L.M. and Nyamangara, J., 1998, Organic carbon and plant nutrients in soil under maize in Chinamhora communal area, Zimbabwe, in: *Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems,* L. Bergström and H. Kirchmann, eds., CAB International, Wallingford, UK, pp. 15-21.
Murwira, H.K. and Kirchmann, H., 1993, Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under maize fertilisation, *Commun. Soil Sci. Plant Anal.* 24: 2343-2359
National Research Council, 1989, *Alternative Agriculture*, National Academy Press, Washington, DC, 448 p.
Nolte, C. and Werner, W., 1994, Investigations on the nutrient cycle and its components of a biodynamically-managed farm, *Biol. Agric. Hort.* 10: 235-254.
Nonhebel, S., 2005, Renewable energy and food supply: will there be enough land? *Renew. Sustain. Energy Rev.* 9: 191-201.

Nguyen, M.L., Haynes, R.J., and Goh, K.M., 1995, Nutrient budgets and status in three pairs of conventional and alternative mixed cropping farms in Canterbury, New Zealand, *Agric. Ecosys. Environ.* 52: 149-162.

Palm, C.A., Myers, R.J.K., and Nandwa, S.M., 1997, Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment, in: *Replenishing Soil Fertility in Africa*, R.J. Buresh, P.A. Sanchez, and F. Calhourn, eds., SSSA Special Publications No. 51, Madison, WI, pp. 193-217.

Palm, C.A., Gachengo, C.N., Delve, G., Cadish, G., and Giller, K.E., 2001, Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database, *Agric. Ecosys. Environ*. 83: 27-42.

Pang, X.P. and Letey, J., 2000, Organic farming: challenges of timing nitrogen availability to crop nitrogen requirements, *Soil Sci. Soc. Am. J.* 64: 247-253.

Parry, M., Rosenzweig, C., and Livermore, M., 2005, Climate change, global food supply and risk of hunger, *Philosophical Trans. Royal Soc. B: Biol. Sci.* 360: 2125-2138.

Peigné, J., Ball, B.C., Roger-Estrade, J., and David, C., 2007, Is conservation tillage suitable for organic farming? A review, *Soil Use Manage*. 23: 129-144.

Pieri, C., 1995, Long-term soil management experiments in semiarid Francophone Africa, in: R. Lal and B.A. Stewart, eds., *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, CRC Press, Boca Raton, FL, pp. 225-266.

Pimentel, D., Hepperley, P., Hanson, J., Douds, D., and Seidel, R., 2005, Environmental, energetic, and economic comparisons of organic and conventional farming systems, *BioSci.* 55: 673-582.

Porter, P.M., Huggins, D.R., Perillo, C.A., Quirling, S.R., and Crookston, R.K., 2003, Organic and other management strategies with two- and four-year crop rotations in Minnesota, *Agron. J.* 95: 233-244.

Posner, J.L., Baldock, J.O., and Hedtcke, J.L., 2008, Organic and conventional cropping systems in the Wisconsin integrated cropping systems trials: I. Productivity 1990-2002, *Agron. J.* 100: 265-260.

Poudel, D.D., Horwarth, W.R., Lanini, W.T., Temple, S.R., and van Bruggen, A.H.C., 2002, Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California, *Agric. Ecosys. Environ.* 90: 125-137.

Pretty, J.N. and Hine, R.E., 2001, Reducing food poverty with sustainable agriculture: a summary of new evidence, Centre for Environment and Society, Essex University, UK, www.essex.ac.uk/ces/esu/occasionalpapers/SAFE%20FINAL%20-%20Pages1-22.pdf. Assessed 29 December 2007.

Pretty, J.N., Morison, J.L.L., and Hine, R.E., 2003, Reducing food poverty by increasing agricultural sustainability in developing countries, *Agric. Ecosys. Environ.* 95: 217-234.

Prudencio, C.Y., 1993, Ring management of soils and crops in the West African semi-arid tropics: The case of the mossi farming systems in Burkina Faso, *Agric. Ecosys. Environ.* 47: 237-264.

Quinones, N.A., Borlaug, N.E., and Dowswell, C.R., 1997, A fertilizer-based green revolution for Africa, in: *Replenishing Soil Fertility in Africa*, R.J. Buresh, P.A. Sanchez and F. Calhourn, eds., SSSA Special Publications No. 51, Madison, WI, pp. 81-95.

Rundgren, G., 2002, *Organic Agriculture and Food Security*, IFOAM, Dossier 1, Bonn, Germany, 20 p.

Rusch, H.P., 1978, *Bodenfruchtbarkeit. Eine Studie biologischen Denkens*, 3rd Printing. Haug Verlag, Heidelberg, Germany, 243 p. (In German).

Ryan, M.H., Derrick, J.W., and Dann, P.R., 2004, Grain mineral concentrations and yield of wheat grown under organic and conventional management, *J. Sci. Food Agric.* 84: 207-216.
Sanchez, J.E., Harwood, R.R., Willson, T.C., Kizilkaya, K., Smeenk, J., Parker, E., Paul, E.A., Knezek, B.D., and Robertson, G.P., 2004, Managing soil carbon and nitrogen for productivity and environmental quality, *Agron. J.* 96: 769-775.
Sanchez, P.A., 2002, Soil fertility and hunger in Africa, *Science* 295: 2019-2020.
SCB, 2006, *Yearbook of Agricultural Statistics*, Official Statistics of Sweden, SCB, Örebro, Sweden.
Sheehy, J.E., Peng, S., Dobermann, A., Mitchell, P.L., Ferrer, A., Yang, J., Zou, Y., Zhong, X., and Huang, J., 2004, Fantastic yields in the system of rice intensification: Fact or fallacy? *Field Crops Res.* 88: 1-8.
Singh, L. and Balasubramanian, V., 1979, Effects of continuous fertilizer use on a ferruginous soil (Halustalf) in Nigera, *Exp. Agric.* 15: 257-265.
Sjursen, H., 2001, Change of weed seed bank during the first complete six-course rotation after conversion from conventional to organic farming, *Biol. Agric. Hortic.* 19: 71-90.
Smaling, E.M.A. and Braun, A.R., 1996, Soil fertility research in sub-Saharan Africa: New dimensions, new challenges, *Commun. Soil Sci. Plant Anal.* 27: 365-386.
Smaling, E.M.A., Nandwa, S.M., and Jansson, B., 1997, Soil fertility in Africa is at stake, in: *Replenishing Soil Fertility in Africa*, R. J. Buresh, P. A. Sachez and F. Calhourn, eds., SSSA Special Publications No. 51, Madison, WI, pp. 47-62.
Smil, V., 2001, Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production, MIT Press, Cambridge, MA, 338 p.
Smil, V., 2002, Nitrogen and food production: proteins for human diets, *Ambio* 31: 126-131.
Smith, R.G., and Gross, K.L., 2006, Weed community and corn yield variability in diverse management systems, *Weed Sci.* 54: 106-113.
Smith, R.G., Menalled, F.D., and Robertson, G.P., 2007, Temporal yield variability under conventional and alternative management systems, *Agron. J.* 99: 1629-1634.
Smolik, J.D., Dobbs, T.L., and Rickerl, D.H., 1995, The relative sustainability of alternative, conventional and reduced-till farming systems, *Am. J. Alter. Agric*. 10: 25-35.
Smolik, J.D., Dobbs, T.L., Rickerl, D.H., Wrage, L.J., Buchenau, G.W., and Machacek, T.A., 1993, Agronomic, economic, and ecological relationships in alternative (organic), conventional, and reduced-till farming systems, Bull. 718, South Dakota Agric. Exp. Stat., Brookings, USA.
Spiess, E., Stauffer, W., Niggli, U., and Besson, J.M., 1993, DOK-Versuch: Vergleichende Langzeit-Untersuchungen in den drei Anbausystemen biologisch-dynamisch, organisch-biologisch und konventionell. IV. Aufwand und Ertrag: Nährstoffbilanzen, 1. und 2. Fruchtfolgeperiode, *Schweiz. Landw. Forsch*. 32: 565-579. (In German).
Statistics Finland, 2007, Finland in Figures. Agriculture, Forestry and Fishery, Statistics Finland, Helsinki. http://www.stat.fi/tup/suoluk/suoluk_maatalous_en.html. Assessed 18 December 2007.
Steiner, R., 1924, Geisteswissenschaftliche Grundlagen zum Gedeihen der Landwirtschaft. Steiner Verlag, 5. Auflage 1975. Dornach, Schweiz, 256 p. (In German).
Svensson, K, Odlare, M., and Pell, M., 2004, The fertilizing effect of compost and biogas residues from source separated household waste, *J. Agric. Sci.* 142: 461-467.
Swift, M.J., Seward, P.D., Frost, P.G.H., Qureshi, J.N., and Muchena, F.N., 1994, Long-term experiments in Africa: Developing a database for sustainable land use under global change, in: R.A. Leigh and A.E. Jonston, eds., *Long-term Experiments in Agricultural and Ecological Sciences*, CAB Int. Wallingford, England, pp. 229-251.

Teasdale, J.R., Rosecrance, R.C., Coffman, C.B., Starr, J.L., Paltineanu, I.C., Lu, Y.C., and Watkins, B.K., 2000, Performance of reduced-tillage cropping systems for sustainable grain production in Maryland, *Am. J. Alternative Agric.* 15: 79-87.

Teasdale, J.R., Mangum, R.W., Radhakrishnan, J., and Cavigelli, M.A., 2004, Weed seedbank dynamics in three organic farming crop rotations, *Agron. J.* 96: 1429-1435.

Teasdale, J.R., Coffman, B., and Mangum, R.W., 2007, Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement, *Agron. J.* 99: 1297-1305.

Toomsan, B., McDonagh, J.F., Limpinuntana, V., and Giller, K.E., 1995, Nitrogen fixation by groundnut and soyabean and residual nitrogen benefits to rice farmers' fields in Northeast Thailand, *Pl. Soil* 175: 45-56.

Torstensson, G., Aronsson, H., and Bergström, L., 2006, Nutrient use efficiency and leaching of N, P and K of organic and conventional cropping systems in Sweden, *Agron. J.* 98: 603-615.

TSBF, CIAT, 2006, Integrated soil fertility management in the tropics, http://www.tsbf.org/pdf/tsbf_ciat_achievements_2002-2005.pdf, Nairobi, Kenya. Assessed 29 December 2007.

Trewavas, A., 2001, The population/biodiversity paradox. Agricultural efficiency to save wilderness, *Plant Physiol.* 125: 174-179.

Tudge, C., 2005, Can organic farming feed the world? http://www.colintudge.com, Oxford, England. Assessed 29 December 2007.

UN Millennium Project, 2005, *Halving Hunger: It Can Be Done*, P. Sanchez (ed.), Task Force on Hunger. Earthscan, UK, 245 p.

Warman, P.R. and Harvard, K.A., 1997, Yield vitamin and mineral contents of organically and conventionally grown carrots and cabbage, *Agric. Ecosys. Environ.* 61: 155-162.

Watson, C.A., Atkinson, D., Gosling. P., Jackson, L.R., and Rays, F.W., 2002, Managing soil fertility in organic farming systems, *Soil Use Manage. Suppl.* 18: 239-247.

Wieser, I., Heß, J., and Lindenthal, T., 1996, Nutrient balances on organically managed grassland farms in Upper Austria, *Die Bodenkultur* 47: 81-88.

Woodward, L., 1995, Can organic farming feed the world? www.population-growth-migration.info/essays/woodwardorganic.html, Elm Research Centre, England. Assessed 29 December 2007.

Vandermeer, J. and Perfecto, I., 2007, The agricultural matrix and a future paradigm for conservation, *Cons. Biol.* 21: 274-277.

Vanlauwe, B., Wendt, J., and Diels, J., 2001, Combined application of organic matter and fertilizer, in: *Sustaining Soil Fertility in West-Africa*, G. Tian, F. Ishida and J.D.H. Keatinge, eds., SSSA Special Publications No 58, Madison, WI, pp. 247-280.

Vanlauwe, B. and Giller, K.E., 2006, Popular myths around soil fertility management in sub-Saharan Africa, *Agric. Ecosys. Environ.* 116: 34-46.

Vasilikiotis, C., 2000, Can organic farming "Feed the World"? http://nature.berkeley.edu/~christos/espm118/articles/organic_feed_world.pdf, University of California Berkeley, CA. Assessed 29 December 2007.

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