ELSEVIER

Agriculture, Ecosystems and Environment 76 (1999) 17–30

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Indicators of resource use and environmental impact for use in a decision aid for Danish livestock farmers

N. Halberg *

Danish Institute of Agricultural Sciences, Department of Agricultural Systems, P.O. Box 50, DK-8830 Tjele, Denmark

Received 15 June 1998; received in revised form 21 December 1998; accepted 23 February 1999

Abstract

Farmers lack well documented sets of farm level indicators to allow their own evaluation of environmental impact and to stimulate the development of more environment friendly farming practices. A set of farm level indicators of resource use and environmental impact on livestock farms was developed as part of a decision aid for farmers. The indicators were meant to be part of an extended farm account and included the surpluses and efficiencies of N, P and Cu, the energy use per kg grain and per kg milk or meat, pesticide treatment index (TFI), % unsprayed area, % small biotopes on the farm, and % weeds in grain crops. The indicators were tested on 20 Danish dairy and pig farms over a period of 3 years in order to see if they were suitable for use in the farmer's management. The third year, farm gate surpluses varied between 89 and 265 kg N ha^{-1}, 2 and 31 kg P ha^{-1} and 0.1 and 0.8 kg Cu ha^{-1}. Energy use varied between 2.1 and 4.1 MJ kg^{-1} milk and between 14 and 20 MJ kg^{-1} live weight pig sold. For all indicators, except energy use per kg grain, the variation in indicator levels between farms was more important than the variation between years within each farm. There was significant variation between farms after correction for stocking rates and soil-and farm types, which suggests that the indicators reflect differences in management practise on comparable farms. It was demonstrated that these differences between similar farms and between the years on the individual farms might be explained by the detailed knowledge of management of the farms' different subsystems (herd and crops). The information given by the indicators is discussed from environmental and management points of view and problems of defining and interpreting the indicators are identified. Given further development of indicators for soil quality and nature values, the farm level indicators seem a promising way of enabling farmers to include environmental topics in their management.

Keywords: Energy use; Environmental accounting; Farming systems; Indicators; Nature quality; Nutrient surplus

1. Introduction

As a reaction to the increased focus on the environmental impacts from intensive farming there have been attempts to develop agri-environmental indicators under the headings of sustainability (Douglass, 1984; Harrington, 1992; Dalsgaard et al., 1995; de Wit et al., 1995), green accounting or environmental auditing (Anonymous, 1993; Vereijken, 1994; Nocquet, 1995; Willeke-Wetstein et al., 1996; OECD, 1997). It has, however, not always been clear what the purpose was or for whom the indicators were meant. There might for instance be a difference between the feasible indicators on a sector level for use by politicians and on a farm level for use by the farm manager, or on

* Tel.: +45-8999-1206; fax: +45-8999-1200
E-mail address: niels.halberg[a]agrsci.dk (N. Halberg)

0167-8809/99/$ – see front matter
PII: S0167-8809(99)00055-9

field level for use by researchers. Groups of farmers have begun to formulate goals that address society's interest in the impact of intensive farming on the environment (Anonymous, 1996). Farmers lack tools to assess their environmental impact and to find the right balance between production economics and environmental goals (Kristensen and Halberg, 1997).

Among the proposed sets of indicators in the literature very few have documented the feasibility of the proposed indicators on a broad selection of existing farms. Therefore, there are a number of unanswered questions. For instance, which indicators are sensitive to management strategies, i.e., do the farmers have any influence on the results? Do the proposed indicators make sense to the farmers? Can they demonstrate improvement over time on a given farm? Which resources are needed to collect the data? These questions indicate that there is a need to test and document the feasibility of key indicators of the resource use and environmental impact on livestock farms.

On the basis of the above background the aims of this paper are, (1) to present a set of indicators describing the most important issues of resource use and environmental impact connected to the management of livestock farms; (2) to present results from the test of these indicators on 20 farms over 3 years; and (3) to discuss the feasibility of the indicators from an agronomic and environmental point of view.

2. Materials and methods

2.1. The framework of the indicators

A set of indicators has been developed to be a part of a decision aid for Danish livestock farmers, called the ethical accounting (Jensen and Sørensen, 1998). The idea of this ethical accounting for a livestock farm is to give information to the farm family about the impact of the farm on relevant interests of present and future generations, livestock and the farm family itself. The aim is to facilitate a reflection on values and goals and, if desired, an adjustment of the farming practice to the family's values and goals. The ethical accounting procedure consists of group dialogues between farm families, several accounting cycles where the annual account with all indicators is presented to the farm family, and a strategic planning procedure.The annual ethical accounting statement comprises indicators of animal welfare, resource use and environmental impact, the farmers' non-economic values and goals, product quality, and the traditional technical–economic indicators of farm accounting (e.g., yields ha^{-1} and net margin per cow). In this paper, only the indicators of resource use and environmental impact are presented. The indicators were expected to fulfil the requirements shown in Table 1.

The selection of the environmental indicators for the ethical accounting was based on an analysis of the effects of Danish animal husbandry on relevant interests of future and present generations (Halberg, 1996; Kristensen and Halberg, 1997). Indicators were meant to reflect the farm's use of non-renewable resources (fossil energy, phosphorus), the impact on the farm's natural basis for production (the soil) and the impact on the environment. The set of indicators is presented in Table 2 together with an indication of their motivation. Nitrogen and pesticides are included because of their potential negative impact on terrestrial and marine ecosystems and on ground water. Other impacts from farming practices on the diversity of wild flora and fauna and on landscape aesthetics were operationalized by the percentage of area untreated with pesticides the given year, the amount of weeds left in grain crops at the heading growth stage (visually assessed at stage 53–59; following the decimal code of Lancashire et al., 1991) and by the percentage of uncultivated area on the farm (small biotopes).

The impact on soil quality was described by the surplus of copper (Cu), which is used as a growth promoter for the pigs, but can have detrimental effects on different soil organisms (Bååth, 1989; Huysman et al., 1994) and on animals (especially sheep) grazing on the soil in the future. The risk of deep soil compaction (Håkansson and Reeder, 1994) was described by the number of ha subjected to traffic by machines with a high axle load (only the third year).

2.2. Evaluation

The indicators were tested via collaboration with 20 livestock farms over 3 years: From May 1994 to April 1995, five pig farms and 11 dairy farms participated. As of the second year (May 1995–April 1996) another

Table 1
Requirements for indicators of resource use and environmental impact to be used in a decision aid for Danish livestock farmers

Criteria from a societal point of view	Criteria from the farmer's point of view
The indicators should	The indicators should
• describe and operationalize relevant aspects of the farms' resource use and potential environmental impact on farm level	• be meaningful to managers and possible for them to influence
• be meaningful and valid from a scientific point of view	• be sensitive to changed management practise, thus reflecting possible changes over time
• be meaningful and valid from a scientific point of view	• be possible to collect and calculate at a reasonable time and cost

Table 2
Operationalization of a livestock farm's resource use and potential impact on the environment

Topic	Reason, localisation of potential impact	Indicator
Nitrogen (N)	Pollution of the ground water, eutrophication of marine waters	Surplus, kg N ha^{-1} N efficiency (kg N sold in products per kg N net input)
Phosphorus (P)	Limited resource, long-term pollution risk	Surplus, kg P ha^{-1} P efficiency (kg P sold in products per kg P net input)
Energy	Limited resource Pollution, CO_2 etc.	MJ ha^{-1} MJ kg^{-1} milk or meat MJ kg^{-1} grain
Pesticides	Pollution of ground water Wild flora and fauna	Frequency of treatment (TFI)
Windbreaks, small biotopes, meadows, streams	Wild flora and fauna	% unsprayed area % weeds in grain crops
	Landscape aesthetics	% uncultivated area (biotopes)
Soil	Pollution Soil structure	Cu surplus, kg ha^{-1} (pig farms) Number of ha run over with axle loads >10 Mg

four dairy farms were included, giving a total of 20 livestock farms. Two pig farms and two dairy farms were situated on Luvisols on Zealand and a Cambisol on Lolland, while the rest of the farms were situated in different parts of Jutland on Podzols, Luvisols and Arenosols (FAO, 1974). Farm size and dominant soil texture classes are shown in Tables 3 and 4 . The cows were mostly Danish Holstein-Friesian, but three farms had Red Danish and one had Jersey. The pigs were crossbreeds of Duroc, Danish Landrace and Yorkshire. Half the farms followed the official Danish rules for organic farming. The farmers all used the local advisory services before the start of the project. The methods for data collecting and control are presented in Jensen and Kristensen (1997).

Every year, the accounting and the preliminary interpretations were discussed with each farm family at a visit where the researchers mimicked the role of the local advisors. The aims were to let the farmer reflect on his results and possibilities for improvements and to check the 'advisor's' explanations in terms of management with the farmers' perceptions.

2.3. Data collection and calculation methods

The majority of the indicator values were calculated on the basis of existing farm bookkeeping systems. Details concerning the use of pesticides, fertiliser and manure in the different crops were collected by the farmers in their 'field diary' and formally controlled against total amounts purchased. The internal flow of feed on the farm and the animal production were registered by a skilled technician at monthly visits using a traditional Danish production control service offered by the local advisers. The content of weeds in grain, *Triticum aestivum* L., *Secale cereale* L., *Avena sativa* L., *Hordeum vulgare* L., and the percentage of clover, *Trifolium repens* L., *T. pratense* L. and *T. hybridum*

Table 3
Farm descriptors, indicators and results from the ethical accounts over 3 years for 15 dairy farms

Farm descriptor	Year	Farm number[a]														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Soil texture class[b]		4	3	2+	3+	2+	2+	3	3	2	3	2+	3	2+	3	1+
Area, hectares	1994–1995	142	51	79	72	160	77	59	103	68	69	–	–	–	–	67
	1995-1996	133	50	95	72	155	78	69	93	68	119	61	138	55	107	86
	1996-1997	133	55	114	71	155	78	71	93	68	106	60	143	57	99	86
Stocking rate, LU ha^{-1}	1994–1995	1.0	0.9	1.1	1.0	1.2	1.0	1.1	1.2	1.4	1.0	–	–	–	–	1.4
	1995–1996	1.2	1.0	0.9	1.0	0.9	1.1	0.9	1.3	1.3	0.8	1.8	0.8	2.1	1.9	1.1
	1996–1997	1.3	1.0	0.8	1.0	1.2	1.1	0.9	1.3	1.3	0.9	1.9	0.7	2.0	2.0	1.2
Indicator[c] MJ kg^{-1} grain	1994–1995	0.99	0.58	2.00	0.80	1.20	1.10	1.40	1.00	–	1.50	–	–	–	–	2.30
	1995–1996	0.94	0.73	1.48	0.72	1.51	0.99	0.73	0.73	1.16	0.69	2.08	1.36	1.39	1.25	1.89
	1996–1997	0.90	0.47	0.75	0.74	0.94	0.80	0.59	0.77	0.89	0.69	–	1.74	1.21	0.81	1.89
Indicator MJ kg^{-1} milk	1994–1995	3.3	3.1	3.8	2.3	2.1	2.9	2.4	2.9	2.9	2.5	–	–	–	–	3.6
	1995–1996	3.0	2.6	2.9	3.0	2.3	3.3	2.1	3.2	3.0	2.2	3.9	3.2	3.9	3.5	3.0
	1996–1997	3.1	3.3	2.8	2.9	2.4	2.6	2.1	2.7	2.8	2.4	3.9	3.6	4.1	3.1	3.0
N-surplus, kg ha^{-1}	1994–1995	136	77	135	69	115	128	93	118	137	138	–	–	–	–	158
	1995–1996	119	62	103	58	103	144	98	127	115	99	272	124	203	204	147
	1996–1997	118	96	108	89	118	143	85	129	117	134	214	104	223	217	143
P-surplus, kg ha^{-1}	1994–1995	11	−1	21	−1	3	10	6	7	11	7	–	–	–	–	41
	1995–1996	8	0	8	6	5	16	4	11	14	3	28	3	22	19	17
	1996–1997	5	2	4	6	6	10	5	11	8	8	29	14	22	14	18
N efficiency, farm level	1994–1995	22	24	23	31	23	18	26	27	25	21	–	–	–	–	23
	1995–1996	24	30	25	35	27	16	24	25	26	20	19	16	25	29	21
	1996–1997	26	20	22	26	24	19	23	24	27	19	24	17	23	35	21
P efficiency, farm level	1994–1995	39	133	26	111	70	34	51	55	41	52	–	–	–	–	16
	1995–1996	45	92	43	51	58	24	57	41	33	58	30	61	36	45	27
	1996–1997	58	65	56	49	52	38	50	42	48	43	30	21	36	62	27
Pesticides, TFI[d]	1994–1995	0	0	0.2	0	0	0	0	0	0	0	–	–	–	–	2.8
	1995–1996	0	0	0	0	0	0	0	0	0	0	0.8	1.1	1.1	0.8	3.0
	1996–1997	0	0	0	0	0	0	0	0	0	0	0.4	2.0	0.7	1.1	2.9
% untreated area	1994–1995	100	100	52	100	100	100	100	100	100	100	–	–	–	–	46
	1995–1996	100	100	100	100	100	100	100	100	100	100	38	31	24	48	31
	1996–1997	100	100	100	100	100	100	100	100	100	100	61	21	28	37	24
% weeds in small grain	1994–1995	7	4	1	1	32	16	3	19	9	15	–	–	–	–	1
	1995–1996	1	8	4	1	18	7	3	3	6	11	0	0	2	1	0
	1996–1997	22	29	3	10	8	23	3	5	4	26	5	2	2	1	0
% small biotopes	1996–1997	5	0	8	5	4	8	0	5	3	4	5	2	2	3	10

[a] Farms Nos. 1–10 are organic dairy farms, 11–15 are conventional dairy farms.
[b] Soil texture classes according to USDA (1990): 1, sand; 2, loamy sand; 3, sandy loam; 4, loam; 5, sandy clay loam; 6, sandy clay; 7, clay loam. Types 1–3<10% clay; types 4–7>10% clay. + denotes possibility for irrigation.
[c] For definition and calculation methods, see text.
[d] TFI: Treatment frequency index = number of applications with standard approved dosages.

Table 4
Farm descriptors, indicators and results from the ethical accounts over 3 years for five pig farms

Farm descriptor	Year	Farm number[a]				
		16	17	18	19	20
Soil texture class[b]		1+	1	3	2	3
Area, hectares	1994–1995	185	36	112	61	215
	1995–1996	180	38	112	77	215
	1996–1997	184	38	129	105	245
Stocking rate, LU ha^{-1}	1994–1995	0.5	2.9	2.7	2.8	0.6
	1995–1996	0.5	3.1	2.5	2.3	0.6
	1996–1997	0.6	2.9	2.2	2.3	0.7
Indicator[c], MJ kg^{-1} grain	1994–1995	1.30	1.80	1.20	1.80	1.40
	1995–1996	1.70	0.77	1.30	1.65	1.45
	1996–1997	1.82	0.80	1.26	1.77	1.46
Indicator[c] MJ kg^{-1} live weight pig	1994–1995	–	13	13	19	17
	1995–1996	–	10	15	18	15
	1996–1997	–	14	14	20	15
N-surplus, kg ha^{-1}	1994–1995	143	256	150	269	108
	1995–1996	164	238	126	198	110
	1996–1997	166	265	120	205	86
P-surplus, kg ha^{-1}	1994–1995	26	18	8	59	8
	1995–1996	23	22	4	29	9
	1996–1997	26	23	6	31	8
Cu-surplus, kg ha^{-1}	1994–1995	–	–	–	–	
	1995–1996	0.4	0.7	0.2	1.0	0.1
	1996–1997	0.7	0.8	0.2	1.1	0.1
N efficiency, farm level	1994–1995	20	46	41	44	25
	1995–1996	20	47	42	39	27
	1996–1997	23	41	42	38	36
P efficiency, farm level	1994–1995	26	18	8	59	8
	1995–1996	27	66	89	47	46
	1996–1997	29	62	80	45	56
Pesticides, TFI[d]	1994–1995	2.2	1.3	3.0	2.3	2.4
	1995–1996	2.5	0.5	1.4	1.5	2.6
	1996–1997	2.7	1.5	2.3	1.3	3.0
% untreated area	1994–1995	14	21	0	19	8
	1995–1996	13	17	0	18	0
	1996–1997	14	3	0	13	8
% weeds in small grain	1994–1995	1	1	0	1	1
	1995–1996	1	2	0	1	0
	1996–1997	0	0	0	2	0
% small biotopes	1996–1997	20	8	6	19	4

[a] Farms Nos. 16–19 have sows, farms Nos. 17–20 produce hogs.

[b] Soil texture classes according to USDA (1990): 1, sand; 2, loamy sand; 3, sandy loam; 4, loam; 5, sandy clay loam; 6, sandy clay; 7, clay loam. Types 1–3 < 10% clay; types 4–7 > 10% clay. + denotes possibility for irrigation.

[c] For definition and calculation methods, see text.

[d] TFI: Treatment frequency index = number of applications with standard approved dosages.

L. in grass/clover fields were assessed visually by the technicians, who also registered the abundance and content of the small biotopes (hedges, streams, ponds and other uncultivated areas) on the farms.

The nitrogen (N) surplus was calculated as a farm gate balance including N fixation and deposition as described in Halberg et al. (1995). The surplus of phosphorus (P) and Cu were calculated in a similar way. For the calculation of nutrient input with concentrate mixtures the declarations were used. For grain, soybean (*Glycine max* L.) meal, sunflower, (*Helianthus annuus* L.) meal and rapeseed (*Brassica napus* L.) meal standard values were used. When calculating the export of Cu with live pigs a content in the liver ten-fold higher than standard was assumed when Cu was used as growth promoter. The amount of milk and the protein content registered by the dairy was used in the farm balance. In all other cases, standard values for the content of N, P and Cu in sold products were used.

To account for the farms' dependence on fossil energy, the energy use per unit produced was calculated. The energy use included both direct (diesel and electricity) and indirect (energy used for the production of fertiliser, concentrate etc) fossil energy. The total energy use per produced unit was calculated via a process analysis as described in Refsgaard et al. (1998). The total amount of diesel was partitioned to the individual crops using a model based on values for each single operation (Dalgaard, 1996). This allowed for the calculation of separate energy costs of home-grown feed and of the cash crops, so that only the diesel and fertiliser inputs proportional to the use of home-grown feed were charged to the herds.

To account for the pesticide use the average number of standard treatments in all crops was calculated (Treatment frequency index (TFI)) using the official Danish approved dosages of each pesticide and the farmers' registrations on field level. The TFI indicates the possible application with full dosages in each crop regardless of the number of actual treatments. Also the percentage of untreated area was included in the accounting.

2.4. Statistical analysis

The variation in indicator values between the 20 farms over 3 years was evaluated for each indicator separately with multiple linear regression, (Weisberg, 1985) using General Linear Models (GLM) procedure (SAS, 1985). Farm type (pig farm, conventional dairy farm or organic dairy farm), soil type (loamy, sandy, irrigated sandy soils, for definition see Table 5), harvest year and farm id (farm number) were tested as class predictors (Dummy variables, Weisberg, 1985), and stocking rate was included as a regression predictor. To test the significance of the individual predictor a partial testing method was used, allowing each predictor to be tested against the full variation in the data set. After the selection of significant predictors, successive testing was used. That is, testing the second predictor after correcting the variation with the first predictor, thereafter testing the third predictor while keeping the two first ones in the model (stepwise procedure, Weisberg, 1985). The effects of farm and soil texture class were tested against the farm id mean square (MS). The first-order interactions between year and farm type, soil type and stocking rate, respectively, were tested in simple models with only two predictors at a time. Correlations between the predictor stocking rate and the class predictors were checked using a GLM model with stocking rate as dependent variable. The results presented are from the final model using successive testing since the aim was to show the farm id effect after correction for the other predictors. Means presented are least square means (LS Means). The existence of correlation between the different indicators was checked within the three groups of farms using a simple Pearson's correlations test (Weisberg, 1985) on the average indicator values for each farm.

3. Results

The following presentation of results will focus on the variation in indicator values between years and farms and seek to show to which degree this variation was explainable by different conditions and management practices.

3.1. Statistical analysis of farm results

From Tables 5 and 6 it appears that both N and P surplus and N efficiency depended on stocking rate and increased with higher stocking rates whereas P efficiency, energy use, percentage of biotopes and per-

Table 5
Statistical analyses using general linear models of the importance of general and farm specific factors for the level of 10 indicators on 20 farms over 3 years (degrees of freedom = 55)

Indicators	N surplus	N efficiency	P surplus	P efficiency	$MJ\,kg^{-1}$ grain	$MJ\,kg^{-1}$ milk[d]	% biotopes[e]	TFI[f]	% unsprayed	% weeds
Predictors										
Stocking rate[a]	***[g]	***	***	ns	ns (0.09)	ns (0.09)	ns (0.8)	**	ns (0.2)	ns (0.3)
Soil texture class[b]	ns (0.6)	ns (0.2)	ns (0.5)	ns (0.2)	***	ns (0.9)	*	ns (0.9)	ns (0.5)	ns (0.9)
Type[c]	*	**	*	ns (0.08)	***	***	***	***	***	***
Year	ns (0.5)	ns (0.9)	ns (0.2)	ns	*	ns (0.9)	–	ns	ns (0.26)	ns (0.15)
Farm id	***	***	***	***	ns (0.12)	**	***	***	***	ns (0.3)
Year × type	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year × soil texture class	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$LU\,ha^{-1}$ × type[a]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Stocking rate measured in livestock units (LU) ha^{-1}, 1 LU corresponding to one Holstein-Friesian dairy cow or three sows with piglets or 30 pigs fattened from 25 to 95 kg live weight.

[b] Three classes: loamy, sandy, irrigated sandy soils. Loamy soils include USDA groups of sandy loam, loam and sandy clay loam. Sandy soils include sand and loamy sand (USDA, 1990).

[c] Three classes: pig farms, conventional dairy farms, organic dairy farms.

[d] DF = 40.

[e] DF = 20.

[f] TFI: Treatment frequency index = number of applications with standard approved dosages.

[g] *Significant differences at level $p \le 0.05$; **significant differences at level $p \le 0.01$;*** significant differences at level $p \le 0.001$; ns: not significant; –: not tested (0.a) $p = 0.a$.

Table 6
Least square means for farm and soil texture classes and regression coefficient for stocking rate on selected indicators

Indicators	N surplus	N efficiency	P surplus	$MJ\,kg^{-1}$ grain	$MJ\,kg^{-1}$ milk	Biotopes	TFI[a]	% sprayed	% weeds
Farm type									
Pig	167 a[b]	33 a	17 a	1.60 a		11 a	1.9 a	9 a	1 a
Conventional dairy	176 a	23 b	20 a	1.68 a	3.6 a	3 b	1.0 b	36 b	1 a
Organic dairy	114 b	25 b	9 b	1.00 b	2.7 b	4 b	0.1 c	100 c	10 b
Soil texture class									
Clay				1.23 a		5 a			
Sandy				1.53 b		5 a			
Irrigated sand				1.52 b		9 b			
Stocking rate									
Increase by 1 LU ha^{-1}[c]	13.3	3.5	5.4	–	–	–	0.3		

[a] TFI: Treatment frequency index = number of applications with standard approved dosages.

[b] Results followed by the same letter were not significantly different at $p \ge 0.05$ level.

[c] Stocking rate measured in livestock units (LU) ha^{-1}, 1 LU corresponding to one Holstein-Friesian dairy cow or three sows with piglets or 30 pigs fattened from 25 to 95 kg live weight.

centage of weeds did not depend on the farms' stocking rates. Soil type was a significant predictor for energy use per kg grain and for percentage of biotopes only. After correction for stocking rate and soil type there were significant differences between the three farm types in all indicators except for P efficiency. The LS means in Table 6 show that the organic farms had the lowest surplus of N and P while the pig farms had the highest N efficiency. Also, the pig farms had a significantly larger part of their land covered by small biotopes and a higher pesticides use than did the dairy farms.

The organic dairy farms used significantly less energy per kg grain and per kg milk than the conventional dairy and pig farms (1.0 MJ versus 1.68 and 1.60, respectively) after correction for differences in soil texture classes. Farms on the sandy soils (with and without irrigation) used more energy in per kg grain but not more energy in per kg milk. Energy use per kg grain was significantly higher in 1994 than in 1996 across all farms and there was no interaction between year and farm or soil type.

For all other indicators than energy use in grain, the variation between the 3 years was insignificant. There were no interactions between years and the other predictors for any of the indicators. Also, there was no interaction between stocking rate and system for any of the indicators. Farm id was significant for all indicators except for energy use kg^{-1} grain and percentage of weeds in grain, and with no interaction with the other predictors. Thus, in all other indicators there was still a large variation between farms after correction for stocking rate and type.

In the group of organic dairy farms P efficiency was correlated with N surplus ($p \leq 0.003$) and P surplus ($p \leq 0.001$), and N and P surpluses were also correlated ($p \leq 0.002$; results not shown). Among the conventional dairy farms, P efficiency was only correlated with MJ kg^{-1} grain ($p \leq 0.01$) and % biotopes was correlated with TFI ($p \leq 0.03$). In the group of pig farms, MJ kg^{-1} live weight pig was correlated with MJ kg^{-1} grain ($p \leq 0.001$) and P surplus was correlated with Cu surplus and % biotopes. There were only conventional pig farms and due to the rules for organic farming, there were no organic farms with stocking rates over 1.4 LU ha^{-1}. Apart from these, there were no correlations between predictors.

3.2. Variation between farms and years in the key indicators

It is a general result that the indicator levels to a high extent depend on farm management. This will be documented by selected explanations of differences between farms and examples of changes between years on individual farms based on the detailed knowledge of each farm's management and production systems.

Table 3 shows the variation in indicator values between dairy farms during the third year, 1996–1997. The energy use in per kg milk varied between 2.1 and 4.1 MJ, and 25% of the farms used less than 2.6 MJ kg^{-1} milk. Within the groups of organic and conventional farms important factors explaining different levels of energy use were feeding strategy and management (indoor or outdoor). Farm Nos. 1 and 13 fed fresh grass indoors (high diesel use) whereas the rest let the cows graze in the summer. Farm No. 2 imported a high amount of dried grass pellets, due to shortage of feed, resulting in a relatively high energy use in per kg of milk (3.3 MJ) in spite of very low energy costs in the crop production (0.47 MJ kg^{-1} grain).

On seven farms the energy use of per kg milk increased or decreased more than 10% at least once during the 3-year period. Important factors contributing to higher energy costs some years on farms Nos. 4, 6 and 8 were: increased use of dried grass pellets, higher energy costs of silage due to increased irrigation and the introduction of a deep litter straw bedding for the cows (more diesel to handle straw and manure). The energy use of per kg live weight pig sold varied between 14 and 20 MJ in the third year (Table 6). In most pig farms, the largest energy input to the herds came from imported feeds.

The N surplus ha^{-1} varied in the last year between 89 and 223 kg on dairy farms (Table 3) and between 56 and 265 on the five pig farms (Table 4). As an average over 3 years, the N fixation and deposition accounted for 89 of the total supply of 150 kg N ha^{-1} on the organic farms (Table 7). Fodder was the largest single N input as an average of the conventional dairy and pig farms. Milk sales accounted for 74% of the N export on the organic farms, while on the conventional dairy farms also sales of crops (on three out of the five farms) and manure (one farm) were important for N export. On the pig farms, N in animals accounted for an average of 44% of the N export and manure accounted for 36% of the N export (four out of five farms sold slurry). Farm-specific feeding and fertilisation strategies were important for the N surplus. For example, farm Nos. 5, 6, 8, 9 and 15 all had comparable stocking rates (1.1–1.3 LU ha^{-1}) but farm Nos. 6 and 15 had higher N surpluses due to a higher manure and fertiliser import, respectively, (Table 3). On most of the farms, the N surplus varied less than 10% annually and, when it did, it most often could be explained by a changed management practice. Important factors were thus increased import or export of pig

Table 7
Input and export of N and P in kg ha^{-1} by farm type averaged over 3 years

	Organic dairy		Conventional dairy		Pig farms	
	N	P	N	P	N	P
Fodder	47	11	129	30	312	67
Fertilizer/manure	14	3	100	7	92	6
Fixation/deposition	89	0	45	0	30	0
Total import	150	14	274	37	434	73
Meat	6	1	18	4	114	23
Milk	28	5	39	7	0	0
Cash crops	4	1	22	2	53	8
Manure		0	21	5	93	22
Total export	38	7	101	18	260	54
Surplus	112	7	173	19	174	19

slurry (farm No. 10 first and third year respectively, farms Nos. 17 and 19) and increased area units with N fixating crops (farm No. 11 second year).

The N efficiency varied between 16% and 35% over the 3 years on the dairy farms with only 25% of the farms above 25% efficiency (Table 3). The N efficiency on the pig farms varied between 20% and 47% (Table 4) partly reflecting differences in feed conversion efficiency and protein balance in the herds (nutrient efficiencies at herd level not shown). The high efficiencies on farms Nos. 17–19 were partly caused by the export of slurry to other farmers.

The major part of P input on all farm types comes with the fodder import and on the organic farms, milk accounted for most of the output (Table 7). On the conventional dairy and pig farms, P export with manure accounted for an average of almost the same amount of P, as did the export of milk and pigs, respectively. Farms Nos. 6 and 10 (the first and third year) with low stocking rates import large amounts of P with conventional pig slurry and have high P surpluses and low P efficiencies compared with other organic farms.

Copper was supplied as a growth promoter in pig feed on all five farms but in different concentrations resulting in different surpluses ha^{-1}, but relatively stable during the 2 years within each farm (Table 4). On farm No. 16, a high input of Cu was partly compensated for by a high export via straw for a local power plant. Only two farms used machines with axle loads over the critical 10 Mg and only on a smaller part of the fields every year (results not shown).

On the ten farms that used pesticides, the TFI varied between 0.4 and 3.0 with the highest values on farms Nos. 15, 17 and 12 in the third year (preventive fungicides in potatoes, *Solanum tuberosum* L.), and Nos. 18 and 20 (herbicides in sugar beets, Beta saccharitera). On the farms Nos. 17, 18 and 19 the TFI was lower in the third year as the farmers observed only very low levels of mildew in their grain crops. Two pig farms had nearly 20% of their area covered with biotopes because of special natural conditions (farm No. 19) and a high preference for six-rowed hedges for wildlife and windbreak (farm No. 16). On farms Nos. 3, 6 and 15 with irrigated sandy soils, the area with small biotopes varied between 8% and 10% and it was below 1% on two organic farms with loamy soils.

4. Discussion

The results above serve to document the level and variability of the indicator values across a group of Danish livestock farms. Few attempts have been made to develop a broad set of environmental appraisal indicators for European livestock farms (Willeke-Wetstein, 1996) and mostly in qualitative terms like in Nocquet (1995) and LEAF (Anonymous, 1993) or focusing only on a few issues like nutrient bookkeeping (Doluschitz et al., 1992). Recent European work establishing principles of farm level sustainability appraisal has focused on arable farming systems (Girardin and Bockstaller, 1994; Vereijken, 1994). Livestock farms are more complicated to describe because of interdependencies between livestock and crops (for example, nutrient efficiency and energy use).

4.1. The indicators in relation to the environmental impact of farming

The indicators should reflect the farm's impact on relevant interests in resource use and the environment. The normative motivation for each indicator, e.g., the philosophical discussion about which relevant interests would be affected by Danish livestock farming, is presented in Halberg (1996). The relation between the indicator values and the farm's actual environmental impact is not simple, for the pollution from farming is often diffuse in the sense that the major losses of nutrients and pesticides do not originate from point sources. This makes it expensive or difficult to measure the actual pollution from a given farm and, often, environmental deterioration cannot be related to a single farm. Therefore, mostly indicators of potential environmental impact were chosen.

Nitrogen surplus is thus not an account of the actual loss over the given period, but expresses the potential loss from a farm over time if stocking rate or crop rotation is not changed significantly. Even if soil organic matter increases for many years under continuous manure supply (Uhlén, 1991; Christensen and Johnston, 1997) mineralisation will also increase (Barraclough and Jarvis, 1989; Johnston, 1995; Hansen and Djurhus, 1996) and a new equilibrium will therefore, be reached eventually. The N surplus is expressed in $\mathrm{kg\,ha^{-1}}$ as most of the losses are related to the fields and because tolerable limits of losses/pollution most often are formulated on an area basis. As land is a limited factor and N surplus increases with increasing stocking rate it is also relevant to indicate the N loss per unit produced. The N efficiency expresses the production in relation to the amount of N in exported products. N efficiency thus reflects the success of converting the N input into exported animal products and might therefore, act as an intermediate between the stocking rate and the surplus. It is a problem, however, that the export of N with manure makes the N efficiency unrealistically high on some farms, e.g., the pig farms Nos. 17–19, and it would be false not to include the slurry export in the efficiency calculations.

The indicator, fossil energy use per produced unit calculated by a process analysis, was chosen in place of an input/output analysis calculating the net energy production in the products. This was done because the idea was not to compare different products but different ways of producing a given product (see Refsgaard et al., 1998). Imported feed and fertilisers were included in the energy analysis as indirect energy and they accounted for a large part of the energy use on most conventional farms as was also found by Refsgaard et al. (1998). This was not the case on the organic farms, but since imported manure in a way substitutes artificial fertiliser on some farms (Nos. 6 and 10), an energy price comparable to the 39 $\mathrm{MJ\,kg^{-1}}$ N in fertiliser could have been ascribed to the nutrient content. Farms Nos. 6 and 15 thus have comparable stocking rates and milk production $\mathrm{ha^{-1}}$ and while No. 6 (organic) imports slurry and No. 15 (conventional) uses fertiliser, their N surpluses are almost identical. But the energy use per kg grain and per kg milk is higher on No. 15, primarily due to the fertiliser use.

Using TFI of pesticides it is possible to correct the amounts used for changes to low dosage pesticides like sulfonyl urea based herbicides, but it is a problem that the indicator does not characterise the pesticides by their toxicity or risk of leaching and volatilisation. Secher and Gyldenkærne (1996) and Wijnands (1997) have proposed methods for environmental ranking of pesticides based on combinations of their volatility and their LD50 values towards different non-target organisms. However, the complex relationships between pesticide characteristics (toxicity, persistence and mobility) and many different types of environmental impact, they can have, makes it difficult to rank pesticides unambiguously, and no general agreement on one system seems to exist (OECD, 1997). If valid data can be established, it might also be relevant to include the indirect pesticide use resulting from the import of up to 15% conventional concentrates on organic farms as well as the import of sunflower and soybean meal on conventional farms analogous to the concept of indirect energy use.

The current impact on soil quality is of great interest to future generations. Farming may enhance or reduce soil fertility, improve or damage soil structure and might cause the loss of topsoil by erosion or poisoning by, for instance, heavy metals. However, soil quality is a multidimensional concept depending on interacting physical, chemical and biological factors and there is no consensus on the right indicators for soil quality (Karlen et al., 1990; Doran and Parkin, 1994). Therefore, no indicator for the actual status of soil fertility was included in the prototype of the ethical accounting. The chosen indicators, Cu surplus and traffic with high axle loads, describe specific potential impacts relevant under Danish conditions. The average Cu content in most Danish soils is thus around 35 kg ha^{-1} (Larsen et al., 1996), which is why a yearly surplus of 1 kg Cu ha^{-1} as on farm No. 19 might double the soil content within a farmer's lifetime. The indicator of nature or landscape values in terms of the percentage of area with small biotopes is also used at a regional level in Denmark (Agger and Brandt, 1986), and similar indicators have been proposed in other European countries (Vereijken, 1994). This structural indicator, however, tells little of the actual nature quality on the farms (e.g., whether the flora in the biotopes has been reduced to the N- or pesticide-tolerant species, Ejrnæs, 1998). Preliminary work therefore, suggests other indicators using the abundance of certain butterflies (Clausen et al., 1998) or sensitive wild plants (Hald, 1998).

The selection of indicators presented here was based on Danish conditions, but most of the issues addressed will probably be relevant for other European regions with high intensity livestock farming. However, other indicators such as the amount of water used per ha or per kg milk produced or topographically induced erosion might be relevant to address in other regions of Europe. Since, in principle, land is a limited resource, the area used for a given production is very important. It is, however, difficult to calculate output ha^{-1} in one single figure on mixed farms with both milk, meat and cash crop production. Therefore, the classic indicator yield in kg ha^{-1} is presently included in the ethical accounting. More work is needed in order to find an acceptable common indicator for different types of agricultural output that allows for comparison of different farming systems. The emissions of CH_4 and N_2O, which are major contributors to the increasing green house effect (Duxbury et al., 1993) were not included since this is something on which the farmer has little influence given present technology and knowledge (Robertson, 1993).

4.2. Evaluation of the indicators in relation to farm management

The farmers were not selected to be representative of Danish farmers in a statistical sense, but they are typical for dairy and pig farms and represent a large variation in terms of size, geographical location, farmer's age, strategies, values and financial performance (Noe, 1998). However, most of them had participated in farm studies for some years and were used to being confronted with researchers' opinions and many data. The farmers' reactions to the indicators were researched via external evaluation of the process based on yearly interviews with the farmers as described by Michelsen and AlSeadi (1998). The main conclusions were that the indicators were meaningful to the farmers, covered all issues of relevance in their opinion and that the farmers appreciated the whole-farm evaluation that was offered by the combined set of indicators. Moreover, the indicators stimulated the learning process, changing the farmers' procedural rationality (rules of thumb, Hargreaves-Heap, 1989) for instance in the way in which they perceived the need to use pesticides. The farmers, however, requested more help to interpret their results, i.e., the size of the indicator values.

As the indicators are meant as a decision aid for farmers, it is important that they actually reflect the individual farmer's management practise. In most of the indicators there were significant differences between farms after correction for stocking rate, soil type and production type and year. In other words, the variation between comparable farms was larger than the variation between years within the farms. Thus, the large variation between the farms was not coincidental and the farmers' choices of livestock housing, feeding strategy, crop rotation and import of fertiliser or manure could often explain the differences. Moreover, when an indicator value changed more than ca. 10–15% on a given farm this could often be explained by a changed management practise. Therefore, the indicators fulfil to a high degree the goals of being sensitive to changed management practise and reflecting changes over time. Sometimes, however, changes were induced by climatic conditions, a fact that must be taken into account when interpreting the result on the farm in relation to the farmer's strategy. Phosphorus efficiency appeared to be closely correlated with

P surplus on the organic farms and might therefore, be excluded from the indicator set if only an analysis of organic farms is the objective. The few correlations between indicators in the groups of conventional farms are probably coincidental and only reflect the very limited number of farms for such an analysis. Consequently, the set of indicators could not be reduced on this basis.

On this background, the central problems connected to the farmers' use of the indicators were the questions of explanation and interpretation as a basis for considering changes. The farm level indicators offer a summary of the consequences of many management decisions over a year, but do not in themselves offer explanations. To understand the differences between years and farms more details are needed, most often in the form of a systematic breakdown of the farm level results to herd and crop level or even to the level of individual fields as demonstrated for N surplus by Halberg et al. (1995) and for energy by Refsgaard et al. (1998). The detailed energy use and nutrient turnover in the herd and crop subsystems were thus presented in the ethical accountings together with detailed accountings of pesticide use in the different crops, but have only briefly been referred to here.

The problems with the interpretation of the indicator values on the individual farm are connected to the fact that the indicators do not describe the farms' actual impact on the environment. This is due to the diffuse character of most of the environmental impacts from agriculture and to the small marginal impact of a single farm on the depletion of non-renewable resources. Moreover, the actual loss of nutrients or pesticides at a given time is influenced by climatic conditions, which would make an interpretation of the farmer's role difficult. Therefore, the indication of the potential environmental impact as a result of a given practice as described by the indicators could be more relevant. This leaves, however, farmer's with the questions, how severe is the impact from their farm and how good or bad are their results? The above arguments lead to the conclusion that the best way of interpreting a farm's indicator values is to compare them either with the possible results, as given by modelling farmer's alternatives, or with results from other farms as in econometric analyses of resource use efficiency (Reinhard and Thijsen, 1996; Lund and Ørum, 1996).

When registration and calculation of indicators were made as part of the existing advisory services (fodder planning, milk control schemes, etc.) and farm bookkeeping/accounting systems, the extra time consumed was estimated to be 6–10 h per year per farm. The single most time consuming task was the registration of the small biotopes (3–5 h, but only conducted in 1 year) and of the clover contents in the fields. By including values for the nutrient content of inputs and products in the computer-based bookkeeping systems the calculation of nutrient balances could be made relatively efficient. This presupposes the use of rather precise accounting and control programmes comparable with the Danish programmes.

5. Conclusion

A set of indicators of a farm's resource use and potential environmental impact were selected to describe the aggregated effects of the farmer's practise over a year. Included were the surplus and efficiency of N, P and Cu, the energy use per kg grain and per kg milk or meat, pesticide treatment index and indicators of nature quality. A test on 20 dairy and pig farms over 3 years showed that the chosen indicators generally reflected differences and changes in management practise and did not fluctuate coincidentally without explanation between years on a given farm. The indicator values were comparable over time on the same farm and reflected improvements/changes in management. More research is needed to develop statistical models to determine the levels of possible incidental fluctuations in the indicator values and to develop data sources for a better interpretation of the results on the individual farm.

References

Agger, P., Brandt, J., 1986. Udviklingen i agerlandets småbiotoper i Østdanmark (The development of small biotopes in farmed areas). Research report No. 48. Roskilde Universitetscenter, 541 pp.

Anonymous, 1993. LEAF, Farm audits: Linking environment and farming. Integrated crop management. NAC, Stoneleigh, UK.

Anonymous, 1996. Godt landmandskab år 2000 (Good Farming Practise, Year 2000). Dansk landbrugs oplæg til integreret produktion. Landbrugets Rådgivningscenter Danish Farmers' goals for IP farming). 46 pp.

Barraclough, D., Jarvis, S.C., 1989. The responsible management of nitrogen in grassland. Br. Grass. Soc. Winter Meeting, London.
Bååth, E., 1989. Effects of heavy metals on soil microbial processes and populations (a review). Water Air Soil Pollut. 47, 335–379.
Christensen, B.T., Johnston, A.E., 1997. Soil organic matter and soil quality: lessons learned from long-term field experiments at Askov and Rothamsted. In: Gregorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Production. Elsevier, Amsterdam, pp. 399–430.
Clausen, H.D., Holbeck, H.B., Reddersen, J., 1998. Butterflies on organic farmland: association to uncropped small biotopes and their nectar sources. Entomologiske Meddelelser, in press.
Dalgaard, T., 1996. Resource Management of Fossil Energy in Crop Production (in Danish with an English summary). M.Sc. Thesis. Royal Veterinary and Agricultural University, 116 pp.
Dalsgaard, J.P.T., Lightfoot, C., Christensen, V., 1995. Towards quantification of ecological sustainability in farming systems analysis. Ecol. Eng. 4, 181–189.
Doluschitz, R., Welck, H., Zeddies, J., 1992. Nitrogen balances at farm level – a first step towards an ecological bookkeeping system (German with English summary). Berichte über Landwirtschaft 70, 551–565.
Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Colemann, D.C., Bezdicek, D.F., Harris, R.F. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America, (SSSA) Special Publication Number 35, pp. 3–22.
Douglass, G., 1984. The meaning of agricultural sustainability. In: Douglas, G. (Ed.), Agricultural Sustainability in a Changing World Order. Westview Press, Boulder, pp. 3–29.
Duxbury, J.M., Harper, L.A., Mosier, A.R., 1993. Contributions of Agroecosystems to global climate change. Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. ASA Special Publication 55. pp. 1–18.
Ejrnæs, 1998. Structure and processes in temperate grassland vegetation. Ph.D. Thesis. Nat. Env. R. Inst. 126 pp.
FAO, 1974. Soil Map of the World, vol. 1. Legend. Unesco, Paris.
Grardin, Ph., Bockstaller, C., 1994. Evaluation Agri-environnementale des exploitations agricoles au moyen d'indices agro-écologiques. INRA, COLMAR. 9 pp.
Halberg, N., 1996. Indicators of resource use and environmental impact to be used in an ethical account for a livestock farm (in Danish with an English summary). Ph.D. Thesis. Danish Institute of Agricultural Sciences. 222 pp.
Halberg, N., Kristensen, E.S., Kristensen, I.S., 1995. Nitrogen turnover on organic and conventional mixed farms. J. Agric. Environ. Ethics. 8, 30–51.
Hald, A.B., 1998. Sustainable agriculture and nature values using Vejle County as a study area. NERI Technical Report No. 222. 95 pp.
Hansen, E.M., Djurhus, J., 1996. Nitrate leaching as affected by long-term N fertilization on a coarse sandy soil. Soil Use Manage. 12, 1–7.
Hargreaves-Heap, S., 1989. Rationality in Economics. Basil Blackwell, Oxford, 270 pp.
Harrington, L.W., 1992. Measuring sustainability: issues and alternatives. J. Farming Syst. Res. Extension 3 (1), 1–20.
Huysman, F., Verstraete, W., Bruce, P.C., 1994. Effect of manuring practices and increased copper concentrations on soil microbial populations. Soil Biol. Biochem. 26, 103–110.
Håkansson, I., Reeder, C., 1994. Subsoil compaction by vehicles with high axle load-extent, persistence and crop response. Soil Tillage Res. 29, 277–304.
Jensen, C.H., Kristensen, T., 1997. Data handling and analysis. Working paper presented at Workshop on LSR Methodologies. Danish Institute of Agricultural Sciences, Foulum September 1997, 26 pp.
Jensen, K.K., Sørensen, J.J., 1998. The idea of an ethical account for livestock farms. J. Agric. Environ. Ethics, in press.
Johnston, A.E., 1995. The value of long-term field experiments in agricultural and environmental research. In: Christensen, B.T., Trentemøller, U. (Eds.), The Askov Long-Term Experiments on Animal Manure and Mineral Fertilizers. SP-report No. 29. Danish Institute of Agricultural Sciences.
Karlen, D.L., Erbach, D.C., Kaspar, T.C., Colvin, T.S., Berry, E.C., Timmons, D.R., 1990. Soil tilth: a review of past perceptions and future needs. Soil Sci. Soc. Am. J. 54, 153–161.
Kristensen, E.S., Halberg, N., 1997. A systems approach for assessing sustainability in livestock farms. In: Sørensen, J., Tind, Flamant, J.C., Rubino, R., Sibbald, A.R. (Eds.), Livestock Farming Systems, More than food production. EAAP Publication No. 89. pp. 16–29
Lancashire, P.D., Bleiholder, H., van den Boom, T., Langelüddeke, P., Strauss, R., Weber, E., Witzenberger, A., 1991. A uniform decimal code for the growth stages of crops and weeds. Ann. Appl. Biol. 119, 561–601.
Larsen, M.M., Bak, J., Scott-Fordsmand, J., 1996. Monitering af tungmetaller
i danske dyrknings- og naturjorder. Prøveudtagninger 1992/93. (Monitoring of heavy metals in Danish Soils). Faglig rapport nr. 157 fra Danmarks Miljøundersøgelser (National Environmental Research Institute). 77 pp. (with summary in English)
Lund, M., Ørum, P.B., 1996. Effektivitetsanalyser for landbrugsbedriften - beskrivelse af sammenligningstal (Efficiency analyses on the farm). SJFI report No. 88. 99 pp.
Michelsen, J., AlSeadi, T., 1998. What did the farmers think of the ethical accounting for livestock farms? In: Sørensen, J. Tind, Sandøe, P., Halberg, N. (Eds.), Etisk regnskab for husdyrbrug. Internal report No. 103, Danish Institute of Agricultural Sciences, pp. 75–90.
Nocquet, J., 1995. Gestion de l'espace et maîtrise des risques de pollution. Une méthode de diagnostic environnemental d'exploitations d'élevage. Ann Zootech 44 (Suppl. 338).
Noe, E., 1998. Værdier, rationalitet og landbrugsproduktion. (Values, rationality and farming.) Ph.D. Thesis. Sydjysk Universitetsforlag, Esbjerg. 230 pp.
OECD, 1997. Environmental Indicators for Agriculture. 62 pp.
Refsgaard, K., Halberg, N., Kristensen, E.S., 1998. Energy utilisation in crop production on organic and conventional livestock farms. Agric. Syst. 57, 599–630.
Reinhard, S., Thijsen, G., 1996. Econometric measurement of technical and environmental efficiency of Dutch dairy farms. Paper presented at Georgia Productivity Workshop, Athens, Georgia, November 1996.

Robertson, G.P., 1993. Fluxes of nitrous oxide and other nitrogen trace gases from intensively managed landscapes. Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. ASA Special Publication 55. pp. 95–108.
SAS, 1985. SAS/STAT Guide, version 6, SAS Institute Inc., Gary, NC, USA., pp. 183–261.
Secher, B.J.M., Gyldenkærne, S., 1996. Regulating pesticide use and environmental impacts. In: Walther-Jørgensen, A., Pilegaard, S. (Eds.), Integrated environmental and economic analyses in agriculture. SJFI, Copenhagen, report 89, pp. 163–172.
Uhlén, G., 1991. Long-term effects of fertilizers, manure, straw, straw and crop rotation on total-N and total-C in soil. Acta Agric. Scand. 41, 119–127.
USDA, 1990. Keys to Soil Taxonomy, 4th ed. SMSS Technical Monographs No. 19.
Vereijken, P., 1994. Designing Prototypes. Progress Report 1. Research Network for EU and Associated Countries on Integrated and Ecological Arable Farming Systems. AB-DLO, Wageningen, 87 pp.
Weisberg, S., 1985. Applied Linear Regression, 2nd ed. Wiley, New York, 323 pp.
Wijnands, F.G., 1997. Integrated crop protection and environment exposure to pesticides. Eur. J. Agron. 7, 251–260.
Willeke-Wetstein, Schmidt, A., Abresh, J.-P., Steinbach, J., Bauer, S., 1996. Methodological approach to evaluate the environmental impact of livestock production systems. In: Dent, J.B., MacGregor, M.B., Sibbald, A.R. (Eds.), Livestock Farming Systems, Research Development, Socio-economics and the Land manager. EAAP publication No. 79, pp. 187–199.
de Wit, J., Oldenbroek, J.K., van Keulen, H., Zwart, D., 1995. Criteria for sustainable livestock production: a proposal for implementation. Agric. Ecosyst. Environ. 53, 219–229.