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Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems

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Abstract

The paper describes the model software REPRO (REPROduction of soil fertility) designed for analyzing interlinked carbon (C) and nitrogen (N) fluxes in the system soil–plant–animal–environment. The model couples the balancing of C, N and energy fluxes with the target to estimate the climate-relevant CO_2, CH_4 and N_2O sources and sinks of farming systems. For the determination of the net greenhouse effect, calculations of C sequestration in the soil, CO_2 emissions from the use of fossil energy, CH_4 emissions from livestock keeping and N_2O emissions from the soil have been made. The results were converted into CO_2 equivalents using its specific global warming potential (GWP). The model has been applied in the experimental farm Scheyern in southern Germany, which had been divided into an organic (org) and a conventional (con) farming system in 1992. Rather detailed series of long-term measuring data are available for the farm in Scheyern, which have been used for validating the software for its efficiency and applicability under very different management yet nearly equal site conditions.

The organic farm is multi-structured with a legume-based crop rotation (N_2 fixation: 83 kg ha^{-1} yr^{-1}). The livestock density (LSU = Livestock Unit according to FAO) is 1.4 LSU ha^{-1}. The farm is oriented on closed mass cycles; from the energetic point of view it represents a low-input system (energy input 4.5 GJ ha^{-1} yr^{-1}). The conventional farm is a simple-structured cash crop system, based on mineral N (N input 145 kg ha^{-1} yr^{-1}). Regarding the energy consumption, the system is run on high inputs (energy input 14.0 GJ ha^{-1} yr^{-1}). The organic crop rotation reaches about 57% (8.3 Mg ha^{-1} yr^{-1}) of the DM yield, about 66% (163 kg ha^{-1} yr^{-1}) of the N removal and roughly 56% (3741 kg ha^{-1} yr^{-1}) of the C fixation of the conventional crop rotation. In the organic rotation, 18 GJ per GJ of fossil energy input are bound in the harvested biomass *vis-à-vis* 11.1 GJ in the conventional rotation. The strongest influence on the greenhouse effect is exerted by C sequestration and N_2O emissions. In Scheyern, C sequestration has set in under organic management (+0.37 Mg ha^{-1} yr^{-1}), while humus depletion has been recorded in the conventional system (−0.25 Mg ha^{-1} yr^{-1}).

Greenhouse gas emissions (GGEs) due to fuel consumption and the use of machines are nearly on the same level in both crop rotations. However, the conventional system emits an additional 637 kg CO_2 eq ha^{-1} yr^{-1}, which had been consumed in the manufacture of mineral N and pesticides in the upstream industry.

Besides the analyses in the experimental farm Scheyern, the model has been applied in 28 commercial farms (18 org and 10 con) with comparable soil and climate conditions in the surroundings of Scheyern (mean distance 60 km). The program calculations are aimed at benchmarking the results obtained in the farming systems Scheyern; they are expected to disclose management-specific variations in the emission of climate-relevant gases and to rate the suitability of the model for describing such management-specific effects. In order to make the situation in the farms comparable, only the emissions from cropping systems were analyzed. Livestock keeping remained unconsidered. Due to lower N and energy inputs, clearly lower N_2O and CO_2 emissions were obtained for the organic farms than for the conventional systems.

The analyses have shown possibilities for the optimization of management and the mitigation of GGE. Our findings underline that organic farming includes a high potential for C sequestration and the reduction of GGEs. Currently, the model REPRO is tested by 90 farms in the Federal Republic of Germany with the aim to apply it in the future not only in the field of research but also in the management of commercial farms.

Key words: carbon cycle, farming system, modeling, global warming potential, C sequestration, greenhouse gas emissions, REPRO

Introduction

The carbon budget of agricultural systems has been the focus of numerous studies on different scales, from the elucidation of molecular mechanisms in the C metabolism of plants up to the analysis of the influence of land use systems on biogeochemical C cycles[1–3]. Especially the dramatic rise of the CO_2 concentration in the atmosphere has led to a worldwide search for possibilities of C sequestration in agriculturally used soils and for the reduction of CO_2 emissions under specific soil, climate and management conditions[3].

A large number of research findings are available on the effect of management practices on C sequestration and CO_2 emissions. Experiments have shown that a considerable CO_2 reduction potential lies in reduced and zero tillage versus conventional tillage[2], in the growing of perennial legumes rather than cereals and maize[4] and in the conversion of arable land to grassland[5]. Some studies contain analyses of greenhouse gas emissions (GGEs) from complex production systems (for example organic versus conventional farming) on the basis of field experiments[3], experimental and commercial farms[6] or in model calculations with statistic data material[7]. However, so far few scientific studies have been published that deal with the analysis of C cycles in farming systems and the interrelated on-farm C fluxes between soils, plants, animals and the environment. This is surprising as C cycles, beyond their climatic relevance, are of major significance for the efficiency of production. The carbon input to the soil has a decisive influence on humus level, biological activities and soil structure, thus considerably controlling the biomass yield.

Especially systems with limited inputs like organically managed farms require a sufficient recycling of organic C in order to support the yield capacity of the soil.

In studies of the net greenhouse effect of farming systems, not only are CO_2 and CH_4 emissions important, but, due to their high specific greenhouse potential, also the site- and management-related N_2O emissions[8]. Model approaches have been elaborated for emission inventories on the farm level, which consider all relevant outputs[2,9]; however, on the basis of partly simplified model algorithms. An overall view of the net greenhouse effect of farming systems must take into account, beside the biological C fluxes, also technical C fluxes, i.e., all CO_2 emissions involved by the input of fossil energy. This comprises (see[10]):

- on-farm CO_2 emissions resulting from the use of diesel fuel, electrical power, solid fuels and other energy carriers (= direct energy input),
- CO_2 emissions from the industrial upstream sector for the manufacture and transport of fertilizers, pesticides and machines (= indirect energy input).

The present paper has the following aims, to:

- outline an approach to the modeling of C cycles in farming systems and to integrate the methods into a complex farming model,
- describe and validate the results computed by use of the model software in example farms of different structure and intensity and to evaluate the practicability of the program,
- come to conclusions on the influence of a given farming system on the greenhouse effect and on practicable reduction strategies for GGEs.

The investigations took place in the experimental farm Scheyern in southern Germany, where two management systems are practiced (organic and conventional) and in 28 commercial farms, also in the south of Germany.

The experimental farm Scheyern had been chosen as test farm for the model applications because here very detailed and scientifically profound data are available (management records, measuring data on C fluxes, C pools and GGEs), which are suited for validating the program.

In contrast to this, commercial farms do not dispose of comparable databases. The records in the experimental farm Scheyern were made independently of data sampled for the design of the model software. In Scheyern, under nearly equal site conditions, two completely different management systems were established: an organically run mixed farm and a conventional cash crop farm. The target was to analyze their effects on the agroecosystem[11].

The primary target of the application is to test its efficiency and validity, to juxtapose computed and measured results, to check the sensitivity of the software for the consequences of management activities and to find out to which extent the results allow an interpretation.

The application of the program in 28 commercial farms is to benchmark the results obtained in the experimental farm Scheyern on a larger scale, to disclose management-specific variations in the GGEs and to evaluate the aptitude of the model for depicting such management effects. In order to make these farms with their highly different structure comparable, only emissions from the cropping systems were analyzed; livestock keeping was not considered.

The studies were based on the hypothesis that (1) modeling C cycles contributes to a better understanding of farming systems, thus providing the preconditions for an emission inventory; (2) farming systems have a particular importance for the implementation of CO_2 reduction strategies, because climate-related management decisions are due to be made on farm level; (3) tools for the analysis of C cycles have to be integrated into complex management systems, in order to estimate the ecological and economic effects of climate-protecting measures and to assess their feasibility.

Methods and Materials

Modeling approach

In the described investigations C cycles on farm level were depicted by using the computer program REPRO (REPROduction of soil fertility[12,13]). REPRO is software for analyzing, evaluating and optimizing the environmental

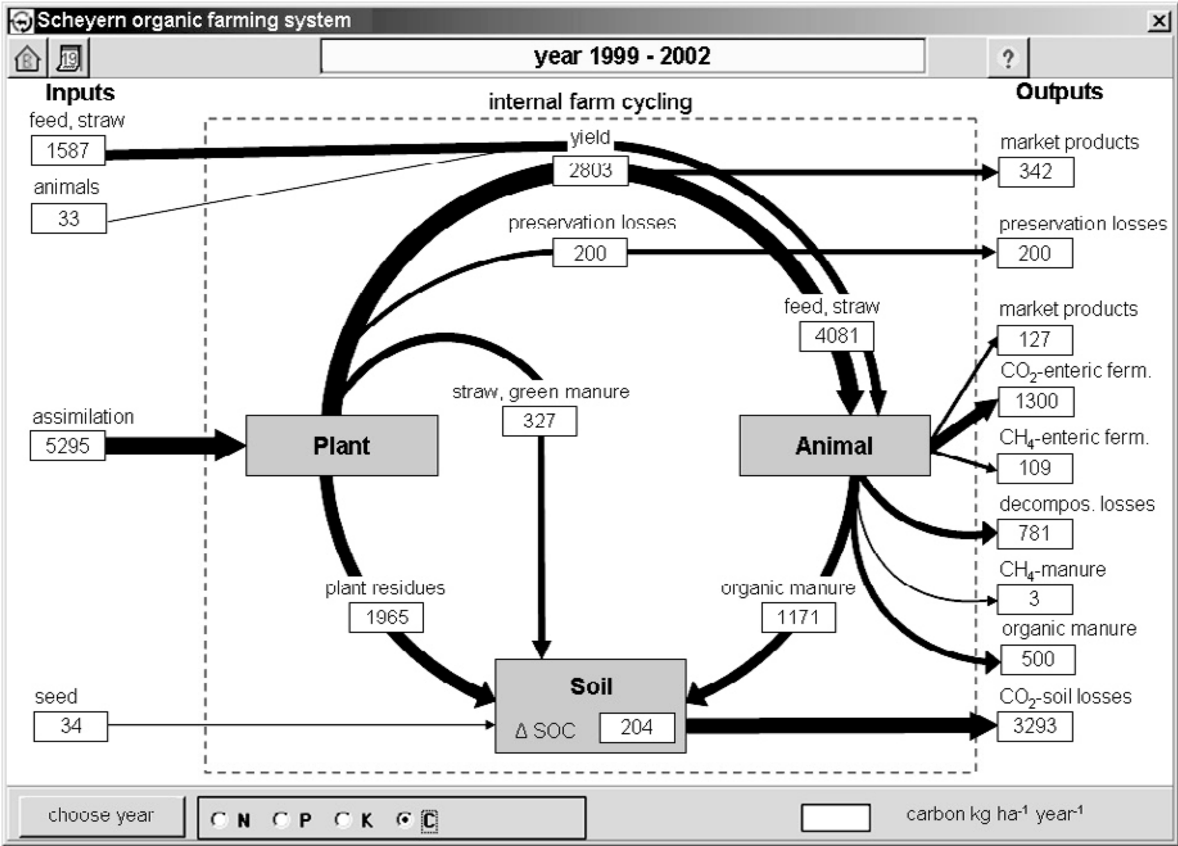

Figure 1. On-farm carbon cycle of the organic farming system Scheyern, kg C ha^{-1} yr^{-1} (av. 1999–2002), screenshot of the model REPRO.

effects of agricultural enterprises. The model describes a given farm as a functioning system. REPRO has a hierarchical set-up: Lower system levels, i.e., subfields, crop stands and products are regarded as elements of the higher system levels like crop rotation or farm. Interactions between different sectors of the farm and the relationships to the environment are depicted as mass and energy fluxes (see Figs. 1 and 2). REPRO has a modular set-up and comprises the following components:

- relational databases for the handling of site and management information,
- balancing models for the description of farm-specific mass and energy fluxes[13–15],
- empirical models, for example for the estimation of soil loss by water erosion[16] and for the assessment of soil compaction damage caused by machine passage[17],
- interfaces to C/N simulation models[18],
- interfaces to Geographic Information Systems[16],
- rating methods, for example for indicators and evaluation functions[12].

In the program, on-farm mass fluxes are described as closed cycles. The partial balances are interlocked, the outputs of one subsystem are the inputs of the other, as shown by the following example: the path of the produced feed is completely traced in quantity and quality from the field via preservation, storage and use down to the stable. Farm manure produced in dependence on feed input, animal performance and technological design is depicted both in quantity and quality from the very beginning via excreta storage to spreading it on the field. On-farm N transfers and N emissions are thoroughly considered by the program[13]. The objective to balance the C containing mass fluxes made it necessary to identify relevant C fluxes and C pools, to derive appropriate algorithms and model parameters using findings from the literature and our own research results, to design the software module and to link it with the already existing modules[13]. To balance the net greenhouse effect, the quantities of N_2O, CH_4 and CO_2 emissions are determined and evaluated. All emissions were converted to CO_2 equivalents [CO_2 eq] using their specific global warming potential (GWP), which determines the relative contribution of a gas to the greenhouse effect. The GWP index is defined as the cumulative radiative forcing between the present and a selected time in the future, caused by a unit mass of gas emitted now[19]. The GWP (with a time span of 100 years) of CO_2, CH_4 and N_2O is 1, 23 and 296, respectively.

In order to quantify the C fluxes, primarily the following approaches have been used.

Δ Soil organic carbon (Δ SOC). Changes in SOC were determined by use of humus balancing[12]. This method includes analyses of the crop-specific effects (depending on site, yield and mineral N doses) and of the organic fertilizers (depending on quantity and quality) on the humus level of the soil. The parameters were derived in long-term

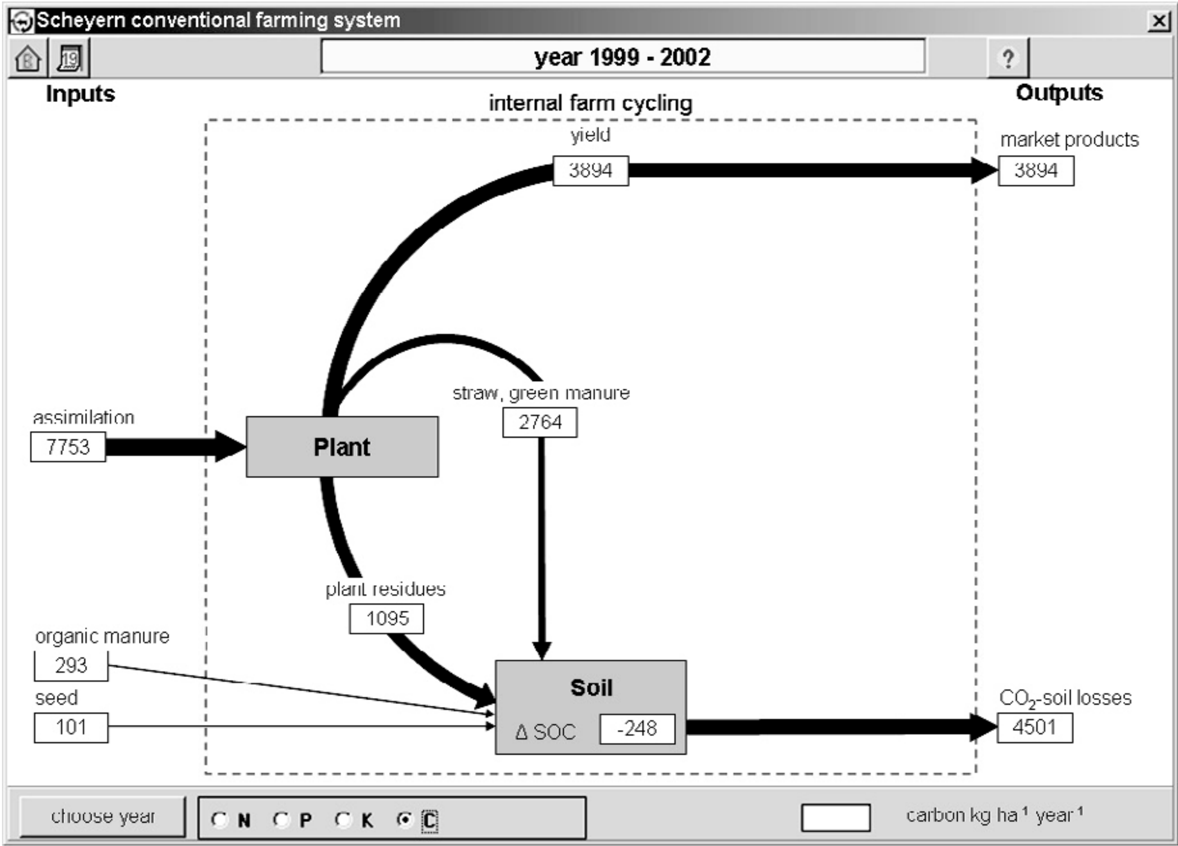

Figure 2. On-farm carbon cycle of the conventional farming system Scheyern, kg C ha^{-1} yr^{-1} (av. 1999–2002), screenshot of the model REPRO.

field experiments run with various crop rotations and fertilization patterns in regions of different soil and climate conditions, for example on diluvial, loess and highland sites, surveying the development of SOC over more than 20 years. Indirectly, the parameters also take into account root mass and rhizodeposition of the crops, as well as type and intensity of tillage. The mean crop-specific coefficients Δ SOC [Mg ha^{-1} yr^{-1}] are: potato, –1.0 to –1.6; maize, –0.7 to –1.2; winter wheat, –0.4 to –0.8; grass–clover–alfalfa (GCA), 0.9 to 1.2. The indicated variability ensues from the influence of factors such as yield (yield-related root mass and C input), production technology (e.g., effect of fertilization) and site conditions (e.g., soil texture). These factors do not include the effects of the byproducts (straw, beet tops, potato vines) and of mulched biomass (GCA) on SOC; they were determined on the basis of biomass input. The mean humus reproduction coefficients Δ SOC [kg C (kg C Input)$^{-1}$] are: farmyard manure (FYM), 0.35; slurry, 0.26; straw, 0.21 and green manure, 0.14. Slurry provides 75%, straw 60% and green manure 40% of the humus reproduction performance of FYM. The parameters were determined with regard to the C turnover in open field trials. Apart from this, analyses were also made of the C turnover of organic matter in incubation tests under controlled laboratory conditions[12,20,21].

C assimilation and C inputs to soils by plants. The net C assimilation of the plants was estimated from the measured aboveground net primary production (ANPP) and the C contents in the biomass. The harvested yield of the main products was entered as measured value. The soil C inputs were estimated as crop, yield and site specific values with consideration of: (1) byproducts, (2) crop residues (stubble), (3) roots and (4) rhizodeposition (exudates and root turnover in the growth period). The parameters were based on measurements in field experiments[22,23] and on data obtained in a literature study. By use of this method, the following values were obtained for winter wheat, for example: dry matter (DM) and C quantities [Mg ha^{-1} yr^{-1}]: grain as main product 5.0 Mg DM, 2.22 Mg C; straw as byproduct 4.0 Mg DM, 1.84 Mg C; stubble 0.8 Mg DM, 0.37 kg C; roots 1.3 Mg DM, 0.52 Mg C; rhizodeposition 0.8 Mg DM, 0.31 Mg C; total biomass 11.9 Mg DM, 5.26 Mg C. Thus, the C harvest index (harvested biomass [kg C ha^{-1}]/total biomass [kg C ha^{-1}]) amounted to 0.42 for mere grain harvesting and 0.77 when grain and straw were harvested as well.

CO_2 emissions from the use of fossil energy. CO_2 and energy balances are interlocked; they consider direct and indirect inputs of fossil energy and the involved CO_2 emissions. Energy balancing has been performed according to Hülsbergen et al.[10,15]. Energy inputs and CO_2 emissions have been estimated by use of the parameters listed in Tables 1 and 5; the determined energy outputs are based on the calorific values per kilogram DM as given in Table 3.

CH_4 emissions. The metabolic methane emissions from livestock keeping were estimated with regard to animal species, performance and feeding. On the basis of the feed gross energy, methane releases were estimated by means of conversion factors. For quantifying the methane release from organic fertilizer during storage, the excreta output (quantity, chemical components, degradability) was chosen as the basis for calculating the methane formation potential; the amount of produced methane was then determined with regard to the storage system[24].

N fluxes relevant for an emission inventory were estimated as follows:

N_2O emissions. N_2O emissions were estimated following the IPCC approach[24]. It was assumed, albeit very simplified, that 1.25% of the nitrogen supplied to the soils by organic and mineral fertilization, N_2 fixation and N deposition is emitted in the form of N_2O–N. Alternatively, a N_2O–N emission factor of 2.53% of the total N input as obtained in numerous measurements at the experimental farm[8] was applied. The indirect N_2O emissions from gaseous NH_3 and NO_x losses as well as from N losses via leaching were quantified using emission factors[24].

N_2 fixation. The symbiotic N_2 fixation by legumes has been estimated under the assumption that the fixation rate rises with increasing yields[12,25]. The yields were entered into the calculations in the form of measured values. For each legume crop a specific N_{dfa} value (N_{dfa} = nitrogen derived from atmosphere) was assumed which was modified according to the given conditions, among others the content of plant available nitrogen in the soil (i.e., GCA under organic conditions: $N_{dfa} = 0.90$, under conventional conditions: $N_{dfa} = 0.80$). The N quantities bound in roots, crop residues and rhizodeposition were estimated using crop specific parameters[12]. The legume share of the crop blends (mass %) was entered as measured or estimated value.

Experimental site and test farms

The described model was applied (1) in the experimental farm Scheyern located 40 km north of Munich in southern Germany (48°30.0′N, 11°20.7′E) and (2) in 28 commercial farms under comparable climate and soil conditions.

(1) In the experimental farm Scheyern, investigations of processes taking place in agroecosystems were made as well as analyses and optimization studies of the sustainability of management systems[11]. In 1992, the farm was divided into two independent farming systems with experimental character. One farm (31.5 ha arable land and 25.4 ha grassland) has been managed according to the principles of organic farming (org), the other (30.0 ha arable land) has remained under conventional management (con).

The research station is located 445–498 m above sea level, in a hilly landscape derived from tertiary sediments partly covered by loess. There is a high variability of soil types and soil properties; most soils have a loamy texture and are classified as Cambisols or Eutrochrepts. The mean annual precipitation is 833 mm, the mean annual temperature 7.4°C[11].

The productivity of the two farm sites is not absolutely the same. The organic farm works land of a slightly lower yield potential and steeper sloping than the conventional counterpart. The arable areas (AAs) of the organic farm scores 48, the conventional farm 52 points on an average (100 scores correspond to the highest cropping capacity according to German Soil Classification Scheme[26]). The organic farm keeps a suckler cowherd. The stock density had increased step by step from 0 LSU ha^{-1} (in 1992) to 1.4 LSU ha^{-1} (av. 1999–2002) and was then continuously reduced again (LSU = Livestock Unit according to FAO). Thus, different intensity levels and on-farm mass fluxes were reached. In compliance with the guidelines for organic farming, mineral N and chemico-synthetic plant protection products have been omitted. Since arable and grassland soils in both farms show high to very high nutrient levels, no mineral P and K doses needed to be applied in the reference period. The crop rotation of the organic system comprised: (1) GCA, (2) potatoes + undersown mustard, (3) winter wheat, (4) sunflower + undersown GCA, (5) GCA, (6) winter wheat, and (7) winter rye + undersown GCA.

The conventional farm has specialized on cash crop production. The crop rotation included: (1) potatoes + mustard as catch crop, (2) winter wheat, (3) maize + mustard as catch crop and (4) winter wheat. Occasionally, silage maize was sold to a neighboring farm for an equivalent import of cattle slurry. The organic crop rotation has a much broader crop diversity than the conventional. The mean size of a crop rotation field is 4.5 ha (org) and 7.5 ha (con).

Tillage was adjusted to the cropping systems. In the seven-field organic rotation, usually three operations with a moldboard plough are carried out and two with a chisel plough. In years of GCA cultivation, tillage is omitted. The conventional crop rotation refrains completely from ploughing.

The characterization of the systems according to tillage (org = with ploughing, con = no ploughing) reflects the practice in the commercial farms of the region. It becomes evident that the two management systems in Scheyern have very different structures and production features, but this is typical for the different farming systems (org and con) and also for the region. The farming systems of Scheyern have been subjected to numerous evaluations and comparisons of the effects of organic and conventional farming on the abiotic and biotic environment (among others[8,27–29]).

For more than 15 years an intensive monitoring program has been run on the farm areas. From the very beginning of the investigations, all operations have been documented in electronic field files.

Yields, DM and nutrient contents of the harvested products were documented on field and subfield level

Table 1. Mass and energy input in the organic farm Scheyern averaging the years 1999–2002.

Field	Crop[1] *+catch crop*[3]	N_2 fixation ($kg\,ha^{-1}$)	Organic matter input Type	N ($kg\,ha^{-1}$)	C ($kg\,ha^{-1}$)	Energy input[2] ($GJ\,ha^{-1}$)
1	GCA	261				5.0
2	Potatoes		FYM	186	3099	10.5
			Residues[4]	31	1377	
	+undersown mustard		*Green manure*[4]	*46*	*851*	*1.1*
3	Winter wheat		FYM	99	1714	4.7
			Slurry	18	107	
4	Sunflower		FYM	82	1310	3.5
			Slurry	8	50	
			Straw[4]	39	1096	
	+undersown GCA	*31*	*Green manure*[4]	*46*	*808*	*1.5*
5	GCA	236				4.6
6	Winter wheat		FYM	26	477	4.9
			Slurry	23	139	
7	Winter rye		FYM	95	1625	4.3
			Slurry	17	102	
	+undersown GCA	*50*				*1.4*
	Crop rotation	**83**		**102**	**1822**	**5.9**
	Grassland	33	FYM	10	156	2.7
			Slurry	8	50	
			Excreta	87	890	
	Agricultural area (AA)	**60**		**104**	**1499**	**4.5**

[1] Crop rotation: (1) GCA (*Lolium perenne* L. + *Trifolium pratense* L. + *Medicago sativa* L.), (2) potatoes (*Solanum tuberosum* L.) + undersown mustard (*Sinapis alba* L.), (3) winter wheat (*Triticum aestivum* L.), (4) sunflower (*Helianthus annuus* L.) + undersown GCA, (5) GCA, (6) winter wheat, and (7) winter rye (*Secale cereale* L.) + undersown GCA.
[2] To calculate the energy input, the following energy equivalents per kilogram were assumed: diesel, 46.6 MJ; mineral N, 35.3 MJ; P fertilizer, 36.2 MJ; K fertilizer, 11.2 MJ; herbicides, 288 MJ; insecticides, 237 MJ; seed of winter wheat, 5.5 MJ; potato seed, 1.3 MJ; machines, 108 MJ[12,44].
[3] *All information on catch crops in italic*.
[4] Non-harvested plant biomass (potato vines, non-harvested biomass of mustard and GCA and sunflower straw). Stubble, roots and rhizodeposition are not included.

separately. Before spreading, the doses of farm manure were weighed and their nutrient contents determined in laboratory analyses. In 50×50 m grids, SOC, SON and nutrient levels have been sampled at time intervals of 5 years. The Ap-horizon revealed SOC levels of 1.39% (0.78–2.69, $n = 116$) in the organic and 1.25% (1.05–2.08, $n = 106$) in the conventional farm (sampling of 2001[30]). In some places, relevant C and N fluxes were measured, for example the N_2O emissions[8]. Thus, a rich data pool is now available which is used for the validation of the model software. As reference period the years 1999–2002 were chosen because during this time no management changes took place, and the systems had principally became established since the management shift in 1992.

(2) The 28 commercial farms are located in the surroundings of the experimental farm Scheyern (mean distance 60 km). Of the monitored farms, 18 are run organically (org), 10 conventionally (con). The soils are similar to those in Scheyern; their mean yield productivity, however, ranks slightly higher in view of scores average of 58 (40–70) (org) and 61 (45–77) (con). The livestock density is 0.5 (0.0–1.4) LSU ha^{-1} (org) and 0.8 (0.0–2.2) LSU ha^{-1} (con). The crop rotations vary broadly. The proportion of grain crops amounts to 60 (35–80)% of the AA (org) and 70 (50–80)% (con), respectively. Legumes occupy 25 (15–45)% (org) and 5 (0–20)% (con) of the AA, row crops 3 (0–25)% (org) and 15 (0–50)% (con), respectively.

Results

Experimental farm Scheyern

Mass and energy inputs in the cropping system. At a N_2 fixation rate of 83 $kg\,ha^{-1}\,yr^{-1}$ (Table 1), the organic crop rotation is based on legumes. Due to a stock density of 1.4 LSU ha^{-1}, large C and N quantities circulate at farm level. For each hectare of arable land, 70 kg N bound in FYM and 9 kg N bound in slurry are available. The residues of sunflower and potatoes, non-harvested GCA and the residues of the cover crop (mustard) are usually incorporated into the soil. The straw of the small grain crops is used as bedding material and returns to the land as FYM. The C/N ratio of the organic matter supplied to the soil in the organic system is 18 : 1 on

Table 2. Mass and energy input in the conventional farm Scheyern averaging the years 1999–2002.

Field	Crop[1] +*catch crop*[3]	Mineral N ($kg\,ha^{-1}$)	Organic matter input Type	N ($kg\,ha^{-1}$)	C ($kg\,ha^{-1}$)	Energy input[2] ($GJ\,ha^{-1}$)
1	Potatoes	90	Residues[4]	75	2495	16.1
	+catch crop mustard	*20*	*Green manure*[4]	*127*	*2011*	*2.0*
2	Winter wheat	160	Slurry	46	360	11.6
			Straw[4]	28	2182	
3	Maize	130	Slurry	21	215	12.5
	+catch crop mustard	*20*	*Slurry*	*37*	*390*	
			Green manure[4]	*127*	*2011*	*2.0*
4	Winter wheat	160	Slurry	28	208	11.6
			Straw[4]	30	2355	
	Crop rotation	**145**		**130**	**3057**	**14.0**

[1] Crop rotation: (1) potatoes + mustard as catch crop, (2) winter wheat, (3) maize (*Zea mays* L.) + mustard as catch crop, (4) winter wheat.
[2] Energy equivalents: see Table 1.
[3] *All information on catch crops in italic.*
[4] Non-harvested plant biomass (potato vines, non-harvested biomass of mustard and cereal straw). Stubble, roots and rhizodeposition are not included.

an average (FYM 17 : 1, slurry 6 : 1 and residues 24 : 1–30 : 1). The nitrogen returns mainly as organically fixed N; the NH_4–N proportion in FYM amounts to 25%.

From the energetic point of view, the organic crop rotation is run as a low-input system with 5.9 $GJ\,ha^{-1}\,yr^{-1}$; only potato cropping requires higher energy inputs (10.5 $GJ\,ha^{-1}\,yr^{-1}$) compared to cereals. This has to be attributed to the labor-intensive planting, cultivation and harvesting of potatoes. The grassland area is under extensive use (energy input 2.7 $GJ\,ha^{-1}$).

The conventional farm is oriented on mineral nitrogen (Table 2); the N doses (145 $kg\,ha^{-1}\,yr^{-1}$) are typical for the region. Although the farm has specialized on cash crops, over the whole crop rotation period more C and N are returned in organic form than in the stocked organic system. The reasons are: large quantities of straw remaining on the land for shallow incorporation and also large amounts of cover crop residues, due to favorable growth conditions. The mean C/N ratio of the supplied organic matter is relatively high (24 : 1) owing to the big share of straw (slurry 6 : 1, wheat straw and maize residues 80 : 1, residues of cover crops and potatoes 27 : 1).

In view of the energy input of 14 $GJ\,ha^{-1}\,yr^{-1}$, the system is run on a high-input level.

Production performance and efficiency levels in the cropping system. Depending on the type of management, yields are clearly differentiated. Potatoes and winter wheat are grown in both crop rotations; a juxtaposition of the yield productivity of these crops underlines the higher yield level under conventional management (Tables 3 and 4). In the organic crop rotation, the recorded 8.3 Mg $ha^{-1}\,yr^{-1}$ corresponds to about 57% of the conventional DM yield, 163 $kg\,N\,ha^{-1}\,yr^{-1}$ equal to about 66% of the N removal, and 3741 $kg\,C\,ha^{-1}\,yr^{-1}$ to roughly 56% of the C bound in the conventional rotation (Tables 3 and 4).

The N surplus (N input minus N removal) amounts to 22 $kg\,ha^{-1}\,yr^{-1}$ (org) versus 28 $kg\,ha^{-1}\,yr^{-1}$ (con). Considering the measured N emissions of 16 $kg\,ha^{-1}\,yr^{-1}$ and the calculated changes of 35 $kg\,ha^{-1}\,yr^{-1}$ (org) and –24 $kg\,ha^{-1}\,yr^{-1}$ (con) in the soil N reserves due to changes in humus level (Tables 5 and 6), N surplus figures have to be adjusted to 3 $kg\,ha^{-1}\,yr^{-1}$ (org) and 68 $kg\,ha^{-1}\,yr^{-1}$ (con), respectively. This reveals higher N loss potentials in the conventional system.

The energy output/input ratio displays clear differences in the energy efficiency of crops and crop rotations. By far the highest energy efficiency is reached in GCA cropping due to low inputs (no fertilizer application), but high energy binding in the harvested biomass. Averaging the organic crop rotation, 18 GJ are bound per GJ of supplied energy; this value ranks about 60% above that of the conventional farm. If the straw harvested in the organic farm were evaluated in an energy balance sheet, the energy output/input ratio would rise to at least 21. Interpreting this value, it must be underlined that the harvested straw is destined only for animal bedding without any utilization in feeding or as energy source.

On-farm C cycles. Depending on the farm structure, mass fluxes in both systems are basically different; the organic system is oriented on closed cycles, the conventional counterpart on transitional fluxes (Figs. 1 and 2). The organic farm imports considerable forage quantities from adjacent organic areas, thus supporting its C fluxes.

The C assimilation efficiency of the organic farm reaches nearly 70% of that of the conventional farm, because GCA and grassland leave a large root mass in the soil. In the organic system, the C input with crop and root residues is 80% higher than in the conventional variant. On the other hand, extremely large C quantities are supplied to the soils of the conventional farm as straw and green biomass, which raises the total C input in the conventional system to 4253 $kg\,ha^{-1}\,yr^{-1}$ and exceeds the C supply to the organic system (3497 $kg\,ha^{-1}\,yr^{-1}$). Depending on the different humus replacement potential of FYM and slurry compared

Table 3. ANPP and energy efficiency in the organic farm Scheyern averaging the years 1999–2002.

Field	Crop +*catch crop*[1]	ANPP Type	DM (Mg ha^{-1})	N (kg ha^{-1})	C (kg ha^{-1})	GJ[2] (ha^{-1})	Energy output/input ratio[4]
1	GCA	Forage	11.8	304	5335	213	42.6
2	Potatoes	Tubers	4.9	66	2044	84	8.0
		Green manure	3.4	31	1377	59	
	+undersown mustard	*Green manure*	*1.9*	*46*	*851*	*32*	
3	Winter wheat	Grain	2.4	49	1110	45	9.6
		Straw	2.2	10	1016	39	
4	Sunflower	Grain	1.6	46	864	43	12.2
		Straw	2.4	39	1096	43	
	+undersown GCA	*Green manure*	*1.8*	*46*	*808*	*32*	
5	GCA	Forage	10.9	283	4942	197	42.8
6	Winter wheat	Grain	3.1	69	1403	58	11.9
		Straw	2.8	13	1320	50	
7	Winter rye	Grain	2.9	48	1317	54	12.6
		Straw	2.9	16	1365	53	
	+undersown GCA	*Forage*	*2.9*	*76*	*1339*	*53*	*37.9*
	Crop rotation		**8.3**	**163**	**3741**	**107**[3]	**18.0**
	Grassland	Forage	6.2	136	2819	111	41.1
	Agricultural area		**7.3**	**151**	**3330**	**109**[3]	**28.3**

[1] *All information on catch crops in italic.*
[2] To calculate the energy recovery in ANPP, the following calorific values per kg DM were assumed: potato tubers, 17.2 MJ; potato vines, 17.0 MJ; winter wheat grain, 18.6 MJ; winter wheat straw, 17.7 MJ; winter rye grain, 18.3 MJ; winter rye straw, 18.3 MJ; GCA, 18.1 MJ; sunflower grain, 26.8 MJ; sunflower straw, 18.0 MJ; mustard, 16.6 MJ[10].
[3] Energy recovery in ANPP of the main products (without byproducts and non-harvested biomass).
[4] Energy output/input ratio = energy recovery in ANPP of the main products/energy input.

Table 4. ANPP and energy efficiency in the conventional farm Scheyern averaging the years 1999–2002.

Field	Crop +*catch crop*[1]		ANPP DM (Mg ha^{-1})	N (kg ha^{-1})	C (kg ha^{-1})	GJ[2] (ha^{-1})	Energy output/input ratio[4]
1	Potatoes	Tubers	8.9	128	3695	153	9.5
		Green manure	6.2	75	2495	106	
	+catch crop mustard	*Green manure*	*4.2*	*127*	*2011*	*71*	
2	Winter wheat	Grain	5.9	144	2760	110	9.5
		Straw	4.7	28	2182	84	
3	Maize	Silage	13.8	178	6204	255	20.4
	+catch crop mustard	*Green manure*	*4.2*	*127*	*2011*	*71*	
4	Winter wheat	Grain	5.5	149	2917	103	8.9
		Straw	4.4	30	2355	78	
	Crop rotation		**14.5**	**247**	**6658**	**155**[3]	**11.1**

[1] *All information on catch crops in italic.*
[2] Calorific values: see Table 3.
[3] Energy recovery in ANPP of the main products (without byproducts and non-harvested biomass).
[4] Energy output/input ratio = energy recovery in ANPP of the main products/energy input.

to straw and the humus accumulation by GCA, a rise in the SOC was estimated for the AA of the organic system and a decline for the conventional system. A C steady state (Δ SOC = 0) has been assumed for the grassland during the regarded period, because it represents permanent grassland without any changes in management.

By way of computing, the soil-borne CO_2 respiration (= $\Sigma\Delta$ C input − Δ SOC) turned out to be 3293 kg ha^{-1} yr^{-1} (org) and 4501 kg ha^{-1} yr^{-1} (con) (Figs. 1 and 2).

The differing yield levels, but mainly the different use of the products, produce substantial variations in the C output. In the cash crops, 342 kg ha^{-1} yr^{-1} (org) and 3894 kg ha^{-1} yr^{-1} (con), respectively, are fixed. The C quantities in animal products amount to 127 kg ha^{-1} yr^{-1} (org). The stock-keeping organic farm involves C loss processes that do not take place in the cash crop farm, for example metabolic CH_4 (109 kg C ha^{-1} yr^{-1}) and CO_2 emissions from the animals (1300 kg C ha^{-1} yr^{-1}) as well

Table 5. Annual C sequestration and estimated emissions of greenhouse gases in the organic farm Scheyern averaging the years 1999–2002.

		C sequestration in SOM			Fertilizer	Fuel	Pesticides	Machines	N_2O	Net GGE[5–7]
Field	**Crop** *+ catch crop*[1]	**Δ C, Crop**[2] **(kg ha^{-1})**	**Δ C, Manure**[3] **(kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**	**CO_2 eq (kg ha^{-1})**
1	GCA	916	0	−3362	0	345	0	121	1733	−1203
2	Potatoes	−1073	1259	−681	0	366	62	352	1358	1417
	+ undersown mustard	*110*	*110*	*−808*	*0*	*94*	*0*	*9*	*247*	*−471*
3	Winter wheat	−626	696	−255	0	213	0	168	782	869
4	Sunflower	−719	412	1128	0	204	0	145	602	2039
	+ undersown GCA	*307*	*516*	*−3022*	*0*	*92*	*0*	*11*	*683*	*−2277*
5	GCA	945	0	−3470	0	316	0	114	1644	−1436
6	Winter wheat	−806	191	2256	0	252	0	153	375	2996
7	Winter rye	−650	592	213	0	225	0	177	720	1295
	+ undersown GCA	*394*	*0*	*−1447*	*0*	*95*	*0*	*9*	*416*	*−967*
	Crop rotation	**−172**[4]	**539**[4]	**−1350**	**0**	**315**	**9**	**180**	**1227**	**323**
	Grassland	0	0	0	0	195	0	55	813	1023
	Agricultural area	**−95**	**299**	**−748**	**0**	**261**	**5**	**124**	**1042**	**635**

[1] *All information on catch crops in italic.*
[2] C sequestration, net effect of the grown crop on SOC, caused by C inputs (stubble, roots, C rhizodeposition), influence on C mineralization and C immobilization, including the effects of the production technology (i.e., type and intensity of tillage), computed with humus balancing. Negative values indicate a SOC decrease, positive values a SOC increase.
[3] C sequestration, net effect of the applied fertilizer (FYM and slurry) and the supply of plant biomass to the soil (straw, residues, non-harvested biomass of mustard and GCA) on SOC, with consideration of the specific humus replacement rate (see Methods and Materials), computed with humus balancing.
[4] Averaging the crop rotation, C sequestration amounts to 367 (539–172) kg C ha^{-1} yr^{-1}, this equals a N immobilization in SOM of 35 kg N ha^{-1} yr^{-1} at a C/N-ratio of 10.5:1 in SOM.
[5] To calculate the GGEs, the following CO_2 emissions per kilogram were assumed: diesel, 4.19 kg; mineral N, 2.86 kg; P fertilizer, 2.57 kg; K fertilizer, 0.73 kg; herbicides, 23.10 kg; insecticides, 23.10 kg; seed of winter wheat, 0.55 kg; potato seed, 0.13 kg; machines, 4.71 kg[44].
[6] Plus denotes an increase, minus a reduction in net GGEs.
[7] To calculate the net GGEs, a methane uptake by the soil of 40 kg CO_2 eq ha^{-1} yr^{-1} is considered.

Table 6. Annual C sequestration and estimated emissions of greenhouse gases in the conventional farm Scheyern averaging the years 1999–2002.

Field	Crop *+catch crop*[1]	C sequestration in SOM Δ C, crop[2] (kg ha^{-1})	Δ C, manure[3] (kg ha^{-1})	CO_2 eq (kg ha^{-1})	Fertilizer CO_2 eq (kg ha^{-1})	Fuel CO_2 eq (kg ha^{-1})	Pesticides CO_2 eq (kg ha^{-1})	Machines CO_2 eq (kg ha^{-1})	N_2O CO_2 eq (kg ha^{-1})	Net GGE[5–7] CO_2 eq (kg ha^{-1})
1	Potatoes	−1230	296	3426	254	352	341	268	1115	5717
	+catch crop mustard	*116*	*261*	*−1384*	*61*	*250*	*34*	*55*	*853*	*−170*
2	Winter wheat	−563	545	64	467	220	132	132	1422	2397
3	Maize	−795	70	2661	481	268	84	136	947	4537
	+catch crop mustard	*116*	*261*	*−1384*	*61*	*250*	*34*	*55*	*853*	*−170*
4	Winter wheat	−603	534	255	462	217	139	128	1317	2479
	Crop rotation	**−740**[4]	**492**[4]	**910**	**446**	**389**	**191**	**194**	**1627**	**3697**

[1] *All information on catch crops in italic.*
[2,3] Estimation of C sequestration see Table 5.
[4] Averaging the crop rotation, C sequestration was −248 (492–740) kg C ha^{-1} yr^{-1}, this equals to a N immobilization in SOM of −24 kg N ha^{-1} yr^{-1} at a C/N-ratio of 10.5 : 1 in SOM.
[5] Calculation of the GGEs see Table 5.
[6] Plus denotes an increase, minus a reduction in net GGEs.
[7] To calculate the net GGEs, a methane uptake by the soil of 40 kg CO_2 eq ha^{-1} yr^{-1} is considered.

as losses from farm manure on store (Fig. 1). Due to their high specific GWP, CH_4 emissions have a particular importance.

Inventory of climate relevant gases. The inventory of climate relevant gases (Tables 5 and 6) includes exclusively the cropping sector and allows comparisons of the systems on the levels arable land, crop rotation and crop species. Emissions from the livestock sector were not considered.

The results elucidate the influence of crops and fertilization (Δ SOC), cropping intensity (energy input) and crop rotation pattern on the emission of greenhouse gases. The biggest influence on the greenhouse effect is exerted by the Δ SOC and N_2O emissions. The GGEs [CO_2 eq] caused by fuel input (org: 315 kg ha^{-1} yr^{-1} and con: 389 kg ha^{-1} yr^{-1}) and the manufacture of the machines (org: 180 kg ha^{-1} yr^{-1} and con: 194 kg ha^{-1} yr^{-1}) are equally high in both crop rotations. More intensive tillage, manure spreading operations and more field passages for mechanical crop cultivation in the organic farm are compensated in the conventional farm by operations for spreading mineral fertilizer and pesticides and also by a higher input for harvesting the larger biomass yields. As a result of mineral N and pesticide applications, additional 637 kg ha^{-1} yr^{-1} CO_2 eq from the upstream sector are emitted in the conventional system.

Pertaining to the mitigation of GGEs, the most favorable effect among the crops with a negative greenhouse effect is reached by GCA, owing to C sequestration in the range of about 0.9 Mg ha^{-1} yr^{-1}. High GGE values were obtained for the row crops potato and maize, favorable levels for catch crops. Related to the cultivated area, the organic rotation produces only 10% of the greenhouse effect of the conventional rotation; related to the energy fixed in the harvested products, approximately 18%.

Results of 28 farms in the region

The mean energy input in the organic farms amounts to 5.3 GJ ha^{-1} yr^{-1} (Table 7) which corresponds to the situation in the organic farm in Scheyern. Due to differences in cropping structures and management, some farms rank above this level by up to 50%. The application of mineral fertilizers and chemical plant protection involves clearly higher energy inputs in the conventional farms (11.7 GJ ha^{-1} yr^{-1}). Within the range of fluctuation (9.5–15.0 GJ ha^{-1} yr^{-1}), only one farm exceeded the cropping intensity of the conventional system in Scheyern (14.0 GJ ha^{-1} yr^{-1}).

In the organic farms DM yields (2.0–7.7 Mg ha^{-1} yr^{-1}) vary much more than in the conventional farms (4.5–9.0 Mg ha^{-1} yr^{-1}). The highest-yielding organic farms reach the mean yield level of the conventional farms. The DM yields are not only conditioned by the management system (org versus con) but also by the disposal of the grown biomass. High DM yields were recorded mainly in connection with a high harvest index (i.e., use of byproducts and catch crops). The energy efficiency,

Table 7. Coefficients of mass and energy budget, C sequestration and estimated GGEs in the monitored farms, averaging the arable land.

		Organic farms (18+1)				Conventional farms (10+1)			
Parameter	**Unit**	**Scheyern**	**Medium**	**Min**	**Max**	**Scheyern**	**Medium**	**Min**	**Max**
Energy input[1]	GJ ha^{-1}	5.9	5.3	4.1	7.8	14.0	11.7	9.5	15.0
N input[2]	kg N ha^{-1}	204	152	108	227	296	246	193	304
DM yield	Mg ha^{-1}	5.8	3.8	2.0	7.7	8.5	7.6	4.5	9.0
Energy output/input ratio		18.0	13.0	6.0	19.3	11.1	11.8	6.1	16.2
C sequestration[3]	CO_2 eq kg ha^{-1}	−1350	−452	−1830	489	910	266	−659	910
N_2O emissions	CO_2 eq kg ha^{-1}	1227	887	631	1322	1627	1418	1123	1771
Emissions from fossil energy input	CO_2 eq kg ha^{-1}	504	454	320	750	1220	1037	819	1220
Net GGE[4,5]	CO_2 eq kg ha^{-1}	323	887	106	1875	3697	2717	1878	3697
Net GGE winter wheat[5]	CO_2 eq kg ha^{-1}	1968	1669	−278	2966	2514	2333	1478	3680
Net GGE[6]	CO_2 eq kg Mg^{-1}	56	263	23	431	434	376	271	434
Net GGE winter wheat[6]	CO_2 eq kg Mg^{-1}	715	496	−102	958	441	355	213	545

[1] Energy equivalents: see Table 1.
[2] N input = sum of N emissions (16 kg ha^{-1} yr^{-1}), N_2 fixation, organic and mineral fertilizer and non-harvested residues.
[3] Plus denotes mineralization and loss of SOC to the atmosphere, minus denotes an immobilization and sequestration of C in the soil.
[4] Plus denotes an increase, minus a reduction in net GGEs.
[5] Area-related calculation of the GGEs.
[6] Product-related calculation of the GGEs.

expressed as energy output/input ratio, is on the same level in organic and conventional farms.

The calculated C sequestration [CO_2 eq] varies broadly both in organic and conventional farms. Averaging all organic farms, C sequestration amounts to (+123 kg C ha^{-1} yr^{-1} = reduction of the greenhouse effect by 452 kg CO_2 eq ha^{-1} yr^{-1}), while the conventional farms reveal depleting SOC levels (−73 kg C ha^{-1} yr^{-1}, with an increase of the greenhouse effect by 266 kg CO_2 eq ha^{-1} yr^{-1}). The deviating development of the SOC stock is caused by different crop rotations (high legume proportion (org) versus high proportion of cereals and row crops (con)) and by the quantity and quality of the organic matter supplied to the soil (mainly FYM (org) versus straw and slurry input (con)).

In view of lower N and energy inputs in the organic farms, their N_2O and CO_2 emissions are clearly lower. The area-related total GGEs from the conventional farms (2717 kg CO_2 eq ha^{-1} yr^{-1}) with consideration of SOC changes are nearly threefold higher than the GGE from the organic farms (887 kg CO_2 eq ha^{-1} yr^{-1}).

The differences are lower when we regard the single crop species. Winter wheat is directly comparable because of its major position in the cropping structure of both farming systems (org and con). Regarding the 1669 kg CO_2 eq ha^{-1} averaging all organic farms, we come to 72% of the emissions from conventional systems. When we focus on the harvested product [per Mg DM], lower yields in organic farming involve higher emissions (496 kg CO_2 eq Mg^{-1} (org) and 355 kg CO_2 eq Mg^{-1} con). When all products [Mg DM] of the analyzed crop rotation are taken into account, organic management produced emissions of 263 kg CO_2 eq Mg^{-1}, for the conventional management 376 kg CO_2 eq Mg^{-1} were computed.

Breaking down the farms according to their stock density, the following emissions were computed (in kg CO_2 eq ha^{-1} yr^{-1}):

- organic farms keeping livestock: 851 kg CO_2 eq (thereof emissions from fossil energy input, 523 kg CO_2 eq; C sequestration, −658 kg CO_2 eq; N_2O emissions, 986 kg CO_2 eq):
- organic farms without livestock: 936 kg CO_2 eq (thereof emissions from fossil energy input, 359 kg CO_2 eq; C sequestration, −167 kg CO_2 eq; N_2O emissions, 744 kg CO_2 eq),
- conventional farms with livestock: 2531 kg CO_2 eq (thereof emissions from fossil energy input, 990 kg CO_2 eq; C sequestration, 64 kg CO_2 eq; N_2O emissions, 1477 kg CO_2 eq),
- conventional farms without livestock: 2939 kg CO_2 eq (thereof emissions from fossil energy input, 1093 kg CO_2 eq; C sequestration, 510 kg CO_2 eq; N_2O emissions, 1336 kg CO_2 eq).

Stocked farms reach higher C sequestration values due to the benefits of crop rotation (more forage cropping) and the effects of organic fertilizer. There is a tendency to increased N_2O emissions in stocked farms caused by higher N inputs with manure and legume fodder crops. Organic farms with stock require higher energy inputs connected with increased C emission due to additional harvesting and transport operations for forage provision. In principal it can be stated that the basic system-related differences in the emission potentials between organic and conventional farms continue to exist also, when we distinguish between stocked and stockless systems.

Relationship between energy input and GWP. The parameters energy input and net greenhouse effect in the

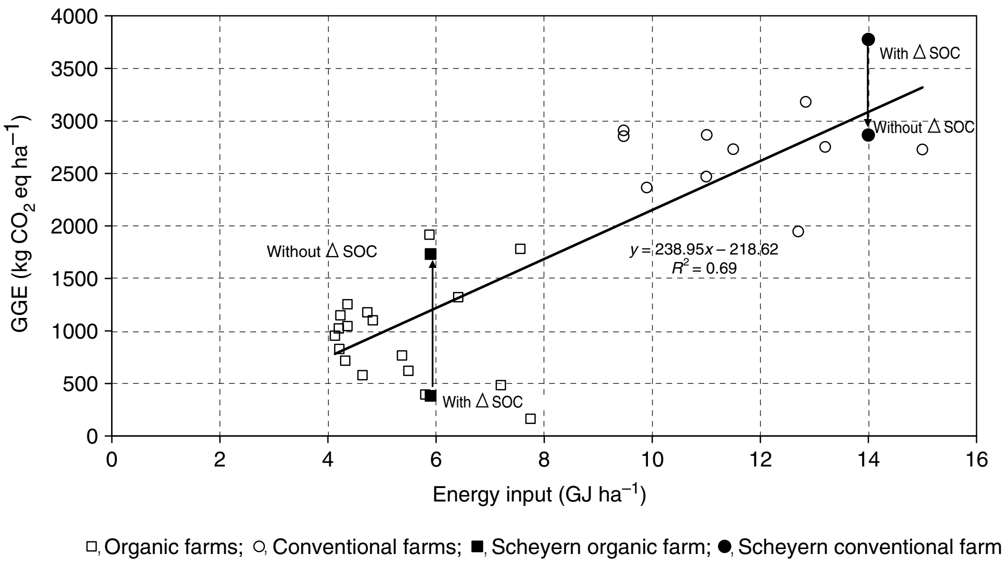

Figure 3. Energy input and GGE, kg CO_2 eq ha^{-1} of the arable area in the organic and conventional farm in Scheyern and in the analyzed organic ($n = 18$) and conventional ($n = 10$) commercial farms.

experimental farm Scheyern and in the analyzed commercial farms ($n = 28 + 2$) have been compared in Figure 3. When all test farms are regarded as a basic population, a linear relationship is recorded between energy input and net greenhouse effect ($r^2 = 0.69$). Emissions rise with increasing input of fuel, fertilizer, pesticides and machines and the involved energy consumption.

Distinguishing between organic and conventional farms produces two clusters and a possible distinction between low and high-input systems. The organic farms are characterized by low energy inputs (4.1–7.8 GJ ha^{-1} yr^{-1}) and low GGE values (106–1875 kg CO_2 eq ha^{-1} yr^{-1}). They are in contrast with the conventional farms and their principally higher energy inputs (9.5–15.0 GJ ha^{-1} yr^{-1}) and higher GGE values (1878–3697 kg CO_2 eq ha^{-1} yr^{-1}). The relationship between energy input and greenhouse effect appears to be fuzzy because it has been affected by Δ SOC and N_2O emissions. Supposing the Δ SOC of the experimental farm Scheyern were not considered, the net greenhouse effect of the organic rotation would rise markedly, while that of the conventional rotation would decrease (Fig. 3).

Discussion

While sophisticated software programs for the analysis of nitrogen and energy fluxes at the farm level have been developed (e.g.[14,31–33]), few tools are available for the balancing of carbon fluxes in the system soil–plant–animal–environment. In the literature, various models have been described for the estimation of relevant CO_2, CH_4 and N_2O sources and sinks. There exist, for example, economic models with linear programming supplemented by algorithms for the estimation of the GWP of farms[34,35]. However, they do not link technical and biological C fluxes. The model REPRO is oriented on the description of such on-farm C fluxes; it combines the balancing of C, N and energy fluxes. A guiding principle during the development of the model was the depiction of farms as systems (Figs. 1 and 2). This distinguishes REPRO from other approaches. Analyses of farm enterprises on the basis of REPRO have shown that the analysed mass cycles depend on site conditions (soil and climate), farm structure (livestock density and crop rotation), inputs (fertilizers, pesticides and energy), outputs (plant and animal products for market presentation), cropping technologies (tillage and harvest procedure) and also on the interactions between these factors (see[12,14]). The relationships between management, C cycles and emission potentials have been demonstrated in detail in the example of the experimental farm Scheyern. Scheyern was divided into two independent farming systems with highly different mass fluxes despite comparable site conditions. The organic farm is characterized by a high crop diversity. The multiple, legume-based rotation favors high N_2 fixation rates; high stock numbers allow an intensive recycling of the organic matter, mainly by recirculating high-quality fertilizers in the form of FYM. The mass fluxes in the farm are oriented on closed matter cycles, from the energetic point of view the system is run on a low-input basis. Thus, Scheyern largely fulfills a basic criterion of organic farming: a principally closed mass cycle in a multi-structured farm. Only the relatively high feed extra-purchase and the involved C and N imports intensify the farm-internal mass fluxes decisively, thus restricting nutrient self-sufficiency. The conventional farm in Scheyern represents a very simply structured cash crop system with a crop rotation of low diversity. The farm is based on mineral nitrogen with transit character, from the energetic point of view a high-input system.

A rich database is available for the experimental farm. Part of the measured values, for example yields and nutrient contents, were used in the model calculations. Other data, for instance emission and SOC measurements, are useful for the verification of the computed results.

The cropping systems in Scheyern have differentiated effects on SOC. For the years 1999–2002, the calculated mean C sequestration was 0.37 Mg ha^{-1} (org) and –0.25 Mg ha^{-1} (con), respectively (Tables 5 and 6). The levels determined for 1991–2001 are lower: 0.16 Mg ha^{-1} yr^{-1} (org) and –0.08 Mg ha^{-1} yr^{-1} (con), due to lower livestock density, lower use intensity in the early 90s and a modified crop rotation.

The chemico-analytical determination of SOC after 10 years of differentiated land use (1991–2001) revealed a SOC increase by 0.18 Mg ha^{-1} yr^{-1} (org; $n = 106$) and a SOC decrease by 0.12 Mg ha^{-1} yr^{-1} (con; $n = 116$), respectively[30]. It becomes obvious that measured and computed results are in good agreement. For a final evaluation, however, a longer period of monitoring will be necessary (see[36]).

C sequestration in the soil is often more influenced by the quality of the organic primary matter (probably because organic matter and residues with close C/N ratio are already partly decomposed and contain an increased proportion of chemically recalcitrant organic compounds) than by the quantity of the supplied matter (see[37]); this has to be taken into account when C cycles are to be described.

In Scheyern, SOC values increased under organic and declined under conventional farming, although the conventional crop rotation is a reduced-till system with higher C inputs. According to the humus balance, C sequestration relies strongly on the quality of the organic fertilizer (FYM versus straw) as well as on the legume share in the rotation. For GCA, C sequestration turned out to be 0.93 Mg ha^{-1} yr^{-1}; for maize (–0.72 Mg ha^{-1} yr^{-1}) and potatoes (–0.93 Mg ha^{-1} yr^{-1}; con) negative effects on SOC were computed. In Scheyern, only the overall influence of a cropping system on the SOC can be measured and not the separate effects by crops and fertilization measures. This would require a different approach, for example factorial field experiments. Experiments on C sequestration by perennial legumes, however, were already described in detail in literature and confirm the values communicated here. For example, the C sequestration rate of alfalfa obtained in field experiments under different climatic and soil conditions was reported to be 0.5 to >1.0 Mg ha^{-1} yr^{-1} ([3,4,12,38]).

In the present paper, the net greenhouse effect has been estimated with regard to the C sequestration. It should be pointed out that C accumulation and depletion as induced by management shifts are temporarily limited, and that with the development of new steady states Δ SOC finally falls to zero[39]. In view of this situation (Δ SOC = 0), the GGEs [CO_2 eq] in Scheyern reached 1673 kg ha^{-1} yr^{-1} (org) versus 2787 kg ha^{-1} yr^{-1} (con), which is clearly different from Tables 5 and 6. According to these findings, in the organic crop rotation about 60% of the GGEs from the conventional rotation are area-related and >100% product-related.

The N_2O emissions were quantified following IPCC[19]. To simplify the calculation it was assumed that 0.0125 kg N_2O–N kg^{-1} N input (deposition, mineral N, organic N and symbiotic N_2 fixation) is emitted. In recent publications, this relationship between N input and N_2O emission was principally confirmed. Petersen et al.[40] found an emission factor of 0.016 kg N_2O–N kg^{-1} N input ($r^2 = 0.56$) in European crop rotations, Gregorich et al.[41] reported for Canadian conditions 0.012 kg N_2O–N kg^{-1} N input ($r^2 = 0.43$).

Long-term measurements in Scheyern revealed that the IPCC method may lead to an underestimation of N_2O emissions (Tables 5 and 6)[8]. The N_2O emissions [kg N_2O–N ha^{-1} yr^{-1}] computed by us per hectare and year amounted to 0.8–3.1 kg for winter wheat, 2.4–2.9 kg for potatoes; the measured values were 1.8–16.8 kg for winter wheat and 5.3–8.2 kg for potatoes. Some N_2O measurement series in Scheyern, for example in wheat[42], furnished N_2O emission levels in the order of IPCC values; other measurements like those in potatoes[42] ranked clearly above the computed levels. It turned out that in potato crops very high N_2O quantities were emitted from the inter-ridge space[42]. According to Flessa et al.[8], the high N_2O emissions in Scheyern may probably be attributed to the local soil properties (high soil bulk density and soil water content, low O_2 availability) and the climatic conditions favoring denitrification. Also, increased emissions induced by freezing and thawing events occurred each year and accounted for a substantial part (30–50%) of the annual emissions[8,42].

The N_2O measurement series made in Scheyern shows that it is principally extremely difficult to project selective and temporarily limited measurements to large areas or even whole farms. Unfortunately, a generally applicable algorithm that considers, beside N inputs, other influential parameters like site conditions, crop species, tillage and soil N turnover, could not yet be derived from the values measured in Scheyern. Tools for a more precise estimation of emissions are simulation models, for example the software DNDC[43]. Currently, this software is in validation using N_2O measurement data from Scheyern.

Supposing a higher N_2O–N emission factor (2.53% of the total N input according to Flessa et al.[8], instead of 1.25% as calculated by IPCC[24]) is assumed, the emission inventory would be modified as follows: The GGEs [CO_2 eq] resulting from N_2O would rise from 1227 to 2483 kg ha^{-1} yr^{-1} (org) and from 1627 to 3294 kg ha^{-1} yr^{-1} (con), respectively; the total GGEs from both crop rotations would increase to 1579 kg ha^{-1} yr^{-1} (org) and 5363 kg ha^{-1} yr^{-1} (con). Accordingly, the organic rotation would reach 30% of the net greenhouse effect recorded in the conventional rotation.

The application of the model REPRO in 28 farms in southern Germany (Tables 7 and Fig. 3) revealed, under the given local conditions, distinct differences between organic and conventional farms concerning their structure, mass and energy inputs, yields, C sequestration and GGEs. From the energetic point of view, the organic farms are low-input, the conventional farms high-input systems. The energy input is primarily related to the mineral N input. Increasing mineral N and energy inputs enhance also the area-related N_2O and CO_2 emissions; there is a linear relationship between energy input and GGEs per hectare (Fig. 3). Further factors are integrated in the computing of net GGEs like C sequestration, symbiotic N_2 fixation, energy input by the use of machines and fuel. This explains the enormous variability of the net greenhouse effect in organic and conventional farms (Fig. 3).

Our investigations have revealed that organic farms produce less area-related GGEs than conventional farms; this was also confirmed by other authors (e.g.,[7,8,40]). The mean product-related emissions from organic farms are also lower but they vary broadly (see Table 7). It is quite possible that there are organic farms with higher product-related GGEs than their conventional counterparts. One reason among others is the broad variation of yields.

Conclusions

The results communicated in this paper refer to farms under organic and conventional management. The criteria for farm selection and the model-based analyses were not targeted at drawing general conclusions on the climatic relevance of organic and conventional farming or even at giving recommendations to policy-makers. The main emphasis was placed on testing the model software under practice conditions. The consideration of both organically and conventionally run farms was to allow the sampling of the largest possible range of management conditions. The results presented reflect only the system level crop production in the surveyed agricultural region.

Despite of this restriction, the investigations admit preliminary conclusions for the optimization of farm management and the reduction of GGEs. According to our results, organic farming includes a high potential of C sequestration, preferably by the growing of perennial legume–grass blends and the input of FYM. In conventional farming, legumes and FYM are nearly neglectable; humus balance sheets point to declining SOC values. In some farms, however, the situation may be completely different depending on crop rotation and technological design, and therefore, in the final run, recommendations and optimization strategies will always require a farm-specific approach. The farm as such has been in the focus of our studies, because management decisions taken at this level have effects on climate and environment. In order to mitigate emissions, problem areas must be identified with attention to farm specifics; subsequently, coordinated measures and strategies must be elaborated. In order to gain acceptance by the farmers, the possible economic and ecological consequences of the implementation of these activities must be predictable. The REPRO model is therefore oriented to an overall rating of farms according to multiple criteria. Besides the balancing of C, N and energy fluxes as described in this paper, further modules are under construction analyzing harmful soil compaction, erosion and biodiversity.

Under the umbrella of the German Agricultural Society, an organization for the promotion of technical and scientific progress in the food and agricultural sector with over 17,000 German and international members, more than 90 farms in the Federal Republic of Germany are currently testing the software, with the purpose of using it not only in research but in the future also in the management of farms.

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