ELSEVIER

Agriculture, Ecosystems and Environment 83 (2001) 11–26

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Review

Approaches to assess the environmental impact of organic farming with particular regard to Denmark

Birgitte Hansen*, Hugo Fjelsted Alrøe, Erik Steen Kristensen

Danish Research Centre for Organic Farming (DARCOF), Research Centre Foulum, PO Box 50, DK-8830 Tjele, Denmark

Received 6 January 2000; received in revised form 14 June 2000; accepted 25 July 2000

Abstract

Ever increasing attention is being paid to the environmental impact of intensive agricultural practices, and in this context organic farming is gaining recognition as a relatively friendly production system. In general, the risk of harmful environmental effects is lower with organic than with conventional farming methods, though not necessarily so. This review examines organic farming in the light of European conditions with special regard to recent research findings from Denmark. It specifies the environmental problems caused by modern farming practices and discusses appropriate indicators for assessing their impact. A driving force-state-response (DSR) framework is employed to organise and understand the processes and mechanisms that lie behind the impact of agriculture on nature and the environment. Important groups of environmental indicators are selected that characterise (a) the aquatic environment (nitrate and phosphorus leaching), (b) the soil (organic matter, biology and structure), (c) the ecosystem (arable land, semi-cultivated areas, small biotopes and landscape), and (d) resource usage and balances (nitrogen, phosphorus, potassium and energy use).

The paper also reviews several empirical studies. With regard to soil biology, organic farming is usually associated with a significantly higher level of biological activity (bacteria (*Monera*), fungi (*Mycota*), springtails (*Collembola*), mites (*Arachnida*), earthworms (*Lumbricus terrestris*)), due to its versatile crop rotations, reduced applications of nutrients, and the ban on pesticides. In most cases there is also a lower surplus of nutrients and less leaching with organic than with conventional farming. However, poor management (e.g., the ploughing of grass and legumes (*Fabates*) at the wrong time of year with no subsequent crops to capture the mineralised nitrogen), low self-sufficiency in feed, and problems with certain production systems (such as those involved in organic pig farming, i.e., grazing sows, low crop yields), can lead to a high level of leaching in some organic systems. Organic farming is faced with a need to expand and develop in line with increasing demands for organic food and growing environmental concerns. This requires closer attention to the goals, values and principles on which organic practices are based, and more research into the influence of organic farming on different aspects of the environment.

Keywords: Environmental indicator; Nitrogen leaching; Soil organic matter; Soil biology; Biodiversity; Energy use; Denmark; Organic farming

1. Introduction

Over the last few decades attention in Denmark and other industrialised countries has focused on reducing pollution by fertilisers and synthetic pesticides in

---

* Corresponding author. Tel.: +45-8999-1677;
fax: +45-8999-1200.
E-mail address: birgitte.hansen@agrsci.dk (B. Hansen).

PII: S0167-8809(00)00257-7

intensive agriculture. In particular, the leaching of nitrogen causes the extensive deoxidation of inland water reserves and a reduction in the quality of ground water. The loss of nitrogen in agriculture is also responsible for much of the environmental damage caused to many sensitive and natural terrestrial and marine ecosystems. Furthermore, the use of synthetic pesticides has (1) reduced the quality of ground water, (2) raised suspicions of adverse health effects, and (3) caused changes in the habitats of many species of flora and fauna.

Interest in organic farming has grown appreciably over the last few years. Between 1988 and 1999, the proportion of Danish agricultural land devoted to this type of farming is thought to have increased from 0.2 to 5%. In line with this, market analyses currently show a 25% increase in consumer demand for organic products in Denmark. Organic farming has also developed rapidly throughout the rest of western Europe in response to increasing customer demands and Government policy initiatives. In the period from 1993 to 1998, the area of land devoted to organic production more than trebled, from 0.9 to 2.9 million ha (EU-Conference Statement, 1999).

A fundamental principle in organic farming is to minimise environmental impacts as much as possible while sustaining an economically viable level of production. The key aspects of organic farming (Stolze et al., 2000) thus aim

- to increase or at least maintain soil fertility over the long term,
- to avoid the use of highly soluble mineral and synthetic nitrogenous fertilisers,
- to avoid the use of synthetic pesticides and feed additives,
- to maximise animal welfare, and
- to restrict stocking densities.

In view of the recent expansion in organic farming there is, however, a need to evaluate its environmental impact with particular regard to problems relating to the nitrogen and carbon cycles. To do this, different environmental indicators have to be identified and selected. These must focus on European conditions, and describe the state of the environment (nutrient leaching, soil organic matter, soil biology, soil structure, crop rotation, semi-cultivated areas, small biotopes, and the landscape) and the organic driving forces (nutrient input and output, energy use) responsible for observed changes in the environment. Organic farming can also provide solutions to other kinds of environmental problems, e.g., by promoting reductions in erosion and run-off, and decreasing the salinity of soil and water in such regions as Australia (Conacher and Conacher, 1998). This paper assimilates some of the extensive work undertaken by experts on the recently disbanded (March 1999) Danish Bichel Committee (DEPA, 1999). The committee undertook an inter-disciplinary analysis of the consequences of phasing out pesticides from Danish agriculture and a total transition to organic farming.

2. Indicators of environmental impact

Since the underlying principles of organic farming may not automatically reduce its impact on the environment relative to that produced by conventional farming, scientific investigations are needed to confirm this. Alternative types of indicators have, therefore, been adopted to measure the impact and resource use of different farming systems. A generally accepted model is the driving force-state-response (DSR) framework (Fig. 1), which was developed by the OECD (OECD, 1997; CSD, 1997; Stolze et al., 2000) to ensure consistency between environmental and agricultural policies, and promote a sustainable development in agriculture. Within this framework

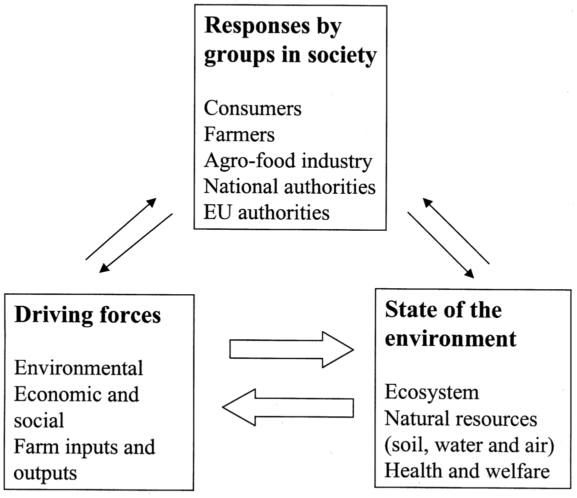

Fig. 1. The DSR framework for agri-environmental linkages and indicators (modified from OECD, 1997).

different agri-environmental linkages and indicators are identified and qualified.

The DSR framework incorporates the causes of environmental change (the so-called driving forces). These can be environmental (e.g., meteorology), economic and social, or relate to farm inputs and outputs (e.g., nutrient and energy use). The changes in (or state of) the environment can be identified in the ecosystem, the quality and quantity of natural resources (e.g., nitrate leaching), and health and welfare. A third aspect of the framework comprises the reaction of social groups, such as consumers, farmers, the agri-food industry and the authorities, to problematic driving forces and impacts on the environment. All three aspects are inter-related and influence each other.

In this review, the DSR framework is used to organise the various environmental indicators. Table 1 thus gives a comparison of all the different indicators employed by the Danish Bichel Committee (DEPA, 1999) as well as those used in a recently terminated EU FAIR project that aimed to describe the environmental impact and resource uses of organic farming within Europe (Stolze et al., 2000). The work of the Bichel Committee included inter-disciplinary analyses of the consequences for agricultural production, economics, the environment, the working environment, public health and energy consumption of a total transition to organic farming in Denmark. These analyses included a synthesis of background knowledge, and required the efforts of approximately 44 experts working from the spring of 1998 until the spring of 1999. They involved a lot of assumptions, scenario calculations, and specific expert knowledge relating to different environmental indicators.

Table 1
Indicators for the environmental impacts of organic farming used in: (1) a terminated EU FAIR project (Stolze et al., 2000), (2) the Danish Bichel Committee (DEPA, 1999), and (3) in this paper

	Category	Group of indicators	Stolze et al. (2000)	DEPA (1999)	This paper
State	Soil	Organic matter	+	+	+
		Biology	+	+	+
		Structure	+	+	+
	Aquatic environment	Nitrate leaching	+	+	+
		Phosphorous leaching		+	+
	Air	CO_2	+	+	+
		N_2O	+	+	+
		CH_4	+	+	+
		NH_3	+	+	
	Ecosystem	Crop rotation	+	+	+
		Semi-cultivated areas	+	+	+
		Small biotopes	+	+	+
		Landscape	+	+	+
	Human health	Food quality	+	+	
		Resistance to antibiotics	+	+	
Driving forces	Input, output and structure	Nutrient use and balance	+	+	+
		Energy use and balance	+	+	+
		Pesticide use		+	+
		Crop rotation		+	+
		Water use	+		
		Farm layout and management		+	
Response	Consumers			+	(+)
	Farmers			+	(+)
	Authorities			+	(+)

3. State of the environment

The indicators described in Table 1 will be used to evaluate the environmental changes brought about by organic farming. This will be done by first reviewing relevant empirical studies that compared the environmental impacts of organic and conventional farming systems.

3.1. Leaching losses to ground and surface water

Since the use of synthetic pesticides is banned in organic farming, such natural resources as ground and surface water are completely protected against these pollutants (in contrast to other systems).

Organic farming also aims to minimise nutrient losses for two main reasons. Firstly, nutrients constitute an important resource and contribute to the maintenance of production levels. Secondly, a major theme in organic practices is to operate in tight nutrient cycles to minimise losses to the air and water reserves.

3.1.1. Nitrogen

Of all the nutrients, nitrogen (N) presents the greatest problems with leaching. This is due to the mobility of nitrate in water and also the emission of NH_3, N_2O and N_2 from the soil to the air. Only a few published field investigations relate to the leaching of N in organic farming, and their findings are not directly comparable because of differences in methodology, soil type, climate, and the over-representation of dairy farms, etc. (Table 2). In general, the results show that nitrate leaching in organic farming is very low — from 8 to 34 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ — outside Denmark (Brandhuber and Hege, 1992; Eltun, 1995; Granstedt, 1992; Nolte and Werner, 1994; Philipps et al., 1995; Stopes and Philipps, 1992; Watson et al., 1993; van der Werff et al., 1995; Younie and Watson, 1992) and from 27 to 40 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ within Denmark (Askegaard and Eriksen, 1997; Kristensen et al., 1994; Magid and Kølster, 1995).

Some studies have directly compared conventional and organic farming. Scottish, German and Norwegian investigations thus demonstrated a higher nitrate leaching potential with conventional as opposed to organic farming (Younie and Watson, 1992; Brandhuber and Hege, 1992; Eltun, 1995), while one Danish analysis (Kristensen et al., 1994) showed no significant difference in this regard. Another Danish investigation employed a modelling approach to evaluate N leaching from conventional and organic farming systems (Hansen et al., 2000). It produced evidence of less leaching in an organic arable crop production system and an organic dairy farming system on sandy soil, when compared to parallel conventional farming systems (Table 3). However, on the basis of limited research findings, these authors were unable to decide whether N leaching was greater or less for organic crop production on a loamy soil and organic pig production on loamy and sandy soil, when compared with the same conventional systems (Hansen et al., 2000). Reduced leaching with organic farming (compared to conventional farming) is due to (1) lower stocking densities, (2) lower total inputs of N, and (3) the greater use of catch crops in autumn and winter in the organic system. Nevertheless, pollution of ground and surface water may occur through poor management of the organic farm, for example: (1) by ploughing grass and legumes at the wrong time with no subsequent crops to capture the mineralised N, or (2) by allowing grazing sows to destroy crop cover and root systems. Low self-sufficiency in feed and low crop yields can also lead to a high level of N leaching in some organic systems.

3.1.2. Phosphorus

Insufficient research data are available to provide quantitative estimates of phosphorus (P) losses due to leaching in organic farming. The Bichel Committee concluded that in Denmark, transition to 100% organic farming would result in a more even supply and smaller surpluses of this mineral (DEPA, 1999). Consequently, the accumulation of P in the soil and the risk of leaching will probably be minimised by following organic rather than conventional principles. Nevertheless, organic farming carries a high risk of P leaching in particular situations, for example: (1) with grazing sows (Olesen, 1999) and (2) in fields receiving or producing sources of organic matter (animal manure, green manure, catch crops, clover-grass, etc.) that raise the mobility of P in the soil (Johnston, 1998).

3.2. Soil quality and fertility

A principal objective of organic farming is to maintain the natural fertility of the soil. The fertility of soil

Table 2
Field investigations of nitrogen leaching in organic farming (from Hansen, 1998)

Reference	Location, farm system and soil type	Method	Organic N-leaching ($\mathrm{kg\,ha^{-1}\,yr^{-1}}$)	Conventional N-leaching ($\mathrm{kg\,ha^{-1}\,yr^{-1}}$)
Magid and Kølster (1995)	Denmark, Tåstrup, dairy farm, clay loam	The DAISY-model	40	
Kristensen et al. (1994)	Denmark, different farm and soil types	$\mathrm{N_{min}}$	31	29
Askegaard and Eriksen (1997)	Denmark, Foulum, dairy farm, loamy sand	Suction cells and the EVACROP water balance model	27–32	
van der Werff et al. (1995)	The Netherlands, dairy farm, sandy soil	Extraction of soil water	20	
Granstedt (1992)	Sweden, dairy farm, clay loam	$\mathrm{N_{min}}$	8	
Nolte and Werner (1994)	Germany, Rhine valley, pig- and dairy farm, loamy sand to sandy loam	Hess (1989)	25	38.2
Younie and Watson (1992)	Scotland, Aberdeen, dairy farm, sandy loam	$\mathrm{N_{min}}$	28.3	42–79 (mg/l)
Brandhuber and Hege (1992)	Germany, Bayer, dairy farm, loamy sand to sandy loam	$\mathrm{N_{min}}$	27 (mg/l)	
Watson et al. (1993)	England, dairy- and arable farm, clay loam to sandy loam	$\mathrm{N_{min}}$	<34	
Stopes and Philipps (1992)	England	Suction cells	20	
Philipps et al. (1995)	England, Gloucestershire, sheep farm, clay loam	Suction cells	12.3–20.3	21.7–33.8
Eltun (1995)	Norway, Apelsvoll, arable farm, loamy sand to clay loam	Drains pipes and collection of surface run-off	12.6–13.9	

Table 3
N balances and modelled N-leaching for conventional (Conv.) and organic (Org.) agricultural production systems (kg N ha^{-1} yr^{-1})

			LU (ha^{-1})[a]	Total N[b]	$N_{atmosphere}$[c]	N_{manure}	$N_{fertiliser}$	N_{yield}	N_{net}[d]	$N_{leaching}$[e]
Arable farm	Loam	Conv.		146	22	4	120	121	25	32
		Org.		116	69	47	0	56	60	19
	Sand	Conv.		212	31	96	85	105	107	90
		Org.		104	61	43	0	44	60	36
Pig farm	Loam	Conv.	1.4	212	25	102	86	115	97	46
		Org.	0.8 (1.4)	214	73	141	0	87	126	30
	Sand	Conv.	1.5	227	31	126	70	106	122	111
		Org.	0.6 (1.4)	211	67	144	0	68	143	61
Dairy farm	Loam	Conv.	1.4	241	25	130	87	150	91	48
		Org.	1.0	215	90	126	0	120	95	28
	Sand	Conv.	1.8	311	41	160	111	156	155	103
		Org.	1.0	216	91	124	0	117	99	65

[a] Livestock units per hectare.

[b] Nitrogen inputs (Total N) comprise: atmospheric depositions and N_2 fixation ($N_{atmosphere}$), animal manure (N_{manure}), and artificial fertiliser ($N_{fertiliser}$), while nitrogen outputs equal N in crops (N_{yield}).

[c] N_2-fixation plus atmospheric deposition (the latter set at 20 kg N ha^{-1} yr^{-1}).

[d] The surplus of nitrogen for the soil surface (N_{net}) equals inputs minus output.

[e] $N_{leaching}$ is the modelled (Simmelsgaard, 1998) leached nitrogen (Hansen et al., 2000).

may be defined as its ability to produce a satisfactory crop with minimal use of such resources as manures and fertilisers. Soil quality is closely related to soil fertility, and may be defined as the ability of the soil to function within the limits of the ecosystem by sustaining biological activity and promoting the immediate environment of plants and animals (Doran et al., 1994).

3.2.1. *Soil organic matter*

The supply of organic matter plays a central role in the maintenance of soil fertility. Changes in soil organic matter caused by new farming practices may manifest themselves for the first time many years later (>100 years). In the longer term, use of the same agricultural practice will produce a balance between decomposition and accumulation processes with the pool of organic matter remaining constant. It is, however, difficult to assess changes in organic matter concentrations using model simulations or direct measurements (Christensen and Johnston, 1997).

Long-term field experiments on sandy soils in Denmark have shown that over the last 100–150 years there has generally been a decline in their pools of soil organic matter and N (Christensen and Johnston, 1997). On the other hand, investigations on clayey soils in England show that it is possible to build up the pool of organic matter through the application of large amounts of animal manure (Christensen and Johnston, 1997). Regular tillage of sandy soils makes it difficult to build up organic matter levels, whereas the cool climates and heavy annual precipitation levels of Norway and Sweden are conducive to an increase in the total carbon content of the soil. It has been shown that between 1989 and 1995, organic dairy farming in Norway significantly increased the carbon content of soils that originally contained less than 1.7% of their weight as carbon (Løes and Øgaard, 1997).

It may be possible to build up organic matter levels in agricultural soils by cropping with perennial grass, or by applying large amounts of organic matter in the form of crop residues or animal manure (Johnston et al., 1994). Organic farming systems which involve the use of catch crops, the recycling of crop residues, the use of organic rather than artificial fertilisers, and the use of perennial crops are assumed to promote higher levels of organic matter in the soil, although appropriate research is needed to confirm this. From their comprehensive study of European literature, Stolze et al. (2000) concluded that organic farming performs better than conventional farming with regard to soil organic matter, the content of soil carbon decreasing less or increasing more than with the former system.

3.2.2. Soil biology

A major objective of organic farming is to encourage a high level of biological activity in the soil, in order to sustain its quality and thereby promote metabolic interactions between the soil and plants (Stolze et al., 2000). It is also important to sustain a wide diversity of soil organisms to secure the stability of this ecosystem. Soil contains a large number of different organisms, and amongst its micro-organisms there exist about one million different species of bacteria and about 1.5 million species of fungi (Hawksworth, 1991; Tiedje, 1994; Brussard, 1997). Different sensitive and key organisms (bacteria and fungi, springtails and mites, and earthworms) are therefore employed as environmental indicators to describe the biology of the soil.

Micro-organisms (bacteria and fungi) play a central role in maintaining the fertility of the soil, and are therefore crucial to organic farming. Within the soil, the decomposition of organic matter is primarily due to microbial activity, these organisms also contributing to the food chain of a great many of the soil fauna. Springtails and mites constitute the main species of the meso-fauna in the soil. They increase the rate of release of plant-available N from the soil organic matter by "grazing" the micro-flora (Hanlon and Anderson, 1979; Ineson et al., 1982; Seastedt, 1984; Setälä and Huhta, 1990), and they also play a central role as prey for predatory animals in spring time (Sunderland et al., 1986). Earthworms are a key species of the macro-fauna, and are very important for soil fertility. They are one of the first links in the decomposition of plant constituents.

The number of organisms in the soil is influenced by many factors, including soil type, type of fertiliser, crop rotation, cultivation, climate, time of the year, etc. It is therefore difficult to separate the effects of organic farming from other factors. In the case of moulds the evidence suggests greater numbers of these fungi in organic farming systems (Table 4). Furthermore, propagules of the genus *Penicillium* tends to occur in larger numbers at organic locations, although not in numbers that are significantly greater than for conventional arable farming. Yeast (*Ascomycetes*) numbers are significantly higher in organic and conventional dairy farm systems than in conventional arable systems (Axelsen and Elmholt, 1998).

Krogh (1994) found that the occurrence of micro-arthropods (springtails and mites) was higher with organic than with integrated and conventional farming systems (Table 5). A similar observation was made in a Welsh investigation, in which largest numbers of mites were found in organically managed soil (Yeates et al., 1997). The supply of organic manure clearly influences the number of earthworms in the soil. For example, between 1986 and 1997 the population of earthworms increased by a factor of 20 as a consequence of converting a location at the Research Centre Foulum, Denmark from conventional arable production to organic farming (Christensen and Mather, 1997). In general terms it is estimated that the density of earthworms will increase by a factor of more than 2.88 after making this transition (Table 6), depending on the type of fertiliser used (Axelsen and Elmholt, 1998).

In an extension of the work done by the Danish Bichel Committee, Axelsen and Elmholt (1998) estimated that a transition to 100% organic farming in Denmark would increase the microbial biomass by

Table 4
Statistical estimates (mixed model) of the occurrence of moulds (total occurrence), the genus *Penicillium*, and yeasts (total occurrence) at 24 organic, 20 conventional (with manure) and 21 conventional (with artificial fertiliser) locations (modified from Axelsen and Elmholt, (1998))[a]

	Mould fungi		*Penicillium*		Yeast fungi	
Organic	85570 a	*3600*	39650 a	*2700*	28090 a	*2000*
Conventional (animal manure)	56930 b	*5300*	25160 b	*3700*	28800 a	*3200*
Conventional (artificial fertiliser)	60370 b	*5300*	37960 a	*4000*	15070 b	*2700*

[a] Total spore counts per gram of soil. Standard deviations in italics. Means in the same column with different letters are significantly different ($p < 0.05$).

Table 5
The mean occurrence of micro-arthropods (springtails and mites) with four different production systems at the Research Centre Foulum, Denmark where data refer to total numbers per square meter (from Krogh, 1994)

	Organic	Integr. feed production	Integr. arable crop production	Conv. arable crop production
Springtails	16900	8100	13000	6800
Mites	15700	14000	14200	9700
Micro-arthropods	32600	22100	28200	16500

77%, raise the concentration of springtails by 37%, and augment the density of earthworms by 154% as a national average. Conversion to organic farming therefore provides opportunities for significantly increasing the biological activity of the soil.

3.2.3. *Soil structure*

A well-structured soil is an important asset for sustaining high crop yields and controlling erosion, and is crucial to organic farming. The high level of biological activity in organically managed systems encourages good soil structure, and vice versa. Soil structure is improved by the incorporation of organic matter, the gums and mucilages formed during its breakdown by bacteria helping to bind the peds together (Bridges, 1978). Earthworms also influence soil structure profoundly through the process of bioturbation.

The structure of soil can be weakened by the passage of vehicles with high axle loads across fields, this resulting in compaction and damage to both surface soil and deeper horizons (>40 cm). The result is a permanent reduction in crop yields (Håkansson and Reeder, 1994). Even low-pressure compaction by vehicles has been shown to have a big effect on the biology of the soil and crop yields in organically farmed fields (Bakken et al., 1987; Jensen et al., 1996; Hansen, 1996).

3.3. *Diversity of the ecosystem*

Agricultural practices dominate the landscape in many parts of Europe, thereby influencing wildlife conservation as well. It is generally recognised that through its use of simplified crop rotations and the extensive use of synthetic fertilisers and pesticides, conventional farming is responsible for many of the adverse changes in the habitats of many floral and faunal species Stolze et al. (2000).

Table 6
This density index for earthworms shows the percentage difference in earthworm numbers in alternative production systems measured relative to those obtained in conventional arable production (from Axelsen and Elmholt, 1998)

Production type	Density index
Conventional dairy farming	288
Conventional pig farming	125
Conventional arable farming	100
Organic farming	>288

The naturally occurring flora and fauna is affected by a transition to organic farming. Consequently, wildlife changes will be considered in the context of crop rotations, semi-cultivated areas, and small biotopes. The semi-cultivated areas consist of extensively used agricultural land, such as meadows, grasslands, heathlands, fringes. Small biotopes comprise uncultivated areas close to fields, such as windbreaks, grass- and stone dikes, ditches, riverside banks, roadsides, marl pits, boundaries of woods, etc.

3.3.1. *Arable land*

In organically farmed fields the density and species diversity of the weed flora is larger than with conventional management. At both English and Danish locations, about five times as much weed biomass, 2.4–5.3 times greater weed density, significantly greater species diversity (Hald and Reddersen, 1990) and about 1.8 times greater weed cover (Moreby et al., 1994) have been observed in organically cultivated fields of cereals (Reddersen, 1999). These effects on the weed flora are primarily due to the ban on herbicides in organic farming (Reddersen, 1999).

It is established that, compared to conventional farming, organic practices result in a lower density of aphids (*Homoptera*) (Moreby et al., 1994; Reddersen, 1997). This may reflect slower crop growth and a smaller supply of N with this system. On the other hand, several investigations have shown higher densities of beneficial insects (e.g., ground beetles (*Carabidae*) and spiders (*Araneae*)) in association with the organic approach (Reddersen, 1999).

Only a few species of birds, such as the skylark (*Alauda arvensis*) and lapwing (*Vanellus vanellus*), are restricted to agricultural land, and several studies have shown that these have suffered a decline in numbers in recent years (e.g., Wilson et al., 1997). The numbers and diversity of birds in a farming area are very dependant on the total distribution of small biotopes (Reddersen, 1999). One Danish investigation found markedly more birds and greater bird diversity with organic, than with conventional farming (Braae et al., 1988; Christensen et al., 1996). Similarly, in association with organic farming, an English study (Chamberlain et al., 1995) observed larger numbers of birds at edge-biotopes during the summer and in the fields during winter. The use of insecticides reduces the supply of insect food for skylarks, and this may explain why this bird is favoured by organic practices (Christensen et al., 1996; Fuller, 1997). However, mechanical weed control is frequently used in organic farming, and tillage has been shown to cause high mortality amongst the eggs and young of skylarks (Odderskær, personal communication; Reddersen, 1999).

The influence of agricultural practices on the lives of mammals has only been comprehensively investigated for hares (*Lepus timidus*) and roe deer (*Capreolus capreolus*) (Reddersen, 1999). The recording of hare numbers at Danish organic and conventional farm sites showed no significant difference in population density (Braae et al., 1988).

3.3.2. Semi-cultivated land

The semi-cultivated areas constitute sensitive ecosystems which contain a high proportion of plant and animal species that are on the red list. Fertiliser applications, herbicide usage, and intensive grazing threaten the wildlife flora in these areas through eutrophication, species exodus, etc. It is assumed that because of the herbicide and insecticide bans, organic practices will protect semi-cultivated areas more effectively than does conventional farming. There is, however, a lack of comparative studies to prove this, although on permanent grassland Younie and Baars (1997) observed higher bio-diversity in favour of organic farming.

3.3.3. Small biotopes

Small biotopes are greatly influenced by neighbouring agricultural practices, because of their proximity to arable land and a high boundary: area relationship. For example, airborne gases and particles from pesticide and fertiliser applications are readily deposited in small biotopes. Few investigations have been conducted on the vegetation in small biotopes adjacent to organic and conventional farms. However, the negative influences of conventional farming are expected to cease with a transition to organic practices, although previous damage may be irreversible (Reddersen, 1999). Stopes et al. (1995) reported that 11 years of organic farming resulted in a 10% increase in species diversity amongst the ground vegetation of fences when the latter were systematically managed. A Danish investigation showed that the edge biotopes on eight organic farms of 6–40 years standing did not have a large and varied herbal vegetation (Gramstrup, 1998; Jens Reddersen, personal communication).

Compared to conventional holdings, larger numbers of butterflies have been found in the edge biotopes of organic farms (Feber et al., 1997), although the numbers of harmful butterflies, such as the cabbage white (*Piesris* spp.) were not effected.

3.3.4. The landscape

Organic farming promotes more versatile crop rotations and more grazing animals in the countryside. It thus alters the aesthetics of the whole landscape. Braae et al. (1988) found 2–3 times more individual birds on organic than on conventional farms. This is probably not due to the ban on artificial fertilisers or pesticides in organic practices but rather to the structural diversity of the landscape (Reddersen, 1999). Stolze et al. (2000) concluded that organic farming provides the potential for positive impacts on the landscape, for instance, by offering the opportunity for re-qualifying rural sites. Landscape quality is an area of research that deserves greater attention in the future, to assist in the evaluation of environmental impact by different farming practices.

4. Driving forces

The state of the environment is influenced by several driving forces that are related to agricultural practice.

In organic farming there is a fundamental desire to use natural resources efficiently, thereby maintaining tight nutrient cycles. In this context the present review will focus on N, P and potassium (K), since these nutrients are often growth-limiting in practical agriculture. With regard to energy usage, fossil energy and the emission of greenhouse gases (CO_2, CH_4, and N_2O) will also be considered.

4.1. Nutrients and self-sufficiency

One way to assess nutrient utilisation and the environmental impact is to calculate input/output balances for each element at (1) the soil surface, (2) the farm gate and (3) the national level.

4.1.1. Nitrogen

Soil surface balances for actual conventional farms and model organic farms have shown that the surplus of nitrogen (N) is sometimes lower (dairy and arable farms on sandy soils), and sometimes higher (arable farms on loamy soils, and pig farms on sandy and loamy soils) with organic farming (Hansen et al., 2000).

Large imports of feed (low self-sufficiency) and manure to the organic farm enhance the environmental impact, due, e.g., to the potential risk of leaching losses (Table 7). In studies by Simmelsgaard (1998), different organic models were set up, and soil surface balances and leaching losses of N were calculated according to an empirical formula. A 70% self-sufficiency in feed produced a N surplus of 161 kg ha^{-1} yr^{-1} (88 kg N-leaching ha^{-1} yr^{-1}), while 100% self-sufficiency gave a surplus of only 97 kg N ha^{-1} yr^{-1} (61 kg N-leaching ha^{-1} yr^{-1}). Importation of manure to the farm (Table 7, model 2) up to the maximum allowed, raised the surplus from 99 to 135 kg N ha^{-1} yr^{-1} and nitrogen leaching from 65 to 72 kg ha^{-1} yr^{-1}.

Halberg et al. (1995) investigated 16 conventional and 14 private organic farms in Denmark with mixed animal (dairy) and crop production systems. They found significant differences in N surplus at the farm gate level, on an average 242 kg N ha^{-1} yr^{-1} with the conventional compared to 142 kg N ha^{-1} yr^{-1} at the organic farms. The surplus of N correlated with the stocking rate. Another investigation showed that organic pig production had a higher N surplus per kilogram meat and a lower N efficiency than did conventional pig production (Dalgaard et al., 1998). However, the study also showed the reverse for organic dairy farming.

The Bichel Committee calculated N balances for the whole of the Danish agricultural sector, assuming a transition to 100% organic farming (DEPA, 1999). They found an appreciably lower surplus of N with different 100% organic farming models (146–245 million kg N yr^{-1}) compared to that of current Danish farming methods (418 million kg N yr^{-1}).

4.1.2. Phosphorus

The surplus of phosphorus (P) per hectare rises with increase in stocking rate (5.4 kg P for each livestock unit), and the farm gate level has been observed to be significantly higher with conventional compared to organic dairy farms (Halberg, 1999). Simmelsgaard et al. (1998) calculated the soil surface balance of P for different model organic farms. For model dairy farms this surplus varied between 2 and 15 kg P ha^{-1} yr^{-1} according to the degree of self-sufficiency with feed. Depending on the amount of manure brought onto the farm, the surplus for arable crops varied from −16 to

Table 7
Soil surface balance and modelled N leaching for different model organic farms with different degrees of self-sufficiency in feed and manure (Hansen and Kristensen, 1998)

	LU (ha^{-1})[a]	N input (kg ha^{-1} yr^{-1})	N output (kg ha^{-1} yr^{-1})	N surplus (kg ha^{-1} yr^{-1})	Modelled N-leaching (kg ha^{-1} yr^{-1})
Model 1 (70% self-sufficiency)	1.39	300	139	161	88
Model 2a (85% self-sufficiency)	1.00	216	117	99	65
Model 2b (85% self-sufficiency + import of manure)	1.05	256	120	135	72
Model 3 (100% self-sufficiency)	1.00	234	137	97	61

[a] Livestock units.

8 kg P ha^{-1} yr^{-1}. In the case of pig farms, the surplus ranged between 3 and 25 kg P ha^{-1} yr^{-1} according to stocking rate and the imports of feed and manure. Current organic practices in Denmark thus show an ability to both exhaust and accumulate P in the soil (Olesen, 1999), particularly in the case of grazing sows.

The Bichel Committee's assessment for the 100% organic farming scenario in Denmark (DEPA, 1999) also included a calculation of P balances for the whole agricultural sector. With different models, a lower surplus was calculated (−4 to 23 million kg P yr^{-1}) than are found with current farming practices (40 million kg P yr^{-1}).

4.1.3. Potassium

In organic farming potassium (K) is supplied in manure and plant residues. Simmelsgaard et al. (1998) calculated K balances at the soil surface for different models of organic farming. They found that arable, pig and dairy farming can all exhaust or accumulate K in the soil. Organic farming on sandy soils cannot maintain the supply of K to the crop, if this element is not imported in feed, manure or sanctioned fertilisers. Because of the weathering of K-rich minerals, a negative surplus of K on loamy soils is generally not a problem.

The Bichel Committee also included calculations for K balances for the whole of the Danish agricultural sector, assuming a transition to 100% organic farming in Denmark (DEPA, 1999). Using different models they found lower surpluses of K (−10 to 20 million kg K yr^{-1}) compared to those associated with current conventional farming practices (94 million kg K yr^{-1}).

4.2. Fossil energy and the production of greenhouse gases

The use of energy influences natural fossil resources and may also affect the climate. The agricultural consumption of fossil energy has both direct and indirect aspects (i.e., related to the production of fertilisers and pesticides, etc.). A study of energy use and efficiency on livestock farms showed a lower total (direct and indirect) usage of energy per hectare in organic than in conventional feed production (Refsgaard et al., 1998). The differences were 29–35% for small grains, 51–72% for grass-clover (*Trifolium* L. + *Lolium* L.)/Lucerne (*Medicago sativa* L.) and whole-crop silage, and 22–26% for fodder beet (*Beta vulgaris* var. *crassa Mansf*.). These differences mainly reflected the indirect energy supplied in fertilisers on conventional farms (Table 8). Even though the yields per hectare were lower on the organic farms, this did not counterbalance the difference in energy usage. The organic farms used less energy per unit of fodder produced, and the overall energy use per unit of milk sold was 19–35% less. However, the feeding of grass pellets in organic dairy farming raises the energy requirements per unit of milk to a level close to that of conventional dairy farming systems.

In their extension of work done for the Bichel Committee, Dalgaard et al. (2000) estimated that a transition to 100% organic farming would result in a 9–51% reduction in the net consumption of fossil energy, depending on the amount of feed brought in and the level of animal production. The decrease in (i) agricultural energy consumption, (ii) N turnover, and (iii) animal production in a 100% organic Denmark would produce a corresponding decrease (13–38%) in the national emission of greenhouse gases (CO_2, CH_4, and N_2O).

Stolze et al. (2000) concluded that the most important factors for securing the better use of energy in organic farming (compared to conventional farming systems) are (a) no input of mineral N-fertilisers (which require a lot of energy for their production and transportation), (b) the lower use of energy-demanding

Table 8
Total energy inputs (MJ) for different crops with organic (Org.) and conventional (Conv.) farming systems (modified from Refsgaard et al., 1998)

	Not irrigated sand		Irrigated sand		Clay	
	Conv.	Org.	Conv.	Org.	Conv.	Org.
Spring-sown grain and winter-sown grain	10054	6529	12097	8543	9983	6572
Fodder beet	17080	12619	20478	15904	16821	12619
Clover-grass/Lucerne and whole crop silage	13667	3832	20260	9865	13846	4137

feed products (concentrates), (c) lower inputs of mineral fertilisers (P and K), and (d) the ban on pesticides.

5. Discussion

5.1. Selection of indicators

Assessment of the environmental impacts of organic farming requires the selection of indicators that appropriately describe the state of the environment and the forces which bring about its observed changes. Individual environmental indicators are studied according to typical empirical methods which have a high degree of objectivity. The selection of appropriate indicators is thus value-weighted (Bossel, 1999) in accordance with the inevitable and necessary choices associated with this inter-disciplinary analysis.

5.2. The most positive environmental effects of organic farming

In Table 9, a weighted assessment of the overall effect of organic farming on the environment is achieved by synthesising existing knowledge for the environmental indicators described. The values used in the assessment are based on the results of comprehensive analyses conducted in the different research areas covered by the Danish Bichel Committee. It is evident that, compared to conventional farming, the largest beneficial effect of organic farming is associated with the lack of pesticides leaching and soil biology (bacteria, fungi, springtails, mites, earthworms), the higher level of biological activity being driven by the use of versatile crop rotations and the reduced use of nutrients in the organic system. At the ecosystem level, organic farming also benefits arable land by promoting (a) greater densities and species diversity in the weed flora, (b) lower concentrations of aphids, (c) greater numbers of beneficial insects (ground beetles and spiders), and (d) bigger populations of birds (skylark and lapwing). These positive effects are driven by the associated ban on pesticides and the versatile crop rotation. The use of fossil energy and the production of greenhouse gases is also markedly lower in organic than in conventional agriculture, mainly because of the lower use of indirect energy related to the ban on synthetic nitrogen fertilisers.

5.3. Positive and neutral environmental effects of organic farming

The content of organic matter in soils can be assumed to be greater with organic farming because

Table 9
A weighted assessment of the overall effect of organic farming on the environment relative to conventional farming achieved by synthesising the existing knowledge described[a]

	Category	Group of indicators	Effect	Major driving force
State of the environment	Aquatic environment	Pesticides leaching	++	Ban of pesticides
		Nitrate leaching	+/0	Crop rotation, nutrient use
		Phosphorous leaching	+/0	
	Soil	Organic matter	+/0	
		Biology	++	
		Structure	+/0	
	Ecosystem	Arable land	++/+	Crop rotation, ban of pesticides
		Semi-cultivated areas	+/0	Ban of pesticides, nutrient use
		Small biotopes	+/0	
		Landscape	+/0	Crop rotation, farm layout
Driving forces	Resource use and balance	Nitrogen	+/0/−	
		Phosphorus	+/0	
		Potassium	+/0	
		Energy use	++/+	

[a] (++) much better; (+) better; (0) the same; (−) worse.

of the production of catch crops, the recycling of crop residues, the use of organic rather than artificial fertilisers, and the growing of perennial crops. This has been demonstrated in field trials in England (Christensen and Johnston, 1997), Norway, Sweden (Løes and Øgaard, 1997) and Australia (Conacher and Conacher, 1998). For sandy Danish soil conditions, however, more research is required to test this hypothesis (Hansen et al., 2000). Soil structure is assumed to be positively affected by organic farming as a consequence of the high level of biological activity in these systems. However, organically managed fields are also sensitive to structural damage, even that caused by low pressure compaction by vehicles.

With regard to nutrients (leaching, resource use and balance), compared to conventional systems, organic farming usually produces lower nutrient surpluses (with less leaching) at the soil surface, at the farm gate and at the national level. This reflects the type of crop rotation (i.e., the use of catch crops in association with soils of high leaching potential) and the lower input of nutrients with organic systems. Nevertheless, poor management practices (e.g., the ploughing of grass and legume fields at the wrong time of year), low self-sufficiency in feed, and problems with certain organic production systems (such as grazing pigs, low crop yields) can result in similar or even higher leaching losses from organic than from conventional farming practices.

Regarding the ecosystem, semi-natural areas and small biotopes are assumed to be better protected by organic practices because of the associated ban on pesticides and the reduced use of nutrients. However, changes already incurred may be irreversible. Landscape is expected to be improved by organic farming, with greater structural diversity reflecting versatile crop rotations and larger numbers of grazing animals.

5.4. Using the DSR framework to pursuit the basic principles of organic farming

It has been shown that the basic principles of organic farming do not automatically ensure that this form of agriculture is always less harmful to the environment than conventional practices. According to Stolze et al. (2000), the key points of organic farming relate either to the state of the environment (increasing/maintaining soil fertility, ensuring maximum animal welfare) or to the forces responsible for causing environmental changes (exclusion of artificial fertilisers, synthetic pesticides and feed additives, restrictions on nutrient use/stocking densities). It is relatively easy for organic farming to live up to the latter principles because they can be measured and are controlled by regulations and legislation. There is a direct link between the responses by groups in society (National and EU authorities) and the driving forces (exclusion of artificial fertilisers, etc.). On the other hand, it is more difficult to assess principles that relate to the state of the environment, since there is a lack of scientific information on how to achieve these goals. There is no direct connection between human activities and some states of the environment (increasing/maintaining soil fertility, etc.). How, e.g., does one measure and secure high fertility in the soil?

Previously, the intention of organic farming was to introduce goals relating to the driving forces and local environmental conditions (e.g., soil and animal conditions, and farm inputs and outputs). However, society now demands the achievement of certain goals for the regional and global environment in the name of sustainable agriculture. This is reflected in the latest principles and ideas of International Federation of Organic Agriculture Movements (IFOAM, 1998), which have been broadened into comprehensive statements of objectives, e.g., “to interact in a constructive and life-enhancing way with natural systems and cycles” and “to minimise all forms of pollution”. This development in IFOAM’s principles of organic farming makes it even harder to connect responses by groups in society and the state of the environment caused by organic farming.

The future goals for organic farming are, therefore, to continue the pursuit of organic principles, test hypotheses, redefine principles where necessary, and improve the state of the environment. In this way organic farming will continue to be distinguished from conventional systems by its positive effects on nature and the environment.

6. Conclusions

Over the last few decades, consumer pressures and Governments policy initiatives have stimulated a rapid growth in organic farming throughout western Europe according to the mechanisms depicted in Fig. 1. Organic farming is now being challenged by the need for further expansion and development to meet the increase in demand for organic food and growing concerns for the environment. To satisfy the consumer, therefore, the relationships between production and environmental concern must be balanced. The aims of organic farming are not just to minimise environmental impact and optimise production, but to combine these two concerns.

In general, the risk of harmful environmental effects is lower with organic than with conventional farming practices. These findings are in agreement with the conclusions of the European investigation by Stolze et al. (2000) and the British case study by Cobb et al. (1999).

It has been shown that the DSR framework is a very usable tool in organising and analysing the processes and mechanisms that lie behind the impact of organic farming on nature and the environment. The basic principles of organic farming make it distinguishable from conventional farming. IFOAM's (1998) latest redefinition of the basic principles of organic farming has resulted in very broad and comprehensive statements of objectives relating to the regional and global level. This development constitutes a risk for making the connection very unclear between the desired state of the environment and the responses by groups in society. In this way there is a risk for loosing control of the impact of organic farming. It is therefore advisable to formulate principles in organic farming as local as possible in order to be able to live up to the principles and control the impact of the organic farming on nature and environment.

Acknowledgements

We thank Dr. V.C. Mason for improving the English, and Susanne Elmholt and Jørgen AA. Axelsen for correcting the manuscript.

References

Askegaard, M., Eriksen, J., 1997. 3. Udbytter og kvælstofudvaskning i relation til gødningsniveau og type. SP Report No. 15. Danish Institute of Agricultural Science, pp. 37–46 (in Danish).

Axelsen, J.A., Elmholt, S., 1998. Jordbundens biologi. The Bichel committee, Report from the interdisciplinary working group on organic farming, Sub-report A3.4. (In danish). Available on request from the Danish Environmental Protection Agency.

Axelsen, J.A.A., Elmholt, S., 1998. Scenarium om 100% økologisk jordbrug i Danmark, A3.4. Jordbundens biologi. Rapport for Bichel-Udvalget (in Danish).

Bakken, L.R., Børresen, T., Njøs, A., 1987. Effect of soil compaction by tractor traffic on soil structure, denitrification, and yield of wheat (*Triticum aestivum* L.). J. Soil Sci. 38, 541–552.

Bossel, H., 1999. Indicators for sustainable development: theory, method, applications. A Report for the Balaton Group. International Institute for Sustainable Development, 124 pp.

Braae, L., Nøhr, H., Petersen, B.S., 1988. Fuglefaunaen på konventionelle of økologiske landbrug. Miljøprojekt 102. Danish Environmental Projection Agency, Copenhagen, 116 pp.

Brandhuber, R., Hege, U., 1992. Teifeundersuchungen auf nitrat unter ackerschlägen des ökologischen landbaus. Aus des bayerischen landesanstalt für bodenkultur und planzenbau, Freising-München. Landwirtschaftliches Jahrbuch 69 (1), 111–119.

Bridges, E.M., 1978. World Soils, 2nd Edition. Cambridge University Press, Cambridge, 128 pp.

Brussard, L., 1997. Biodiversity and ecosystem functioning in soil. Ambio 26, 563–570.

Chamberlain, D., Evans, J., Fuller, R., Langston, R., 1995. Where there's muck, there's birds. The BTO's organic farm project. BTO News 200, 15–17.

Christensen, B.T., Johnston, A.E., 1997. Soil organic matter and soil quality-lessons learned from long-term field experiments at Askov and Rothamsted. In: Gregorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Production. Soil Quality for Crop Production and Ecosystem Health. Developments in Soil Science, Vol. 25. Elsevier, Amsterdam, pp. 399–430.

Christensen, O.M., Mather, J.G., 1997. Regnorme som øko-ingeniører i jordbruget: fra konventionelt til økologisk jordbrug. In: Kristensen, E.S. (Ed.), Økologisk Planteproduktion. SP Rapport No. 15. Forskningscenter for Økologisk Jordbrug.

Christensen, K.D., Jacobsen, E.M., Nøhr, H., 1996. A comparative study of bird faunas in conventionally and organically farmed areas. Dansk Ornithologisk Forenings Tidsskrift 90, 21–28.

Cobb, D., Feber, R., Hopkins, A., Stockdale, L., O'Riordan, T., Clements, B., Firbank, L., Goulding, K., Jarvis, S., Macdonald, D., 1999. Integrating the environmental and economic consequences of converting to organic agriculture: evidence from a case study. Land Use Policy 16, 207–221.

Conacher, J., Conacher, A., 1998. Organic farming and the environment, with particular reference to Australia: a review. Biol. Agric. Hort. 16, 145–171.

CSD, 1997. Programme of work on indicators for sustainable development of the commission on sustainable development. http://www.un.org/esa/sustdev/program.htm.

Dalgaard, T., Halberg, N., Kristensen, I.S., 1998. Can organic farming help reduce N-losses? Experiences from Denmark. Nutr. Cyc. Agroecosyst. 52, 277–287.

Dalgaard, T., Halberg, N., Fenger, J., 2000. Simulering af fossilt energiforbrug og emmision af drivhusgasser (Fossil energy use and emission of greenhouse gasses in three scenarios for conversion to 100% organic farming in Denmark). FØJO Rapport 5 (in Danish).

DEPA, 1999. Økologiske scenarier for Danmark. Danish Environmental Protection Agency. http://www.mst.dk/199903publikat/87-7909-292-6/oekologi.pdf.

Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), 1994. Defining Soil Quality for a Sustainable Environment. SSSA Special Publication No. 35.

Eltun, R., 1995. Comparisons of nitrogen leaching in ecological and conventional cropping systems. Nitrogen Leaching in Ecological Agriculture. A B Academic Publishers, pp. 103–114.

EU-Conference Statement, 1999. Organic farming in the European Union — Perspectives for the 21st Century, 27–28 May, 1999, Baden, Austria.

Feber, R.E., Firbank, L.G., Johnson, P.J., Macdonald, D.W., 1997. The effects of organic farming on pest and non-pest butterfly abundance. Agric. Ecosyst. Environ. 64, 133–139.

Fuller, R.J., 1997. Responses of birds to organic arable farming: mechanisms and evidence. In: Proceedings of the Brighton Crop Protection Conference on Weeds, pp. 897–905.

Gramstrup, M., 1998. En vegetationsanalyse af agerlandets småbiotoper. Report til Biologisk Projektarbejde. Biologisk Institut, Aarhus University (in Danish).

Granstedt, A., 1992. Case studies on the flow and supply of nitrogen in alternative farming in Sweden. 1. Skilleby-farm 1981–1987. Biol. Agric. Hort. 9, 15–63.

Håkansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with a high axle load — extent, persistence and crop response. Soil Till. Res. 29, 277–304.

Halberg, N., 1999. Indicators of resource use and environmental impact for use in decision aid for Danish livestock farmers. Agric. Ecosyst. Environ. 76, 17–30.

Halberg, N., Kristensen, E.S., Kristensen, I.S., 1995. Nitrogen turnover on organic and conventional mixed farms. J. Agric. Environ. Ethics 8 (1), 30–51.

Hald, A.B., Reddersen, J., 1990. Fugleføde i kornmarker — insekter og vilde planter. Miljøprojekt 125. Miljøstyrelsen, Kbh, 112 pp.

Hanlon, R.D.G., Anderson, J.M., 1979. The effect of Collembola grazing on microbial activity in decomposition of leaf litter. Oecologia (Berlin) 38, 93–99.

Hansen, S., 1996. Effects of manure treatment and soil compaction on plant production of a dairy farm system converting to organic farming practice. Agric. Ecosyst. Environ. 56, 173–186.

Hansen, B., 1998. Kvælstofomsætning og review af undersøgelser omkring N-udvaskning i økologisk jordbrug. FØJO Rapport 2. Forskningscenter for Økologisk Jordbrug, pp. 15–26.

Hansen, B., Kristensen, E.S., 1998. N-udvaskning og — balancer ved omlægning fra konventionelt til økologisk jordbrug. FØJO Rapport 2. Forskningscenter for Økologisk Jordbrug, pp. 87–114.

Hansen, B., Kristensen, E.S., Grant, R., Høgh-Jensen, H., Simmelsgaard, S.E., Olesen, J.E., 2000. Nitrogen leaching from conventional versus organic farming systems — a modelling approach. Eur. J. Agric., in press.

Hawksworth, D.L., 1991. The fungal dimension of biodiversity: magnitude, significance, and conservation. Mycol. Res. 95, 641–655.

Ineson, P., Leonard, M.A., Anderson, J.M., 1982. Effect of Collembolan grazing upon nitrogen and cation leaching from decomposing leaf litter. Soil Biol. Biochem. 14, 601–605.

International Federation of Organic Agriculture Movements, 1998. Basic Standards for Organic Production and Processing. International Federation of Organic Agriculture Movements, Mar del Plata, Argentina, 1998.

Jensen, L.S., McQueen, D.J., Shepherd, T.G., 1996. Effects of soil compaction on N-mineralisation and microbial C and N. In: Field Measurements. Soil Till. Res. 38, 175–188.

Johnston, A.E., 1998. Phosphorus: essential plant nutrient, possible pollutant. In: Phosphorus Balance and Utilization in Agriculture Towards Sustainability. Kungl. Skogs- och Lantbruksakademiens Tidsskrift 135 (7), 11–22.

Johnston, A.E., McEwen, J., Lane, P.W., Hewitt, M.V., Poulton, P.R., Yeoman, D.P., 1994. Effects of one to six year old ryegrass-clover leys on soil nitrogen and on the subsequent yields and fertilizer nitrogen requirements of the arable sequence winter wheat, potatoes, winter wheat, winter beans (Vicia faba) grown on sandy loam soil. J. Agric. Sci. 122, 73–89.

Kristensen, S.P., Mathiasen, J., Lassen, J., Madsen, H.B., Reenberg, A., 1994. A comparison of the leachable inorganic nitrogen content in organic and conventional farming systems. Acta Agric. Scand. Sect. B: Soil Plant Sci. 44, 19–27.

Krogh, P.H., 1994. Microarthropods as bioindicators. A study of disturbed populations. In: Terrestrial Ecology. Natural Environmental Research Institute, Silkeborg, 96 pp.

Løes, A.-K., Øgaard, A.F., 1997. Changes in the nutrient content of agricultural soil on conversion to organic farming in relation to farm-level nutrient balances and soil contents of clay and organic matter. Acta Agric. Scand. Sect. B: Soil Plant Sci. 47, 201–214.

Magid, J., Kølster, P., 1995. Modelling nitrogen cycling in an ecological crop rotation and explorative trial. Biol. Agric. Hort. 11, 77–87.

Moreby, S.J., Aebisher, N.J., Sotherton, N.W., 1994. A comparison of the flora and arthropod fauna of organically and conventionally grown winter wheat in southern England. Ann. Appl. Biol. 125, 13–27.

Nolte, C., Werner, W., 1994. Investigations on the nutrient cycle and its components of a biodynamically managed farm. Biol. Agric. Hort. 10, 235–254.

OECD, 1997. Environmental Indicators for Agriculture. OECD, Paris.

Olesen, J.E., 1999. Tab af næringsstoffer. Natur, miljø og ressourcer i økologisk jordbrug. FØJO Rapport 3. Forskningscenter for Økologisk Jordbrug, pp. 17–33.

Philipps, L., Stopes, C.E., Woodward, L., 1995. The impact of cultivation practice on nitrate leaching from organic farming systems. Soil management in sustainable agriculture. In: Proceedings of the Third International Conference on Sustainable Agriculture, 31 August–4 September, 1993, Wye College, University of London, UK.

Reddersen, J., 1997. The arthropod fauna of organic versus conventional cereal fields in Denmark. In: Proceedings of the Entomological Research in Organic Agriculture, March 1995, Vienna. Biol. Agric. Hort. 15, 61–71.

Reddersen, J., 1999. Naturindhold i økologisk jordbrug. Natur, miljø og ressourcer i økologisk jordbrug. FØJO Rapport 3. Forskningscenter for Økologisk Jordbrug, pp. 69–84.

Refsgaard, K., Halberg, N., Kristensen, E.S., 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agric. Syst. 57, 599–630.

Seastedt, T.R., 1984. The role of microarthropods in decomposition and mineralization processes. Ann. Rev. Entomol. 29, 25–46.

Setälä, H., Huhta, V., 1990. Effects of soil fauna on leaching of nitrogen and phosphorus from experimental systems simulating coniferous forest floor. Biol. Fertil. Soils 10, 170–177.

Simmelsgaard, S.E., 1998. The effect of crop, N-level, soil type and drainage on nitrate leaching from Danish soil. Soil Use Mgmt. 14, 30–36.

Simmelsgaard, S.E., Kristensen, I.S., Mogensen, L., 1998. Planteproduktion på forskellige økologiske brugstyper. FØJO Rapport 2. Forskningscenter for Økologisk Jordbrug, pp. 43–68.

Stolze, M., Piorr, A., Häring, A., Dabbert, S., 2000. The environmental impact of organic farming in Europe. Organic Farming in Europe: Economics and Policy, Vol. 6. University of Hohenheim, Germany. ISBN 3-933403-05-7, ISSN 1437–6512.

Stopes, C., Philipps, L., 1992. Organic farming and nitrate leaching. New Farmer and Grower, 1992, pp. 25–28.

Stopes, C., Measures, M., Smith, C., Foster, L., 1995. Hedgerow management in organic farming — impact on biodiversity. In: Isart, J., Llerena, J.J. (Eds.), Biodiversity and Land Use: The Role of Organic Farming. Proceedings of the First ENOF Workshop, Bonn 1995, Barcelona, pp. 121–125.

Sunderland, K.D., Fraser, A.M., Dixon, A.F.G., 1986. Field and laboratory studies on money spiders (*Linyphiidae*) as predators of cereal aphids. J. Appl. Ecol. 23, 433–447.

Tiedje, J.M., 1994. Microbial diversity: Of value to whom? ASM News 60, 523–578.

van der Werff, P.A., Baars, A., Oomen, G.J.M., 1995. Nutrient balances and measurement of nitrogen losses on mixed ecological farms on sandy soils in the Netherlands. Biol. Agric. Hort. 11, 41–50.

Watson, C.A., Fowler, S.M., Wilman, D., 1993. Soil inorganic-N and nitrate leaching on organic farms. J. Agric. Sci. 120, 361–369.

Wilson, J.D., Evans, J., Browne, S.J., King, J.R., 1997. Territory distribution and breeding success of skylarks *Alauda arvensis* on organic and intensive farmland in southern England. J. Appl. Ecol. 34, 1462–1478.

Yeates, G.W., Bardgett, R.D., Cook, R., Hobbs, P.J., Bowling, P.J., Potter, J.F., 1997. Faunal and microbial diversity in three Welsh grassland soils under conventional and organic management regimes. J. Appl. Ecol. 34, 453–470.

Younie, D., Baars, T., 1997. Resource use in organic grassland. The central bank and the art gallery of organic farming. In: Isart, J., Llerena, J.J. (Eds.), Resource Use in Organic Farming. Proceedings of the Third ENOF Workshop, Ancona 1997, Barcelona.

Younie, D., Watson, C.A., 1992. Soil nitrate-N levels in organically and intensively managed grassland systems. Aspects Appl. Biol. 30, 235–238.