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"Investigations on the resource efficiency of different farming systems with specific emphasis on pesticide use intensity"

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Abbrevations and symbols

a	year
A 70%	70% target control level of *Apera spica-venti*
A 90%	90% target control level of *Apera spica-venti*
APESV	*Apera spica-venti*
A. spica-venti	*Apera spica-venti*
AU	no herbicide application against *Apera spica-venti*
BBA	Biologische Bundesanstalt für Land- und Forstwirtschaft
C	carbon or untreated control with respect to pesticide use
°C	degree Celsius
CENCY	*Centaurea cyanus*
cf.	confer
cm	centimetre
CO_2	carbon dioxide
C_{org}	content of organic carbon
D	direct drilling
DBU	Deutsche Bundesstiftung Umwelt
DM	dry matter
DR	crop rotation at the research site Dahnsdorf
ECa	apparent electrical conductivity
e.g.	exempli gratia, for example
ENDURE	European Network for the Durable Eploitation of Crop Protection Strategies
et al.	et alii, and others
ETR	exposure toxicity ratio
ETR_{acute}	exposure toxicity ratio for acute risk potential
$ETR_{chronic}$	exposure toxicity ratio for chronic risk potential
F	treatment with fungicide or insecticide application
FM	fresh matter
FR	crop rotation at the research site Flakkebjerg
FS	farming system at the research site Dahnsdorf
g	gram
GE	grain equivalent
GEMIS	Globales Emissions-Modell Integrierter Systeme
GJ	Giga joule
GLM	General Linear Models Procedure of SAS
H	treatment with herbicide application
H_{8-10}	tine tillage
ha	hectare
HF	treatment with herbicide and fungicide or insecticide application
HU	humus unit
i.e.	id est, that is
IF	integrated farming system
IFPRI	International Food and Policy Research Institute
IPM	Integrated Pest Management
kg	kilogramme
km	kilometre
K_2O	potassium oxide
l	litre
LC_{50}	median lethal concentration
m	metre
m^2	square metre
MAT	*Matricaria*
MIT	mineralization-immobilisation-turnover

MJ	Mega joule
mm	millimetre
mS	milli Siemens
MSD	minimum significant difference
n	number of samples
N	nitrogen
N_2	dinitrogen
NH_3	ammonia
NH_4	ammonium
NO	nitric oxide
NO_3^-	nitrate
N_2O	nitrous oxide
NOEC	no observed effect level
no-till	direct drilling
n.s.	not significant
OECD	Organisation for Economic Co-operation and Development
OF	organic farming system
P	ploughing
p/P_α	probability of error
PAR	photosynthetically active radiation
PEC	predicted environmental concentration
pH	potentia hydrogenii
P_2O_5	phosphorus pentoxide
SAS	Statistical Analysis Software
SHC	soil humus content
SON	soil organic nitrogen
spp.	species
t	ton
UBA	Umweltbundesamt
UK	United Kingdom of Great Britain and Northern Ireland
VIOAR	*Viola arvensis*
WRR	Wetenschappelijke Raad voor het Regeringsbeleid
%	per cent
*	significant at the 0.05 level of probability
***	significant at the 0.001 level of probability

1 INTRODUCTION

1.1 General background

The goals and requirements of the agricultural sector have considerably changed during recent years. Formerly, crop production and livestock farming had been characterised by noteworthy over production, particularly in the countries of the European Union. In the recent past, agricultural goods became a scarcer commodity, since increased food demands due to the growing world population and large requirements for the production of renewable energy joined together. EICKHOUT et al. (2006) reported that global food production can keep pace with the increase in food demand in the coming three decades only if further improvement of agronomic management will be obtained. It has been proposed that world agricultural production has to triple during the same time-frame to meet growing food demand due to increasing population and changing consumption habit (WRR, 1995). It is consequently of fundamental interest to maintain and enhance the quality of all resources on which agricultural production depends. Arable land is regarded as a limited resource in many parts of the world (HÜLSBERGEN et al., 2001; KELM et al., 2003). Furthermore, a large area of land is lost day by day as a result of ground sealing due to the construction of residential areas or industrial facilities. For that reason, an increase in agricultural production will have to come from increased productivity (ALEXANDRATOS, 1995). This is particularly true, as future area expansion would predominantly imply the cultivation of fragile lands (BINDRABAN et al., 2000). In fact, agricultural productivity has been enhanced significantly in the past. In the last three decades, only a quarter of the increase in world food production resulted from the expansion of agricultural land and the remainder, however, from an increase per unit area (IFPRI, 1994). On the other hand, these growing demands pertaining to a limited land area can compromise the quality and the natural regulating functions of essential resources (BINDRABAN et al., 2000; DUMANSKI and PIERI, 2000). Estimates are that about 40 per cent of agricultural lands are affected by human induced land degradation (OLDEMAN et al., 1990). Ensuring the agricultural production capacity of the remaining land resources is therefore of great importance with respect to sustainable land use (DICK, 1992; CHRISTEN, 1996; BINDRABAN et al., 2000).

Besides these increasing demands regarding productivity, environmental effects of farming are of growing concern. In particular, enhanced soil fertility and improved environmental quality are important goals of today’s agriculture (POUDEL et al., 2001). It can be supposed that an increasing competition for arable land will occur and a high output per unit land area will be aimed at, often accompanied by higher inputs of production means like fertilizers and pesticides or the intensification of crop rotations. Nevertheless, obtaining high yields and minimizing environmental effects are not inevitably conflicting purposes. If resources within farming, such as fertilizers, pesticides or energy, are used more efficiently, associated environmental effects will decrease (UBA, 1997). When growing energy crops, for example, higher yields per unit land area requiring the same fossil energy inputs within the production would lead to greater savings of carbon dioxide emissions, because they substitute a higher amount of fossil fuels. Intensive production systems which obtain higher yields may, moreover, allow a reduction in the area needed for food production and therefore allow alternative usage of the land, for instance for producing bio-energy or as residual areas (UHLIN, 1999; BAILEY et al., 2003; SIELING and KAGE, 2006). Assuming that low intensity cropping is environmentally favourable ignores the effect of reduced productivity, which could simply lead to pollution shifting to other places (CHARLES et al., 2006). Several authors argue that the risks of harmful environmental effects are lower with low-input farming systems like organic farming compared to conventional farming methods, though not necessarily so (HANSEN et al., 2001; PACINI et al., 2003). On the other hand, yields will often significantly decrease in the case of considerably reduced production intensity. In this connexion, HÜLSBERGEN et al. (2002) noted that local and global goals conflict, since a lower level of production intensity results in lower outputs.

Fertilizers and pesticides are potential pollutants of the environment. The application of pesticides is the focus of attention, since possible contaminations of soil, water, and air, as well as the endangerment of non-target organisms and toxic residues remaining on food may occur. It is also possible that pollutions of the environment originate from using fertilizers by leaching, gaseous losses or eutrophication due to surface runoff or erosion. The utilization of mineral fertilizers represents, moreover, a large contribution to the total energy input in conventional farming systems (BERARDI, 1978; MUDAHAR and HIGNETT, 1987; ZENTNER et al., 1989; MCLAUGHLIN et al., 2000; MOERSCHNER, 2000; HÜLSBERGEN et al., 2001; KELM et al., 2003; OZKAN et al., 2004; RATHKE and DIEPENBROCK, 2006). Some authors therefore postulate to completely refrain from using mineral fertilizers and pesticides in agricultural production (e.g. LOSKE and BÖHMER, 1997). A production without using fertilizers and pesticides would, however, often cause significant yield losses, as these measures play an important role in tapping the full yield potential of the crops grown. (cf. MANNA et al., 2006; OERKE and STEINER, 1996). Moreover, former investigations have shown that the energy use efficiency (KLINGAUF and PALLUTT, 2002) or nitrogen (N) balances (HANUS and FAHNERT, 1987) can be enhanced as a result of pesticide application.

Fertilizers as well as pesticides hold a fundamental capacity in regard to yields and environmental effects of arable farming. They are essential measures of the farming management and affected by site-specific conditions, the inherent properties of the husbandry system as well as other farming practices, such as crop rotation and soil tillage intensity. For a meaningful assessment of all influencing factors mentioned and for describing and understanding their interactions, an appropriate sample of indicators is required. These indicators must hold a straight link to both productivity and environmental effects.

1.2 Assessment of resource use efficiency with specific emphasis on energy and nitrogen

Sustainability has become an overall concept for agriculture. It is important to know if current land management is leading towards or away from sustainability (DUMANSKI and PIERI, 2000). There is a range of sustainability indicators, whereas it is impossible to condensate all into a single definition of sustainability (PANELL and GLENN, 2000). Compared to the economical and socio-economic aspects of sustainability, the effects of agricultural activities on the environment are of major social concern. Integrative indicators are required to assess and compare the sustainability of management practices or farming systems. Though careful interpretation is required, management indicators reveal options to improve land quality and productivity (BINDRABAN et al., 2000). HALBERG (1999) is of the opinion that indicators at the level of the agricultural production processes can help to optimize production intensity with respect to both economical and environmental goals – right there where production decisions are made. However, PACINI et al. (2003) criticise that most sustainability indicators lack a close link to the decision making of farm management. It is hence of particular importance to select appropriate and meaningful indicators according to the given problems and requirements. In this connexion, KRISTENSEN and HALBERG (1997) accentuated that energy use efficiency, nutrient surpluses and the intensity of pesticide use should be considered when comparing and assessing different farming systems in regard to terms of sustainability.

1.2.1 Energy efficiency

Modern farming practices strongly depend on non-renewable energy (REFSGAARD et al., 1998). On the other hand, support energy used within cropping, for instance in the form of fertilizers, pesticides or fuel for soil tillage, can increase the use efficiency of solar radiation by the crops (OHEIMB et al., 1987; HÜLSBERGEN et al., 2002). CONFORTI and GIAMPIETRO (1997) emphasized as well that the more intensive use of fossil energy significantly increased agricultural productivity in the last centuries. Since the input of fossil energy correlates with the emissions of carbon dioxide (DYER and DESJARDIN, 2003, TZILIVAKIS et al., 2005), and by taking into account that about 5 per cent of the global energy use is attributable to agriculture (STOUT, 1990; PINSTRUP-ANDERSON, 1999), the current debate on human influences on climate change and global warming consequently comprises the contribution due to agricultural production. Furthermore, energy prices are rising due to the growing demands for fossil energy while supplies are finite. This implies that energy must be used as efficiently as possible within cropping for ecological and economical reasons.

Energy efficiency is therefore an important indicator for the sustainability of agriculture (SCHROLL, 1994). Efficient energy use allows, moreover, financial savings (PERVANCHON et al., 2002) and can lead to more environment-friendly production systems (GÜNDOGMUS and BAYRAMOGLU, 2006). For that reason, energy input and output are necessary indicators to determine the energetic and ecological efficiency of crop production (RATHKE and DIEPENBROCK, 2006). Energy parameters are, moreover, meaningful indicators for the assessment of the environmental impacts from agricultural practices (CONFORTI and GIAMPIETRO, 1997; KELM, 2004). They seem to be suitable to estimate the influence of different management intensities with respect to their environmental effects, such as fertilizer application and pesticide use, if both energy outputs and inputs are considered. Energy balances are particularly useful to make comparisons among husbandry systems (HACISEFEROGULLARI et al., 2003). When comparing conventional and organic farming systems, energy balance can thus be regarded as an appropriate tool permitting an impartial and meaningful assessment.

The indicators derived from energy balance calculations often lead to different conclusions concerning the effects of different management practices. Energy intensity (= energy input per unit grain equivalent) and the output/input ratio are suitable to asses the environmental effects associated with the production of crops, thus these parameters can be used to determine the optimum intensity level of land and crop management (HÜLSBERGEN et al., 2001). Producing renewable energy, a maximum net energy output (= energy output minus energy input) is advantageous (KUEMMEL et al., 1998) as well as when the availability of arable land is limited (HÜLSBERGEN et al., 2001). In view of the growing demands for agricultural products and the limited area of arable land, this indicator may be of increasing importance. Nevertheless, to cover both environmental and productivity aspects, all energy balance indicators mentioned should be considered.

1.2.2 Nitrogen use efficiency

The efficient use of nutrients within agricultural production systems has been in focus for several decades (TORSTENSSON et al., 2006). Ideally, fertilizing provides sufficient nutrients for crop and forage growth while simultaneously avoiding the risk of water and air pollution due to nutrient surpluses (SALO and TURTOLA, 2006). N is an essential element holding great importance with respect to plant growth and yield. Significant yield increases became possible when synthetic N fertilizer became available after the discovery of the Haber-Bosch process in the early 20th century (SMIL, 2001). Increased N supply to crops may increase yield but decreases N use efficiency (KUHLMANN and ENGELS, 1989; SIELING and HANUS, 1997). Hence, N losses generally correlate with the N supply, whereas decreasing N runoff with decreasing N fertilizer level is commonly reported for arable crops (BERGSTRÖM, 1987; UHLEN, 1994). GOULDING et al. (2000) found, however, that with mineral N application, only N rates exceeding the economic optimum progressively increase N losses. Thus, in accordance with efficient energy use, a balanced N supply renders possible both ecological and economical benefits. Estimates are that the recovery of fertilizer N in global crop production is about 50 per cent (SMIL, 1999; KRUPNIK et al., 2004). It is therefore likely that there is potential for reducing N losses through improved management (cf. THORBURN et al., 2003; THORP et al., 2006). Losses from the soil-plant system may arise due to denitrification in the form of gaseous dinitrogen (N_2), nitrous oxide (N_2O), and nitric oxide (NO), volatilization of ammonia (NH_3), leaching of nitrate (NO_3^-), runoff and erosion (BOUWMANN et al., 2002). In particular, NO_3^- is an important pollutant of groundwater and surface water (HEATHWAITE, 1993; JOHNES and BURT, 1993; THORBURN et al., 2003) and agriculture is regarded as the major contributor to nitrate contamination (CARPENTER et al., 1998; FRATERS et al., 1998; OECD, 2001).

N balances are often used as part of sustainability assessment as well as to describe N flows and to reveal potential losses as a result of N surpluses. The N balance is an expression of the total potential for N losses from an agro-ecosystem, and thus an indirect indicator of N runoff (HALBERG et al., 1995). It provides, moreover, information for a more efficient use of fertilizers and animal manure on the different crops (BECHMANN et al., 1998) and have therefore been recognised as being important even by the farmers themselves (BEEGLE et al., 2000; HALBERG et al., 2005). N balances are usually adopted as policy tools to reduce N leaching risks and to monitor the effectiveness of environmental measures (VAN BEEK et al., 2003; KOELSCH, 2005). They are reliable indicators to help discriminate poor management practices and to compare different farm types (BASSANINO et al., 2007), even though there is often no linear relationship between N surplus and N leaching when investigated in the short-term (SALO and TURTOLA, 2006; SIELING and KAGE, 2006),.

A crucial influence on the environmental effects of farming is exerted by N stored in soil organic matter, because organic matter dynamics and N turnover in the soil-plant ecosystem are closely linked (VAN FAASSEN and LEBBINK, 1994; POUDEL et al., 2001). Furthermore, PERSSON and KIRCHMANN (1994) reported that not only carbon (C) must be added to the soil to build up organic matter, but also an adequate N supply is essentially needed. As soil organic matter or humus represents a large store of mineralizable N available for the crop, efficient management of soil mineral N in agricultural fields is necessary to sustain crop yield and to minimize negative environmental impacts (POUDEL et al., 2001). The quantification of changes in soil nutrient stocks is crucial to identify problematic land use systems (BINDRABAN et al., 2000), while maintaining the level of soil organic matter or soil organic N in particular is essential for a sustainable agriculture (VAN FAASSEN and LEBBINK, 1994). KORSÆTH and ELTUN (2000) suppose, moreover, that low input farming systems may attain fairly high productivity at the cost of a gradual decline of the soil organic N. They arrive at the conclusion that in an ideal cropping system, both maintaining the site-specific content of soil organic N and minimising the N runoff should be aimed at. Due to the characteristically slow turnover, changes of the soil N pool can only be observed over an extended time (POULTON, 1995). Long-term experiments are therefore likewise needed to clearly assess the impact of different husbandry (DICK, 1992; KÖRSCHENS, 1992; POUDEL et al., 2001).

1.3 The balance and assessment model REPRO

The majority of all underlying investigations presented in this thesis were carried out by using the indicator-based balance and assessment model REPRO (HÜLSBERGEN, 2003), which had been developed to comprehensively describe mass and energy fluxes within agricultural systems. The basic principle is to analyse and evaluate the sustainability of farming systems as well as their environmental effects. The farming system is characterised by considering the basic subsystems crop production, livestock and soil. Mass and energy fluxes between these subsystems are described by different balance approaches, which are linked with each other to quantify the interactions within the soil-plant-livestock system and, therefore, to consistently characterise the farming system on the whole. This contrasts with simple input/output calculations or investigations at the farm gate scale, in which the farming system is regarded as a “black box”.

The model has a hierarchic design. Low system levels like subfields or crops are considered as elements of higher levels like crop rotations or the entire farm. The influence of site conditions and varying husbandry practices are taken into account on the basis of relational databases. REPRO owns a modular structure of data recording and assessment. The following agri-environmental scopes are included and can be investigated separately according to the actual requirements or the available data:

- a humus balance approach (LEITHOLD et al., 1997; HÜLSBERGEN, 2003),
- balancing models for the description of the farm-specific nutrient (HÜLSBERGEN, 2003), carbon (KÜSTERMANN et al., 2008), and energy fluxes (KALK et al., 1998; HÜLSBERGEN et al., 2001),
- interfaces to C/N simulation models (ABRAHAM, 2001).

REPRO provides further assessment approaches, which were not used for these investigations:

- evaluation of bio-diversity and ecological effects of farming practices (HEYER et al., 2003),
- an empirical approach to estimate soil compaction (RÜCKNAGEL et. al., 2007),
- interfaces to Geographic Information Systems to estimate soil erosion and to evaluate structural landscape elements (SIEBRECHT et al., 2005).

Different indicators can be chosen depending on the individual problem. The indicators can be subjected to different rating methods, for example evaluation functions which are determined on the basis of sustainability thresholds (HÜLSBERGEN, 2003). PACINI et al. (2003) recommend using thresholds for sustainability indicators implemented by regulations and laws or found in the literature. A limitation of using such thresholds is, however, that they are difficult to determine, particularly in relation to the intrinsic carrying capacity and the resilience of a given ecosystem. Furthermore, sustainability indicators are often of limited value to draw conclusions either on the farming system or on the pedo-climatic impact. The results of the investigations can be illustrated in tables, radar charts or in the form of internal mass cycles of the farming system.

The balance approaches used will be explained more in detail in the respective chapters of this thesis. The method of **humus balancing** is according to the humus unit (HU) approach (LEITHOLD et al., 1997). One HU is defined to be 1 t of humus containing 580 kg C and 50 kg N. The basic principle of this balance approach is to compare humus requirement and replacement with the objective of an indirect assessment of total humus replacement instead of a direct determination of soil humus content. Humus requirement and replacement were calculated dynamically as related to the main and by-product yields of the crop (HÜLSBERGEN, 2003). The more the actual humus replacement differs from the humus requirement, the more disadvantageous will be the estimation of the humus replacement rate of the respective agricultural system. Calculating **N balances**, the N inputs by means of seed, mineral and organic fertilizers as well as symbiotic N fixation by legumes and N deposition are taken into account (HÜLSBERGEN, 2003). N output is calculated by multiplying dry matter yield of harvested main and by-products by crop specific N contents. The amount of N fixed by legumes is estimated as related to the yields obtained. For mixtures of fodder crops, the actual proportion of legumes and non-legumes within the crop composition can be adapted. The mineralization-immobilisation-turnover (MIT) and, accordingly, the changes of soil organic N are estimated by linking the N balance calculation with the humus balance approach. The method of **energy balancing** corresponds to the process analysis (JONES, 1989), thus human labour and solar energy were not considered. For the estimation of fossil energy input in crop production, both direct and indirect energy components were considered (HÜLSBERGEN et al., 2001). The consumption of Diesel fuel required for field operations mainly represents the direct energy inputs in crop production. Indirect energy input includes fossil energy consumed beyond the farm for the manufacture of production means, such as mineral and organic fertilizers, seed material, machines, and pesticides. The inputs of energy associated with the manufacture of production means as well as fuels were converted to energy equivalents, and multiplied by the amount of production means actually used within cropping. For the calculation of **C balances**, the same system boundaries were used (KÜSTERMANN et al., 2008), while all inputs in crop production were expressed as C emission factors. There is, moreover, an interface to the humus balance approach, thus C sequestration or mineralization of the soil can be estimated due to changes of soil humus content.

1.4 Objectives and structure of the work

The investigations presented in this thesis are based on two long-term field experiments carried out on a loamy sand site with continentally influenced climate at Dahnsdorf (Federal State of Brandenburg, Germany) and one experiment at the experimental site Flakkebjerg (Denmark) with coastal climate and sandy loam soil. Detailed descriptions of all experiments are given in the respective chapters of this work. At Dahnsdorf, one organic farming system and one integrated farming system were conducted. Both were established in autumn 1995. The experiment with integrated husbandry comprised one arable crop rotation and one fodder crop rotation. Moreover, different intensities of pesticide application were tested. The Danish experiment was set up in autumn 2002. Different crop rotations and soil tillage intensities were compared as well as the control level of *Apera spica-venti*. In order to assess long-term effects of the varied management practices, in each year the rotations and treatments were located on the same plots at both sites.

The present thesis comprises four studies, which deal with different aspects of efficient resource use and of environmental effects associated with different husbandry practices:

- Effect of different weed control strategies on the nitrogen efficiency in cereal cropping systems.
- Effects of herbicide application on energy use efficiency and carbon dioxide emissions of cereal cropping systems.
- Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity.
- Sustainable productivity and environmental effects of arable farming as affected by crop rotation, soil tillage intensity and pesticide use: a case-study of two long-term field experiments in Germany and Denmark.

The predominant purpose was to quantify the influence of varying management practices on the N and energy efficiencies. Specific emphasis was placed on the effects of different pesticide use intensity, while several other important aspects of crop production were also investigated, such as crop rotation, fertilizer application, tillage intensity as well as different husbandry systems by comparing integrated and organic farming. Most of these management practices show complex interactions. Even though N and energy represent integrative measures within arable farming, other directly or indirectly related aspects with respect to sustainability or environmental effects of farming have been analyzed, namely humus replacement, carbon dioxide emissions and the potential endangerment of the biotic environment due to the application of pesticides. Moreover, being an important characteristic of sustainability, long-term effects of husbandry were considered in particular.

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Effect of different weed control strategies on the nitrogen efficiency in cereal cropping systems

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2.1 Summary

Information on the long-term effect of a reduction of herbicides on the weed population, yield, and nitrogen balances are scarce. Therefore a 9-year field trial in Brandenburg, Germany, was conducted, which compared the effect of a situation-related herbicide treatment with a 50 percent reduced rate and an untreated control. This paper is restricted to winter wheat, winter barley and winter rye.

During the first period of the field experiment (1997-2001), the reduced herbicide treatment also received a reduced mineral fertilization. This caused a very small competitive ability of the cereal crops and caused a great population development of *Apera spica-venti*. Accordingly, the yield increase after application of the reduced herbicide rate was higher compared with the situation-related treatment, though the effectiveness was 10 to 30 percent lower. During the course of the experiment, an increase in the noxious weeds in the treatment with the reduced herbicide application occurred. This consequently caused only a small yield increase compared with the situation-related treatment. The relative yield increase after herbicide application was larger if a fungicide was applied, which reduced the infestation of fungal diseases. The efficiency of nitrogen fertilization was significantly increased after the application of herbicides due to yield increases.

2.2 Introduction

The effects of different strategies of pesticide use can only be quantified in long-term experiments. This is especially true for herbicides, since various husbandry and weeding treatments cause changes in the weed population dynamics not until before several years. This includes weed density, species composition and the occurrence of noxious weeds (PALLUTT and GRÜBNER, 2004). Additionally, changes in the soil organic matter content and different steady-state-situations, with consequences for the nitrogen turnover, will take a number of years to develop (KÖRSCHENS, 1992; CAMPBELL et al., 2000; HÜLSBERGEN, 2003). Once a new steady-state in the organic matter balance has been established, sound quantifications of the effect of the husbandry on the nitrogen efficiency are possible (HÜLSBERGEN, 2003).

In order to establish strategies for an economically successful and ecologically sound application of pesticides, a long-term field experiment was set up in 1995 at the experimental site of the Federal Biological Research Centre for Agriculture and Forestry (BBA) “Dahnsdorf” in the state of Brandenburg, Germany. In a complex field trial, the effect of a situation-related herbicide application was compared with a 50 percent reduced herbicide rate. With the experimental design chosen it was possible to quantify the long-term effects of the different application strategies on population dynamics of weeds as well as yields and the nitrogen efficiency. The nitrogen efficiency was calculated by using the indicator nitrogen balance.

2.3 Materials und methods

The experimental site “Dahnsdorf“ is located in the German state Brandenburg. The soil is of moraine origin of the Saale glacial period, and is covered by sandy loess with great variation in depth. This is the reason for a high spatial variability of soil properties at the experimental site. The average soil characteristics were 57.9 % sand, 37.5 % silt, 4.6 % clay, 1.4 % organic matter and a pH of 5.8. According to the German classification system the soil had 48 points. The precipitation averaged 536 mm with prolonged dry periods at the end of spring and in early summer. The average temperature was 8.4 °C (PALLUTT, 2002).

The experiment consisted of two different crop rotations:

- arable rotation: winter oilseed rape – winter wheat – winter rye – fallow (peas since 2002) – winter wheat – winter barley, with six replicates,
- fodder crop rotation: winter oilseed rape – winter barley – clover-grass-mixture – winter rye – silage maize – winter wheat, with four replicates.

The experimental design was a two-factorial split plot. The following treatments in cereals were compared:

Factor A: Intensity of pesticide application

- a_1 optimum = situation-related application of pesticides
- a_2 extensive = 50 % reduced application rates compared to a_1

Factor B: Type of pesticide treatments

- b_1 untreated control (C)
- b_2 herbicide (H)
- b_3 fungicide (F)
- b_4 herbicide + fungicide (HF).

Each rotational field in the experiment had the size 800 m^2 (25 m x 32 m). It was split according to the two levels of factor A (intensity of pesticide application). The area for factor B was 80 m^2, whereas the harvest area for each plot was 44 m^2.

The occurrence of weeds affected by the different weed control strategies was evaluated as following:

- the weed coverage of dicots was assessed approximately four to six weeks after beginning of the growing season in spring,

- the number of *Apera spica-venti* panicles was counted on an area of 0.25 m² four times in each plot four weeks before harvest.

The comparison of the effect of the weed control strategies was always calculated between the respective treatments on the same level of factor A. The yield increase caused by herbicide application was calculated either with or without fungicide application. The calculations for the nitrogen balances were performed accordingly, using the model REPRO for all approaches (HÜLSBERGEN, 2003). Nitrogen content of grains was measured every year in all treatments. The results were included in the calculations of the nitrogen balances as well as average depositions of nitrogen of 30 kg N ha^{-1} a^{-1}. Another special feature of the REPRO approach is the link between the nitrogen balance and changes of nitrogen and organic matter content in the soil, with consequences for the nitrogen mineralization-immobilisation-turnover (MIT). The amount of mineral fertilization applied in the experiment was between 60 and 160 kg N ha^{-1} (Table 2. 1). Additionally, in the second experimental period (2002-2005) different sowing rates were tested.

Due to the different nitrogen fertilizer application rates, the statistical analysis was split for the two experimental periods 1997 to 2001 and 2002 to 2005. The grain yields and nitrogen balances were compared using a t-test on a yearly basis. The development of the yield differences was calculated in a linear regression approach by using "years" as an independent variable. The slope of the functions was also checked for significance by a t-test.

Table 2. 1

Mineral nitrogen fertilization and sowing rates in cereals in the period 1997 to 2005

	Period	Optimum	Extensive
N-fertilization	1997-2001	120-160 kg N ha^{-1}	60-80 kg N ha^{-1}
	2002-2005	100-120 kg N ha^{-1}	
Sowing rate	1997-2001	Site specific	
	2002-2005	Site specific	+ 20 %

2.4 Results

The results of the treatment with an application of fungicides (F) as well as the combination of herbicide and fungicide applications (HF) on weed population are not shown, since no differences were tested with respect to the chemical weed control. This is also justified because differences in weed population between the untreated control (C) and an application of fungicides (F) as well as between an application of herbicides (H) and the combination of herbicides and fungicides (HF) were not observed due to the corresponding weed control.

The number of panicles of *A. spica-venti* in the first period (1997 to 2001) was lower in the optimum treatment compared with the extensive treatment of the controls (Table 2. 2). In contrast, in the following period (2002 to 2005) the number of panicles was lower in the extensive treatment with the exception of winter rye. The occurrence of dicot weeds was not affected by these treatments to a large extent. In all experimental years, the occurrence of weeds in the cereal crops was low after situation-related application of herbicides. A reduced herbicide application rate only slightly increased the coverage of dicot weeds in cereals, but significantly increased the coverage of *A. spica-venti*.

In the first period (1997 to 2001) a higher yield increase in the extensive treatment was observed compared with the optimum treatment (Table 2. 3). However, winter wheat responded to the optimum treatment with corresponding yield increase. A combination of herbicide and fungicide applications had only small effects on the grain yield increase caused by herbicide application. This contrasts with the results of the second experimental period 2002 to 2005. All cereal crops showed a substantial yield increase after herbicide application. This was especially true for the situation-related (optimum) herbicide treatments. The yield increase of winter wheat and winter barley after herbicide application was larger in the plots additionally treated with fungicides.

Table 2. 2

Panicles of *A. spica-venti* (m^{-2}) and weed coverage of dicot weeds (%) in cereals in the period 1997 to 2005

	Panicles of *A. spica-venti* m^{-2}				Weed coverage of dicots (%)			
Intensity of treatment	Optimum		Extensive		Optimum		Extensive	
Treatment	C	H	C	H	C	H	C	H
Winter wheat								
1997-2001	38.5	1.8	88.0	26.3	13.6	0.3	15.1	2.1
2002-2005	136.5	7.5	103.4	23.4	10.1	0.3	11.3	0.9
Winter barley								
1997-2001	32.8	2.3	84.3	17.3	17.6	0.1	17.9	0.4
2002-2005	155.3	4.0	133.1	46.8	11.5	0.6	11.9	0.9
Winter rye								
1997-2001	37.0	3.1	67.1	31.9	10.3	0.9	9.9	2.1
2002-2005	67.2	2.9	66.2	11.4	8.5	0.5	8.1	1.1

Table 2. 3

Yield increase caused by herbicide application affected by the interaction of herbicide and fungicide treatments in t per ha

Intensity of treatment	Herbicide application, without fungicides			Herbicide and fungicide applications		
	Optimum	Extensive	t-test significant	Optimum	Extensive	t-test significant
Winter wheat						
1997-2001	0.68	0.74	0*/5 years	0.75	0.80	1*/5 years
2002-2005	1.76	1.19	1*/4 years	2.10	1.23	3*/4 years
Winter barley						
1997-2001	0.22	0.87	2*/5 years	0.41	0.86	2*/5 years
2002-2005	1.22	0.71	2*/4 years	1.62	0.95	2*/4 years
Winter rye						
1997-2001	0.07	0.48	1*/5 years	0.27	0.52	1*/5 years
2002-2005	0.97	0.76	1*/4 years	1.13	0.85	1*/4 years

* Number of years with significant differences in the respective period, $p < 0.05$

No significant effect of herbicide application was found for the differences of yield increase in all crops except rye in the course of the two experimental periods (data not shown). During the first period from 1997 to 2001, no significant differences in yield increase over the course of time were observed for winter rye between the optimum and the extensive treatments (Figure 2. 1). There was, however, a tendency for larger yield increases in treatment with extensive herbicide application. This contrasts with the results from the second experimental period (2002 to 2005). While functions start approximately at the same level, the slope of the yield increase in the optimum herbicide treatment was significantly larger. In the treatment with fungicide application additionally to herbicides, the development of yield increase over time was larger in the optimum treatment over the period 1997–2001 compared with the extensive treatment (Figure 2. 2). There were no significant differences in the development of yield in the different treatments for the 2002–2005 period.

The herbicide application to winter barley and winter rye reduced the nitrogen balance to a small extent in the period 1997–2001 (Table 2. 4). With exception of winter wheat, the nitrogen balance was relatively more reduced in the extensive treatment, which corresponds with the results of the effect on yields shown above. In the second period (2002–2005) the reduction in the nitrogen balances was more pronounced after herbicide application in all cereal crops. This was especially evident in the optimum herbicide treatments. Averaged over the different experimental years, this effect was most important in wheat and barley especially in combination with a fungicide application and occurred with a greater magnitude after situation-related (optimum) pesticide application.

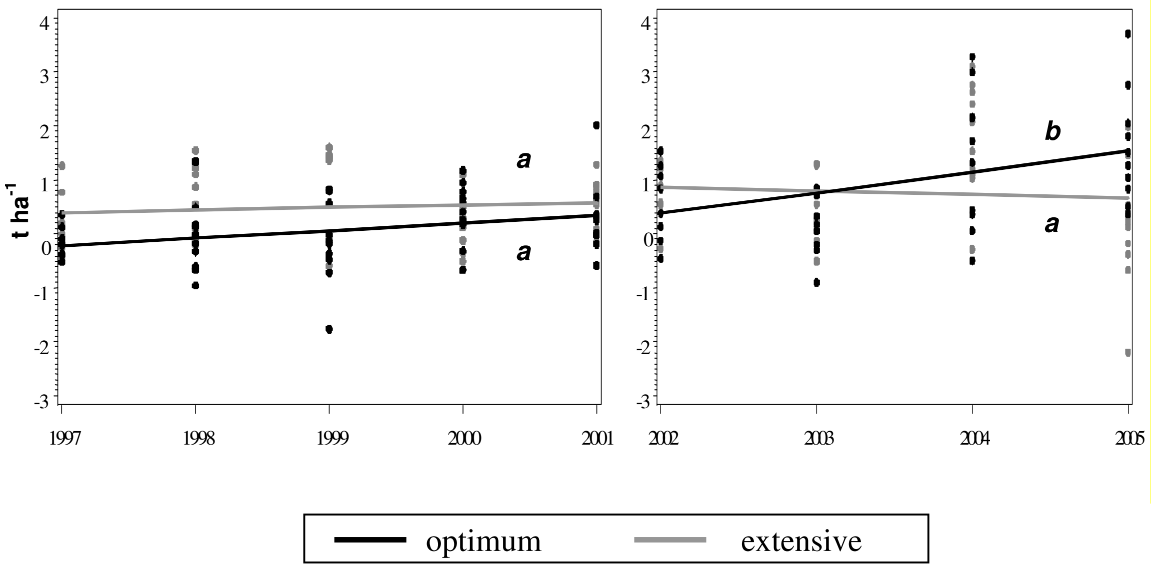

Figure 2. 1

Time course of yield increase in winter rye affected by herbicide application rate from 1997 to 2005; slopes of the yield increase with the same letter are not statistically different ($p < 0.05$).

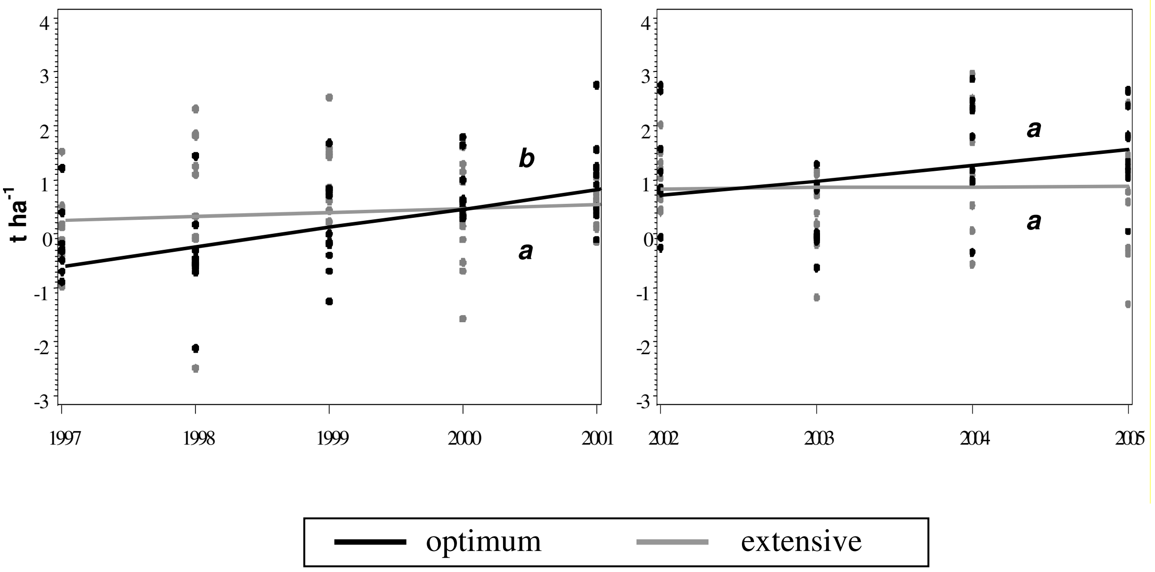

Figure 2. 2

Time course of yield increases in winter rye after herbicide application affected by application rate and the interaction with fungicide treatments from 1997 to 2005, slopes of the yield increase with the same letter are not statistically different ($p < 0.05$).

Table 2. 4

Decrease of nitrogen balance caused by herbicide application affected by the interaction of herbicide and fungicide treatments in kg N ha^{-1}

Intensity of treatment	Herbicide application, without fungicides			Herbicide and fungicide applications		
	Optimum	Extensive	t-test significant	Optimum	Extensive	t-test significant
Winter wheat						
1997-2001	13.2	11.5	0*/5 years	12.9	12.0	1*/5 years
2002-2005	32.2	19.8	1*/4 years	37.1	22.3	3*/4 years
Winter barley						
1997-2001	6.8	9.4	0*/5 years	6.5	8.5	1*/5 years
2002-2005	27.7	15.8	3*/4 years	33.6	18.7	2*/4 years
Winter rye						
1997-2001	1.7	4.2	1*/5 years	2.8	3.5	2*/5 years
2002-2005	17.1	9.9	1*/4 years	17.7	13.4	1*/4 years

* Number of years with significant differences in the respective period, $p < 0.05$

2.5 Discussion

In the first experimental period 1997–2001, differences in weed density and species composition between the control treatments of the extensive and the optimum treatment were caused by differences in the nitrogen fertilization (Table 2. 1). The crops could not compete well with the weeds in the extensive treatments due to the low fertilizer applications compared with the optimum treatments. In the second experimental period (2002-2005), similar effects were caused by differences in sowing rates. Although the nitrogen dressing was identical in the extensive control and the optimum treatment the number of *A. spica-venti* plants was slightly lower. This has been caused by the higher seeding rate and a consequently better competition of the crops in the extensive treatment. This result is in accordance with reports by COURTNEY (1991) and MEINLSCHMIDT (1997). Also PALLUTT (2000) emphasised the importance of the competitive ability of crops for weed growth and development.

Averaged over the optimum and extensive treatments, the weed coverage of dicots was less affected. Competition was therefore not different in the treatments. Even a reduced herbicide application showed a sufficient effect on dicot weeds due to the low occurrence at the beginning of the field experiment. This was not true for the monocot weed *A. spica-venti*. A further increase in the number of panicles per m² could not be controlled by a reduced herbicide application rate.

An important consequence of a long-term reduction in herbicide application rates is the shift of the weed population to increasingly noxious weeds. Depending on the number of noxious weeds at the start of the weed control strategy, however, it may take more than ten years until such a development occurs (PALLUTT and GRÜBNER, 2004). A higher weed infestation in the cereal crops occurred in the extensive treatment from 1997 to 2001, due to less competitive ability. This was the reason for the higher yield increase after reduced herbicide application compared with an optimum application and agrees with results from PALLUTT (2000), who has reported a larger increase after herbicide treatment in crops with smaller competitive abilities.

In contrast, in the second period (2002–2005) the yield increase was larger after the optimum treatment compared with the extensive treatment. This probably was mainly due to the fact that the weed population density increased sharply in the control treatments. The results contrast with the study of OERKE and STEINER (1996) who have found yield reduction of between 16 to 18 percent without herbicide application in the first experimental year. This difference might be caused by the low original weed population density at the experimental site “Dahnsdorf”. Additionally, a strong increase of noxious weeds was observed after a long-term reduction in herbicide application rates especially *A. spica-venti, Matricaria* spp., and during the last years also *Centaurea cyanus.*

An additional fungicide application did not cause significantly higher yield increases after herbicide application in the first experimental years. This is in contrast to the results from the second experimental period. From 2002 to 2005, especially in winter wheat and winter barley, the yield increase after herbicide application was more pronounced in plots treated with fungicides. There are two explanations for this interaction. An early herbicide application reduces the inter-species competition between crops and weeds and thus increases the tillering and biomass of cereals. On the other hand, fungicide treated crops have a higher yield potential, remain green for a longer time during the summer and therefore benefit from less competition with weeds. Results from PALLUTT (2002) also demonstrate that *A. spica-venti* might directly benefit from a fungicide treatment. The competitive ability of the weed is increased and consequently a higher number of panicles after a fungicide treatment was found.

The development of the crop yields in the experiment clearly indicates that the effects of a reduced pesticide and, in particular, herbicide strategy require long-term experiments for surveying. It was possible to increase yield with a reduced herbicide application in crops with low competitive capacity - extensive treatment in our experiment – as shown in the first years of the field trial. However, this is a sharp contrast to the results of the second experimental period due to the problems with noxious weeds like *A. spica-venti*. It was not possible to control the noxious weeds with the reduced application rates in the second period of the experiment. Therefore, the yield increases following the situation-related herbicide application were larger. In such a complex situation, short-term experiments would give inadequate results and lead to an underestimation of the effect of reduced herbicide application strategies. The yield trends in the second experimental period indicate an advantage of the situation-related herbicide treatment compared with the reduced herbicide application rates. This effect occurred earlier if herbicide and fungicide treatments were both applied. Short-term experiments would substantially underestimate the effect of a reduced herbicide application rate. A quantification of the interaction of fungicide and herbicide treatments based on a short-term experiment is therefore not recommended.

The effects of the different herbicide and fungicide treatments on crop yields correspond with changes in the nitrogen balances. During the first experimental period, the effect of different herbicide application strategies on the nitrogen balance in cereals was negligible, apart from a small reduction in the extensive treatment due to a small yield increase. This yield effect, however, did not completely translate into differences in the nitrogen balance, because grain nitrogen content was lower in the extensive treatment. In the optimum treatment, higher grain nitrogen content consequently caused a higher nitrogen uptake, though yield increases were not different. During the course of the experiment, the nitrogen balances were significantly decreased in the treatment with the situation-related herbicide application based on population dynamics and weather conditions. Similar results have been reported by HANUS and FAHNERT (1987), who observed a reduction of the nitrogen balance in wheat and barley by 40 to 80 kg N ha^{-1} following a fungicide application. Based on the results presented in this study and reports by other authors it can be concluded that the application of pesticides can decrease the nitrogen balance and thus reduce the risk of nitrogen pollution in ground water.

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Effects of herbicide application on energy use efficiency and carbon dioxide emissions of cereal cropping systems

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3.1 Summary

Data from a long-term field trial carried out at the experimental site “Dahnsdorf” (Federal State of Brandenburg, Germany) were used to investigate the effects of herbicide application on the energy use efficiency and the carbon dioxide (CO_2) emissions of cereal cropping systems. In each case, one treatment with a situation-related dosage of herbicides and one without any herbicide application were compared in winter rye, winter barley, and winter wheat. Net energy output (energy output minus energy input), energy intensity (energy input per unit grain equivalent/GE), and output/input ratio were used as indicators to determine the energy efficiency. The CO_2 emissions were measured per unit land area and per unit GE produced.

In general, herbicide application enhanced the energy use efficiency. However, significant differences between the untreated controls and the treatments with herbicide application did not occur until 3 to 5 experimental years. The effect of herbicide application on the energy output was greater if fungal diseases were controlled as well. In this case, the yield increase and the increase of energy output due to herbicide application were on average by 20 % higher compared with the treatments without fungicide application. The CO_2 emissions of the treatments with herbicide application were higher by 4.4 % compared to the untreated controls, because of the energy requirements for the production and the application of herbicides as well as the greater amount of energy required for harvesting caused by higher yields. Nevertheless, the CO_2 emissions per unit GE were by 34.6 % lower if herbicides were applied compared with the treatments without herbicide application.

3.2 Introduction

The fixation of solar energy by generating herbal biomass is the basis of human and animal existence on earth. By using additional support energy, for instance for tillage or the application of fertilizers and pesticides, the use efficiency of sun energy can be further enhanced (HÜLSBERGEN et al*.,* 2002). On the other hand, the consumption of fossil energy by agriculture is of growing concern because of increasing energy prizes due to the finite supplies of fossil energy as well as in regard to its negative environmental effects. In fact, several studies have shown that the release of carbon dioxide from a particular agricultural system is closely related to the amount of used fossil energy (DYER and DESJARDIN, 2003; TZILIVAKIS et al., 2005). Primary agricultural production is responsible for about 5 % of the global energy use (PINSTRUP-ANDERSON, 1999). Thus, agriculture considerably contributes to the negative human impacts on climate and causes global warming.

Although fertilizers as well as synthetic chemicals are regarded as major sources of energy use in agriculture (WOOD et al., 2006), these measures play an important role in tapping the full yield potential of the crops grown. A production without using pesticides in general, and herbicides in particular, would cause significant yield losses (OERKE and STEINER, 1996). This has to be taken into account since arable land is a limited resource in many densely populated parts of the world (HÜLSBERGEN et al., 2001, KELM et al., 2003), as well as because of increased food demands due to the continuously growing world population and large requirements for the generation of renewable energy. Therefore, all inputs used within crop production have to be assessed with regard to their effects on the energy balance by considering their effects on both energy input and energy output. In order to obtain a high energy efficiency, it is necessary that all items of energy input have to be compensated for by correspondingly higher yields or, specifically, by higher energy outputs.

In 1995, a long-term field trial was set up at the experimental site "Dahnsdorf" (Federal State of Brandenburg, Germany) in order to develop and evaluate strategies for an economically successful and ecologically sound use of pesticides. Within this complex field trial, treatments without any herbicide application and with a situation-related application rate of herbicides were compared. The experimental design chosen makes possible a sound assessment of the different herbicide strategies on the basis of yields obtained and the population dynamics of weeds by considering long-term effects (DEIKE et al., 2006a). Moreover, the substantiated data available enables us to investigate the extent to which energy and carbon balances of today's farming practices are affected by different weed control strategies.

3.3 Materials and methods

3.3.1 Description of the site

The experimental site "Dahnsdorf" is located in the Federal State of Brandenburg, Germany. The soil is of moraine origin of the Saale glacial period, and is covered by sandy loess with great variations in depth as well as in texture composition. This is the reason for a high spatial variability of soil properties at the experimental site. The dominant soil type is loamy sand and the average soil characteristics are 579 g kg^{-1} sand, 375 g kg^{-1} silt, 46.0 g kg^{-1} clay, 14.2 g kg^{-1} organic matter, and a pH of 5.8. Furthermore, the precipitation averaged 526 mm with prolonged dry periods at the end of spring and early summer. The mean annual temperature was 8.5 °C (DEIKE et al., 2006b).

3.3.2 Experimental details

One arable crop rotation (referred to as 'FS 1'), containing winter oilseed rape – winter wheat – winter rye – fallow (peas since 2002) – winter wheat – winter barley, and one fodder crop rotation (referred to as 'FS 2'), containing winter oilseed rape – winter barley – alfalfa/red clover/grass mixture – winter rye – silage maize – winter wheat, were simulated. In 'FS 1', the straw of the cereal crops and oilseed rape remained on the field, whereas both grains and straw of cereals were harvested in 'FS 2'.

The experimental design was a two-factorial split plot with six replicates in 'FS 1' and four replicates in 'FS 2', respectively. The following treatments were compared:

Factor A: Intensity of pesticide application

- a_1 situation-related application of pesticides and determination of the appropriate plant protection product to be applied
- a_2 application rates reduced by 50 % compared with a_1

Factor B: Type of pesticide treatments

- b_1 untreated control (referred to as C)
- b_2 herbicide application (referred to as H)
- b_3 fungicide application in cereals or insecticide application in winter oilseed rape and in pea cropping (referred to as F)
- b_4 herbicide and fungicide or insecticide application (referred to as HF).

Each rotational field in the experiment had the size of 800 m^2 (25 m x 32 m). It is split according to the two levels of factor A (intensity of pesticide application). The area for factor B was 80 m^2, while the harvest area for each plot was 44 m^2.

A detailed listing of the application rates of herbicides used was given by MOHAMMAD AGHA and PALLUTT (2006). The occurrence of weeds affected by the different weed control strategies was evaluated as following:

- The weed coverage of dicots was assessed approximately four to six weeks after beginning of the growing season in spring.
- The number of *Apera spica-venti* panicles was counted on an area of 0.25 m^2 four times in each plot four weeks before harvest.

The investigations shown in this paper were restricted to winter wheat, winter barley and winter rye. Both farming systems were presented separately, while in 'FS 1' the results of the two winter wheat fields grown after oilseed rape and peas were summarized. In the first experimental period from 1997 to 2001, the application rates of mineral nitrogen (N) fertilizers were averagely 160 kg N ha^{-1} a^{-1} in winter wheat and 120 to 130 kg N ha^{-1} a^{-1} in winter rye and winter barley. From 2002 to 2006, approximately 120 kg N ha^{-1} a^{-1} were applied to winter wheat, whilst the application rates were about 100 kg N ha^{-1} a^{-1} in winter rye and winter barley. The energy and carbon balance indicators were subjected to analyses of variance (data not shown). Thereafter, the mean values were checked by using a t-test on a yearly basis.

Table 3. 1

Energy equivalents and carbon (C) emission factors for outputs and inputs in crop production (summarized by HÜLSBERGEN et al. (2001) and KALK et al. (2005); according to different authors, modified)

Item	Unit	Energy equivalent		Unit	C emission factor	
Grain	MJ kg^{-1}	18.6	1)	kg C kg^{-1}	0.450	8)
Straw	MJ kg^{-1}	17.7	1)	kg C kg^{-1}	0.450	8)
Diesel fuel	MJ l^{-1}	39.6	2)	kg C kg^{-1}	0.972	9)
Mineral fertilizers						
N	MJ kg^{-1}	35.3	3)	kg C kg^{-1}	0.777	10)
P_2O_5	MJ kg^{-1}	15.8	4)	kg C kg^{-1}	0.701	10)
K_2O	MJ kg^{-1}	2.1	4)	kg C kg^{-1}	0.205	10)
Pesticides				kg C kg^{-1}	6.295	11)
Herbicides	MJ kg^{-1}	288	5)			
Fungicides	MJ kg^{-1}	196	5)			
Insecticides	MJ kg^{-1}	237	5)			
Machines	MJ kg^{-1}	108	6)	kg C kg^{-1} a^{-1}	0.107	12)
Transport	MJ t^{-1} km^{-1}	6.3	7)	kg C t^{-1} km^{-1}	0.029	13)

1) Energy content of grains or straw per kg dry matter (SCHIEMANN, 1981).
2) The conversion factor for diesel fuel according to REINHARDT (1993).
3) Energy equivalent for mineral N fertilizer according to APPL (1997), the amount of energy required for transport is included (1.3 MJ kg^{-1}).
4) Energy equivalents for phosphate and potassium according to KALTSCHMITT and REINHARDT (1997).
5) The energy equivalents for pesticides calculated by GREEN (1987) relate to the content of active ingredients plus energy inputs for storage and transport.
6) According to KALK and HÜLSBERGEN (1999), the energy equivalent for machines refers to the energy used for manufacture and maintenance over the machine's useful life.
7) Energy equivalent for transports within the farm (according to MÜLLER, 1989).
8) Average carbon content per kg dry matter (KÜSTERMANN et al., 2008).
9) The amount of C released per combustion of Diesel fuel was calculated by GEMIS (2002).
10) The C emission factors for mineral fertilizers are according to PATYK and REINHARDT (1997).
11) The C emission equivalent for pesticides according to GEMIS (2002) relates to one unit of manufactured pesticides. No further explanation was made for the different plant production products.
12) According to GEMIS (2002), the C emission factor for machines was calculated as a regression of C emissions over the machine's useful life.
13) The C emission equivalent refers to transports with a truck and a trailer (according to GEMIS, 2002).

Table 3. 2

Panicles of *A. spica-venti* (m^{-2}) and weed coverage of dicot weeds (%) in cereals in the period 1997 to 2006

Year	Treatment	Panicles of *A. spica-venti* m^{-2}						Weed coverage of dicot weeds (%)					
		Winter barley		Winter rye		Winter wheat		Winter barley		Winter rye		Winter wheat	
1997	C	66	134	32	29	20	32	25.3	24.8	8.3	10.3	16.8	17.3
	H	7	2	7	2	0	0	0.1	0.2	2.5	4.3	0.5	0.3
1998	C	4	26	1	32	22	41	22.0	9.8	3.6	4.0	6.4	5.9
	H	0	9	0	0	1	1	0.1	0.2	0.1	0.2	0.3	0.1
1999	C	10	12	24	23	28	16	13.1	11.8	16.8	10.5	13.0	13.5
	H	3	0	0	0	1	0	0.0	0.0	0.1	0.0	0.2	0.1
2000	C	8	35	58	50	75	34	15.7	7.3	14.1	7.4	18.6	16.2
	H	0	6	8	4	4	0	0.0	0.0	0.8	0.4	0.7	0.2
2001	C	7	42	53	79	53	66	24.0	21.1	16.1	11.2	14.7	14.7
	H	0	0	1	11	0	18	0.2	0.2	0.3	0.1	0.1	0.4
2002	C	233	74	87	135	54	67	5.6	4.3	8.7	9.4	5.6	6.2
	H	7	1	3	5	2	1	0.1	0.0	0.4	0.3	0.1	0.1
2003	C	287	330	89	56	164	284	17.5	8.6	5.0	3.3	7.7	11.0
	H	7	4	0	0	18	17	0.0	0.0	0.1	0.1	0.2	0.3
2004	C	61	136	77	101	196	180	11.7	13.8	12.9	15.3	12.5	12.4
	H	1	1	0	0	2	3	0.3	0.0	0.1	0.1	0.3	0.2
2005	C	63	48	99	22	146	73	16.3	12.3	16.4	14.0	16.7	15.8
	H	5	5	11	10	13	3	3.3	0.1	0.4	0.2	0.7	0.3
2006	C	111	121	48	84	576	215	11.1	12.0	5.5	3.3	8.5	3.7
	H	19	5	4	3	37	0	0.2	0.2	0.0	0.1	0.2	0.2
Mean 1997-	C	85	96	57	61	133	101	16.2	12.6	10.7	8.9	12.1	11.7
2006	H	5	3	3	4	8	4	0.4	0.1	0.5	0.6	0.3	0.2
Farming system		'FS 1'	'FS 2	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'

3.3.3 Calculation of energy and carbon balances

The method of energy balancing used in this study was described elaborately by HÜLSBERGEN et al. (2001). It corresponds to the process analysis (JONES, 1989), thus human labour and solar energy were not considered. For the estimation of fossil energy input in crop production, both direct and indirect energy components were considered. The consumption of diesel fuel required for field operations mainly represents the direct energy inputs in crop production. Accordingly, each field operation was taken into account by considering the influence of site-specific and management conditions (cf. KALK and HÜLSBERGEN, 1999). Energy inputs for drying, storage, and transport from the farm to the customers were not included. HÜLSBERGEN et al. (2001) assumed an average field size of 20 ha and an average inner-farm transport distance of 2 km. Indirect energy input includes fossil energy consumed beyond the farm for the manufacture of production means, such as mineral and organic fertilizers, seed material, machines, and pesticides. Calculating carbon (C) balances, the same system boundaries were used (KÜSTERMANN et al., 2008). The energy input as well as the amount of the C emissions associated with the manufacture of production means and fuels were converted to energy equivalents or C emission factors, respectively (Table 3. 1), and multiplied by the amount of production means actually used within cropping. The amount of carbon dioxide (CO_2) released can be calculated by multiplying the C emissions by the factor 3.67.

The energy efficiency was determined by using the indicators net energy output (energy output minus energy input), output/input ratio and energy intensity (i.e. energy input per unit grain equivalent/GE, which makes possible comparisons between different crops due to their contributions to human or animal nutrition). The C balances were also assessed by relating the amount of C released to one unit of land area and the yield expressed in GE.

3.4 Results

By affecting the grain yields to a large extent, the occurrence of weeds was a major factor for the explanation of the energy balances in this experiment. In all cereal crops, the mean occurrence of *A. spica-venti* and dicot weeds was lower by far when herbicides were applied compared with the untreated controls (Table 3. 2). Small differences were recorded between ‘FS 1’ and ‘FS 2’. On average of the treatments without any herbicide application, least numbers of panicles of *A. spica-venti* and the lowest weed coverage of dicots were found in winter rye. The number of panicles of *A. spica-venti* strongly increased in the untreated controls of all cereal crops since the second experimental period started in 2002. In this period, a slightly higher occurrence of *A.*

spica-venti was recorded for the treatments with herbicide application as well, whereas the mean coverage of dicot weeds did not differ considerably from the first to the second experimental period.

In winter barley cropping, net energy output was twice as high in 'FS 1' compared with 'FS 2' (Table 3. 3). In general, higher net energy outputs and output/input ratios as well as lower energy intensities were found in the treatments with herbicide application than in the untreated controls. Nevertheless, significant differences did not frequently occur until the 5th year of the experiment. The CO_2 emissions per unit land area were significantly higher in the treatments with herbicide application compared with the untreated controls. However, the amount of CO_2 emitted per unit GE was lower in the treatments with herbicide application. Averaged across all years and all treatments, higher net energy outputs and output/input ratios as well as lower values for energy intensity were calculated for winter rye cropping compared with winter barley cropping. Moreover, smaller differences were recorded between the treatments with or without herbicide application in winter rye (Table 3. 4). On average, the amount of CO_2 emitted per unit GE was slightly lower in the treatments with herbicide application compared with the untreated controls. While the CO_2 emissions per unit land area in winter rye cropping were comparable to the values found for winter barley, the CO_2 emissions per unit GE were lower in winter rye.

In winter wheat cropping, significant differences in energy output and output/input ratio between the treatments 'C' and 'H' were found since 2000 in 'FS 1' and since 2001 in 'FS 2', respectively (Table 3. 5). On average, the differences between 'C' and 'H' with regard to the energy balance indicators calculated were bigger in winter wheat compared with winter rye or winter barley. Furthermore, the CO_2 emissions per unit land area were higher in winter wheat cropping than in the other cereal crops. On the other hand, the amount of CO_2 emitted per GE was comparable to the values calculated for winter rye and winter barley when herbicides were applied.

The yield increase as well as the increase of energy output caused by herbicide application was generally higher when fungicides were applied compared with the treatments without fungicide application (Table 3. 6). The biggest differences between the treatments with and without herbicide application were recorded in winter wheat. Averaged across all crops and farming systems, the increase of energy output derived from herbicide application was approximately by 20 % lower when no fungicides were applied compared with the treatments with additional fungicide application.

Table 3. 3

Energy balance indicators and carbon dioxide emissions in winter barley cropping as related to herbicide application and the harvested biomass in the period from 1997 to 2006

Year	Treatment [1]	Net energy output (GJ ha^{-1})		Energy intensity (MJ GE^{-1})		Output/input ratio		Carbon dioxide emissions (kg CO_2 ha^{-1})		Carbon dioxide emissions (kg CO_2 GE^{-1})	
1997	C	30.3 *a*	66.6 *a*	449.4 *a*	349.5 *a*	3.9 *a*	8.1 *a*	876.3 *a*	764.4 *a*	35.4 *a*	27.1 *a*
	H	36.7 *b*	86.4 *a*	376.4 *a*	279.9 *a*	4.3 *a*	9.7 *a*	921.6 *b*	815.3 *b*	30.1 *a*	22.1 *a*
1998	C	43.7 *a*	102.2 *a*	440.9 *a*	328.2 *a*	3.7 *a*	8.8 *a*	1326.8 *a*	1066.4 *a*	34.5 *a*	25.7 *a*
	H	45.6 *a*	104.4 *a*	438.1 *a*	310.1 *a*	3.7 *a*	8.7 *a*	1370.7 *b*	1110.9 *b*	34.3 *a*	24.5 *a*
1999	C	106.3 *a*	204.9 *a*	154.0 *a*	129.1 *a*	10.4 *a*	20.6 *a*	944.6 *a*	895.8 *a*	12.7 *a*	10.9 *a*
	H	109.7 *a*	214.2 *a*	155.4 *a*	131.9 *a*	10.3 *a*	20.5 *a*	990.3 *b*	941.5 *b*	12.9 *a*	11.1 *a*
2000	C	73.4 *a*	154.4 *a*	262.9 *a*	171.9 *a*	7.0 *a*	16.2 *a*	1060.0 *a*	871.3 *a*	22.1 *a*	14.5 *a*
	H	64.1 *a*	157.9 *a*	316.8 *a*	174.2 *a*	6.0 *a*	15.7 *a*	1102.0 *b*	919.2 *b*	26.5 *a*	14.7 *a*
2001	C	113.4 *a*	210.0 *a*	132.4 *a*	107.3 *a*	11.7 *a*	24.7 *a*	908.1 *a*	767.4 *a*	11.1 *a*	9.2 *b*
	H	112.5 *a*	245.0 *b*	140.6 *a*	98.4 *a*	11.1 *a*	27.0 *b*	952.2 *b*	816.6 *b*	11.8 *a*	8.4 *a*
2002	C	42.8 *a*	108.7 *a*	277.6 *b*	171.2 *b*	5.6 *a*	15.7 *a*	776.8 *a*	624.6 *a*	22.6 *b*	14.0 *a*
	H	56.2 *b*	107.1 *a*	229.1 *a*	181.4 *a*	6.9 *b*	14.7 *a*	806.5 *b*	658.0 *b*	18.8 *a*	14.9 *a*
2003	C	10.7 *a*	28.5 *a*	1168.4 *b*	1287.6 *b*	1.9 *a*	3.4 *a*	1000.6 *a*	969.4 *a*	81.3 *b*	87.1 *b*
	H	43.2 *b*	107.1 *b*	388.6 *a*	281.8 *a*	4.3 *b*	9.5 *b*	1041.3 *b*	1024.4 *b*	30.0 *a*	22.2 *a*
2004	C	81.2 *a*	139.1 *a*	205.3 *b*	164.7 *b*	7.8 *a*	16.2 *a*	961.2 *a*	787.6 *a*	16.2 *b*	13.8 *b*
	H	98.9 *b*	167.9 *b*	172.7 *a*	144.8 *a*	9.0 *b*	18.5 *b*	1008.1 *b*	828.6 *b*	13.8 *a*	12.2 *a*
2005	C	96.0 *a*	214.9 *a*	173.0 *b*	135.9 *a*	9.3 *a*	19.5 *a*	912.3 *a*	916.9 *a*	13.4 *b*	10.6 *a*
	H	113.9 *b*	236.4 *b*	155.4 *a*	128.5 *a*	10.4 *b*	20.7 *a*	964.2 *b*	953.7 *b*	12.1 *a*	10.0 *a*
2006	C	41.7 *a*	86.8 *a*	319.4 *b*	246.3 *b*	5.8 *a*	11.5 *a*	715.5 *a*	682.6 *a*	24.9 *b*	19.5 *b*
	H	80.7 *b*	200.9 *b*	168.9 *a*	113.7 *a*	9.8 *b*	23.4 *b*	762.6 *b*	752.0 *b*	13.7 *a*	9.4 *a*
Mean 1997-2006	C	63.9	131.6	358.3	309.2	6.7	14.5	948.2	834.6	27.4	23.2
	H	76.1	162.7	254.2	184.5	7.6	16.8	992.0	882.0	20.4	15.0
Farming system		'FS 1'	'FS 2' [2]	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'

[1] Means with different letters in the same column and in the same year are significantly different ($P_{\alpha} = 0.05$).
[2] Grains and straw were harvested in 'FS 2'.

Table 3. 4

Energy balance indicators and carbon dioxide emissions in winter rye cropping as related to herbicide application and the harvested biomass in the period from 1997 to 2006

Year	Treat-ment [1]	Net energy output ($GJ\ ha^{-1}$)		Energy intensity ($MJ\ GE^{-1}$)		Output/input ratio		Carbon dioxide emissions ($kg\ CO_2\ ha^{-1}$)		Carbon dioxide emissions ($kg\ CO_2\ GE^{-1}$)	
1997	C	62.3 *a*	146.1 *a*	203.8 *a*	147.4 *a*	8.3 *a*	19.2 *b*	740.4 *a*	695.2 *a*	17.3 *a*	12.5 *a*
	H	60.6 *a*	138.3 *a*	215.7 *a*	169.2 *a*	7.6 *a*	16.9 *a*	797.0 *b*	749.5 *b*	18.3 *a*	14.3 *b*
1998	C	71.3 *a*	141.2 *a*	258.0 *a*	239.4 *a*	5.9 *a*	11.5 *a*	1187.4 *a*	1119.1 *a*	20.7 *a*	19.5 *a*
	H	67.8 *a*	144.8 *a*	278.1 *a*	249.6 *a*	5.5 *a*	11.2 *a*	1243.8 *b*	1176.6 *b*	22.3 *a*	20.3 *a*
1999	C	109.4 *a*	232.0 *a*	144.3 *a*	120.8 *a*	11.0 *a*	22.6 *a*	929.0 *a*	935.2 *a*	12.1 *a*	10.4 *a*
	H	106.5 *a*	227.9 *a*	153.7 *a*	129.0 *a*	10.3 *a*	21.3 *a*	974.1 *b*	980.1 *b*	12.9 *a*	11.1 *a*
2000	C	88.0 *a*	160.9 *a*	172.3 *a*	161.1 *a*	8.7 *a*	17.1 *a*	998.5 *a*	865.9 *a*	14.9 *a*	13.8 *a*
	H	93.7 *a*	173.6 *a*	163.7 *a*	156.3 *a*	9.1 *a*	18.2 *a*	1011.9 *b*	879.8 *b*	14.2 *a*	13.4 *a*
2001	C	107.1 *a*	212.6 *a*	130.3 *a*	105.0 *a*	11.6 *a*	26.1 *a*	869.1 *a*	751.8 *a*	11.1 *a*	9.2 *a*
	H	110.8 *a*	221.5 *a*	129.6 *a*	104.9 *a*	11.4 *a*	26.0 *a*	916.3 *b*	782.3 *b*	11.1 *a*	9.2 *a*
2002	C	74.8 *a*	127.5 *a*	173.7 *a*	157.3 *a*	9.3 *a*	17.6 *a*	776.3 *a*	659.8 *a*	14.7 *a*	13.3 *a*
	H	83.1 *b*	155.5 *b*	163.0 *a*	134.6 *a*	9.9 *a*	20.4 *a*	807.1 *b*	692.9 *b*	13.8 *a*	11.4 *a*
2003	C	66.1 *a*	151.3 *a*	258.4 *a*	207.3 *a*	6.2 *a*	13.6 *a*	1034.8 *a*	990.8 *a*	20.8 *a*	16.8 *a*
	H	69.8 *a*	151.1 *a*	248.6 *a*	213.2 *a*	6.4 *a*	13.2 *a*	1062.8 *b*	1015.6 *b*	20.1 *a*	17.3 *a*
2004	C	132.8 *a*	214.5 *a*	138.8 *a*	104.4 *b*	11.7 *a*	26.3 *a*	1040.7 *a*	748.3 *a*	11.5 *a*	9.1 *b*
	H	144.1 *a*	287.1 *b*	130.7 *a*	81.4 *a*	12.3 *a*	33.5 *b*	1071.5 b	785.0 *b*	10.9 *a*	7.2 *a*
2005	C	67.6 *a*	183.7 *a*	218.1 *b*	163.7 *b*	7.3 *a*	16.7 *a*	854.4 *a*	946.5 *a*	17.0 *b*	13.1 *b*
	H	101.8 *b*	211.5 *b*	154.9 *a*	147.0 *a*	10.1 *b*	18.6 *b*	894.7 *b*	978.0 *b*	12.2 *a*	11.8 *a*
2006	C	100.1 *a*	198.2 *a*	117.0 *b*	112.8 *a*	13.5 *a*	25.0 *a*	696.6 *a*	722.2 *a*	10.1 *b*	9.8 *a*
	H	116.5 *b*	214.7 *a*	104.4 *a*	106.3 *a*	14.9 *b*	26.0 *a*	727.7 *b*	752.9 *b*	9.0 *a*	9.2 *a*
Mean 1997-	C	87.9	176.8	181.5	151.9	9.4	19.6	912.7	843.5	15.0	12.8
2006	H	95.5	192.6	174.2	149.2	9.7	20.5	950.7	879.3	14.5	12.5
Farming system		'FS 1'	'FS 2' [2]	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'

[1] Means with different letters in the same column and in the same year are significantly different ($P_\alpha = 0.05$).
[2] Grains and straw were harvested in 'FS 2'.

Table 3. 5

Energy balance indicators and carbon dioxide emissions in winter wheat cropping as related to herbicide application and the harvested biomass in the period from 1997 to 2006

Year	Treat-ment [1]	Net energy output ($GJ\ ha^{-1}$)		Energy intensity ($MJ\ GE^{-1}$)		Output/input ratio		Carbon dioxide emissions ($kg\ CO_2\ ha^{-1}$)		Carbon dioxide emissions ($kg\ CO_2\ GE^{-1}$)	
1997	C	39.5 *a*	86.9 *a*	341.2 *a*	293.6 *a*	4.5 *a*	9.0 *a*	898.3 *a*	867.7 *a*	25.4 *a*	22.0 *a*
	H	43.9 *a*	107.9 *b*	325.7 *a*	261.9 *a*	4.5 *a*	9.8 *a*	1003.4 *a*	980.2 *b*	24.7 *a*	20.0 *a*
1998	C	88.9 *a*	158.8 *a*	218.9 *a*	152.2 *a*	7.0 *a*	16.3 *a*	1176.7 *a*	856.8 *a*	16.9 *a*	12.2 *a*
	H	91.0 *a*	173.9 *b*	226.0 *a*	150.5 *a*	6.8 *a*	16.5 *a*	1246.0 *b*	927.9 *b*	17.5 *a*	12.1 *a*
1999	C	109.2 *a*	222.0 *a*	167.8 *a*	120.0 *a*	9.4 *a*	20.8 *a*	1053.0 *a*	914.5 *a*	13.2 *a*	9.6 *a*
	H	115.4 *a*	225.6 *a*	161.4 *a*	119.1 *a*	9.8 *a*	20.9 *a*	1066.8 *a*	927.2 *b*	12.7 *a*	9.5 *a*
2000	C	63.3 *a*	151.3 *a*	297.6 *a*	178.8 *a*	5.5 *a*	14.1 *a*	1177.8 *a*	970.2 *a*	24.1 *a*	14.7 *a*
	H	80.8 *b*	168.1 *a*	251.6 *a*	168.9 *a*	6.7 *b*	15.2 *a*	1203.4 *b*	997.6 *b*	20.5 *a*	13.9 *a*
2001	C	90.3 *a*	176.9 *a*	181.9 *b*	139.5 *b*	8.2 *a*	17.8 *a*	1018.2 *a*	850.9 *a*	14.4 *b*	11.0 *b*
	H	109.1 *b*	213.7 *b*	157.0 *a*	120.1 *a*	9.5 *b*	20.6 *b*	1056.5 *b*	885.1 *b*	12.6 *a*	9.5 *a*
2002	C	62.6 *a*	126.6 a	227.3 *b*	176.5 *b*	6.9 *a*	14.2 *a*	839.0 *a*	760.3 *a*	17.1 *b*	13.4 *b*
	H	75.4 *b*	148.3 *b*	192.5 *a*	154.0 *a*	8.0 *b*	16.1 *b*	856.4 *b*	780.2 *b*	14.7 *a*	11.8 *a*
2003	C	35.8 *a*	62.8 *a*	522.8 *b*	442.7 *b*	3.6 *a*	5.9 *a*	1076.0 *a*	995.7 *a*	37.0 *b*	32.2 *b*
	H	55.1 *b*	113.7 *b*	322.3 *a*	269.6 *a*	4.9 *b*	9.5 *b*	1115.4 *b*	1048.4 *b*	24.1 *a*	20.2 *a*
2004	C	83.1 *a*	172.4 *a*	213.1 *b*	126.5 *b*	7.3 *a*	19.9 *a*	1080.9 *a*	768.8 *a*	17.0 *b*	10.5 *b*
	H	138.6 *b*	257.0 *b*	134.3 *a*	86.9 *a*	11.2 *b*	28.5 *b*	1118.2 *b*	795.4 *b*	10.9 *a*	7.3 *a*
2005	C	75.6 *a*	180.6 *a*	229.4 *b*	169.0 *a*	7.0 *a*	15.1 *a*	962.9 *a*	988.4 *a*	16.8 *b*	12.6 *b*
	H	100.8 *b*	198.1 *b*	174.8 *a*	154.4 *a*	8.8 *b*	16.2 *a*	992.7 *b*	1005.6 *b*	13.1 *a*	11.6 *a*
2006	C	4.5 *a*	82.6 *a*	1758.0 *b*	267.1 *b*	1.5 *a*	9.6 *a*	794.4 *a*	780.4 *a*	277.1 *b*	20.7 *b*
	H	70.6 *b*	173.2 *b*	198.4 *a*	139.7 *a*	8.1 *b*	18.3 *b*	822.4 *b*	824.4 *b*	15.8 a	11.2 *a*
Mean 1997-	C	65.3	142.1	415.8	206.6	6.1	14.3	1007.7	875.4	45.9	15.9
2006	H	88.1	177.9	214.4	162.5	7.8	17.2	1048.1	917.2	16.6	12.7
Farming system		'FS 1'	'FS 2' [2]	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'	'FS 1'	'FS 2'

[1] Means with different letters in the same column and in the same year are significantly different ($P_{\alpha} = 0.05$).
[2] Grains and straw were harvested in 'FS 2'.

3.5 Discussion

By applying situation-related dosages of herbicides both *A. spica-venti* and dicot weeds were well controlled. In the treatments without any herbicide application, lowest weed occurrence was found in winter rye because of the higher competitive ability of rye compared with winter wheat or winter barley. The vital importance of the competitive ability of crops in regard to weed growth and development as emphasized by PALLUTT (2000) can also be demonstrated by the increased number of panicles of *A. spica-venti* in the untreated controls since 2002. As a result of the smaller application rates of mineral N fertilizer since 2002, the cereal crops showed a lower competitive ability compared with the crops in the previous experimental period. Thus, weed occurrence increased beyond the existing long-term effects regarding weed population in the treatments without herbicides application. Therefore, a great number of panicles of *A. spica-venti* could be found in winter barley in 2003 in ‘FS 1’ and ‘FS 2’ as well as in winter wheat in ‘FS 1’ in 2006. In 2003, the barley crops were very thin as a result of a long frosty period without any protective snow coverings in winter and the following long dry period at the end of spring and in early summer. However, in 2006 the late beginning of the growing season in conjunction with less vital wheat plants due to a bad quality of the seed used was attributable for the poor growth of winter wheat in ‘FS 1’ and the high weed occurrence in the untreated controls. Similarly, yield and energy efficiency were low while C emissions per GE were very high in this treatment accordingly.

Table 3. 6

Increases of yield (t ha^{-1}) and energy output (GJ ha^{-1}) caused by herbicide application with and without additional fungicide application in the farming system ‘FS 1’ in the period from 1997 to 2006

Crop	Yield increase (t ha^{-1})		Increase of energy output (GJ ha^{-1})	
Winter barley	0.81	1.16	12.9	18.5
Winter rye	0.52	0.62	8.3	9.9
Winter wheat	1.49	1.79	23.9	28.7
Fungicide application	No application	Situation-related	No application	Situation-related

The net energy output in ‘FS 2’ was twice as much as in ‘FS 1’ because both grains and straw were harvested in ‘FS 2’, whereas only grains were used in ‘FS 1’. This is in accordance with results given by TSATSARELIS (1993), and is due to the fact that that the energy contents of grains and straw per weight unit of dry matter do not substantially differ (SCHIEMANN, 1981). Furthermore, the straw yield of cereals is not much smaller compared to the grain yield if the current harvest indices are considered. The net energy output and the output/input ratio of the treatments with herbicide application were generally higher compared with the untreated controls. Therefore, the higher energy requirements for the production and the application of herbicides as well as the greater amount of energy required for harvesting due to the higher yields obtained was compensated for by correspondingly higher yields. Investigating farming systems, FRANZLUEBBERS and FRANCIS (1995) also calculated higher output/input ratios for maize and sorghum cropping with herbicide usage than without. Owing to the higher energy requirements in the treatments with herbicide application as mentioned above, the CO_2 emissions per unit land area were significantly higher in these treatments compared with the untreated controls. However, the CO_2 emissions per unit GE were lower due to the fact that much higher yields were obtained after an efficient weed control when using situation-related herbicide doses. In this context, UHLIN (1999) emphasized that the potential of agriculture to bind solar energy creates a much larger effect on energy and carbon flows than savings on input. Particularly when producing renewable energy, the savings of carbon dioxide by substituting energy crops for fossil energy sources were greater if higher yields were obtained with equal fossil energy inputs for cropping. By considering the growing global demand for food, animal feed, and renewable energy, the net energy output of agriculture should be maximised.

The higher energy use efficiency due to herbicide application was partly set off by taking into account higher energy requirements for harvesting due to the higher yields obtained compared with the untreated controls. It has to be noted that approximately 10 to 30 % more energy for harvesting cereal crops is required if a high weed occurrence is present (RADEMACHER, 2006; personal communication). Moreover, the effect of herbicide application on the energy efficiency presented would be more pronounced in crops with fungicide application (cf. Table 3. 6). This application extends the assimilation period and, therefore, the crops benefit from the low weed occurrence to a larger extent compared with the treatments with only herbicide applications.

The enhancement of the energy use efficiency caused by herbicide application differed in the cereal crops investigated and was mainly attributable to the different competitive ability of the crops. The increased energy use efficiency in the treatments herbicide were applied to, is mainly due to the fact that the situation-related herbicides application led to a better nitrogen use efficiency as reported by DEIKE et al. (2006a). The use of mineral N fertilizers represents a large contribution to the fossil energy input in modern farming. Thus, high nitrogen efficiency is necessary to attain high energy use efficiency. Accordingly, the elimination of yield losses caused by weeds is an important and essential part of energy efficient production systems. However, the intensity of herbicide application has to be measured situation-related by considering the present weed occurrence and species composition because of the possible impairments of the environment or financial losses.

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Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity

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4.1 Abstract

One organic farming treatment (OF) and two integrated farming treatments (IF) with (i) situation-related pesticide use (100% HF), and (ii) application rates reduced by 50 per cent in relation to (i), (50% HF), were compared with regard to energy efficiency. Data were used from a long-term field experiment (1997-2006) conducted on a sandy soil with moderate soil fertility and continental climate in the Federal State of Brandenburg, Germany. Net energy output, energy intensity (i.e. energy input per unit grain equivalent/GE, which makes possible comparisons between different crops related to their contributions to human or animal nutrition), and output/input ratio were used as indicators to determine the energy efficiency. Owing to different rates of mineral nitrogen (N) fertilizers in the two IF treatments from 1997 to 2001, all calculations were split for the periods 1997 to 2001 and 2002 to 2006, respectively.

Energy efficiency tended to be lower in winter wheat compared with winter rye in OF and IF because of higher yields obtained while less energy was required for rye cropping. Averaged across all years and crops, the fossil energy inputs in OF (8.1 GJ ha^{-1}) were 35 per cent lower than in the IF treatment 100% HF (12.4 GJ ha^{-1}). The largest shares of energy input in IF were diesel fuel (29 per cent) and mineral fertilizers (37 per cent). Mineral nitrogen (N) fertilizers represented 28 per cent of the total energy input in IF. Pesticide use was attributable for 5 per cent of the total energy input in 100% HF. In OF, most energy was needed for diesel fuel (46 per cent). Significantly higher net energy outputs were recorded for 100% HF compared with OF in winter rye and winter wheat as well as in the entire crop rotation. However, no significant differences in net energy output were found between 100% HF and 50% HF. The energy intensity was significantly lower and the output/input ratio higher in OF compared with IF in the period from 1997 to 2001, whilst no significant differences between both farming systems concerning the two indicators were recorded from 2002 to 2006.

4.2 Introduction

The effects of agricultural activities on the environment are of growing concern. Particularly, the consumption of fossil energy, increasing energy prices, and the current debate on human influences on climate change and global warming hold a strong link to agriculture. In fact, today's agricultural production relies heavily on using non-renewable fossil fuels (REFSGAARD et al., 1998). On a global scale, agriculture is responsible for about 5 per cent of the total energy used (STOUT, 1990; PINSTRUP-ANDERSON, 1999). Several studies have shown that the amount of fossil energy input is closely related to the release of carbon dioxide from a particular agricultural system

(DYER and DESJARDIN, 2003; TZILIVAKIS et al., 2005). Thus, reducing the energy derived from fossil fuels within agricultural systems has important implications for decreasing atmospheric emissions of greenhouse gases (TZILIVAKIS et al., 2005).

Consequently, one main goal for improving the environmental performance of agricultural production has been minimizing energy consumption (KILEY-WORTHINGTON, 1981). This contrasts with most investigations concerning fossil energy inputs, where an increasing fossil energy use was described over the last decades mainly due to the fact that human or animal power was substituted for by machine power (STEINHART and STEINHART, 1974; CAMBEL and WARDER, 1976; OZKAN et al., 2004). However, not only fossil energy but also arable land must be seen as a limited resource in agricultural production (KELM et al., 2003). As a result, countries with limited agricultural land available produce and adopt mainly land-saving techniques to increase agricultural output per hectare (CONFORTI and GIAMPIETRO, 1997). Hence, for the evaluation of environmental effects of agricultural production not only input indicators but also output as well as output-related indicators must be considered.

All inputs into agro-ecosystems can be expressed in terms of energy. In this context, energy analysis can be applied as an integrative measure concerning the intensity of crop production (HÜLSBERGEN et al., 2001). RATHKE and DIEPENBROCK (2006) emphasized that the input and the output of energy are two important factors for determining the energetic and ecological efficiency of crop production, thus improvements in energy efficiency will lead to more environment-friendly production systems (GÜNDOGMUS and BAYRAMOGLU, 2006). In contrast, OZKAN et al. (2004) assumed that a less efficient energy use can result in problems associated with fossil energy inputs such as global warming and nutrient loading. So, efficient energy use is one of the most important conditions for a sustainable agriculture (SCHROLL, 1994). TZILIVAKIS et al. (2005) emphasized that the identification of crop production methods that maximise energy efficiency and minimise greenhouse gas emissions is vital.

In general, it is assumed that the risk of harmful environmental effects is lower with organic than with conventional farming methods, though not necessarily so (HANSEN et al., 2001). In numerous studies organic and conventional farming systems were compared regarding total energy use and energy use efficiency. In most publications, both smaller energy inputs and higher energy use efficiency (= higher output per unit input or less input per unit output) were reported for organic farming. The majority of these comparisons between organic and conventional farming were carried out at the farm level (BERARDI, 1978; KALK et al., 1998; REFSGAARD et al., 1998; DALGAARD et al., 2001; GÜNDOGMUS and BAYRAMOGLU, 2006; WOOD et al., 2006). Studies of published data regarding energy use efficiency in conventional and organic farming were presented by STOLZE et al. (2000) and HANSEN et al. (2001). PIMENTEL et al. (1983), PIMENTEL (1993) as well as DALGAARD et al. (2001) exploited data from national or federal statistics, whereas the study of HELANDER and DELIN (2004) is based on field experiments on a farm-size level. Only a few publications, namely from the Swiss DOC-trial, dealt with long-term data from field experiments (ALFÖLDI et al., 1995; 1999; DUBOIS et al., 1999; MÄDER et al., 2002). Additionally, the majority of results originated from calculations at the crop level. Only restricted conclusions for whole farming systems are justified as different soil characteristics, varying husbandry techniques or different weather conditions can mask the impact of the farming systems. Valid comparisons between organic and conventional or integrated farming systems with regard to environmental impacts should therefore be executed under identical temporal and site conditions as well as by using a standardized examination approach.

When comparing and assessing different farming systems in regard to terms of sustainability not only energy use efficiency but also nutrient surpluses and the intensity of pesticide use should be considered (KRISTENSEN and HALBERG, 1997). In particular, the application of pesticides is the focus of attention, since possible contaminations of soil, water, and air, as well as the endangerment of non-target organisms and toxic residues remaining on food, are evident. Thus, long-term comparison of husbandry systems comprising different levels of management intensity as well as different strategies of pest control, such as presented in this study, is indispensable.

In 1995, the experimental site Dahnsdorf (Federal State of Brandenburg, Germany) was established to compare environment-friendly pest management strategies. The experimental design contains one organic farming system and two integrated farming systems with different intensities of pesticide use. To our knowledge, the experimental design and the long-term approach of the investigations are unique. The substantiated data available make possible a sound assessment of the different husbandry systems because the investigations were carried out under equal site and weather conditions. Moreover, long-term effects of integrated and organic farming practices as well as the long-term effects of different pest management strategies can be comprehensively assessed with regard to energy efficiency.

4.3 Material and methods

4.3.1 Description of the site

The experimental site "Dahnsdorf" is located in the Federal State of Brandenburg, Germany (52º 08' North, 12º 35' East). The soil is of moraine origin of the Saale glacial period, and is covered by sandy loess with great variations in depth as well as texture composition. This is the reason for a high spatial variability of soil properties at the experimental site. The dominant soil type is loamy sand and the average soil characteristics are 579 g kg^{-1} sand, 375 g kg^{-1} silt, 46.0 g kg^{-1} clay, 14.2 g kg^{-1} organic matter, and a pH of 5.8. The precipitation averaged 526 mm with prolonged dry periods at the end of spring and early summer. The mean annual temperature is 8.5 °C (DEIKE et al., 2006b). Both trials are adjacent to each other. Averaged across all plots, the soil fertility was very similar (Table 4. 1). While the organic matter content was higher in IF than in OF due to the slightly higher contents of clay and silt, the main values of the apparent electrical conductivity (ECa) were greater in OF. The ECa is a physical value characterizing the water-retaining ability of soils and depends on clay and water content as well as the concentration of nutrients in solution (BOBERT et al., 2001). Measuring ECa includes the assessment of soil fertility for a depth of 0 to 1.5 m. The slightly lower values for silt and clay on average of the top-soil are therefore compensated for by a higher average water-holding capacity concerning the entire root penetrated soil layer.

Table 4. 1

Average soil characteristics and values for the apparent electrical conductivity (ECa) for integrated (IF) and organic farming (OF) at the beginning of the experiment in the year 1996

Treatment	ECa mS m^{-1}	Content in g kg^{-1}			
		Sand	Silt	Clay	C_{org}
IF	3.8	530	421	49	1.9
OF	4.0	575	391	34	1.6

4.3.2 Experimental details

Comparing organic and integrated farming the crop rotations were: red clover-grass-mixture (since 2003 red clover-alfalfa-grass-mixture) – red clover-grass-mixture (since 2003 red clover-alfalfa-grass-mixture and since 2005 winter oilseed rape) – winter wheat – potatoes – winter rye – winter barley (spring barley since 2002) for organic farming (OF), and winter oilseed rape – winter barley – clover-grass-mixture – winter rye – silage maize – winter wheat for integrated farming (IF). The experimental design for IF was a two-factorial split plot with four replicates. The main plot factor was pesticide use intensity (situation-related application of pesticides, referred to as 100%, and application rates reduced by 50 per cent compared with the situation-related pesticide use intensity, referred to as 50%). Considering Integrated Pest Management (IPM) standards, the situation-related application rates of pesticides and the particular plant protection products to be applied were determined. Sub plots evaluated four types of pesticide treatments (untreated control; herbicide application; fungicide application in cereals or insecticide application in winter oilseed rape; and both herbicide and fungicide or insecticide application, referred to as C, H, F and HF, respectively). Maize only received herbicide applications; different herbicide application rates were only compared from 2002 to 2006. In clover-grass cropping no pesticides were applied. From 1997 to 2001, different pesticide rates and different amounts of mineral nitrogen (N) fertilizers were applied (Table 4. 2). Furthermore, all maize fields received approximately 35000 kg ha^{-1} of farmyard manure per year. In OF, 25000 kg ha^{-1} of farmyard manure were applied to potatoes and 15000 kg ha^{-1} to winter barley or spring barley, on average. Since one field of clover-grass-mixture was replaced by winter oilseed rape in 2005, it was assumed that the return of farmyard manure was lower than with two fields of clover-grass-mixture within the crop rotation because of the decreased fodder amount. Therefore, the application rate of farmyard manure was limited to 20000 kg ha^{-1} per year applied in potato cropping.

In IF each rotational plot in the experiment had the size of 800 m^2 (25 m x 32 m). The area for the different pesticide treatments was 80 m^2, whereas the harvest area for each plot was 44 m^2. The OF system was arranged in a one-factorial block plot with four replicates. A rotational plot had the size of 850 m^2 (25 m x 34 m). For this comparison, merely the integrated farming treatments 100% HF and 50% HF were considered, because it is not practicable to perform integrated farming practices without using any pesticides or by restricting to different pesticide measures like in treatments C, H or F.

Table 4. 2

Mineral nitrogen fertilizer (kg N ha^{-1} per year) applied to various crops in the integrated farming system (IF) in the periods 1997 to 2001 and 2002 to 2006

<table>
<tr><th colspan="2">Mean mineral nitrogen fertilization (kg N ha⁻¹ per year)</th><th colspan="2">Treatment</th></tr>
<tr><th>Crop</th><th>Period</th><th>100% HF</th><th>50% HF</th></tr>
<tr><td>Winter wheat [a]</td><td>1997-2001</td><td>157</td><td>78</td></tr>
<tr><td></td><td>2002-2006</td><td colspan="2">120</td></tr>
<tr><td>Winter rye [a]</td><td>1997-2001</td><td>120</td><td>60</td></tr>
<tr><td></td><td>2002-2006</td><td colspan="2">100</td></tr>
<tr><td>Winter barley [a]</td><td>1997-2001</td><td>130</td><td>63</td></tr>
<tr><td></td><td>2002-2006</td><td colspan="2">97</td></tr>
<tr><td>Winter oilseed rape</td><td>1997-2001</td><td>148</td><td>73</td></tr>
<tr><td></td><td>2002-2006</td><td colspan="2">140</td></tr>
<tr><td>Maize</td><td>1997-2001</td><td colspan="2">95</td></tr>
<tr><td></td><td>2002-2006</td><td colspan="2">87</td></tr>
<tr><td>Clover-grass-mixture [b]</td><td>1997-2001</td><td colspan="2">80</td></tr>
<tr><td></td><td>2002-2006</td><td colspan="2">13</td></tr>
</table>

[a] From 2002 to 2006, sowing rates in the treatment 50% HF were by 20 per cent higher than in the treatment 100% HF.

[b] In the period from 2002 to 2006, only in 2002 mineral N fertilizers were applied (80 kg N ha^{-1} per year), since alfalfa was added to the red clover-grass mixture due to the high symbiotic N fixation rates of alfalfa.

4.3.3 Calculation of energy balances

The method used in this study is described in detail by HÜLSBERGEN et al. (2001). It corresponds to the process analysis (JONES, 1989), thus human labour and solar energy were not considered. Accessible solar radiation is about 1000 times larger per hectare than the fossil energy input. Consequently, an optimal use of solar energy seems important (UHLIN, 1998). While the use efficiency of the sun energy can be enhanced by using support energy, for instance, for tillage and N fertilizer utilization (OHEIMB et al., 1987; HÜLSBERGEN et al., 2002), crops actually exploit only 0.5-5 per cent of the photosynthetically active radiation (PAR) by generating biomass (GREEF et al., 1993). HÜLSBERGEN et al. (2001) emphasised that inclusion of solar radiation in the energy balance would mask the variation of fossil energy input influenced by different husbandry techniques. The energy inputs associated with human labour vary to a large extent according to the approach chosen and the system boundaries. BORIN et al. (1997) calculated less than 0.2 per cent of the total energy input in modern cropping systems deriving from human labour. Furthermore, REFSGAARD et al. (1998) arrived at the conclusion that human labour, which includes physical and additionally intellectual work, and fossil energy are too different to be handled with the same term.

For the estimation of fossil energy input in crop production, both direct and indirect energy components were considered. The consumption of diesel fuel required for field operations mainly represents the direct energy inputs in crop production. Accordingly, each field operation was taken into account considering the influence of site-specific and management conditions (cf. KALK and HÜLSBERGEN, 1999). Energy inputs for drying, storage, and transport from the farm to the customers were not included. HÜLSBERGEN et al. (2001) assumed an average field size of 20 ha and an average inner-farm transport distance of 2 km. Indirect energy input includes fossil energy consumed beyond the farm for the manufacture of production means, such as mineral and organic fertilizers, seed material, machines, and pesticides. The inputs of energy associated with the manufacture of production means as well as fuels were converted to energy equivalents (Table 4. 3), and multiplied by the amount of production means actually used within cropping. According to HEYLAND and SOLANSKY (1979), the energy equivalent of farmyard manure was evaluated by using mineral fertilizer equivalents that correspond to the fertilization effect of manure compared with mineral fertilizer. Fossil energy associated with the manufacture of production means strongly depends on local conditions and manufacturing procedures and, in consequence, a great variation in energy equivalents can be found in the literature. Hence, energy equivalents have to be adapted to regional conditions and improvements in manufacturing (BONNY, 1993; UHLIN, 1999). According to SWANTON et al. (1996) the decrease in energy inputs and the associated increase in energy efficiency in maize and soybean production in Ontario, Canada, from 1975 to 1991 were mainly due to increasing efficiencies in fertilizer and pesticide production. Comparing integrated and organic farming systems, energy equivalents for mineral N fertilizers, in particular, have to be valued impartially. In many investigations higher energy equivalents were used compared with the value in our approach, taken by APPL (1997). In more recent investigations, JENSEN and KONGSHAUG (2003) presented an energy equivalent for mineral N fertilizers that amounts to 32.2 MJ kg^{-1}, though no energy requirements for transporting the fertilizer were considered unlike the value according to APPL (1997, cf. Table 4. 3).

Table 4. 3

Energy equivalents for inputs in crop production (summarized by HÜLSBERGEN et al., 2001; according to different authors, modified)

Item	Unit	Energy equivalent
Diesel fuel	MJ l^{-1}	39.6 [a]
Mineral fertilizers		
N	MJ kg^{-1}	35.3 [b]
P_2O_5	MJ kg^{-1}	15.8 [c]
K_2O	MJ kg^{-1}	2.1 [c]
Pesticides		
Herbicides	MJ kg^{-1}	288 [d]
Fungicides	MJ kg^{-1}	196 [d]
Insecticides	MJ kg^{-1}	237 [d]
Machines	MJ kg^{-1}	108 [e]
Transport	MJ t^{-1} km^{-1}	6.3 [f]

[a] The conversion factor for diesel fuel is according to REINHARDT (1993).

[b] Energy equivalent for mineral N fertilizer according to APPL (1997), the energy required for transport is included (1.3 MJ kg^{-1}).

[c] Energy equivalents for phosphate and potassium according to KALTSCHMITT and REINHARDT (1997).

[d] The energy equivalents for pesticides calculated by GREEN (1987) relate to the content of active ingredients plus energy inputs for storage and transport.

[e] According to KALK and HÜLSBERGEN (1999), the energy equivalent for machines refers to the energy used for manufacture and maintenance over the machine's useful life.

[f] Energy equivalent for transports within the farm (according to MÜLLER, 1989).

The energy output represents the calorific value of the harvested biomass taken from the field, minus seed purchases (KALK et al., 1998; HÜLSBERGEN et al., 2002). It was calculated by multiplying the dry matter yield by the calorific value of the plant material. In IF and OF, both grains and straw of cereals were harvested. Merely rape straw remained on the field in both husbandry systems. Assessing the energy efficiency, different indicators were considered. The net energy output (or energy gain) is the difference between energy output and total energy input, and is given in GJ ha^{-1}. The energy intensity (MJ GE^{-1}) is the fossil energy input per grain equivalent (GE). Depending on their chemical composition and their way of utilization, the yields of different crops make a different contribution to human or animal nutrition. In consequence, by converting the yields into GE, direct consumption and indirect contributions by feeding animals are considered (HÜLSBERGEN et al., 2001). The term 'grain equivalent' or 'cereal unit' was established by WOERMANN (1944), and makes it possible to aggregate and thus compare yields of entire crop rotations or farming systems. Moreover, the dimensionless output/input ratio was calculated by dividing the energy output by the energy input. Analyses by RATHKE and DIEPENBROCK (2006) showed that the net energy output primarily depends on the energy output, while energy intensity and output/input ratio were mainly affected by the energy input. Standardized input-output accountings like energy intensity or input/output ratio are appropriate tools for agro-environmental improvement of farms (HALBERG et al., 2005) and, furthermore, provide an opportunity to evaluate economic interactions of energy use (OZKAN et al., 2004).

4.3.4 Statistical analyses

The data for total energy output, net energy output, energy intensity, and output/input ratio were subjected to analysis of variance (data not shown). Afterwards the mean values of all measures were compared using Tukey´s studentized range test at the 0.05 level of probability. For testing the energetic parameters mentioned above on the crop rotation level, mean values had to be transformed into logarithmic values. This is due to the fact that comparing aggregated values of different crops pertaining to one crop rotation caused heterogeneity of variances. On account of the different application rates of nitrogen fertilizers in IF, the statistical analysis was split for the two experimental periods 1997 to 2001 and 2002 to 2006.

4.4 Results

4.4.1 Fossil energy input

On average, the OF treatment required approximately 35 per cent less fossil energy compared with the IF treatment 100% HF (Table 4. 4). Small differences were found concerning energy input due to the application of farmyard manure. The largest proportion of fossil energy input in IF was mineral fertilizer representing averagely 37 per cent of the total energy input. In particular, there was a high requirement of indirect energy for mineral N fertilizers. The energy used for seed was slightly lower in OF compared with IF. Fossil energy inputs by using pesticides were relatively small in both husbandry systems, whereas by far more energy was used in IF by the use of pesticides compared with OF. Direct energy consumption in the form of diesel fuel and the energy required by use of machines were almost similar for IF and OF.

Table 4. 4

Average shares of fossil energy inputs (GJ ha^{-1}) in integrated (IF) and organic farming (OF) in the period from 1997 to 2006

Item	Energy input (GJ ha^{-1})	
	IF [a]	OF
Farmyard manure	1.33	1.37
Mineral fertilizers	4.53	
- Nitrogen	3.51	
- Phosphate	0.47	
- Potassium	0.55	
Seed[b]	1.78	1.08
Pesticides	0.62	0.02
- Herbicides	0.43	
- Fungicides	0.14	0.02 [c]
- Insecticides	0.01	0.00 [d]
- Growth regulator	0.04	
Diesel fuel	3.64	3.74
- Cropping	2.39	2.00
- Harvesting	1.24	1.74
Machines	1.74	1.87
- Cropping	1.00	0.90
- Harvesting	0.74	0.97
Total energy input	12.37	8.08

[a] Data relate to treatment 100% HF.

[b] Energy for the production of the seed.

[c] Copper compounds were applied to potatoes.

[d] Non-synthetic insecticides (e.g. Neem) were applied to potatoes.

4.4.2 Energy balancing

Fossil energy input in winter rye cropping was by 65 per cent lower in OF compared with 100% HF from 2002 to 2006, and from 1997-2001 it was lower by 59 per cent (Table 4. 5). In both experimental periods, significantly higher energy outputs and net energy outputs were found in IF compared with OF, whereas no significant differences were obtained between 100% HF and 50% HF. In general, the energy intensity was much lower and the output/input ratio[1] much higher in OF compared with IF.

[1] Computing the mean values for output/input ratio, all values for each crop, each treatment, each repetition and each year were considered. Therefore it has to be noticed that $\frac{1}{N}\sum_{k=1}^{N}\left(\frac{Output}{Input}\right)_k \neq \frac{\frac{1}{N}\sum_{k=1}^{N} Output_k}{\frac{1}{N}\sum_{k=1}^{N} Input_k}$.

Table 4. 5

Energy balance indicators for winter rye cropping related to farming system and pesticide use intensity in the period from 1997 to 2006

		Period	
		1997-2001	2002-2006
Item	Treatment	Means [b]	Means [b]
Energy input	100% HF	11.1 a	10.3 a
($GJ\ ha^{-1}$)	50% HF	8.3 b	10.2 a
	OF	4.6 c	3.6 b
	MSD [c]	1.3	1.3
Energy output [a]	100% HF	227.0 a	231.2 a
($GJ\ ha^{-1}$)	50% HF	189.9 ab	220.4 a
	OF	154.9 b	143.7 b
	MSD [c]	39.2	40.4
Net energy output [a]	100% HF	215.9 a	220.9 a
($GJ\ ha^{-1}$)	50% HF	181.6 ab	210.2 a
	OF	150.3 b	140.1 b
	MSD [c]	39.0	40.8
Energy intensity [a]	100% HF	146.5 a	131.1 a
($MJ\ GE^{-1}$)	50% HF	123.9 ab	137.7 a
	OF	102.2 b	89.0 b
	MSD [c]	36.3	41.1
Output/input ratio [a]	100% HF	20.9 b	23.3 b
	50% HF	23.7 b	22.7 b
	OF	34.8 a	44.1 a
	MSD [c]	6.3	8.8

[a] Data relate to harvested biomass.

[b] Means in columns with the same letter are not significantly different.

[c] Minimum significant difference at the 0.05 level of probability.

Averaged across all years and treatments, energy inputs in winter wheat cropping were higher compared with winter rye cropping (Table 4. 6, cf. Table 4. 5). Lowest energy inputs were required for winter wheat cropping in OF in both experimental periods. Greater energy outputs and net energy outputs were consistently recorded for winter rye compared with winter wheat. This was especially true for OF. Concerning winter wheat, both energy output and net energy output were significantly smaller in OF compared with IF. No significant differences could be found in regard to the treatments 100% HF and 50% HF. From 1997 to 2001, the treatment 100% HF obtained the highest values for energy intensity and the lowest values for output/input ratio. In the second experimental period from 2002 to 2006, no significant differences in energy intensity and output/input ratio occurred.

Table 4. 6

Energy balance indicators for winter wheat cropping related to farming system and pesticide use intensity in the period from 1997 to 2006

		Period	
		1997-2001	2002-2006
Item	Treatment	Means [b]	Means [b]
Energy input ($GJ\ ha^{-1}$)	100% HF	11.8 a	11.5 a
	50% HF	8.4 b	11.5 a
	OF	5.7 c	6.5 b
	MSD [c]	0.3	1.3
Energy output [a] ($GJ\ ha^{-1}$)	100% HF	194.1 a	198.4 a
	50% HF	175.2 a	189.9 a
	OF	129.7 b	97.6 b
	MSD [c]	32.2	37.4
Net energy output [a] ($GJ\ ha^{-1}$)	100% HF	182.3 a	187.0 a
	50% HF	166.8 a	178.3 a
	OF	124.0 b	97.1 b
	MSD [c]	32.3	37.8
Energy intensity [a] ($MJ\ GE^{-1}$)	100% HF	162.2 a	158.7 a
	50% HF	125.0 b	170.5 a
	OF	134.0 ab	217.5 a
	MSD [c]	33.4	64.8
Output/input ratio [a]	100% HF	16.6 b	18.0 a
	50% HF	20.9 a	17.1 a
	OF	22.7 a	15.3 a
	MSD [c]	4.2	4.7

[a] Data relate to harvested biomass.

[b] Means in columns with the same letter are not significantly different.

[c] Minimum significant difference at the 0.05 level of probability.

When each crop of the whole rotation was considered, significantly different energy inputs for all treatments were calculated for the period from 1997 to 2001 (Table 4. 7). On average, 36 per cent less energy was required in OF than in the treatment 100% HF. Compared with 50% HF, 23 per cent less energy was required in OF. Averaged across all crops, the amount of energy used was nearly the same in both IF treatments in the period 2002 to 2006. Again, fossil energy consumed by OF was approximately two thirds with relation to IF. From 1997 to 2001, the treatment OF had on average 29 per cent less energy output and 28 per cent less net energy outputs compared with treatment 100% HF, in the period 2002 to 2006, the differences in energy outputs and net energy outputs accounted to 44 per cent and 45 per cent, respectively. No significant differences in energy intensity were found, whilst OF showed the lowest value in the period from 1997 to 2001, and the highest value from 2002 to 2006. On the whole, OF obtained higher output/input ratios compared with IF. Accordingly, the average output/input ratio of 100% HF was 32 per cent lower compared with OF from 1997 to 2001. In the second experimental period from 2002 to 2006, this difference decreased to 16 per cent.

Table 4. 7

Energy balance indicators for organic farming (OF) and integrated farming (IF) as related to different pesticide treatments in the period from 1997 to 2006

		Period					
		1997-2001			2002-2006		
Item	Treatment	Means	ln means [b, c]		Means	ln means [b, c]	
Energy input	100% HF	12.9	2.52	a	12.4	2.46	a
(GJ ha^{-1})	50% HF	10.6	2.27	b	12.3	2.45	a
	OF	8.2	1.95	c	8.0	1.86	b
	MSD [d]		0.12			0.15	
Energy output [a]	100% HF	174.6	5.14	a	199.6	5.28	a
(GJ ha^{-1})	50% HF	156.6	4.99	ab	192.1	5.24	a
	OF	124.3	4.86	b	111.9	4.69	b
	MSD [d]		0.16			0.16	
Net energy output [a]	100% HF	161.6	5.05	a	187.1	5.21	a
(GJ ha^{-1})	50% HF	146.0	4.90	ab	179.8	5.16	a
	OF	116.1	4.77	b	103.9	4.60	b
	MSD [d]		0.19			0.17	
Energy intensity [a]	100% HF	247.9	5.37	a	199.6	5.12	a
(MJ GE^{-1})	50% HF	241.2	5.23	ab	214.6	5.16	a
	OF	196.3	5.11	b	318.3	5.34	a
	MSD [d]		0.18			0.24	
Output/input ratio [a]	100% HF	14.2	3.35	b	17.4	3.45	a
	50% HF	15.9	3.39	b	16.9	3.43	a
	OF	20.8	3.51	a	20.7	3.47	a
	MSD [d]		0.09			0.10	

[a] Data relate to harvested biomass.

[b] Statistical analyses refer to values logarithmically transformed.

[c] Means in columns with the same letter are not significantly different.

[d] Minimum significant difference at the 0.05 level of probability.

4.5 Discussion

4.5.1 Comparing energy inputs of integrated and organic farming

The return of farmyard manure is of utmost importance in organic farming systems where the nutrient supply is generally limited by restrictions on fertilizer inputs. There were only small differences in energy input by organic fertilizers due to the similar application rates in both farming systems (cf. chapter 4.3.2.), whereas it can be supposed that the average application rates of farmyard manure in OF were too high related to the fodder amount of the farming system (KRAATZ, 2006; personal communication).

Presumably, the higher application rates of farmyard manure in OF led to higher yields and, thus, higher energy outputs due to better nutrient supply and improved humus reproduction.

The utilization of mineral fertilizers, and nitrogen fertilizers in particular, represented a large contribution to the total energy input in IF. This is in accordance with results given in studies of BERARDI (1978), MUDAHAR and HIGNETT (1987), ZENTNER et al. (1989), MCLAUGHLIN et al. (2000), MOERSCHNER (2000), HÜLSBERGEN et al. (2001), KELM et al. (2003), OZKAN et al. (2004), RATHKE and DIEPENBROCK (2006). MOERSCHNER (2000) reported that up to 55 per cent of the fossil energy used could be derived from the utilization of mineral N fertilizers in a high-input oilseed rape cropping system. KUESTERS and LAMMEL (1999) found relative shares of mineral N fertilizers from 40 per cent up to 60 per cent of the total energy input in winter wheat and sugar beet production. In our experiment the relative share of mineral N fertilizers for the 100% HF treatment only amounted to approximately 28 per cent of the total energy input due to relatively small application rates of mineral N fertilizers. From 1997 to 2001 lower energy inputs were ascertained for the 50% HF treatment compared with the treatment 100% HF in winter rye and winter wheat as well as concerning the entire farming system as a result of applying lower rates of mineral N fertilizers in 50% HF. Least energy was used in the OF treatment mainly due to the lack of mineral fertilizer application. After the adaptation of the fertilizer application rates in both IF treatments since 2002, the differences in energy input between the two IF treatments were negligible, though higher energy inputs for harvesting as a result of the consistently higher yields in the 100% HF treatment were considered.

Comparing the energy inputs of organic and integrated farming systems, it is necessary to consider both direct and indirect energy inputs (WOOD et al., 2006). As a result of a more intensive tillage and mechanical weed control, the direct energy input tends to be higher in organic farming systems compared with integrated farming systems, such as in our investigations. In numerous studies considering indirect energy inputs as well as direct energy used, it has been reported that, in general, the total energy consumption in organic farming is lower compared with integrated or rather conventional farming systems (e.g. BERARDI, 1978; PIMENTEL et al., 1983; ALFÖLDI et al., 1995; REFSGAARD et al., 1998; ALFÖLDI et al., 1999; DUBOIS et al., 1999; DALGAARD et al., 2001; MÄDER et al., 2002; KELM et al., 2003; HELANDER and DELIN, 2004; GÜNDOGMUS and BAYRAMOGLU, 2006; WOOD et al., 2006). Moreover, integrated or conventional farming systems cause greater releases of carbon dioxide (WOOD et al., 2006).

On average, pesticides accounted for only 5 per cent of the energy input in the treatment 100% HF. UHLIN (1999) calculated 3 per cent, whereas ZENTNER et al. (1989)

found 4 up to 11 per cent of the total energy input to be associated with pesticide utilization. Owing to the low rates of application per unit land area, the contribution of pesticides to the total energy consumption tends to be small (CLEMENTS et al., 1995), however, manufacturing one weight unit of active ingredient is energy intensive on principle (GREEN, 1987). Hence, we assume that reducing the pesticide application rates did not lead to significantly decreased energy requirements.

4.5.2 Influence of pesticide use on energy balances

Pesticide application can significantly reduce yield losses caused by weeds, pests and fungal diseases and, thus, increase the net energy output or the output/input ratio (KLINGAUF and PALLUTT, 2002; DEIKE et al., 2006b). Likewise, FRANZLUEBBERS and FRANCIS (1995) reported that the output/input ratio for maize and sorghum cropping was greater with herbicide usage than without. We argue that the high energy use efficiency in IF is mainly due to the increased nitrogen use efficiency which is a result of effective pesticide application, as reported by DEIKE et al. (2006a).

Concerning energy balancing, it can be concluded that the utilization of pesticides is of minor importance with regard to energy input, but of considerable importance for energy output due to increased biomass harvested. In agreement, recent investigations on the same long-term trials as presented in this paper, showed that net energy output was reduced by 18 per cent while energy intensity was increased by 32 per cent in the IF treatment without pesticide use compared with the treatment with situation-related pesticide application (DEIKE et al., 2007). Nevertheless, the application of pesticides should be restricted to the minimum necessary dosage because of possible contaminations of soil, water, and air as well as the endangerment of non-target organisms and toxic residues remaining on food. Applying reduced pesticide rates without causing significant yield losses is feasible in the short run or with low pest infestation levels. Reducing the intensity of pesticide use on principle in the long run, however, might not have a permanent success mainly due to the shift of the weed population to increasingly noxious weeds causing significant yield losses (DEIKE et al., 2006a). The time scale and long-term consequences of such changes in husbandry must be considered as well when calculating energy balances.

4.5.3 Energy balances at the crop and the crop rotation level

For winter rye and winter wheat high values for energy output and accordingly for net energy output were found. This was especially true for the IF treatments and is due to harvesting both grains and straw. Energy output can be practically doubled, when straw is harvested as well (TSATSARELIS, 1993), because the energy contents of grains and straw per weight unit of dry matter do not differ substantially (SCHIEMANN, 1981). Given the current harvest indices the straw yield of cereals is, in general, not much smaller compared with the grain yield. Averaged across all treatments, energy output and net energy output of winter rye were greater than of winter wheat. It can be argued that winter rye was better adapted to the middle-rate soil fertility at our experimental site and the frequently occurring poor climatic conditions like prolonged dry and hot periods at the end of spring and in early summer or frosty periods without any protective snow covering. Probably, these properties mentioned above and the fact that winter rye is less sensitive to poor nutrient supply, are also accountable for a better average performance of winter rye than of winter wheat in OF.

In the period from 1997 to 2001, the differences in energy output and net energy output between the IF treatments 100% HF and 50% HF were relatively small for winter wheat and winter rye, although only halved rates of mineral N fertilizers were applied in the treatment 50% HF. After equal mineral N fertilizer rates had been applied in both treatments in the second experimental period from 2002 to 2006, the differences between 100% HF and 50% HF became even smaller, though increased weed infestation occurred in the 50% HF treatment as a result of applying the reduced herbicide rates (DEIKE et al., 2006a). Hence, it can be argued that the differences in energy output between 100% HF and 50% HF from 1997 to 2001 are due to both reduced rates of mineral N fertilizers and pesticides.

Averaged across all years and treatments, the energy intensity was lower and the output/input ratio was greater in winter rye compared with winter wheat mainly due to higher energy outputs while less energy was utilized. From 1997 to 2001 energy intensities in winter wheat and winter rye cropping were lowest for OF and 50% HF. The application of reduced rates of mineral N fertilizers in 50% HF or rather the complete lack of mineral fertilizers in OF obviously did not cause a decrease in energy efficiency. This is in accordance with REFSGAARD et al. (1998) who emphasized that lowering input intensity does not generally have negative impacts on crop level energy utilization.

In winter wheat as well as in winter rye comparable mean values for energy intensity were found for the treatment 100% HF in the periods from 1997 to 2001 and 2002 to 2006, while for 50% HF slightly higher values were determined from 2002 to 2006, though higher energy outputs were found from 2002 to 2006 compared with the period from 1997 to 2001. The greater energy input due to higher application rates of mineral N fertilizer was therefore not compensated for by correspondingly higher yields or energy outputs. FRANZLUEBBERS and FRANCIS (1995) as well as LEWANDOWSKI and SCHMIDT (2006), by using the output/input ratio as an indicator, reported that energy efficiency decreased with increasing mineral N fertilizer supply.

4.5.4 Assessment of energy use efficiency by using different energy balance indicators

When comparing organic and integrated or conventional farming systems with regard to energy efficiency, the use of different energy balance indicators seems to be indispensable. KUESTERS and LAMMEL (1999) showed that maximum net energy outputs were obtained at high production intensity, whereas highest output/input ratios were found at low levels of production intensity. Hence, considering only the indicator output/input ratio for assessing energy efficiency of different cropping systems would cause decreased outputs per unit land area. UHLIN (1999) emphasized as well that the potential of agriculture to bind solar energy creates a much larger effect on energy flows than savings on input. HÜLSBERGEN et al. (2002) concluded that maximum net energy outputs and minimum energy use per unit produce are incompatible objectives. This discrepancy was also evident in our investigations, particularly by comparing IF and OF, but to a much smaller extent by comparing both IF treatments. Though energy outputs were generally lower for the OF treatments across all crops, the mean output/input ratio was much higher compared with IF from 1997 to 2001. Accordingly, in the same period, the energy intensity, which is also significantly affected by the energy input, was lower in OF compared with IF. On the other hand, in the second experimental period from 2002 to 2006, the energy intensity increased significantly in OF mainly due to the integration of winter oilseed rape and associated poor yields into the OF crop rotation by replacing one field of alfalfa/clover/grass-mixture since 2005.

Producing renewable energy, a maximum net energy output is desirable (KUEMMEL et al., 1998). Net energy output is also a crucial parameter when the availability of arable land is limited, such as in many densely populated parts of the world (HÜLSBERGEN et al., 2001). This aspect becomes even more important, since increased food demands due to the growing world population and large requirements for the production of renewable energy joined together. Considering the significant differences in energy output or yields between IF and OF, on the global scale, massive yield losses would be caused as a result of omitting mineral fertilizers and pesticides.

4.6 Conclusions

Energy consumption per unit land area and the amount of energy needed for the production of one unit of product or one unit of energy output are fundamental indicators to assess the environmental effects of crop production. According to our investigations, the conversion from conventional or integrated husbandry to organic farming systems would render possible notable savings with regard to energy requirements, whereas the net energy outputs would decrease significantly. The energy needed for the production of one unit of product is not generally lower in organic farming systems. It mainly depends on the type of crop rotations, the site-specific environmental conditions and the production intensity level, meaning namely fertilizer and pesticide application rates as well as tillage intensity. Crops being well adapted to the site-specific and climatic conditions predominantly obtain higher yields because smaller inputs of fertilizers and pesticides are required. As shown, this leads to higher energy use efficiency compared with crops less suitable for the site-specific conditions.

Due to the large energy costs for mineral N fertilizer production, high nitrogen use efficiency is a crucial parameter to obtain high energy use efficiency. To enlarge the nitrogen use efficiency in integrated and conventional farms, nutrient supply has to be adapted to the actual nutrient requirements of the crops. Moreover, yield losses caused by weeds, fungal diseases, and pest insects should be minimized. It can be concluded that situation-related pest control can increase the energy use efficiency to a large extent as a result of relatively small energy requirements for the production and the utilization of pesticides, while the harvested biomass is significantly enlarged after pesticide application in general.

On principle, negative effects on the environment are low with organic farming systems; additionally, the requirements for non-renewable resources are smaller compared with integrated or conventional farming. However, as a result of the smaller yields obtained, significantly more land area is required in organic farming. In conclusion, integrated and conventional farming systems seem to be particularly appropriate for the production of crops used for renewable energies because of the high yields or net energy outputs obtained.

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CHAPTER 5

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Sustainable productivity and environmental effects of arable farming as affected by crop rotation, soil tillage intensity and strategy of pesticide use: a case-study of two long-term field experiments in Germany and Denmark

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5.1 Abstract

On the basis of two long-term experiments in Germany and Denmark, different crop rotations, soil tillage intensities, and strategies of pesticide use were investigated with regard to yield, humus replacement, nitrogen (N) balance, energy use efficiency as well as acute and chronic risk potentials for aquatic and terrestrial organisms by means of pesticide application. The investigation of the Danish experiment concerned two crop rotations (continuous winter wheat cropping, 'FR 1'; winter barley – winter oilseed rape – winter wheat – winter wheat, 'FR 2'), three intensities of soil tillage (ploughing, 'P'; tine tillage 'H_{8-10}'; direct drilling, 'D') and three target control levels against *Apera spica-venti* (untreated, 'AU'; 70% control, 'A 70%'; and 90% control, 'A 90%'), whilst the German experiment comprised one arable crop rotation (winter oilseed rape – winter wheat – winter rye – peas – winter wheat – winter barley, 'DR 1') and one fodder crop rotation (winter oilseed rape – winter barley – alfalfa/clover/grass-mixture – winter rye – silage maize – winter wheat, 'DR 2') each crop with situation-related pesticide use (100% HF) or application rates reduced by 50 per cent (50% HF). At both sites, rotations and treatments were located on the same plots in each year.

Humus requirement could be covered in all crop rotations, while humus replacement rate was highest in 'FR 1'. Total yield potential of the crop rotations was expressed by grain equivalent (GE) yields and energy output. The structure of the crop rotation influenced yield potential to a larger extent than pesticide use intensity or tillage. The average GE yields and energy outputs of 'FR 1' (83.5 GE ha^{-1}; 121.7 GJ ha^{-1}) were significantly higher compared with 'FR 2' (64.2 GE ha^{-1}; 93.2 GJ ha^{-1}); 'DR 2' (72.9 GE ha^{-1}; 192.3 GJ ha^{-1}) exceeded 'DR 1' (70.0 GE ha^{-1}; 100.3 GJ ha^{-1}). Higher N surpluses were found for the Danish crop rotations than for the German experiment, probably due to the relatively low N use efficiency of pig slurry, which was applied to each crop in 'FR 1' and 'FR 2'. Averaged across all treatments, N surplus for 'FR 1', 'FR 2', 'DR 1', and 'DR 2' were 72.9, 94.4, 32.0, and 38.2 kg N ha^{-1}, respectively. According to yield, energy efficiency at both sites was noteworthy affected by crop rotation and minor by pesticide use intensity or tillage. The risk potential due to pesticide application was low in all treatments.

5.2 Introduction

Environmental effects of arable farming are affected by numerous influencing factors. Even though site conditions and regional pedo-climate factors considerably impact the environmental performance of farming (PACINI et al., 2003), the implementation of management practices directly modifiable by the farmer, such as farming system, crop rotation, tillage intensity, or fertilizer and pesticide application, has significant influence on the use efficiency of limited resources and, accordingly, on the potential of environmental endangerments.

Global demands on agricultural products for food, feed, and renewable energies are strongly increasing, whereas the availability of arable land and fossil energy is limited (KELM et al., 2003). Thus, an increase in agricultural production must be achieved by increased productivity (ALEXANDRATOS, 1995). These growing demands for services from a fixed land base are threatening the quality and the natural regulating functions of limited resources on which sustainability depends (BINDRABAN et al., 2000; DUMANSKI and PIERI, 2000). So, sustainable farming systems must obtain high yields while minimizing environmental influence. In this context, maintenance of the agricultural production capacity of land resources is a fundamental element in the discussion on sustainable land use (CHRISTEN, 1996; BINDRABAN et al., 2000).

For the assessment of environmental effects, reproducible, meaningful, and sound indicators are required while being integrative measures to represent the current status of an agricultural system as well as its change over time. HÜLSBERGEN (2003) emphasized that agri-environmental indicators must be straightforward, clear, concise and, moreover, well-founded regarding ecological issues and applicable in short-term examinations. It is imperative that these indicators are reproducible and transparent with respect to deduction of results and, furthermore, make possible aggregation and simplification of complex coherences (WALZ, 1998). PACINI et al. (2003) suggest that useful indicators should have a close link to farm management decision making. The data used for evaluating should be as far as possible derivable from usual farm records. It is, however, not feasible to represent the entirety of environmental effects affected by varying husbandry. Thus, agri-environmental indicators cannot provide an overall assessment of different farming practices (KOLLOGE, 1996).

Energy and nutrient use efficiency as well as the environmentally sound application of pesticides are central indicators for the sustainability assessment of agriculture (KRISTENSEN and HALBERG, 1997). SCHROLL (1994) also emphasized that the efficient use of energy is one of the most important conditions for a sustainable agriculture. Particularly, since several studies have shown that the amount of fossil energy input is closely related to the release of carbon dioxide from a particular agricultural system (DYER and DESJARDIN, 2003; TZILIVAKIS et al., 2005). Energy efficiency can be seen as an integrative indicator as it is strongly correlated to other abiotic indicators (HEISSENHUBER, 1999; HÜLSBERGEN et al., 2001).

The Nitrogen (N) balance or the derived N surplus is often used to estimate the risk of N leaching from arable land (LORD et al., 2002; JANSONS et al., 2003; SACCO et al., 2003; SALO and TURTOLA, 2006), even though SIELING and KAGE (2006) reported that there is often no linear relationship between N surplus and N leaching when investigated in the short-term. If set up over a longer period, N surplus is, however, a good indicator of potential losses originating from different management systems (ÖBORN et al., 2003). It is highly affected by farmer's management strategy and, therefore, an appropriate indicator of efficiency and environmental impact of husbandry practices. Accordingly, N surplus has been identified as a priority agri-environmental indicator (OECD, 2001).

Balanced humus replacement according to the site-specific soil and climate conditions is a basic requirement to obtain high soil fertility (DALAL et al., 1999). Appropriate humus replacement improves soil texture and is conducive to soil biological activity and matter transformation processes (HÜLSBERGEN, 2003). Besides its percolating and buffering function, the capacity of storing and transforming carbon (C) and nutrients, such as N, sulphur, and phosphorus, is of utmost importance (DORAN, 1992; COLE et al., 1997; KIRSCHBAUM, 2000). Hence, changes in soil humus content will influence both C and N fluxes to a large extent and may therefore significantly affect the specific global warming potential of the particular farming system (KÜSTERMANN et al., 2008).

Bio-diversity enhancement is also regarded as an essential principle of resource management (STINNER et al., 1997). However, it can be hardly assessed in field experiments. Since pesticides are driving forces substantially contributing to change in the state of agro-ecosystems (GUTSCHE and ROSSBERG, 1997), the synoptic assessment of pesticide use can be seen as a suitable and representative indicator for estimating the risk potential of direct environmental effects of pesticide application.

The central objective of this study was therefore to investigate to which extent the structure of the crop rotation and the intensity of pesticide use and soil tillage affect the productivity as well as the environmental effects of arable farming systems. Due to the assessment of resource use efficiency, the chosen indicators hold a strong link to both the efficiency of the farming system and the possible impairments of the environment. The two experiments in Germany and Denmark include a broad variation of the most significant measures in arable farming. Both trials are representative for a large part of sites in the respective regions. Thus, the derived information can be useful to improve the performance of numerous farming systems. The experiments provide, moreover, an assessment of long-term effects associated with management practices, which is an important aspect of sustainability.

5.3 Material and methods

5.3.1 Description of the sites

The experimental site "Dahnsdorf" is located in the Federal State of Brandenburg, Germany (52º 08' North, 12º 35' East). The soil is of moraine origin of the Saale glacial period, and is covered by sandy loess with great variations in depth as well as texture composition. The dominant soil type is loamy sand and the average soil characteristics were 579 g kg^{-1} sand, 375 g kg^{-1} silt, 46.0 g kg^{-1} clay, 14.2 g kg^{-1} organic matter, and a pH of 5.8. Prolonged dry periods at the end of spring and early summer frequently occur while the precipitation averages 526 mm per year. The mean annual temperature is 8.5 °C (DEIKE et al., 2006b).

The Danish field experiment was established in autumn 2002 at a sandy loam site at Flakkebjerg Research Centre (55° 20 'North, 11° 23' East) with sand, silt, and clay contents of 696 g kg^{-1}, 137 g kg^{-1}, and 147 g kg^{-1}, respectively. The organic matter content was 20.4 g kg^{-1} and the pH amounted to 7.2. The climatic conditions at Flakkebjerg are strongly affected by coastal climate with a mean annual temperature of 8.5 °C and an average precipitation of 624 mm per year.

5.3.2 Experimental details

The long-term experiment at Dahnsdorf consisted of two different crop rotations. The arable crop rotation, referred to as 'DR 1', was winter oilseed rape – winter wheat – winter rye – peas – winter wheat – winter barley, while the fodder crop rotation (DR 2) contained winter oilseed rape – winter barley – alfalfa-clover-grass-mixture – winter rye – silage maize – winter wheat. The experimental design was a two-factorial split-plot with six and four replicates for 'DR 1' and 'DR 2', respectively. The main plot factor was pesticide use intensity. Situation-related application rates of pesticides, referred to as 100%, and application rates reduced by 50%, referred to as 50%, were compared. Considering Integrated Pest Management (IPM) standards (ZALOM, 2001), the situation-related application rates of pesticides and the particular plant protection products to be applied were determined. Sub plots received four types of pesticide treatments (untreated control; herbicide application; fungicide application in cereals or insecticide application in winter oilseed rape and peas; and both herbicide and fungicide or insecticide application, referred to as C, H, F and HF, respectively). Each rotational plot in the experiment had the size of 800 m^2 (25 m x 32 m). The area for the different pesticide treatments was 80 m^2, whilst the harvest area for each plot was 44 m^2. Cereal straw was chopped and left on the soil surface after harvest in 'DR 1', whereas it was removed in 'DR 2'. The mean application rates of mineral N fertilizers were 140 kg N ha^{-1} for winter oilseed rape, 120 kg N ha^{-1} for winter wheat, 100 kg N ha^{-1} for winter rye, 97 kg N ha^{-1} winter barley, and 87 kg N ha^{-1} for silage maize. Furthermore, all maize plots received approximately 35000 kg ha^{-1} of farmyard manure per year.

A detailed description of the experiment conducted at Flakkebjerg is given by MELANDER et al. (2008). The experimental design was a split-split-plot with four replications. The main plot factor was crop rotation; sub-plots evaluated soil tillage, and sub-sub-plots (net plot size 10 x 2.5 m) the control level of *Apera spica-venti*. Tillage treatments to be investigated consisted of: harrowing to 8-10 cm soil depth (H_{8-10}), none (i.e. direct drilling, 'D'), and mouldboard ploughing to 20 cm depth with subsequent seedbed harrowing (P). One pass of 'H_{8-10}' was made just after harvest to 3-4 cm depth for both tillage treatments and again just before crop sowing to 8-10 cm depth.

The crop rotations chosen for our investigations were continuous winter wheat cropping (FR 1) and winter barley – winter oilseed rape – winter wheat – winter wheat (FR 2). Straw of cereals and oilseed rape was left on the field in both crop rotations. The total N fertilizer applied was 139 kg N ha^{-1} in winter barley, 172 kg N ha^{-1} in winter wheat, and 171 kg N ha^{-1} in winter oil seed rape. In all crops 100 kg NH_4-N ha^{-1} was applied as pig slurry, with the remainder supplied as mineral fertilizer. For oil seed rape, 30 kg N ha^{-1} of the fertilizer was applied in autumn. All other crops were fertilized in spring only. Since *A. spica-venti* had not been present for decades at the experimental site Flakkebjerg, it was introduced artificially by broadcasting seeds of *A. spica-venti* at a rate of 133 g ha^{-1} in all sub-sub-plots immediately after crop sowing at both locations in the autumn of 2002. The *A. spica-venti* population that developed was left untreated in the 2003 growing season to allow the population to increase. Subsequently, in 2004, 2005 and 2006, *A. spica-venti* was controlled by post-emergence herbicide application, with treatments including three target levels: no control (i.e., no herbicide application, referred to as 'AU'); 70% control (A 70%); and 90% control (A 90%), based on the Danish Decision Support System for chemical weed management (RYDAHL, 2004). Herbicides with no expected effect on *A. spica-venti* were likewise used to control broadleaved weeds, with a target control level of 90%. Fungicides were applied to all treatments according to the disease infestation level.

5.3.3 Humus balance approach

The quantification of changes in soil nutrient and humus stocks is crucial to identify problematic land use systems (BINDRABAN et al., 2000). The basic principle of the humus balance approach used in our investigations is to compare humus requirement and replacement with the objective of an indirect assessment of total humus replacement instead of a direct determination of soil humus content (SHC). The more the actual humus replacement differs from the humus requirement, the more disadvantageous is the estimation of the humus replacement rate of the respective agricultural system.

The method of humus balancing is according to the humus unit (HU) approach (LEITHOLD et al., 1997). One HU is defined to be 1000 kg of humus containing 580 kg C and 50 kg N. Humus requirement is mainly caused by growing crops, which decrease the SHC, such as silage maize, potatoes, and sugar beet. The amount of humus requirement is measured up to the humus replacement attributable to growing crops that increase the SHC, such as legumes, grass, or catch crops, as well as due to the application of organic manures. Humus requirement as well as humus replacement of crops is estimated dynamically as related to the obtained main and by-product yields. Humus replacement of organic manures is estimated according to their matter composition, nutrient content, and decomposition rate (Table 5. 1).

Table 5. 1

Humus balance coefficients for several crops and organic fertilizers (according to LEITHOLD et al., 1997; and LEITHOLD and HÜLSBERGEN, 1998; modified)

Crop	HU ha^{-1}	kg C ha^{-1} [a]
Sugar beet	-2.30	-1334
Silage maize	-1.35	-783
Winter oilseed rape (straw removed)	-0.70	-406
Cereals (straw removed)	-0.70	-406
Peas	0.15	87
Clover-grass-mixture	2.10	1218
Grass-mixture (as catch crop)	0.50	290
Organic fertilizers	**HU t^{-1} FM[b]**	**kg C kg^{-1} FM**
Farmyard manure (fresh)	0.050	29
Farmyard manure (decomposed)	0.070	41
Cattle slurry (8 % DM[c])	0.016	9
Pig slurry (6 % DM)	0.011	6
Straw (cereals)	0.120	70

[a] Carbon in humus, which is not subjected to primary respiration.

[b] FM – fresh matter

[c] DM – dry matter

5.3.4 Method of N balancing

Calculating N balances, the N inputs by means of seed, mineral and organic fertilizers as well as symbiotic N fixation by legumes and N deposition are taken into account (HÜLSBERGEN, 2003). The average N deposition for both sites was assumed to be 30 kg N ha^{-1} per year approximately according to investigations by ZIMMER and ROSCHKE (2005) or ELLERMANN et al. (2006). The amount of N fixed by legumes is estimated as related to yields obtained (HÜLSBERGEN, 2003). For mixtures of fodder crops, the actual proportion of legumes and non-legumes within the crop composition was considered. N output is calculated by multiplying dry matter yield of harvested main and by-products with corresponding N contents. For both sites, N contents of grains were measured every year in all treatments. The results were included in the calculations of the N balances. The mineralization-immobilisation-turnover (MIT) and, accordingly, the changes of soil organic N (SON) are estimated by linking the N balance calculation with the humus balance approach. So, the difference of N inputs and N outputs modified by changes of SON results in the N surplus of the farming system investigated.

5.3.5 Calculation of energy balances

The method of energy balancing used in this study is described in detail by HÜLSBERGEN et al. (2001). It corresponds to the process analysis (JONES, 1989), thus human labour and solar energy were not considered. HÜLSBERGEN et al. (2001) emphasized that inclusion of solar radiation in the energy balance would mask the variation of fossil energy input influenced by different husbandry techniques. The energy inputs associated with human labour vary to a large extent according to the approach chosen and the inherent system boundaries. BORIN et al. (1997) calculated less than 0.2 per cent of the total energy input in modern cropping systems deriving from human labour.

For the estimation of fossil energy input in crop production, both direct and indirect energy components were considered. The consumption of diesel fuel required for field operations mainly represents the direct energy inputs in crop production. Accordingly, each field operation was taken into account considering the influence of site-specific and management conditions (cf. KALK and HÜLSBERGEN, 1999). Energy inputs for drying, storage, and transport from the farm to the customers were not included. HÜLSBERGEN et al. (2001) assumed an average field size of 20 ha and an average inner-farm transport distance of 2 km. Indirect energy input includes fossil energy consumed beyond the farm for the manufacture of production means, such as mineral and organic fertilizers, seed material, machines, and pesticides. The inputs of energy associated with the manufacture of production means as well as fuels were converted to energy equivalents (Table 5. 2), and multiplied by the amount of production means actually used within cropping. According to HEYLAND and SOLANSKY (1979), the energy equivalent of farmyard manure was evaluated by using mineral fertilizer equivalents that correspond to the fertilization effect of manure compared with mineral fertilizer.

Table 5. 2

Energy equivalents for inputs in crop production (summarized by HÜLSBERGEN et al., 2001; according to different authors, modified)

Item	Unit	Energy equivalent
Diesel fuel	MJ l^{-1}	39.6 [a]
Mineral fertilizers		
N	MJ kg^{-1}	35.3 [b]
P_2O_5	MJ kg^{-1}	15.8 [c]
K_2O	MJ kg^{-1}	2.1 [c]
Pesticides		
Herbicides	MJ kg^{-1}	288 [d]
Fungicides	MJ kg^{-1}	196 [d]
Insecticides	MJ kg^{-1}	237 [d]
Machines	MJ kg^{-1}	108 [e]
Transport	MJ t^{-1} km^{-1}	6.3 [f]

[a] The conversion factor for diesel fuel is according to REINHARDT (1993).

[b] Energy equivalent for mineral N fertilizer according to APPL (1997), the energy required for transport is included (1.3 MJ kg^{-1}).

[c] Energy equivalents for phosphate and potassium according to KALTSCHMITT and REINHARDT (1997).

[d] The energy equivalents for pesticides calculated by GREEN (1987) relate to the content of active ingredients plus energy inputs for storage and transport.

[e] According to KALK and HÜLSBERGEN (1999), the energy equivalent for machines refers to the energy used for manufacture and maintenance over the machine's useful life.

[f] Energy equivalent for transports within the farm (according to MÜLLER, 1989).

The energy output represents the calorific value of the harvested biomass taken from the field, minus seed purchases (KALK et al., 1998; HÜLSBERGEN et al., 2002). It was calculated by multiplying the dry matter yield by the calorific value of the plant material. Furthermore, the yields are given per unit grain equivalent (GE). Depending on their chemical composition and their way of utilization, the yields of different crops make a different contribution to human or animal nutrition. In consequence, by converting the yields into GE, direct consumption and indirect contributions by feeding animals are considered (HÜLSBERGEN et al., 2001). The term 'grain equivalent' or 'cereal unit' was established by WOERMANN (1944), and makes possible to aggregate and thus to compare yields of entire crop rotations or farming systems. Assessing the energy efficiency, different indicators were considered. The net energy output (or energy gain) is the difference between energy output and total energy input, and is given in GJ ha^{-1}. The energy intensity (MJ GE^{-1}) is the fossil energy input per GE. Moreover, the dimensionless output/input ratio was calculated by dividing the energy output by the energy input.

5.3.6 Assessment of the environmental risk potential of pesticides by using the model SYNOPS

The model SYNOPS was established for synoptic assessment of risk potential of chemic plant protection products by evaluating potential endangerments for terrestrial organisms in soil and edge-biotopes as well as for aquatic organisms in surface water. A detailed description of the assessment model SYNOPS is given by GUTSCHE and ROSSBERG (1997) or GUTSCHE and STRASSEMEYER (2007).

The indicator model incorporates use data of pesticides with their inherent properties and the environmental and climate conditions while and after applying. For each application, the loads of pesticides and the predicted environmental concentration (PEC) in soil, edge-biotopes and surface water are estimated. Soil loads and PEC's are caused directly by pesticide application while being affected by the interception of the crop. The drift into edge-biotopes is estimated by considering the field-biotope-distance as well as the size and structure of the particular biotope. For surface waters the exposure pathways of drift, run-off, and drainage are considered. The load and PEC in surface water depend on the minimal distance from the field edge to the edge of the surface water as well as its size and structure.

The risk potentials of pesticides are calculated as exposure toxicity ratios (ETR's) for reference organisms in each compartment. These organisms are earthworm for soil, bee for edge-biotopes and daphnia, algae, and fish for surface water. Taking into account the overall application and site conditions and the used plant protection products, the acute and chronic risk potentials for all model organisms are estimated. The ETR for the acute risk potential (ETR_{acute}) is computed by dividing the estimated concentration of the compound in the particular compartment by the median lethal concentration (LC_{50}), whereas the ETR for the chronic risk potential ($ETR_{chronic}$) is the ratio of the accumulated compound concentration and the no observed effect concentration (NOEC). Arising values greater than 0.1 for ETR_{acute} or greater than 1.0 for $ETR_{chronic}$ should be subjected to further investigations as indicating increased risk potential (STRASSEMEYER, personal communication).

For our investigations, we presupposed that national requirements and orders regarding pesticide application were considered. Furthermore, all fields are assumed to have no drainages while each field is located 1 m away from a ditch of stagnant water which is 1 m wide and 0.3 m deep. Owing to the small distance from the field to the water and missing water flow prohibiting the decrease of pesticide concentration in the water, this assumption can be seen as a worst-case scenario. This is also true because rainfall of

30 mm is simulated three days after each pesticide application. For the overall calculations, mean climate data of the last 30 years were taken into account from meteorological stations at Kiel (54º 38' North, 10º 15' East) and Potsdam (52º 40' North, 13º 06' East) as being representative for the experimental sites Flakkebjerg and Dahnsdorf, respectively.

5.3.7 Statistical analyses

Due to the fact that only certain treatments were chosen from the entire experimental setup, the actual experimental design was largely disregarded. The particular rotations of both sites were regarded to be part of a test series while the year was used as a blocking factor. Using the GLM Procedure of the SAS statistical package, analyses of variance were done separately for Flakkebjerg and Dahnsdorf. The mean values of humus, energy and N balance indicators as well as GE yields were compared by using Tukey's studentized range test at the 0.05 level of probability. At this, the respective means for crop rotation, pesticide use intensity and tillage (only Flakkebjerg) were tested by averaging the remaining treatments.

5.4 Results

5.4.1 Analyses of variance and aggregate means

The analysis of variance for Flakkebjerg revealed significant effects of crop rotation on all indicators tested (Table 5. 3). In each case, 'FR 1' was significantly superior to 'FR 2'. Furthermore, tillage intensity had a significant influence on all indicators, with exception of humus balance and output/input ratio. However, no significant interaction of the different treatments and no impact of the tested target levels of *A. spica-venti* control could be verified.

The statistical analysis for the German experiment showed considerable differences by using either GE yield or energy output as indicator, though both are strongly affected by crop yield (Table 5. 4). While there were significant differences between 'DR 1' and 'DR 2' regarding energy output, values for GE yield of 'DR 2' were only slightly higher compared with 'DR 1'. This discrepancy occurred to a much smaller extent when comparing 'FR 1' and 'FR 2' at Flakkebjerg. The mean GE yield of 'FR 2' as well as the respective energy output was 23 per cent lower compared with 'FR. Crop rotation was, moreover, found to significantly influence energy gain and output/input ratio at Dahnsdorf. Pesticide use intensity was accountable for a significant proportion of GE yield and N surplus differences. However, no interactions between crop rotation and the intensity of pesticide use could be confirmed.

Table 5. 3

Effects of crop rotation, tillage intensity and control level of *A. spica-venti* (APESV) on GE yield and several N, humus and energy balance coefficients (experimental site Flakkebjerg, period 2003 to 2006)

Source of variation	GE yield	Energy output	Humus balance	N surplus	Energy input	Energy gain	Energy intensity	Output/input ratio
Crop rotation	***	***	*	*	***	***	***	***
APESV-control	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Tillage	*	*	n.s.	*	***	*	*	n.s.
Crop rotation x APESV-control	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Crop rotation x tillage	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
APESV-control x tillage	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
APESV-control x crop rotation x tillage	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Means	GE ha^{-1}	GJ ha^{-1}	HU ha^{-1}	kg N ha^{-1}	GJ ha^{-1}	GJ ha^{-1}	MJ GE^{-1}	
Crop rotation								
FR 1	83.5 a	121.7 a	0.14 a	72.9 a	11.8 a	109.9 a	151.3 a	10.3 a
FR 2	64.2 b	93.2 b	0.08 b	94.4 b	11.2 b	82.0 b	275.0 b	8.3 b
APESV-control								
AU	71.5 a	103.9 a	0.11 a	86.8 a	11.4 a	92.5 a	218.2 a	9.0 a
A 70%	73.5 a	106.9 a	0.11 a	84.6 a	11.5 a	95.4 a	226.3 a	9.3 a
A 90%	76.6 a	111.5 a	0.11 a	79.6 a	11.5 a	99.9 a	194.9 a	9.6 a
Tillage								
P	78.1 a	113.1 a	0.12 a	78.7 a	11.9 a	102.2 a	167.8 a	9.5 a
$H_{8\text{-}10}$	75.5 a	109.6 ab	0.12 a	81.3 ab	11.7 a	97.9 ab	172.5 a	9.3 a
D	68.1 b	99.6 b	0.08 a	90.9 b	10.9 b	88.7 b	299.1 b	9.1 a

*, ***: F-test for the analysis of variance is significant at the 0.05 or 0.001 level of probability, respectively.

n.s.: F-test is not significant

Mean values of the treatments of one respective indicator are calculated by averaging the other indicators. Means with the same letter for crop rotation, APESV-control or tillage within a column are not significantly different (P_{α} = 0.05).

Table 5. 4

Effects of crop rotation and pesticide use intensity on GE yield and several N, humus and energy balance coefficients (experimental site Dahnsdorf, period 2003 to 2006)

Source of variation	GE yield	Energy output	Humus balance	N surplus	Energy input	Energy gain	Energy intensity	Output/input ratio
Crop rotation	n.s.	***	n.s.	n.s.	n.s.	***	n.s.	*
Pesticide use intensity	*	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.
Crop rotation x pesticide use intensity	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Means	GE ha^{-1}	GJ ha^{-1}	HU ha^{-1}	kg N ha^{-1}	GJ ha^{-1}	GJ ha^{-1}	MJ GE^{-1}	
Crop rotation								
DR 1	70.0 a	100.3 a	0.06 a	32.0 a	12.3 a	88.1 a	219.8 a	8.3 a
DR 2	72.9 a	192.3 b	0.06 a	38.2 a	12.5 a	179.8 b	220.6 a	16.9 b
Pesticide use intensity								
100% HF	73.6 a	141.3 a	0.05 a	29.4 a	12.5 a	128.9 a	206.7 a	12.0 a
50% HF	68.7 b	132.9 a	0.07 a	39.5 b	12.3 a	120.6 a	233.5 a	11.4 a

*, ***: F-test for the analysis of variance is significant at the 0.05 or 0.001 level of probability, respectively.

n.s.: F-test is not significant.

Mean values of the treatments of one respective indicator are calculated by averaging the other indicator. Means with the same letter for crop rotation or pesticide use intensity within a column are not significantly different ($P_\alpha = 0.05$).

5.4.2 Yields and energy outputs

When assessing farming systems or whole crop rotations with respect to their yield capacity, the comparison on the basis of GE yields seems to be appropriate if producing food or fodder for the most part, whilst energy output is more suitable with regard to the assessment of producing biomass for renewable energies or the productivity per unit land area.

The results of both indicators were only slightly different when comparing the different treatments at Flakkebjerg or Dahnsdorf (Table 5. 5). Merely the comparison of the rotations 'DR 1' and 'DR 2' led to significantly different conclusions when considering GE yield or energy output as indicators (cf. Table 5. 4). Considering both indicators, the differences between 'P' and '$H_{8\text{-}10}$' were comparatively small on average, while considerably lower GE yields and energy outputs were obtained with 'D' at Flakkebjerg. Differences between the three herbicide treatments at the same level of tillage intensity were relatively small. However, GE yields and energy outputs tended to increase with more efficient control of *A. spica-venti*. In both rotations, the biggest gap concerning GE yield and energy output was found between the treatments 'A 70%' and 'A 90%' with tine tillage. At Dahnsdorf, the differences due to different pesticide use intensity were more pronounced, whereas significant differences between '100% HF' and '50% HF' could be proved for GE yields but not for energy output (cf. Table 5. 4).

Table 5. 5

Average yields (GE ha^{-1}) and energy outputs (GJ ha^{-1}) as related to site conditions, crop rotation, intensity of pesticide use, or tillage in the period from 2003 to 2006

Flakkebjerg		Yield (GE ha^{-1})		Energy output (GJ ha^{-1})	
Tillage	Pesticide treatment	FR 1	FR 2	FR 1	FR 2
P	AU	86.5	65.1	126.1	93.3
	A 70%	87.2	70.4	127.1	101.3
	A 90%	87.9	71.1	128.1	102.7
$H_{8\text{-}10}$	AU	83.4	60.3	121.5	87.0
	A 70%	83.7	62.8	121.9	90.6
	A 90%	89.9	72.9	131.2	105.4
D	AU	76.8	56.4	111.6	83.1
	A 70%	77.6	59.3	112.7	87.5
	A 90%	79.1	59.6	115.0	87.8
Dahnsdorf		DR 1	DR 2	DR 1	DR 2
100% HF		73.1	74.2	104.9	196.1
50% HF		66.8	71.5	95.8	188.6

5.4.3 Humus balances

In order to show the general impact of different husbandry practices on humus balances, the pesticide treatments ‘A 90%’ for Flakkebjerg and ‘100% HF’ for Dahnsdorf are shown as representing the most common pesticide strategy for the particular site. On average, all treatments of both sites revealed positive humus balances (Table 5. 6), i.e. humus replacement was higher compared with humus requirement. Mean humus balances tended to be higher at Flakkebjerg compared to Dahnsdorf. In Flakkebjerg, no straight influence of tillage on humus balances could be proved, whereas the average humus balances of rotations ‘FR 1’ and ‘FR 2’ were significantly different. No significant differences with respect to humus replacement occurred between both crop rotations at Dahnsdorf.

Table 5. 6

Humus balance (HU ha^{-1}, kg C ha^{-1}) as related to site conditions, crop rotation, or tillage in the period from 2003 to 2006

Flakkebjerg		HU ha^{-1}		kg C ha^{-1} *	
Pesticide treatment	Tillage	FR 1	FR 2	FR 1	FR 2
A 90%	P	0.18	0.07	105	43
	H_{8-10}	0.16	0.06	95	36
	D	0.08	0.08	48	49
Dahnsdorf		DR 1	DR 2	DR 1	DR 2
100% HF		0.05	0.04	30	26

* Carbon in humus, which is not subjected to primary respiration.

5.4.4 N surplus

In Flakkebjerg, the average N surplus of ‘FR 1’ was significantly lower compared with ‘FR 2’. However, differences between the tested tillage and pesticide treatments were relatively small (Table 5. 7). In both crop rotations, the average N surplus was lowest for the treatment ‘A 90%’ and highest for ’AU’. Considerably lower average N surpluses occurred at Dahnsdorf compared with Flakkebjerg. There were no significant differences between the rotations ‘DR 1’ and ‘DR 2’ at Dahnsdorf regarding N surplus. However, a significant influence of different pesticide intensity on N balances was evident (cf. Table 5. 4).

Table 5. 7

Average N surplus (kg N ha^{-1}) as related to site conditions, crop rotation, intensity of pesticide use, or tillage in the period from 2003 to 2006

Flakkebjerg		N surplus (kg N ha^{-1})	
Tillage	Pesticide treatment	FR 1	FR 2
P	AU	71.5	91.5
	A 70%	70.5	85.6
	A 90%	68.6	84.7
H_{8-10}	AU	73.7	99.4
	A 70%	73.4	95.9
	A 90%	62.6	82.9
D	AU	80.1	105.7
	A 70%	78.1	103.0
	A 90%	77.4	101.1
Dahnsdorf		DR 1	DR 2
100% HF		25.6	35.2
50% HF		38.5	41.1

5.4.5 Energy balance

Fossil energy input was lowest with direct drilling in both crop rotations at Flakkebjerg (Table 5. 8). Averaged across rotation and tillage, highest energy input was required in the ‘A 90%’ treatment. Generally, small differences could be found for the particular tillage and pesticide treatments concerning net energy output or output/input ratio. According to GE yields and energy output, relatively large differences in net energy output and output/input ratio were evident between ‘A 70%’ and ‘A 90%’ with tine tillage. Energy input of both crop rotations at Dahnsdorf tended to be higher compared with the average energy input at Flakkebjerg, while differences between ‘DR 1’ and ‘DR 2’ were small. No differences with regard to energy intensity occurred. The average net energy output and output/input ratio were, however, significantly higher in ‘DR 2’ compared with ‘DR 1’ because the energy output due to harvesting by-products, such as straw, which has been harvested in ‘DR 2’, is considered within the calculation of energy balance.

Table 5. 8

Energy balance indicators as related to site conditions, crop rotation, intensity of pesticide use, or tillage in the period from 2003 to 2006

Flakkebjerg		Energy input (GJ ha^{-1})		Net energy output (GJ ha^{-1})		Energy intensity (MJ GE^{-1})		Output/input ratio	
Tillage	Pesticide treatment	FR 1	FR 2	FR 1	FR 2	FR 1	FR 2	FR 1	FR 2
P	AU	12.2	11.4	113.9	81.8	149.3	194.8	10.3	8.1
	A 70%	12.2	11.5	114.9	89.8	149.7	188.6	10.5	8.7
	A 90%	12.2	11.6	115.9	91.1	148.8	175.3	10.5	8.9
H_{8-10}	AU	12.0	11.3	109.6	75.7	152.2	217.4	10.2	7.6
	A 70%	12.0	11.4	109.9	79.2	153.9	210.4	10.2	7.9
	A 90%	12.0	11.5	119.1	93.9	140.4	169.8	10.9	9.1
D	AU	11.1	10.5	100.4	72.6	155.1	517.5	10.0	7.8
	A 70%	11.2	10.6	101.6	76.9	160.1	440.6	10.1	8.2
	A 90%	11.2	10.7	103.9	77.1	151.7	369.8	10.3	8.2
Dahnsdorf		DR 1	DR 2	DR 1	DR 2	DR 1	DR 2	DR 1	DR 2
100% HF		12.4	12.6	92.5	183.5	203.4	211.7	8.6	17.1
50% HF		12.2	12.5	83.6	176.1	236.1	229.5	8.0	16.6

5.4.6 Estimation of risk potential due to pesticide application

For the estimation of the potential risk of terrestrial and aquatic organisms due to pesticide use at Flakkebjerg, merely the ploughed treatments and those with no tillage were considered since the treatments ‘$H_{8\text{-}10}$’ and ‘D’ received the same pesticide application. In both crop rotations at Flakkebjerg, the acute risk potential for aquatic organisms was higher with ‘D’ compared to ‘P’, whereas no differences of the acute risk potential for terrestrial organisms were estimated (Table 5. 9). No effects in regard to the acute risk potentials due to different pesticide treatments at Flakkebjerg occurred, but the chronic risk potentials for both aquatic and terrestrial organisms slightly increased in accordance with higher pesticide use intensity. At Dahnsdorf, only small differences were found between both crop rotations. However, the estimated acute and chronic risk potentials for aquatic and terrestrial organisms were consistently lower in ‘50% HF’ compared with ‘100% HF’.

Table 5. 9

Exposure toxicity ratio for the potential acute risk (ETR_{acute}) and the potential chronic risk ($ETR_{chronic}$) for aquatic or terrestrial organism due to pesticide application as affected by site conditions, crop rotation, and intensity of pesticide use (means for the period from 2003 to 2006)

Site			Aquatic organisms		Terrestrial organisms	
			ETR_{acute}	$ETR_{chronic}$	ETR_{acute}	$ETR_{chronic}$
Flakkebjerg						
Rotation	Tillage	Treatment				
FR 1	P	AU	0.0017	0.0093	0.0442	0.2612
		A 70%	0.0017	0.0094	0.0442	0.2614
		A 90%	0.0017	0.0095	0.0442	0.2616
	D	AU	0.0027	0.0097	0.0442	0.2617
		A 70%	0.0022	0.0098	0.0442	0.2619
		A 90%	0.0022	0.0099	0.0442	0.2621
FR 2	P	AU	0.0022	0.0146	0.0028	0.0280
		A 70%	0.0022	0.0147	0.0028	0.0281
		A 90%	0.0022	0.0148	0.0028	0.0282
	D	AU	0.0032	0.0164	0.0028	0.0281
		A 70%	0.0032	0.0165	0.0028	0.0281
		A 90%	0.0032	0.0166	0.0028	0.0283
Dahnsdorf						
Rotation	Treatment					
DR 1	100% HF		0.0067	0.1204	0.0281	0.2967
	50% HF		0.0034	0.0585	0.0139	0.1427
DR 2	100% HF		0.0031	0.0849	0.0365	0.3326
	50% HF		0.0018	0.0426	0.0183	0.1656

5.5 Discussion

The transferability of conclusions derived from a particular field experiment regarding the environmental effects of different husbandry is limited due to the strong impact of site conditions. Nonetheless, both field trials, which have been investigated for this paper, show a broad variety of management practices, which are important factors for the environmental impact of crop production. The long-term approach of both experiments is advantageous since varying weather conditions could mask the effects of the different treatments. It is vital to promote land management practices, which maintain or improve land productivity and a sustainable use of natural resources (BINDRABAN et al., 2000). Crop yield is an important and reliable indicator for the assessment of land productivity and the evaluation of farming systems while being considerably affected by site conditions. In general, the site Flakkebjerg holds a higher yield potential compared with Dahnsdorf owing to slightly higher soil fertility, milder climate, and more sufficient precipitation. Accordingly, GE yields were highest with continuous wheat cropping in 'FR 1'. However, yields of 'FR 2' were not superior to 'DR 1' or 'DR 2' at Dahnsdorf. One reason is probably the bad performance of winter oilseed rape in 'FR 2' with direct drilling in 2004. Low yields were obtained mainly by reason of the poor crop establishment, which could not be compensated for by the crop. Accordingly, the total yield of the entire crop rotation was impaired. This demonstrates the importance of the structural composition of the crop rotation including the suitability of included crops for different farming systems or management intensities. The small differences of GE yield or energy output caused by varying intensity of herbicide use at Flakkebjerg are probably due to fact that the experiment has been conducted for only four years and the weed to be investigated has not been present at Flakkebjerg for decades. Accordingly, after broadcasting in 2002, no herbicides against *A. spica-venti* were applied to allow the population to increase in following growing season. MELANDER et al. (2008) reported that, with exception of 2006, *A. spica-venti* population was relatively low. These authors likewise revealed that the infestation of *A. spica-venti* tended to be higher in the treatment '$H_{8\text{-}10}$' compared to 'D'. This might be an explanation for the yield gap between the target control levels 'A 70%' and 'A 90%' with non-inversion tillage while the yield differences between these herbicide treatments were lower with direct drilling. Due to the higher occurrence of *A. spica-venti* in '$H_{8\text{-}10}$', the more efficient weed control of 'A 90%' compared to 'A 70%' caused higher yield increases in '$H_{8\text{-}10}$' than in 'D'.

When changing farming practices, there can be a certain changeover time until management caused effects will significantly occur. This is especially true for shifting of weed population dynamics due to different management and weed control strategies (PALLUTT and GRÜBNER, 2004), changes of soil organic C and nutrient stocks as a result of different fertilizer managements (PERSSON and KIRCHMANN, 1994; CAMPBELL et al., 2000), or changed mineralization rates of C and N caused by reduced tillage intensity (FRANZLUEBBERS et al., 1995; RILEY, 1998). We suppose that no overall conclusions in regard to the tested treatments can be given deduced from the results of the first four experimental years at Flakkebjerg and further investigations are needed. The field experiment at Dahnsdorf was established in autumn of 1995. Noteworthy changes in population dynamics of weeds due to different weed control strategies and associated effects on yield have been observed accordingly (e.g. PALLUTT, 2002; DEIKE et al., 2006a; DEIKE et al., 2008b; PALLUTT and MOLL, 2008). Nevertheless, the heterogeneity of the soil and the different crops grown led to considerable variations of GE yield or energy outputs, which cannot be attributed to the treatments tested. Due to the middle rate soil fertility, the yield potential is furthermore often restricted by insufficient precipitation at the end of spring or in early summer in excess of less effective pest, disease or weed control. This was true in particular for the very dry year 2003.

C and N fluxes in agriculturally used soils are closely linked to each other and affect the environmental effects of farming systems to a large extent. Humus depletion may cause increased carbon dioxide release (COLE et al., 1997; KIRSCHBAUM, 2000; KÜSTERMANN et al., 2008) and greater N leaching (HANSEN et al., 2007). Furthermore, increased mineralization rates on account of high SHC can also enlarge the potential of N losses (PERSSON and KIRCHMANN, 1994). In general, humus requirement was larger in Dahnsdorf compared with Flakkebjerg since the higher sand content as well as the lower clay content of the soil at Dahnsdorf is the reason for higher humus mineralization. Humus replacement, however, could be satisfied for 'DR 1' and 'DR 2', although the structure of both crop rotations is fairly different. In the arable crop rotation 'DR 1', humus replacement is implemented by manuring straw of cereals and oilseed rape as well as by growing peas as SHC increasing legume crop. In contrast, growing silage maize and completely harvesting cereal straw lead to decreasing SHC in 'DR 2'. Nevertheless, cropping of alfalfa/clover/grass-mixture and the application of farmyard manure to silage maize seem to cover the arising humus requirement. On average, higher humus replacement rates were found for Flakkebjerg compared with Dahnsdorf since in 'FR 1' and 'FR 2' straw of cereals or oilseed rape is chopped and left on the soil surface throughout. Moreover, pig slurry is applied to each crop in each year. Humus replacement was better in 'FR 1' compared to 'FR 2' because higher by-product yields as a result of higher grain yields in 'FR 1' were obtained. In addition, comprising oilseed rape cropping within 'FR 2' provides smaller amounts of organic matter in terms of straw being furthermore of minor use for humus replacement due to its matter composition. PERSSON and KIRCHMANN (1994) likewise emphasized the importance of the amount and quality of organic raw material for humus replacement.

As shown, humus balance directly affects the amount of N surplus by changing SON. Thus, the mean N surplus of 'DR 1' tended to be lower compared to 'DR 2' because of harvesting cereal straw in 'DR 2' whereby humus requirement was not covered in the particular growing seasons and, therefore, additional N from SON boosted the average N surplus of 'DR 2'. Moreover, the application of farmyard manure to silage maize in 'DR 2' as opposed to 'DR 1', where mineral N fertilizers were used exclusively, impaired the N balance of 'DR 2' since the N use efficiency of organic fertilizers is generally lower compared with inorganic fertilizers (SMITH and CHAMBERS, 1992; SIELING, 2005). Due to the continuous slurry application, this may also be one reason for the high N surpluses at Flakkebjerg. As relatively low yield differences between 'P' and 'H_{8-10}' were found, their N surpluses exhibited small differences as well. This is according to investigations of SIELING and KAGE (2006) who compared reduced tillage and ploughing under similar site conditions. The influence of pesticide use intensity on the N surplus was comparatively low, which is in accordance with investigations of ELTUN et al. (2002) and DEIKE et al. (2006a; 2007) with respect to N runoff or N balance, respectively. Nevertheless, compared to crops without pesticide application, reducing yield losses caused by weeds, fungal diseases, and harmful insects increases N use efficiency and, accordingly, decreases the amount of N potentially subjected to leaching or other loss pathways (DEIKE et al., 2006a; 2007).

The influence of different pesticide use intensity on the potential endangerment of aquatic and terrestrial organisms, expressed in ETR, was of minor importance as well. In general, acute and chronic risk potentials due to pesticide application were low for both sites and all treatments investigated although being calculated by assuming a worst-case scenario when applying. This is true for the majority of pesticide applications on arable farms if national requirements and orders are considered as a result of principally avoiding the application of highly toxic compounds as well as because of relatively low application frequencies compared to growing fruits or vegetables (STRASSEMEYER, personal communication). At Flakkebjerg, there were no differences in acute risk potential for aquatic and terrestrial due to fact that the highest ETR is triggered by the combination of most toxic compound and highest dosage which was hence not given by the herbicides applied against *A. spica-venti*. By reason of the moderately low toxicity of the herbicides used to control *A. spica-venti*, chronic risk potentials were marginally affected as well. Albeit identified to be on a very low level in general, at Dahnsdorf acute and chronic risk potential were much lower for '50% HF' compared to '100% HF' since, with exception of growth regulators, application rates reduced by 50 per cent were applied for all pesticides as opposed to reducing only herbicide dosages at Flakkebjerg.

Besides fuel, fertilizers and pesticides are regarded as major sources of energy use in conventional agriculture (WOOD et al., 2006). In particular, the utilization of N fertilizers represents a large contribution to the total energy input (e.g. KUESTERS and LAMMEL, 1999; MOERSCHNER, 2000; HÜLSBERGEN et al., 2001; DEIKE et al., 2008a). In our investigations, this was evident when comparing energy inputs of ‘FR 1’ and ‘FR 2’ at Flakkebjerg. Fossil energy input was significantly lower in ‘FR 2’ compared to ‘FR 1’ as the average application rates of mineral N fertilizers in ‘FR 2’ were lower attributable to the smaller N fertilizer input in winter barley cropping. Due to this fact, DEIKE et al. (2008a) as well as RATHKE et al. (2007) accentuate the great importance of N use efficiency for obtaining high energy efficiency. The different intensities of pesticide use impaired energy input only to a small extent, even though it was considered that energy requirements for harvest in treatments with more intensive pesticide use were higher due to generally higher yields obtained. However, DEIKE et al. (2008a) emphasized that the utilization of pesticides is of minor importance with regard to energy input, but of considerable importance for energy output due to increased biomass harvested. Former investigations of the experiments conducted in Dahnsdorf demonstrated, moreover, that energy efficiency expressed by net energy output or energy intensity was significantly enhanced in treatments with situation-related pesticide use compared to treatments without pesticide application (DEIKE et al., 2006b; 2007). Reduced tillage intensity at Flakkebjerg decreased total energy input to a smaller extent as expected. Energy requirements for tine cultivation ($H_{8\text{-}10}$) were only slightly lower compared with conventional ploughing tillage. However, energy input for direct drilling was reduced by 8 per cent compared with ploughing. By using the same energy balance approach, RATHKE et al. (2007) found 16 per cent lower energy inputs for direct drilling compared to ploughing in a corn-soybean system. Compared with ploughing, BORIN et al. (1997) recorded energy requirements to be 10 per cent and 32 per cent lower with tine cultivation and direct drilling, respectively. O’CALLAGHAN (1994) stated that the energy savings due to tillage are less important in comparison with the other required energy inputs when comparing conventional and direct-seeding tillage methods. Accordingly, the comparatively low differences between ‘P’ and ‘$H_{8\text{-}10}$’ at Flakkebjerg are probably on account of totally omitting stubble cultivation and shallow ploughing in ‘P’, which significantly reduced energy requirements for ‘P’.

The yields obtained significantly affect the energy balance. Owing to the relatively small yield differences due to different tillage practices or pesticide use intensity, the impact of these measures on energy efficiency was of minor importance. Particularly net energy output and output/input ration were influenced to a much greater extent by the structure of the crop rotation, implying the yield potential of the crops grown and their suitability for the given site conditions. In general, energy efficiency seems to be higher in well-balanced crop rotations containing diverse crops, while the integration of legumes into crop rotation increases energy utilization in particular (FRANZLUEBBERS and FRANCIS, 1995; LI et al., 2002; RATHKE et al., 2007). Nevertheless, net energy output and output/input ratio at Flakkebjerg were higher with continuous wheat cropping (‘FR 1’) compared with ‘FR 2’ containing winter barley – winter oilseed rape – winter wheat – winter wheat despite negative phytopathological effects probably occurring in such monocultures and, moreover, with reduced tillage or direct drilling. Harvesting by-products of crops, such as cereal straw in ‘DR 2’ at Dahnsdorf, can significantly enhance the energy balance of several cropping systems. This should be taken into account when considering growing demands for biomass to generate renewable energy.

5.6 Conclusions

The structure of the crop rotation, implying the yield potential of the crops contained in and their suitability for the given site conditions, affects the resource efficiency and the environmental effects of arable farming to a large extent. Productivity will increase whereas the potential risk of environmental endangerments will decrease if crops are grown, which are well-adapted to the site-specific conditions and properties of the farming system since obtaining high yields with lower rates of fertilizers, pesticides, or fuel. Besides the site-specific and climatic conditions and the use of organic manures, the crops grown are, moreover, of utmost importance for humus replacement, which significantly influences soil fertility and the global warming potential of the farming system.

The application of production means must be generally adapted to the actual requirements of the crop to minimize possible negative environmental effects while obtaining high efficiency of resource use. Fertilizers have to be applied according to the actual crop need. Furthermore, it is necessary to include organic fertilizers into the fertilization strategy to obtain high N use efficiency. High N use efficiency is essential to reduce N losses and required to attain high energy use efficiency. One possibility to reduce energy consumption associated with maintaining high energy efficiency, may therefore be to reduce soil tillage intensity if yields and, accordingly, N efficiency are not significantly decreased compared with conventional ploughing tillage. On the other hand, pesticide use intensity may increase when reducing tillage intensity.

In general, pesticide use can be seen as an integrative measure within the productivity of crop production but as well concerning possible environmental effects. Situation-related pesticide use will reduce yield losses caused by weeds, fungal diseases, and harmful insects, whereby energy and N use efficiency will be enhanced significantly. The risk potential directly affected by pesticide application seems to be low in arable farming if national requirements and orders concerning pesticide application are considered and, in particular, if principles of Integrated Pest Management are followed. The reduction of pesticide use intensity, however, decreases the potential risk of environmental endangerments.

If reducing production intensity without significant yield losses, the overall efficiency of the farming system will increase and the possible endangerments of the environment will decrease. The investigations showed that, in fact, there is a certain potential for the reduction of fertilizer application, pesticide use or tillage intensity. Nevertheless, reducing the application rates of production means must not compromise the sustainable productivity of the farming system. In this connexion, long-term effects have to be taken into account since changes of soil nutrient stocks and nutrient dynamics as well as the shifting of the population dynamics of weeds or soil borne diseases due to different crop rotations or reducing tillage intensity, pesticide use, and fertilizer application take a number of years to develop.

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6 GENERAL DISCUSSION

6.1 Suitability of material and methods used

6.1.1 Experimental basis

It is vital that the investigations concerning this topic be based on experiments which are conducted under identical site and weather conditions as well as within the same time-frame and by using the same balance and assessment methodology, thus permitting a valid comparison across all varied management practices. Owing to the considerable influence of site conditions and regional pedo-climate factors with respect to yields and environmental effects (PACINI et al., 2003), these recommendations should be considered in particular when comparing different husbandry systems, such as integrated and organic farming. At Dahnsdorf, one integrated and one organic farming systems had been tested since 1995. This provided a substantial database for the investigations given in chapter 4. Due to its moraine origin, the experimental site Dahnsdorf shows, however, a high spatial variability of soil properties, often at a small scale. The varying soil fertility significantly affects the yield of each plot and, for that reason, the effects of the treatments tested. This is especially true for plots with poor soil quality since prolonged dry periods at the end of spring and in early summer associated with high temperatures frequently occur. Furthermore, the analysis and interpretation of the results of the integrated farming system have been intricate for the first experimental period from 1997 to 2001, as the application rates of mineral N fertilizer were reduced by 50 per cent in addition to reducing the pesticide use intensity by half. Hence, the effects observed could often not be clearly attributed to the respective measures. The period from 1997 to 2001 has been investigated separately from the subsequent period starting in 2002, as a comparison of both treatments with different pesticide use intensity or application rates of mineral N fertilizers was included.

Since the influence of most farming practices mentioned cannot be clearly assessed before several years have past, it is, moreover, advantageous to implement the investigations under a long-term approach. Probably, the duration of the Danish experiment at Flakkebjerg, which was established in autumn 2002, is, up to now, not sufficient to conclusively assess the varied factors crop rotation, tillage intensity and control of *A. spica-venti* (cf. chapter 5.5). Particularly, when comparing the different control levels of *A. spica-venti*, further investigations are required since this weed has not been present at Flakkebjerg for a long time. In this connexion, PALLUTT and GRÜBNER (2004) reported that significant long-term effects with respect to weed density and species composition as a result of different husbandry occur after 5 years at the earliest. These authors recommend an operating time up to 20 years to completely resolve problems concerning the effects of different management practices on the population dynamics of weeds. Generalizing conclusions derived from field experiments can hardly be extrapolated to other farming systems under different site and husbandry conditions (TAUBE et al., 2005). Though the two experimental sites investigated are representative for a comparatively broad range of arable sites in Germany or Denmark, there is no overall transferability of the results obtained and, accordingly, the given conclusions have to be verified for different sites.

6.1.2 Used balance and assessment approaches

In contrast to the majority of **N balance** methods, the approach used for this investigation includes N depositions as well as the amount of mineralized or immobilized N due to the change of soil organic N. Although representing a significant contribution to N supply in general, N deposition is often not taken into account within common N balances. However, particularly organic and other low-input farming systems benefit from the amount of available N due to dry and wet N deposition (GOULDING et al., 1998). On the other hand, it is not easy to assess its value and timing and, therefore, N deposition is difficult to include into patterns of N fertilizer application. SALO and TURTOLA (2006) argue that the poor relation of N surplus and N losses is due to the fact that N mineralization is not considered within the calculation of N surplus. Within this method of N balancing, the change of soil organic N is estimated by linking the N balance approach to the **humus balance** (cf. chapter 1.3). The amount of mineralized or immobilized N from soil organic matter derived from this method of humus balancing is, however, associated with a certain degree of uncertainty. As opposed to the general assumption of this humus balance approach, N turnover is not only influenced by the humus replacement of the crops grown and their yields obtained, but also by the pH and the enzymatic activity in the soil, its content of organic matter, its physical and chemical properties and, to a large extent, by the climatic conditions (HELLER, 1999). Indeed the impact of soil properties is taken into account by considering soil quality by means of the German Soil Classification System as well as soil texture (HÜLSBERGEN, 2003). For a more accurate estimation of humus and N turnover, more sophisticated C/N simulation models would be needed. Such models often require further input data not available for the majority of commercial farms or even field experiments. Taking this into account, the approach used for these investigations seems to be an appropriate tool for the calculation of humus balances and the derived changes of soil organic N. Nevertheless, further development is needed. In particular, a model validation on sandy soils and an adaptation to the characteristics of organic farming is required (BROCK and LEITHOLD, 2007). Furthermore, by-product yields and the amount of crop residues influence the humus balance calculations. Both are determined as related to the main product yields.

This assumption is true in general, whereas a certain inaccuracy may occur if estimating by-product yields of crops with different fungicide application. Even though JØRGENSEN and OLESEN (2002) found a weak correlation for the yield increases of grain and straw due to fungicide application, this assumption must be verified for dry regions where only one fungicide dressing is applied around ear emergence, such as in the majority of cases at Dahnsdorf. In addition, by-product yields as well as other crop residues are strongly affected by the grown cultivar, the site-specific conditions and management practices. Nevertheless, as no straw or stubble yields were measured, mean values calculated by REPRO as related to the grain yield were used.

The method of **energy balancing** is according to the process analysis (JONES, 1989; cf. chapters 3.3, 4.3, and 5.3), which is considered to be an appropriate and accurate approach to investigate energy balances of farming systems (HÜLSBERGEN et al., 2001). The suitability of this method and the energy equivalents included are discussed in detail in chapter 4. Energy equivalents must be adapted to regional conditions and improvements in manufacturing (BONNY, 1993; UHLIN, 1999), which has been the case for mineral fertilizers (HÜLSBERGEN, 2003). The energy equivalents for organic manures are evaluated by using mineral fertilizer equivalents that correspond to the fertilization effect of manure compared with mineral fertilizer according to HEYLAND and SOLANSKY (1979). Considering the highly varying husbandry of livestock keeping including the different substrate properties as well as the different storage and management techniques of organic fertilizers, it can be supposed that the actual energy requirements for the production of organic fertilizers cannot be accurately estimated by using this approach. Accordingly, further investigations with respect to this aspect are necessary. For pesticides fairly old and unspecific values according to GREEN (1987) are predominantly used. If available, indeed further specifications were made for certain compounds. In the **C balance** approach, there is even no specification for the different products of plant protection and the C emission factor is, moreover, calculated related to the amount of the finished product, which can lead to significant impreciseness due to the varying contents of active ingredients within the pesticides (GEMIS, 2002; cf. chapter 3.3). Since the C balance is linked with the humus balance approach to estimate the C sequestration or emission of the soil, the uncertainties within the calculation of the humus balance shown above are transferred into the carbon balance approach as well.

The maintenance and enhancement of biodiversity in agricultural systems is regarded as an essential principle of sustainable resource use (STINNER et al., 1997). However, particularly the application of pesticides might significantly affect agro-ecosystems (GUTSCHE and ROSSBERG, 1997). As in field experiments, a biodiversity assessment can be valued only with great difficulty, the model **SYNOPS,** which estimates the risk potential of pesticides regarding the biotic environment, was chosen as a representative indicator for the evaluation of different strategies of pesticide application. Nevertheless, the actual loads and impairments owing to pesticide application can hardly be derived from the risk potentials calculated by SYNOPS. This is mainly due to the fact that the data SYNOPS is based upon have been generated under laboratory conditions for the most part (GUTSCHE and STRASSEMEYER, 2007). On the other hand, it seems to be appropriate to compare different strategies of pesticide use with respect to their risk potentials under identical site and weather conditions and to assess different scenarios and patterns of pesticide application.

6.2 Influence of pesticide use intensity

6.2.1 Effect on N use efficiency

Information on the effect of different pesticide use intensity on N balances is scarce. In Norway, KORSÆTH and ELTUN (2000) and ELTUN et al. (2002) investigated the N runoff of one arable and one forage farming systems, each with conventional and integrated husbandry. Both pesticide use intensity and the application rates of mineral N fertilizer were lower in the integrated systems compared with conventional husbandry while each arable and forage farming system had the same crop rotation, respectively. In both rotations, lower N runoff was found with integrated husbandry compared to conventional management although the average N uptake was higher in the conventional farming system. However, just as in the first experimental period at Dahnsdorf when pesticide use intensity and the application rates of mineral N fertilizers were halved at the same time, the effects on N surplus or N runoff cannot be clearly ascribed to one single measure (cf. chapter 2.5). The average reduction of the N surplus at Dahnsdorf due to herbicide application, was greater in the second experimental period (2002-2005) compared with the first period (1997-2002) in all cereal crops and for both intensity levels of herbicide application (cf. chapter 2.4). As weed infestations and the according yield increases were comparatively small in the first experimental period, the decrease of N surplus was low after herbicide application while increasing with greater yield increases as a result of the significantly higher weed infestation in the second period. Generally, the lowest decrease of N surplus was observed for winter rye, whereas it was highest in winter wheat cropping. Resulting from its high competitive ability, weed growth was strongly suppressed. Thus, the yield increase due to herbicide application and, accordingly, the additional N uptake were fairly small in winter rye cropping. Particularly with low weed infestation intensive herbicide use is rarely worthwhile. In the first experimental period, the competitive ability of the crops which received halved application rates of herbicides was, however, impaired as a result of reducing the application rates of mineral N fertilizers at the same time (cf. chapters 2.3 and 2.5). Therefore, considerable decreases of N surplus have been caused by the application of herbicide dosages reduced by 50 per cent in this period, though weed infestation was relatively low. In accordance with former investigations (COURTNEY, 1991; PALLUTT, 2000), this points out the importance of the interactions between the competitive ability of crops and weed growth and development. Minor differences in regard to N surplus were recorded between the different target control levels of *A. spica-venti* at Flakkebjerg in the period from 2003 to 2006 (cf. chapter 5.3) mainly on account of the comparatively low occurrence of *A. spica-venti* after first introducing it in 2002, which led to small yield differences following the different herbicide treatments (MELANDER et al., 2008). On the other hand, greater differences in yield and N surplus were recorded between the 70 per cent and 90 per cent control level of *A. spica-venti* with tine tillage where the infestation of *A. spica-venti* was highest.

In a 9-year lasting field trial with varying application rates and timings of mineral N fertilizer and pig slurry, SIELING and KAGE (2006) calculated an average decrease of N balance through fungicide application for winter oilseed rape, winter barley and winter wheat amounting to 6, 17, and 23 kg N ha^{-1}, respectively. In winter barley and winter wheat cropping, HANUS and FAHNERT (1987) reported reductions of the N surplus due to fungicides from 40 to 80 kg N ha^{-1}. As there is a relatively tight correlation between yield and N uptake, a similar decrease in N surplus can be expected following the yield increases of winter wheat owing to fungicide application given by JØRGENSEN et al. (2000), which amounted up to 2.7 t ha^{-1}. At Dahnsdorf, the average reduction of the N balance due to fungicide application was generally lower as a result of the relatively small yield increases. During the experimental period from 1997 to 2005, a yield increase after fungicide application in winter wheat being greater than 1 t ha^{-1} only occurred in 2002 (JAHN and PALLUTT, 2006). This was mainly on account of the resistant cultivar grown. Furthermore, the prolonged dry periods frequently occurring in spring and early summer may have significantly reduced the further development of fungal diseases. However, yield responses in this dimension were found more often in winter rye and winter barley cropping mostly after controlling *Puccinia recondita* and *Drechslera teres*, respectively (JAHN and PALLUTT, 2006). Indeed the average yield increases due to fungicide application itself were comparatively low during the entire experimental period, there has been, however, a positive additional effect with respect to yield and N surplus when both, herbicides and fungicides, were applied during the respective growing period. This interaction of herbicide and fungicide application with respect to yield or N surplus generally exceeded the sum of each particular effect when herbicides and fungicides were applied separately (cf. chapter 2.4). It has occurred to a larger extent with the situation-related pesticide use than with the application rates reduced by 50 per cent. In general, however, the differences concerning yield and N surplus between the situation-related application rates of pesticides and the halved dosages were smaller compared with the gap between the situation-related pesticide use and the treatments without any pesticide application (cf. DEIKE et al., 2005). Thus, it can be concluded that pesticide use is of fundamental importance in regard to N use efficiency, and refraining from it may significantly increase the potential of N losses, whereas a slight reduction of the pesticide use intensity would affect the N use efficiency to a lesser extent, particularly with low weed, pest, or disease infestation.

6.2.2 Energy balance as affected by different strategies of pesticide use

WOOD et al. (2006) advanced the hypothesis that fossil energy requirements would significantly decrease if conventional agriculture were converted to organic husbandry. These authors particularly accounted pesticide use to be a major source of energy use in conventional farming. In contrast, SWANTON et al. (1996) supposed that refraining from herbicide application may significantly increase energy consumption through more intensive soil tillage and mechanical weed control. Although the manufacturing of pesticides is fairly energy intensive (GREEN, 1987), their contribution to the total energy input is relatively small because of low application rates (CLEMENTS et al., 1995). Numerous investigations have shown that pesticide use generally represents only a small proportion of the total energy input in crop production. Usually, the manufacturing and application of pesticides is accountable for 3 to 11 per cent of the fossil energy requirements (ZENTNER et al., 1989; UHLIN, 1999), which is in accordance with the investigations presented in chapter 4.4. On the other hand, if crops are grown without applying mineral N fertilizers, such as legumes, the share of pesticide use in the total energy input increases. Thus, CLEMENTS et al. (1995) found the proportion of energy input in soybean cropping which is accountable for pesticide manufacture and application to be 23 per cent. RATHKE et al. (2007) even reported a share of pesticide use amounting to more than 30 per cent of the total energy input in soybean cropping as a result of adopting direct drilling. Thereby energy consumption was further decreased while the relative share owing to pesticide use increased accordingly.

Besides energy input and carbon dioxide emissions, the application of pesticides notably affects the energy output of arable farming by increasing the yield of main and by-products. The efficiency of pesticide use in regard to energy balances is therefore strongly influenced by a complex interaction of the crop grown, the crop rotation effects, the site-specific conditions, and the given pest infestation level. Hence, for the experiment at Dahnsdorf, significant differences in energy efficiency between the treatments with herbicide application and the untreated controls did not constantly appear before a time period of 4, 5, and 6 years in winter wheat, winter barley, and winter rye cropping, respectively (cf. chapter 3.4). This is due mainly to the comparatively low initial weed infestation and, thus, to the low yield differences between the treatments with and without herbicide application. Indeed, herbicide application significantly increased the carbon dioxide emissions of cereal cropping. On average of winter barley, winter rye and winter wheat the carbon dioxide emissions per unit of product were, however, by 35 per cent lower with herbicide application compared to the untreated control. The intensity of pesticide use seems to be of minor importance with respect to energy efficiency as long as the differences in energy output are small. In the experimental period from 2003 to 2006, no significant differences in energy efficiency were recorded, neither for the comparison of situation-related pesticide use and application rates reduced by 50 per cent at Dahnsdorf, nor for the different target control levels of *A. spica-venti* at Flakkebjerg (cf. chapter 5.3). However, former investigations of the experiment at Dahnsdorf showed that net energy output was significantly higher and energy intensity was lower with situation-related pesticide use compared to treatments without pesticide application (DEIKE et al., 2006b; 2007).

6.3 Impact of fertilizer application

6.3.1 Effects of different fertilizer regimes on yields and N use efficiency

The fertilizer regime including the use of organic manures and mineral fertilizers, their application rates and the timing of the fertilizer dressing as well as the inherent N use efficiency of the crop or cultivar grown are of utmost importance with respect to yield and potential losses from arable soils. Assessing the efficiency of N fertilizer application, N balance has been identified as an essential agri-environmental indicator (OECD, 2001). Data for calculating N balances are rather easily available, and it is therefore a convenient and low-cost indicator for estimating potential environmental effects, particularly N leaching (SALO and TURTOLA, 2006). However, the derived indicator N surplus only shows the potential pollution but not the actual degree of pollution (PARRIS, 1998). N surplus is regarded as a good indicator of potential losses if set up over a longer period (ÖBORN et al., 2003), although there is often no linear relationship between N surplus and N leaching when investigated in the short-term (SALO and TURTOLA, 2006; SIELING and KAGE, 2006). In order to reduce N leaching from agricultural soils, it is necessary to supply the crop with N when it is needed and to avoid large amounts of N in soil during autumn and winter when no crop is growing (TORSTENSSON et al., 2006). This is in accordance with investigations of SIELING and KAGE (2006) who stated that most of the N leached from arable soils originates from inorganic N present in late summer, autumn or early winter when soils start to drain and plant demand is low or non-existent. There is, moreover, a generally high risk of N losses with crops whose uptake starts relatively late, such as potatoes or maize (VAN FAASSEN and LEBBINK, 1994).

The investigations of the experiment at Dahnsdorf concerning the effects of different strategies of weed control showed differences due to the altered fertilizer regime for the experimental periods from 1997 to 2001 and 2002 to 2005, respectively (cf. chapter 2.4). In the second experimental period, the average decrease of the N surplus of all cereal crops investigated was greater with situation-related herbicide application compared with application rates reduced by 50 per cent. However, with the exception of winter wheat, the decrease of the N surplus was higher with the reduced application rates in the period from 1997 to 2001. Furthermore, the N surplus was significantly lower with application rates reduced by 50 per cent than with the situation-related herbicide dosage in the first period, which was mainly due to the fact that the application rates of mineral N fertilizers were also halved in the treatments with reduced intensity of herbicide use (DEIKE et al., 2004). Several authors reported correspondingly that N use efficiency decreases with increasing N supply while it increases if N availability is limited (e.g. DELOGU et al., 1998; BEHRENS et al., 2003; RATHKE et al., 2006). Limited N supply is not generally associated with yield losses. Particularly cereal crops respond to insufficient N supply primarily by lowering the protein content in the grain while considerable yield losses occur not until N availability is significantly reduced (FEIL, 1998). This effect could be also recorded for the first experimental period at Dahnsdorf. Accordingly, significant yield differences between the treatment with situation-related herbicide use plus site-specific application rates of mineral N fertilizer and the treatment with halved application rates of herbicides and fertilizers rarely occurred (DEIKE et al., 2004; cf. chapter 2.4).

It is essential to consider the nutrients from organic manures within the fertilization strategy in order to obtain high N use efficiency and to reduce potential N losses. In general, the nutrient use efficiency of organic fertilizers is generally lower due to the often poor synchronicity between release of inorganic N from the manures and N uptake by the crop (SMITH and CHAMBERS, 1992; MCLAUGHLIN et al., 2000; SIELING, 2005; TORSTENSSON et al., 2006). On the other hand, the application of organic manures is important for maintaining the content of soil organic matter (VAN FAASSEN and LEBBINK, 1994). Furthermore, the requirements of several macro and micro nutrients can often be covered by the balanced use of organic fertilizers. Both can significantly improve yield performance and soil fertility. Organic fertilization is, however, often conceived to be more difficult to manage than mineral fertilization (THOMSEN et al., 1993), which contributes to lower N use efficiency compared with the exclusive application of mineral fertilizers. Serious problems may arise from the use of organic manures and slurries, which are applied to the stubbles on arable land after harvest, when no plant uptake occurs (SIELING and KAGE, 2006). This was not the case for the experiment at Flakkebjerg, where pig slurry was applied to each crop in both rotations (cf. chapter 5.3). The amount of N contained in the slurry was, moreover, taken into account when applying the remainder N in the form of mineral N fertilizer. Nevertheless, the generally lower N use efficiency of this manure compared with mineral N fertilizers is probably the reason for the comparatively high N surpluses which significantly exceeded the N surpluses of the arable crop rotation and the fodder crop rotation tested at Dahnsdorf where organic fertilizers were not applied or used to a much lesser extent, respectively (cf. chapter 5.3).

6.3.2 Influence of fertilizer application on the energy use efficiency

Mineral fertilizers, and N fertilizers in particular, significantly affect the energy input and, owing to their strong effects on crop yield, the energy output of arable farming systems. The strong influence of mineral N fertilizers on the energy input was clearly evident when comparing the integrated and the organic farming systems at Dahnsdorf shown in chapter 4. In the first experimental period from 1997 to 2001, the energy inputs for winter wheat, winter rye, and the entire crop rotation were significantly higher with situation-related pesticide use compared with the treatments where the application rates of pesticides and fertilizers were reduced by 50 per cent (cf. chapter 4.4). On the other hand, the latter treatment required significantly more energy than the organic farming system, where no mineral fertilizers were used at all. In the literature, generally lower energy inputs have also been recorded as well for organic arable farming systems versus integrated or conventional farming for which refraining from using mineral fertilizers is mostly accounted for (e.g. BERARDI, 1978; PIMENTEL et al., 1983; ALFÖLDI et al., 1995; ALFÖLDI et al., 1999; DUBOIS et al., 1999; DALGAARD et al., 2001; MÄDER et al., 2002; KELM et al., 2003; HELANDER and DELIN, 2004; WOOD et al., 2006). The importance of mineral N fertilizer with regard to energy input could also be confirmed when comparing the continuous winter wheat cropping (FR 1) and the rotation containing winter barley – winter oilseed rape – winter wheat – winter wheat (FR 2) at Flakkebjerg (cf. chapter 5.4). Compared with winter wheat or winter oilseed rape, winter barley received considerably smaller inputs of mineral N fertilizer. Thus, total energy input of ‘FR 1’ was higher compared to ‘FR 2’. However, determining the energy input of the crops grown in the Danish experiment, systematic impreciseness may result from the uncertainty of assessing organic fertilizer (cf. chapter 6.1.2).

However, the effects of different fertilizer regimes on energy output and, accordingly, on net energy output, energy intensity, and output/input ratio cannot be clearly assessed on the basis of the experiments at Dahnsdorf and Flakkebjerg. In the latter experiment, the application rates of mineral and organic fertilizers were not varied in the respective crops. At Dahnsdorf, the N fertilizer and pesticide application rates were halved in the extensive treatments at the same time in the period from 1997 to 2001. Thus, meaningful conclusions with regard to yields or energy efficiency can hardly be deduced from this comparison due to the interactions between pesticide use and fertilizer application, which most likely occurred. On the other hand, fairly reliable estimates regarding the influence of fertilizer application on energy input can be given as both application rates and the energy equivalent for the production of mineral N fertilizer are known. Since mineral fertilizers, just as all other energy inputs in crop production, require fossil energy for their production which is associated with direct negative environmental effects in terms of atmospheric emissions of carbon dioxide and other combustion gases, an increased fertilization must lead to a sufficient increase in yield to justify additional emissions and to be environmentally favourable (GAILLARD and NEMECEK, 2002; CHARLES et al., 2006). Several studies have shown a strong positive relationship between increasing N fertilizer rates and the total energy input (e.g. KUESTERS and LAMMEL, 1999; HÜLSBERGEN et al., 2001; RATHKE and DIEPENBROCK, 2006). Due to this strong effect on energy input, RATHKE et al. (2007) emphasized that improved N use efficiency will enhance the energy efficiency of crop production systems, which could be confirmed by our investigations (cf. chapter 4.5).

When assessing the energy efficiency as related to different application rates of N fertilizers, using energy gain, energy intensity and output/input ratio as indicators may lead to different conclusions. Averaging across all crops within a rotation containing sugar beet, potatoes, winter wheat, winter barley and spring barley, HÜLSBERGEN and DIEPENBROCK (2001) calculated lowest values for energy intensity at much lower mineral N fertilizer rates needed for achieving the site-specific yield potential. RATHKE and DIEPENBROCK (2006) found 240 kg N ha^{-1} to be the most favourable N rate for maximising energy gain of winter oilseed rape, while the N fertilization needed for minimum energy intensity was 80 kg N ha^{-1} and for maximum output/input ratio was 0 kg N ha^{-1}. Investigating several crops, KUESTERS and LAMMEL (1999) and HÜLSBERGEN et al. (2001, 2002) reported correspondingly that there is a positive relationship between energy gain and N fertilization up to a site- and crop-specific maximum, whereas the highest output/input ratios were achieved at low production intensities and declined with increasing production intensity. Thus, the most appropriate indicator must be determined according to the respective problem. However, in order to assess environmental as well as productivity aspects, all energy balance indicators mentioned should be taken into account (cf. chapter 1.2.1).

6.4 Effects of soil tillage intensity

6.4.1 Agronomical and plant protection aspects

A current trend in arable farming is the increased application of reduced or conservation tillage practices, mainly to reduce soil erosion (MARTENS, 2000) and to decrease the requirements for manpower and fossil energy (DEIKE, 1982; TEBRÜGGE and BÖHRNSEN, 1997). Further positive effects are the stabilization of soil structure by accumulating organic matter in the upper soil layer (LAL, 1998) and improved trafficability (LEBERT et al., 2006). ROSNER and KLIK (2005) reported, moreover, that losses of N, phosphorus and pesticides due to leaching or soil erosion decreased with conservation tillage and, to a greater extent, with direct drilling (no-till). Particularly in semi-arid climates, water conservation is one more reason to adopt reduced tillage or no-till (LARNEY and LINDWALL, 1994).

Even though the acreage is continuously increasing, the total percentage of conservation tillage is comparatively low in maritime climates, such as in Denmark. In particular, the implementation of direct drilling is of minor importance. As opposed to the numerous benefits when adopting reduced tillage practices, several phytopathological, herbological, and agronomical problems may occur. No-till or conservation tillage systems often require increased pesticide use due to higher infestation levels of pests, diseases and weeds (CANNEL and HAWES, 1994). Moreover, non-inversion tillage can lead to severe mice and slug infestations (BARTELS, 2002). Large amounts of crop residues left on the soil surface may also reduce the yield as a result of disease transmission (MILLER et al., 1998; KOCH et al., 2006). For instance, *Fusarium* spp. (BAILEY and DUCZEK, 1996; MILLER et al., 1998; KREBS et al., 2000) and *Drechslera tritici-repentis* infections (BARTELS and RODEMANN, 1998; KREYE et al., 1998; VON KRÖCHER, 1998) are often serious problems in reduced tillage systems because the survival of the pathogen almost entirely depends on crop residues of cereals or maize (OBST, 1988; DILL-MACKY and JONES, 2000).

MELANDER et al. (2008) supposed that without the weed management benefits of more tillage-intensive practices, reduced tillage systems often have a greater reliance on herbicides, which can result in weed populations dominated by only a few species, often grass species. This is in accordance with results given by PALLUTT (1999) who found that *A. spica-venti* was strongly promoted by non-inversion tillage and continuous winter cereal cropping. Furthermore, problems with *Bromus* spp. (ORSON, 1991; BALGHEIM and KIRCHNER, 1998) and *Alopecurus myosuroides* (KNAB and HURLE, 1988;

WILSON et al., 1989; AMANN, 1991) may occur due to reduced tillage practices. Depending on site conditions, the structure of the crop rotation and the initial weed infestation, the density of several dicot weeds, such as *Centaurea cyanus*, *Galium aparine*, and *Matricaria* spp., may also increase as a result of conservation tillage (PALLUTT and GRÜBNER, 2004). It can be supposed that the structure of the crop rotation including the associated influence on pest and disease infestation and weed occurrence is of major importance for farming systems practicing reduced tillage. Accordingly, SOANE and BALL (1998) reported that particularly no-till was less successful in conditions of high weed infestation. Negative effects due to short crop rotations occur much earlier with reduced tillage, particularly problems with noxious weeds (PALLUTT, 1999; PALLUTT and GRÜBNER, 2004).

By analyzing the same experiment at Flakkebjerg, which has been investigated for the study shown in chapter 5, MELANDER et al. (2008) found that tine tillage promoted the proliferation of *A. spica-venti*, whereas the *A. spica-venti* population was significantly lower after 4 years of direct drilling. Accordingly, the yield gap between the treatments with no control of *A. spica-venti* and the 90 per cent target control level was greater with tine tillage compared with direct drilling (cf. chapter 5.4). However, the average yield with direct drilling was significantly lower than with tine tillage or ploughing mainly due to the frequently poor crop establishment when no soil tillage was implemented. This is in accordance with former investigation, which reported that plant density is decreasing with reducing tillage intensity (OLOFSSON, 1993; WEISZ and BOWMAN, 1999; RIEGER et al., 2008). Even though crops can compensate for lower plant or shoot numbers by increased tillering or the generation of lateral shoots and higher thousand-kernel weights, yields will significantly decrease if a certain plant density falls below a certain lower limit. This was the case for the direct-drilled winter oilseed rape in 2004, which almost failed (MELANDER, 2007; personal communication).

6.4.2 Effects on nitrogen and energy balances

Energy inputs in management systems with conservation tillage are generally lower compared to conventional tillage with mouldboard ploughing (BORIN et al., 1997; URI, 1999; 2000), mainly due to the smaller fuel consumption (BOERMA et al., 1980; SMITH and FORNSTORM, 1980; FRANZLUEBBERS and FRANCIS, 1995; BORIN et al., 1997; RATHKE et al., 2007). At the Danish experimental site Flakkebjerg, energy requirements for the treatments with reduced tillage were slightly smaller compared with ploughing while energy input was lowest for direct drilling (cf. chapter 5.4. Differences in energy input were, however, relatively small as the energy savings due to reducing tillage intensity are less important in comparison with the other required energy inputs in crop production (O'CALLAGHAN, 1994).

Differences with respect to the yield of cereal crops were not very pronounced among the tillage systems at Flakkebjerg. In this context, it must be noted that the structure of the crop rotation strongly affects the performance of farming systems while there are often significant interactions with tillage intensity. MAIDL et al. (1988) found significantly lower yields for several cereal crops with reduced tillage compared to ploughing, whereas numerous other investigations show results which are in accordance with our findings (e.g. CHRISTIAN and BACON, 1990; EHLERS and CLAUPEIN, 1994; TEBRÜGGE and BÖHRNSEN, 1997; RIEGER et al., 2008). ZENTNER et al. (1998, 2004) reported that the tillage method had little influence on the level of energy output from various production systems. As energy output strongly correlates with crop yield, this was also true for the Danish experiment. On the other hand, the yield of oilseed rape with direct drilling was very poor in 2004, whereby the energy balance of the entire crop rotation 'FR 2' was impaired (cf. chapter 5.4). It can be stated that even though the energy requirements are generally lower with direct drilling as a result of lower fuel consumption, adequate yields or energy outputs must be obtained to exceed the energy efficiency of farming systems with ploughing or tine tillage.

Agronomic practices affect the balance between build-up and mineralization of soil organic N (KORSÆTH and ELTUN, 2000). High amounts of crop residues left on the soil surface can increase N immobilization (KELLEY and SWEENEY, 2005) and therefore reduce the amount of N available for the crop. In this connexion, the C/N ratio of organic residues determines the degree of N mineralization (GASSER, 1968) as available C may retard nitrification or mineralization (DE NEVE et al., 2003; POUDEL et al., 2001; PERSSON and KIRCHMANN, 1994). Furthermore, N mineralization in conservation tillage systems is probably slower as a result of more frequent oxygen deficits due to a generally higher dry bulk density of the soil and less soil mixing (SALO and TURTOLA, 2006). Particularly in soils with higher clay contents, N mineralization may be retarded in the spring (DOWDELL and CANNEL, 1975). FRANZLUEBBERS et al. (1995) assume that different N management may be needed with reduced tillage compared to conventional tillage with ploughing. Since mineralized N from soil organic matter significantly contributes to N leaching (JENKINSON, 1986; MACDONALD et al., 1989), N losses through leaching can be reduced by the implementation of reduced tillage in the short-term (RASMUSSEN, 1999; CATT et al., 2000). Probably, these aspects must be taken into account when estimating the amount of N losses as related to different tillage intensities for the experiment at Flakkebjerg. When merely considering the N surpluses, N losses would be estimated to be highest with direct drilling and lowest with ploughing (cf. chapter 5.3). The differences in N surplus between ploughing and direct drilling were more pronounced in the rotation 'FR 2' than in 'FR 1' due to the generally lower yields in 'FR 2'. In particular, N surplus was high for winter oilseed rape in 2004, which was directly drilled, because of its poor yield and the associated low N uptake (cf. chapter 5.4). Thus, it can be stated that there were interactions between tillage and crop rotation with respect to both yield and N surplus.

6.5 Impact of different farming systems and crop rotations

6.5.1 Effects on yields and potential N losses

The intelligent use of crop rotations can control, diseases, weeds, pests and enhance soil fertility (JORDAN and HUTCHEON, 1993). WEBSTER et al. (1999) emphasized, moreover, the importance of the crop rotation in regard to yields and N leaching. In this connexion, PANSE et al. (1994) as well as CHRISTEN (1998) reported that it is often not possible to completely compensate for the detrimental influences of an unfavourable preceding crop or crop rotation by optimizing crop management. The crop rotations of different farming systems normally contain largely different crops with respect to fertilizer regime, yield potential and the associated nutrient uptake or potential nutrient losses. Comparing different crop production or husbandry systems, it is therefore indispensable to consider the effects of the entire crop rotation. In general, the crops grown must be adapted to the site conditions and the specific properties of the respective farming system to obtain high yields and tolerable variations of yield or nutrient uptake, which is necessary to make possible an accurate measuring of the application rates of fertilizers.

Organic farming has been suggested as a means of reducing leaching and improving the use efficiency of plant nutrients in agriculture (TORSTENSSON et al., 2006). It can be presumed that there are only small nitrogen surpluses or, in general, nutrient surpluses because of the limited nutrient supply in organic farming systems. For instance, several studies have shown that N leaching is lower with organic than with conventional farming (GOSS and GOORAHOO, 1995; VAN DER WERFF et al., 1995; ELTUN and FUGLEBERG, 1996; DALGAARD et al., 1998; HANSEN et al., 2000; KORSÆTH and ELTUN, 2000). On the other hand, DE NEVE et al. (2003) found similar values for organic and conventional farming and KARLEN and COLVIN (1992) recorded no significant differences in mineral N concentration at depths of 2 m in a comparison of one organic and one conventional farm in Iowa. TORSTENSSON et al. (2006) supposed that the management of a particular system is a crucial factor influencing leaching more than the farming system itself. These authors found lower N leaching in a conventional farming system with catch crops compared with two green manure-based or animal manure-based organic farming systems. Nutrient recycling is indispensable to reduce the potential of nutrient losses (GRANSTEDT, 2000), predominantly with associated livestock keeping and crop rotations comprising legume crops. Regarding the internal nutrient flow is essentially required in organic farming to achieve high nutrient use efficiency (STEINSHAMN et al., 2004).

DE NEVE et al. (2003) pointed out that yield uncertainty in organic farming in sensitive crops such as potatoes may lead to considerable nutrient losses, even though fertilization is very limited. This might have been the case in 2005 and 2006 for winter oilseed rape in the organic farming system at Dahnsdorf. There was a severe mice infestation in 2005 decreasing the number of oilseed rape plants per unit land area and the competitive ability of the winter oilseed rape crop as well. As a result, the weed coverage greatly increased and the average grain yield of winter oilseed rape was lower than 0.5 tons per hectare. In 2006, the winter oilseed rape crop froze to death; hence, spring oilseed rape was grown subsequently. However, an infestation of *Meligethes aeneus* caused a total yield loss in early summer. Since an alfalfa/clover/grass-mixture accumulating atmospheric N by symbiotic N fixation was grown prior to oilseed rape cropping in each case and the N uptake by oilseed rape was probably very poor, it can be supposed that the potential of N losses significantly increased in these years. Investigations on the integrated fodder crop rotation and the organic farming system at Dahnsdorf showed that there were only slight differences between integrated farming with situation-related pesticide use and organic farming in the period from 2002 to 2006 (DEIKE et al., 2007). Under the given site conditions, winter oilseed rape seems to be not suitable for the requirements of organic farming. On the other hand, winter rye usually gets moderately over stress caused by weather or soil and efficiently uses the available nutrient supply due to its powerful root growth (KÖHNLEIN and VETTER, 1953; PAPONOV et al., 1999). The high competitive ability of winter rye is, moreover, advantageous as leading to lesser weed growth. Besides its ability to fix atmospheric N and improve soil fertility through the build-up of organic matter, the roots of alfalfa deeply penetrating the soil can catch nitrate that has leached past the rooting zone of most annual crops (KELNER et al., 1997). Thus, both rye and alfalfa seem to be especially appropriate for the conditions of organic farming.

6.5.2 Influence on energy balances

The crops grown and the structure of the crop rotation significantly affect the energy efficiency of arable farming, since they are of major importance for both energy input and output. Thus, energy balances represent the yield potential of the respective crop under the given site-specific conditions and the efficiency of all inputs within cropping. Furthermore, harvesting by-products of crops can considerably enlarge the energy output (cf. chapters 3.4 and 5.4). The integration of legumes into the crop rotation can decrease the requirements for fossil energy since they are less depending on energy intensive mineral fertilizers (HEICHEL and BARNES, 1984; YOUNBERG and BUTTEL, 1984). Several investigations have shown that, with regard to energy efficiency, crop rotations with legumes exceeded crop rotations without due to smaller application rates of mineral N fertilizers (VARVEL and WILHELM, 2003; RATHKE and DIEPENBROCK, 2006; RATHKE et al., 2007). In general, energy efficiency seems to be favourable in well-balanced crop rotations containing diverse crops (FRANZLUEBBERS and FRANCIS, 1995; LI et al., 2002), whereas the investigations of the Danish experiment revealed energy efficiency to be highest for continuous winter wheat cropping (cf. chapter 5.4).

At Dahnsdorf, the results of energy balance calculations of integrated or conventional and organic farming systems were fundamentally different from each other (cf. chapter 4.4). Similar values for direct energy input were recorded for integrated and organic farming, whereas indirect energy input was greatly higher in the integrated farming system. This is mainly on account of using mineral fertilizers and, to a much lesser extent, synthetic pesticides in integrated farming as opposed to organic farming. On average of the period 1997 to 2006, total energy inputs were 8.1 and 12.4 GJ ha^{-1} for organic farming and integrated farming with situation-related pesticide use, respectively. Using the same method of energy balancing, KALK et al. (1998) found energy inputs from 11 up to 16 GJ ha^{-1} for integrated farms and 11 GJ ha^{-1} for an organic farm showing similar husbandry characteristics and climatic conditions but lower soil fertility. HÜLSBERGEN (2003), who also used the same approach, reported that the average energy inputs in crop production were approximately 31 per cent lower for an organic farming system compared with the organic farming treatment at Dahnsdorf. Presumably, this was due to different shares of row crops within these two organic farming systems. Cultivating row crops generally requires a greater amount of energy for tillage and mechanical weed control compared to cereal cropping. Within the crop rotation in the organic farming system at Dahnsdorf, potatoes were grown on 16 per cent of the land area, whereas the organic farming system investigated by HÜLSBERGEN (2003) had on average less than 2 per cent of root crops per unit land area. Furthermore, tillage tends to be more intensive in field trials compared with commercial farms.

On the other hand, energy balances are greatly influenced by energy output. The smallest differences in energy output between integrated and organic farming occurred in years with prolonged dry periods within the growing period, such as in 1997, 2000 and 2003 (data not shown). Under these conditions, the yield was not only restricted by insufficient nutrient supplies or less efficient weed, pest or disease control but particularly by the lack of precipitation. Due to the integration of winter oilseed rape into the organic farming crop rotation, the energy efficiency of the entire system decreased on account of the low yields of oilseed rape (cf. chapters 4.5 and 6.5.1). Thus, particularly in the experimental period from 2002 to 2006, energy outputs and energy gains were higher in integrated farming compared with organic farming while no significant differences were found for energy intensity and output/input ratio (cf. chapter 4.4). This contrasts with numerous studies comparing the energy utilization of conventional or integrated farming systems and organic farming systems generally showing that organic farming systems require less fossil energy to produce one unit output (BERARDI, 1978; PIMENTEL et al., 1983; PIMENTEL, 1993; ALFÖLDI et al., 1995; REFSGAARD et al., 1998; DUBOIS et al., 1999; STOLZE et al., 2000; DALGAARD et al., 2001; MÄDER et al., 2002; GÜNDOGMUS and BAYRAMOGLU, 2006). Accordingly, REFSGAARD et al. (1998) argued that energy utilization of farms might be improved by conversion from conventional or integrated systems to organic production, which cannot be confirmed by our investigations. In a few studies, a smaller product-related energy use was reported for conventional or integrated farming compared with organic cropping. PIMENTEL et al. (1983) found lower energy requirements per weight unit for conventional apple and potato production compared with organic farming practices. ALFÖLDI et al. (1995) recorded lower energy efficiency for organic potato cropping in Switzerland. HELANDER and DELIN (2004) who compared conventional, integrated, and organic farming systems at a farm-size scale, found the highest energy efficiency in the integrated farming system followed by conventional husbandry. KELM et al. (2003) concluded that organic arable farming systems are likely to be inferior to conventional arable farming systems concerning energy efficiency, insofar as farms are located on soils having a high fertility or a high site-specific yield capacity.

It should be noted that no standardised scheme for calculating energy use exists, and comparisons across different analyses are thus of limited value (STOLZE et al., 2000). CHARLES et al. (2006), for instance, interrelated the energy requirements to one unit of energy output with defined quality parameters, e.g. as for winter wheat the crude protein content was assumed to be 13 per cent. For our investigations, it can be supposed that using this approach would be to the advantage of the integrated farming treatments since protein contents were consistently lower in organic farming compared with integrated farming (PALLUTT, 2006; unpublished data).

6.6 Long-term effects of the tested management practices

The effects of many husbandry practices, such as fertilization, pesticide use, tillage and the structure of the crop rotation, cannot clearly be assessed before several years have past. Changes of weed control or tillage will cause shifting of weed density, species composition and the occurrence of noxious weeds, particularly in the long-term (PALLUTT and GRÜBNER, 2004). Under the site conditions at Dahnsdorf, there has been a noteworthy increase of weed infestation due to the continuous application of herbicide dosages reduced by 50 per cent compared to the situation-related dosage. In the period from 2003 to 2007, significantly higher numbers of *A. spica-venti*, *Viola arvensis*, *C. cyanus* and *Matricaria* spp. were found with halved herbicide dosages compared to the situation-related herbicide application. This is mainly on account of the less effective weed control with reduced herbicide application and, hence, the higher number of fertile weed plants which have led to an increase of the seed bank (PALLUTT and MOLL, 2008). However, owing to the relatively slow build-up of the seed bank, significant increases of weed infestation may take three to five years, but, if the initial number of the particular weed is low, even 15 to 20 years (PALLUTT and GRÜBNER, 2004). It can be concluded that applying reduced herbicide dosages without causing significant yield losses is feasible in the short run or with low pest infestation levels. However, reducing the intensity of herbicide use on principle in the long run might not have a permanent success mainly due to the shift of the weed population to increasingly noxious weeds, which may cause significant yield losses (DEIKE et al., 2005; cf. chapter 2.5).

For the experiment at Flakkebjerg, it could be argued that both continuous winter wheat cropping and the rotation comprising winter barley – winter oilseed rape – winter wheat – winter wheat will strongly promote the proliferation of *A. spica-venti* in the long run due to the high proportion of autumn-sown crops and taking into account the investigations of PALLUTT (1999) of non-inversion vs. ploughing tillage under different crop rotations with varying percentages of autumn- and spring-sown crops. Furthermore, MELANDER et al. (2008) reported differences in the *A. spica-venti* occurrence between tine tillage and direct drilling for the experiment at Flakkebjerg. These authors argued that seeds buried through tine tillage may switch into secondary dormancy whereby a built-up of the seed bank is caused. In contrast, with direct drilling all *A. spica-venti* seeds shed before, during or after harvest remain on the soil surface. Thus, population dynamics of *A. spica-venti* are strongly influenced by weather conditions after seed shedding. If there are sufficient conditions for germination, a high number of *A. spica-venti* seedlings emerge and will be subsequently killed by the application of Glyphosate prior to drilling. Therefore, it can be supposed that the first four years of investigations at Flakkebjerg cannot provide definite conclusions with regard to *A. spica-venti* population dynamics as related to different intensities of non-inversion tillage.

Moreover, agricultural practices, particularly soil tillage and crop rotation, have a direct impact on plant health and crop productivity while the management of organic amendments and crop residues influences the viability and distribution of soil-borne diseases (BAILEY and LAZAROVITS, 2003). The continuous winter wheat cropping at Flakkebjerg may promote soil-borne diseases such as *Gaeumannomyces graminis*, *Pseudocerco-*

sporella herpotrichoides, and *Fusarium* spp. (cf. OBST and PAUL, 1993). Though being strongly affected by weather conditions, disease infestation might be high with non-inversion tillage, in particular due to the generally higher disease transmission by crop residues left on the soil surface. However, in most years, the infestation by soil-borne diseases was of minor importance. This was also the fact in continuous winter wheat cropping, mainly because fairly resistant cultivars were grown (JØRGENSEN, 2008; personal communication). Moreover, there were probably secondary effects on diseases infecting the basal culm of cereals by the fungicides applied against leaf diseases at shooting and later. Sufficient humus replacement by a balanced application of organic manures and a good crop residue management and the associated increase in soil fertility and biological activity may suppress disease development through improving soil health and structure (BAILEY and LAZAROVITS, 2003). Even though this process takes time, these benefits accumulate across successive years. Probably, the high humus replacement at Flakkebjerg, particularly in continuous winter wheat cropping (cf. chapter 5.3), may have led to reduced disease inoculum to a certain extent. On the other hand, weed communities also contribute to pathogen carryover and survival, especially if volunteers are promoted, e.g. under crop rotation periodicity with short crop cycles including monoculture (DERKSEN et al., 1994). It can be supposed that these complex interactions of crop rotation, tillage, weed control, and soil fertility and their effects on the infestation of soil-borne diseases cannot be conclusively clarified on the basis of the first four experimental years at Flakkebjerg. On account of the structures of the crop rotations at Dahnsdorf, the infestation of soil-borne diseases is presumed to be low in general. Due to the fact that fungicides in cereals were mostly applied at ear emergence, differences in the infestation of soil-borne diseases as related to different application rates of fungicides are unlikely to be expected, as secondary effects on culm infesting diseases are negligible.

Soil organic matter is known to affect soil aeration, structure, drainage, moisture holding capacity, nutrient availability, and microbial ecology (DAVEY, 1996). Thus, it may be one of the most important soil quality characteristics in relation to tillage (CANNEL and HAWES, 1994). This aspect seems to be of great importance if adopting reduced tillage practices or direct drilling. Even though the soil organic matter content of the entire soil profile is not always increasing when adopting reduced tillage (e.g. WANDER et al., 1998; DEEN and KATAKI, 2003; PUDGET and LAL, 2005; HERMLE et al., 2008), gaining organic matter in the upper soil layer is widely reported. Presumably, the duration of the experiment at Flakkebjerg was too short for a sufficient accumulation of organic matter and for the associated increase of biological activity and earthworm population, which is one fundamental requirement to successfully implement reduced tillage or direct drilling and to obtain adequate yields.

Different husbandry will change the soil stocks of organic matter. However, changes will take a number of years to develop according to the site-specific conditions (KÖRSCHENS, 1992; CAMPBELL et al., 2000). Therefore, small differences affected by different management practices can hardly be identified. Calculating humus balances for the experiment at Dahnsdorf, the average humus replacement rates of the treatment with situation-related pesticide use were slightly lower compared with the untreated control (Table A4, cf. DEIKE et al., 2006c). This might be explained by the higher humus requirement with situation-related pesticide use due to the higher yields obtained. Most likely, the humus replacement rate of the plots without pesticide application would be estimated to be even more advantageous compared to the plots with situation-related pesticide use, if a certain humus replacement by weeds were taken into consideration, for instance by assuming the weed population as an undersown crop. However, when analysing the organic matter contents by the use of a large number of test samples after finishing the second experimental period in 2007, no significant differences occurred between the plots with situation-related pesticide application and the untreated controls in the fodder crop rotation while even slightly higher values were found with situation-related pesticide use in the arable crop rotation (Table A5). Presumably, the higher N use efficiency as well as the larger amount of crop residues and root mass in the plots with situation-related pesticide application which is associated with the higher grain yields, have had a stronger influence on humus replacement than estimated by the balance approach. The results of the soil analysis are in accordance with results from the Broadbalk Wheat Experiment at Rothamsted (UK) where higher contents of soil organic matter were recorded for the treatments with higher application rates of N fertilizer compared with lower rates of N application (GLENDINING et al., 1996). However, following the REPRO balance approach, humus requirements would be estimated to be generally increasing with increasing application rates of N fertilizers due to the higher grain and straw yields obtained. This is especially true, since straw was removed in each treatment in each year. It can be concluded that further investigations are needed to adapt the balance approach to different site-specific conditions and different farming systems while the impact of crop residues and root mass on organic matter should be verified in particular. On the other hand, the experimental period has probably been too short to clearly identify the effects of the different treatments, which differ to a comparatively minor extent.

7 CONCLUSIONS

The presented investigations comprise a broad variation of the most important management practices in arable farming. Deduced conclusions are, however, not entirely transferable to different sites as the site-specific conditions significantly affect the efficiency of production means and, therefore, the productivity and the environmental effects of farming. Energy and nitrogen use efficiency are integrative indicators to assess different farming systems and management practices as they evaluate the productivity of arable farming by considering the associated potential of environmental endangerments. These indicators can be hence regarded as measures to assess the overall efficiency of cropping or of the entire farming system.

One general principle in crop production must be that the application of production means has to be adapted to the actual requirements of the crop and the site-specific conditions implying the given yield potential. The efficient use of factor inputs within cropping is crucial in order to achieve high productivity and a low risk of environmental endangerments at the same time. The management of pesticide use, fertilizer application, and tillage as well as the farming system and the crop rotation are therefore of utmost importance in regard to the over-all performance of arable farming:

- The balanced and targeted application of factor inputs and their efficient use is necessarily required for obtaining steady and adequate yields.
- Pesticide use is a fundamental measure to ensure the yield and the quality of the harvested biomass by reducing negative effects of weeds, pests, or fungal diseases. Moreover, positive interactions may frequently occur when weeds and diseases are both efficiently controlled which should be made use of.

  The application rates of pesticides should be measured situation-related, as this is needed to efficiently use other means of production, particularly fertilizers. The situation-related pesticide use can reduce the potential of nutrient losses by increasing the N uptake of the crop and, accordingly, the nutrient use efficiency.

  For integrated and conventional farming systems, the situation-related application of pesticides is, moreover, essential to attain high energy use efficiency since energy inputs due to pesticide use are relatively small whereas yields or energy outputs are considerably increased by the situation-related pesticide use in general.

- The structure of the crop rotation significantly affects the resource efficiency of arable farming. Well-balanced crop rotations containing crops, which are suitable for the site-specific conditions, can maintain or enhance soil fertility and reduce the requirements for pesticides, fertilizers and fuel without significant yield losses.
- Mineral nitrogen fertilizers are of utmost importance since they are essential in regard to plant growth and yield and are therefore often used extensively within cropping, whereas there are several pathways for nitrogen losses. The efficient use of mineral fertilizers is, moreover, needed to attain high energy use efficiency due to the large energy requirements for their production.
- The application of organic fertilizers must be properly included in the fertilization strategy to obtain a high efficiency of nutrient use. Particularly in arable farming systems, a sound management of organic manures and crop residues is vital regarding the humus replacement. Thus, organic manures and crop residues are of particular importance with respect to soil fertility but also concerning nutrient losses.
- Practising conservation tillage without causing significant yield losses or energy outputs can increase energy efficiency due to smaller fuel consumption. On the other hand, yields are often significantly lower with direct drilling compared with ploughing or tine tillage and the energy efficiency of direct drilling systems can be therefore significantly impaired, although energy inputs in direct drilling systems are usually much lower. Depending on the structure of the crop rotation and the site-specific conditions, reducing tillage intensity may lead to problems with weed, disease or pest infestations, whereby pesticide requirements may be increased.
- The farming system itself has a strong influence on both productivity and environmental effects of crop production, even though being strongly affected by site-specific conditions and the management of the particular farming system. Energy and fertilizer inputs and associated problems like carbon dioxide emissions or nutrient losses are generally lower in organic farming systems compared to conventional or integrated farming. On the other hand, productivity is mostly lower and, therefore, the area required for production is significantly higher with organic farming than with conventional or integrated husbandry.

The investigations presented in this thesis have shown that the production intensity within cropping with respect to pesticide use, fertilizer application, and tillage intensity can be often reduced without significant effects on productivity. However, the potential of input reduction is lower in the long term than in the short term. In the short run, high efficiency of production may be obtained with lower factor inputs, whereas negative effects of lowering input intensity in the form of yield losses and associated impairments of energy and N use efficiency may occur after a certain time. For instance, the continuous application of herbicide rates reduced by 50 per cent compared to the situation-related dosage at Dahnsdorf led to an increase of the infestation of several noxious weeds and caused significant yield losses compared to the situation-related herbicide application in the longer run. Weed infestation has been also boosted as a result of reducing tillage intensity in Denmark. On the other hand, shifting of weed density and species composition generally takes a number of years to develop mainly depending on the given site conditions, the initial weed infestation, the crop grown, the structure of the crop rotation, and the husbandry of the farming system. Changes of soil nutrient stocks and humus content due to different management practices directly influence soil fertility and therefore the productivity of the site. However, significant differences often take a very long time, particularly if the intensities of husbandry differ to a relatively small extent. It is therefore indispensable that a meaningful assessment of the complex effects and interactions of crop rotation, farming system and different intensities of fertilizer application, pesticide use and soil tillage is based on long-term investigations while particularly considering the site-specific conditions.

8 SUMMARY

The present thesis contains investigations on the impact of different farming systems and management practices on the efficient use of limited resources. The emphasis was on the influence of different husbandry intensities on the nitrogen (N) and energy use efficiency. One main objective was to quantify the effects of different pesticide use intensity on yield and on pest infestation in order to make possible recommendations on sustainably successful strategies of pesticide use by taking into account productivity as well as the potential of negative environmental effects. Furthermore, the interactions of pesticide use, farming system, crop rotation, tillage intensity, fertilizer application and site-specific conditions have been analysed. The investigations are based on long-term field trials at the research sites “Dahnsdorf” (Federal State of Brandenburg, Germany) and “Flakkebjerg” (Denmark). The majority of the calculations was implemented by means of the balance model REPRO using primarily the balance approaches for fossil energy, N, humus and carbon.

The thesis comprises four studies whose data base, objectives, and results are presented in summarised form in the following. In the first study, the effects of different intensities of herbicide application on weed infestation, yield, and N balances were investigated for winter wheat, winter rye, and winter barley. These cereal crops were grown within one arable crop rotation containing winter oilseed rape – winter wheat – fallow (peas since 2002) – winter wheat – winter barley and within one fodder crop rotation including winter oilseed rape – winter barley – alfalfa/clover/grass-mixture – winter rye – silage maize – winter wheat. In each case, situation-related application rates of herbicides and dosages reduced by 50 per cent in relation to the situation-related application rate were compared. In the first experimental period from 1997 to 2001, the treatment with reduced herbicide intensity also received halved application rates of mineral N fertilizers compared to those of the treatment with situation-related herbicide use. Both the respective crop grown and the amount of mineral N fertilizer have had a significant effect on the competitive ability of the cereal crops and, accordingly, on weed growth. The reduced N fertilization led to cereal crops with lower competitive ability compared to the regular application rates. In the first experimental period, the yield increases due to the application of halved herbicide dosages were therefore higher compared to those after situation-related herbicide use, even though the effectiveness of weed control was by 10 to 30 per cent lower with halved herbicide intensity. Since the application rates of mineral N fertilizers were the same for both treatments and the weed infestation has been steadily increasing as a result of the less effective weed control with halved application rates of herbicides in the previous years, the average yield increases were considerably higher with situation-related herbicide dosages com-

pared with the reduced application rates in the following experimental period from 2002 to 2005. Generally, herbicide application has led to a decrease of N balance as yields and the associated N uptake have been increased, while the largest decrease occurred in winter wheat cropping and was lowest for winter rye.

On the basis of the arable and the fodder crop rotations mentioned above, the effects of situation-related application rates of herbicides on the energy use efficiency and the carbon dioxide (CO_2) emissions of winter rye, winter barley, and winter wheat cropping were investigated in comparison to the respective treatments without herbicide application. Generally, herbicide use enhanced net energy output, energy intensity, or output/input ratio. Significant differences occurred, however, not before 3 to 5 years had past and a weed population with high competitive ability had been established in the reference plots without herbicide application. Regarding both energy efficiency and N use efficiency, which has been investigated in the first study, the effects due to herbicide application were greater if fungicides were also applied during the growing period. Due to the energy consumption for the production and the application of the herbicides and, moreover, the higher energy requirements for harvesting owing to the higher yields obtained, the CO_2 emissions per hectare were 4.4 per cent higher compared with the untreated control. On the other hand, the CO_2 emissions per unit grain equivalent were 34.6 per cent lower.

In the third study, the energy efficiencies of the fodder crop rotation mentioned and one organic farming system containing alfalfa/clover/grass-mixture – alfalfa/clover/grass-mixture (since 2005 winter oilseed rape) – winter wheat – potatoes – winter rye – winter barley (since 2002 spring barley) were compared. For the farming system with integrated husbandry, one treatment with situation-related pesticide use and one treatment with application rates reduced by 50 per cent compared to the situation-related dosages were considered. Fossil energy requirements were 35 per cent lower in organic farming than in the treatment with situation-related pesticide application in integrated farming. Mineral fertilizers represented 37 per cent of the total energy input of the integrated farming system with situation-related pesticide use. The share of pesticides in energy input only amounted to 5 per cent. In general, net energy output was significantly higher with integrated farming and situation-related pesticide application compared with the organic farming system, whereas no significant differences were found as related to the different pesticide treatments in integrated farming. In the experimental period from 1997 to 2001, energy intensity was lower and output/input ratio was higher in the organic farming system compared with integrated farming. In this regard, no significant differences were recorded in the following period from 2002 to 2006.

For the last study, each treatment with situation-related pesticide use and application rates reduced by 50 per cent of the arable and the fodder crop rotation tested at Dahnsdorf and one winter barley – winter oilseed rape – winter wheat – winter wheat crop rotation and the continuous winter wheat cropping at Flakkebjerg were juxtaposed for the sake of comparison in regard to yield, energy efficiency, humus balance, and N surplus. Besides different crop rotations, three intensities of soil tillage (ploughing, tine tillage, direct drilling) and three target levels of *Apera spica-venti* control (no control, 70% and 90% target control) were tested within the Danish field trial. On average, yields, humus replacement, and energy efficiency were highest in continuous winter wheat cropping. However, the use of pig slurry, which has been applied to each crop in both Danish crop rotations, led to considerably higher N surpluses compared with the N surpluses of the crop rotations at Dahnsdorf. This is mainly due to the fact that the N use efficiency of organic fertilizers is generally lower compared with mineral fertilizers. The different intensities of pesticide use have had minor influence on the tested indicators. In general, the differences between ploughing and tine tillage were small, whereas yields and, accordingly, energy and N use efficiency were often lower with direct drilling.

The investigations have shown that a meaningful assessment of the productivity and the environmental effects of crop production must be based on systematic investigations, since there are complex interactions of management practices like farming system, pesticide use, fertilizer application or soil tillage intensity. In this connexion, the long-term effects of different husbandry and the influence of site-specific conditions have to be regarded in particular.

9 ZUSAMMENFASSUNG

In der vorliegenden Arbeit wurden die Auswirkungen verschiedener Anbausysteme und Bewirtschaftungsverfahren auf die Effizienz begrenzter Ressourcen untersucht. Den Schwerpunkt der Untersuchungen stellten die Auswirkungen unterschiedlicher Bewirtschaftungsintensitäten auf die Stickstoff (N)-Verwertung und die Effizienz des Einsatzes fossiler Energie dar. Ein Hauptziel war, die Effekte unterschiedlicher Intensitäten der Anwendung chemischer Pflanzenschutzmittel auf Erträge und Schaderregerauftreten sowie Energie- und N-Bilanzen zu quantifizieren und Empfehlungen für langfristig erfolgreiche Pflanzenschutzstrategien im Hinblick auf die Produktivität des Verfahrens und ebenso bezüglich potentieller Umweltwirkungen abzuleiten. Ferner wurden Wechselwirkungen des Pflanzenschutzmitteleinsatzes mit unterschiedlichen Anbausystemen, Fruchtfolgen, Bodenbearbeitungsverfahren, Düngungsstrategien und Standortbedingungen geprüft. Als Grundlage der Untersuchungen dienten Langzeitfeldversuche an den Standorten Dahnsdorf (Land Brandenburg, Bundesrepublik Deutschland) und Flakkebjerg (Dänemark). Ein Großteil der Berechnungen wurde mit Hilfe des Bilanzierungsmodells REPRO durchgeführt. Hierbei wurden vorrangig die vorhandenen Energie-, N-, Humus- und Kohlenstoffbilanzmethoden für die Pflanzenproduktion genutzt.

Die Arbeit enthält vier Studien, deren Datengrundlagen, Zielstellungen und Ergebnisse nachfolgend zusammengefasst dargestellt werden sollen. Anhand der Fruchtarten Winterweizen, Winterroggen und Wintergerste wurden in der ersten Studie die Auswirkungen langfristig differenzierter Herbizidanwendung auf den Unkrautbesatz, die Ertragsentwicklung und N-Bilanzen untersucht. Die Wintergetreidearten wurden jeweils innerhalb einer Marktfruchtfolge bestehend aus Winterraps – Winterweizen – Winterroggen – Brache (seit 2002 Erbsen) – Winterweizen – Wintergerste und einer Futterbaufruchtfolge, welche Winterraps – Wintergerste – Luzerne/Klee/Gras – Winterroggen – Silomais – Winterweizen enthielt, angebaut. Hierbei wurden situationsbezogen bemessene Herbizidaufwandmengen und im Vergleich dazu um 50% reduzierte Aufwandmengen geprüft. Im ersten Versuchsabschnitt von 1997 bis 2001 war in den Behandlungsstufen mit reduzierter Herbizidanwendung zudem die Höhe der mineralischen N-Düngung halbiert. Sowohl die Kulturart als auch die Höhe der N-Düngung hatten einen deutlichen Einfluss auf die Konkurrenzkraft der Getreidebestände und folglich auf das Unkrautwachstum. Die verringerte N-Düngung führte im Vergleich zur vollen Applikationsmenge zu konkurrenzschwächeren Beständen. Dadurch wurden im ersten Versuchsabschnitt höhere Mehrerträge durch die Anwendung halbierter Herbizidaufwandmengen erzielt, obwohl Wirkungsverluste von 10-30% verglichen mit der situationsbezogenen Dosierung auftraten. Da im zweiten Untersuchungszeitraum von 2002 bis 2005 in beiden Behandlungsstufen gleiche N-Düngermengen appliziert wurden und die Besatzstärke von Unkräutern infolge der Minderwirkung der reduzierten Herbizidaufwandmengen zunahm, wurden in diesem Zeitraum deutlich höhere Mehrerträge durch die situationsbezogene Anwendung von Herbiziden als durch reduzierte Aufwandmengen erreicht. Grundsätzlich führte die Herbizidbehandlung zu einer Verringerung der N-Bilanz, wobei die durchschnittliche Senkung infolge der erzielten Mehrerträge und damit höheren N-Aufnahme im Winterweizen am höchsten und im Winterroggen am niedrigsten war.

Auf Grundlage der oben genannten Marktfrucht- und Futterbaufruchtfolge wurden in der zweiten Studie die Effekte einer situationsbezogenen Herbizidbehandlung auf die Energieeffizienz und die Kohlenstoffdioxid (CO_2)-Emissionen im Vergleich zu einer Variante ohne Unkrautbekämpfung im Winterroggen-, Wintergersten- und Winterweizenanbau untersucht. Generell führte die Herbizidanwendung zu Verbesserungen des Energiegewinns, der Energieintensität bzw. des Output/Input-Verhältnisses. Signifikante Unterschiede traten jedoch abhängig von der Getreideart erst nach 3-5 Jahren auf, nachdem sich ein konkurrenzstarker Unkrautbesatz in der Vergleichsvariante ohne Herbizidbehandlung etabliert hatte. Sowohl hinsichtlich der Energieeffizienz als auch in Bezug auf die in der ersten Studie untersuchte N-Effizienz konnte beobachtet werden, dass die Effekte der Herbizidbehandlung größer waren, insofern eine Behandlung mit Fungiziden erfolgte. Durch die Produktion und Applikation von Herbiziden sowie dem größeren Energieeinsatz bei der Ernte infolge der höheren Erträge stiegen die CO_2-Emissionen pro Hektar im Durchschnitt um 4,4% im Vergleich zur unbehandelten Kontrolle an. Dem hingegen verringerte sich der CO_2-Ausstoß je Getreideeinheit um 34,6%.

In der dritten Studie wurde die Energieeffizienz des bereits beschriebenen Futterbausystems und eines ökologischen Bewirtschaftungssystems mit der Fruchtfolge Luzerne/Klee/Gras – Luzerne/Klee/Gras (seit 2005 Winterraps) – Winterweizen – Kartoffeln – Winterroggen – Wintergerste (seit 2002 Sommergerste) verglichen. Beim integrierten Futterbausystem wurden eine Behandlungsstufe mit situationsbezogenem Pflanzenschutzmitteleinsatz und eine Variante mit im Vergleich dazu halbierter Pflanzenschutzintensität berücksichtigt. Es zeigte sich, dass der Verbrauch fossiler Energie im Durchschnitt der Fruchtfolge im ökologischen Landbau um 35% niedriger war als bei integrierter Bewirtschaftung mit situationsbezogenem Pflanzenschutzmitteleinsatz. Mineraldünger waren für 37% des Energieeinsatzes im integrierten System mit situationsbezogener Pflanzenschutzmittelanwendung verantwortlich, währenddessen der Anteil für Pflanzenschutzmittel lediglich 5% betrug. Grundsätzlich war der Energiegewinn im integrierten Landbau mit situationsbezogener Pflanzenschutzintensität signifikant höher als im ökologischen Landbau, wohingegen keine signifikanten Unterschiede in Abhängigkeit der unterschiedlichen Pflanzenschutzintensität auftraten. Im Versuchsabschnitt von 1997 bis 2001 war die Energieintensität bei ökologischer Bewirtschaftung niedriger und das Output/Input-Verhältnis höher als im integrierten Landbau. Im Abschnitt von 2002 bis 2006 wurden keine signifikanten Unterschiede ermittelt.

Für die letzte Studie wurden jeweils die Varianten mit situationsbezogener und halbierter Pflanzenschutzintensität der Marktfrucht- und Futterbaufruchtfolge, welche in Dahnsdorf geprüft wurden, und eine Fruchtfolge bestehend aus Wintergerste – Winterraps – Winterweizen – Winterweizen sowie dem Daueranbau von Winterweizen am dänischen Standort Flakkebjerg hinsichtlich Ertrag, Energieeffizienz, Humusbilanz und N-Saldo gegenübergestellt. Neben der Fruchtfolge wurden im dänischen Versuch auch die Bodenbearbeitung (Pflug, Mulch- bzw. Direktsaat) und unterschiedliche Bekämpfungsstrategien gegenüber *Apera spica-venti* (keine Bekämpfung, 70% bzw. 90% angestrebter Bekämpfungserfolg) geprüft. Hierbei wies der Daueranbau von Weizen die höchsten Erträge sowie die höchste Humusversorgung und Energieeffizienz auf. Dem hingegen führte vor allem der Einsatz von Schweinegülle, welche zu jeder Fruchtart appliziert wurde, aufgrund der niedrigerer N-Verwertungsrate im Vergleich zu mineralischen N-Düngern in beiden dänischen Fruchtfolgen zu höheren N-Salden als bei den in Dahnsdorf geprüften Fruchtfolgen. Die unterschiedliche Pflanzenschutzintensität hatte an beiden Standorten geringen Einfluss auf die untersuchten Prüfmerkmale. Zwischen den Varianten mit wendender Bodenbearbeitung und Mulchsaat traten in der Regel nur geringfügige Unterschiede, währenddessen die Direktsaatvariante häufig niedrigere Erträge und eine dementsprechend schlechtere Energie- und N-Effizienz aufwies.

Die Untersuchungen haben gezeigt, dass aufgrund der komplexen Wechselwirkungen von Bewirtschaftungsmaßnahmen wie Anbausystem, Pflanzenschutzmitteleinsatz, Düngung oder Bodenbearbeitung Aussagen zur Produktivität und den Umweltwirkungen der Pflanzenproduktion nur ausgehend von einer systematischen Betrachtung getroffen werden können. Dabei sind die Langzeiteffekte von Bewirtschaftungsmaßnahmen und der Einfluss von Standortbedingungen besonders zu berücksichtigen.

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11 APPENDIX

Table A1

Average air temperature (°C) and total precipitation (mm) from March to September and for the whole year (in parentheses) at the Dahnsdorf research site during the period from 1997 to 2006.

Year	Temperature (°C)	Precipitation (mm)
1997	12.8 (8.6)	280 (453)
1998	13.4 (9.5)	323 (546)
1999	14.0 (9.8)	259 (454)
2000	13.7 (10.1)	345 (539)
2001	12.9 (9.1)	477 (676)
2002	13.9 (9.5)	485 (774)
2003	14.4 (9.3)	219 (392)
2004	13.1 (9.1)	363 (595)
2005	13.0 (9.1)	407 (634)
2006	13.7 (9.7)	316 (484)

Table A2

Average air temperature (°C) and total precipitation (mm) from March to September and for the whole year (in parentheses) at the Flakkebjerg research site during the period from 2003 to 2006 (according to MELANDER et al., 2008; modified).

Year	Temperature (°C)	Precipitation (mm)
2003	12.4 (8.5)	305 (465)
2004	11.6 (8.3)	424 (693)
2005	11.4 (8.5)	260 (449)
2006	12.2 (9.2)	355 (645)

Table A3

Weed infestation under the application of herbicide dosages reduced by 50 per cent compared to situation-related herbicide application in the arable crop rotation at Dahnsdorf during the period from 1997 to 2007 (according to PALLUTT and MOLL, 2008; modified).

Crop	Weed	Period 1997-2002		Period 2003-2007	
		Difference in weed emergence (plants m^{-2})	Level of significance (P value, $\alpha = 0.1$)	Difference in weed emergence (plants m^{-2})	Level of significance (P value, $\alpha = 0.1$)
Winter wheat [1)]	- Dicots	39	0.07	37	0.0001
	· VIOAR	10	0.34	15	0.009
	· MAT spp.	6	0.06	4	0.19
	· CENCY	0.007	0.59	2.6	0.14
	- APESV	28	0.003	23	0.06
Winter barley	- Dicots	33	0.32	24	0.11
	· VIOAR	19	0.44	11	0.12
	· MAT spp.	1	0.78	12	0.14
	· CENCY	0	-	0.3	0.32
	- APESV	19	0.24	20	0.19
Winter rye	- Dicots	25	0.30	55	0.040
	· VIOAR	12	0.14	19	0.18
	· MAT spp.	2	0.18	9	0.12
	· CENCY	0.2	0.48	6	0.31
	- APESV	7	0.18	20	0.10
Average of w. wheat, w. barley, w. rye	- Dicots	34	0.015	38	< 0.0001
	· VIOAR	13	0.10	15	0.0007
	· MAT spp.	4	0.04	7	0.0078
	· CENCY	0.06	0.41	3	0.0697
	- APESV	21	0.001	22	0.0032

[1)] Average weed emergence of both winter wheat plots following winter oilseed rape or peas.
VIOAR – *Viola arvensis*, MAT spp. – *Matricaria* spp., CENCY – *Centaurea cyanus*, APESV – *Apera spica-venti*

Table A4

Average humus replacement rate (HU ha^{-1}) as related to crop rotation and intensity of pesticide use at Dahnsdorf; calculated by using the humus balance approach of the model REPRO (period 1997 to 2006).

Pesticide treatment	Untreated control	Situation-related
	Humus replacement rate (HU ha^{-1})	
Arable crop rotation	-0.01	0.02
Fodder crop rotation	0.08	0.19

Table A5

Average contents of soil organic carbon as affected by crop rotation and intensity of pesticide use at Dahnsdorf (samples taken in February 2007).

Pesticide treatment	Untreated control	Situation-related
	Organic matter content (g kg^{-1})	
Arable crop rotation (n = 60)	0.776	0.818
Fodder crop rotation (n = 40)	0.842	0.842

Erklärung

Hiermit erkläre ich, dass ich diese wissenschaftliche Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Mit dieser Arbeit wurden noch keine vergeblichen Promotionsversuche unternommen.

Des Weiteren erkläre ich, dass keine Strafverfahren gegen mich anhängig sind.

Dreileben, 5. März 2008

Stephan Deike

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