Energy balance of five fodder cropping systems in the irrigated lowlands of Northern Italy

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Abstract

Extensification has recently become an important option in Western European agriculture, driven both by economic considerations (product surpluses together with the fact that developed countries cropping systems have been heavily relying on fossil energy) and growing public concern on the possible adverse effects of intensive farming on the environment and human health. The adoption of rational fodder crop rotations, with the rediscovery of the beneficial effect of the meadow, is viewed as a possible mean to reduce the impact of farming systems in the lowlands of northern Italy, characterised by highly intensive cropping and animal husbandry. For this reason our study examines the effects of crop rotation on the energy balance during 1985-2007 period in a long-term crop rotation trial in Northern Italy comparing five fodder crop systems, different in the degree of crop intensification and for the presence or absence of the meadow: a 1-year continuous cereal double cropping (R1); a 3-year rotation (R3); a 6-year rotation (R6); a permanent meadow (PM); and a continuous grain maize cropping (CM). Each rotation was subjected to two input treatments, defined as high (mostly used in lowlands of northern Italy) and low (input reduction of ca. 30%) respectively, in terms of nutrient levels, herbicide doses, and soil tillage methods. The crop rotations exerted a marked influence on the energy balance. The most efficient rotations in terms of net energy production energy efficiency have been characterized by reduced length and presence of maize and catch-crops.

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Introduction

The outstanding technological progress occurred in the second half of the last century in various fields (e.g. chemistry, mechanics, genetics, etc.) and the actions taken by the E.U. Common Agricultural Policy, were the causes of the agriculture extreme intensification which occurred in the regions with favourable pedo-climatic conditions. A dramatic increase was subsequently induced in the yields of all the crops as well as the simplification, and the consequent specialisation, of farming systems (Parente, 1996). In particular, during the last decades Western European countries experienced some crucial changes to reduce the impact of cropping on soil pollution. On one hand, the surpluses of many agricultural products causing stagnation of prices, and, on the other, the growing concern of public opinion about the possible side effects of intensive farming on environment and human health, because of the massive recourse to potentially pollutant factors, led the Common Agricultural Policy to pursue the goal of agricultural extensification (Smith and Olesen, 2010; Postma-Blaauw *et al*., 2010; Cruse *et al*., 2010).

Therefore, sustainable farming systems based on cropping and/or animal husbandry requiring lower amounts of non-renewable inputs have been increasingly encouraged and, accordingly, financially supported (Parente, 1996; Castoldi and Bechini, 2010).

In the last 40 years, the lowland area of the Po Valley in northern Italy experienced a process of outstanding cropping intensification and simplification together with the related livestock systems so that, nowadays, they are almost exclusively based on continuous cereal cropping (autumn-sown Italian ryegrass, Lolium multiflorum Lam., followed by spring-sown maize, *Zea mais* L., both used for silage), and on the rearing, under confinement, of Holstein dairy cows with high genetic and productive standards. This process caused a drastic reduction of permanent and rotational meadows, which despite representing the main forage resource before the 1960, have decreased of about 50% in land area since then (Giardini and Ziliotto, 1988). The overweening capital input and the large availability of production factors not belonging to the farm allowed carrying out such an extensive agriculture whose products were transformed into milk both for human consumption and dairy industry.

Energy analysis as indicator of farming system sustainability was developed during the 70's as consequence of the *oil crisis* (Bonari *et al*., 1992; Giardini *et al*., 1983; Pimentel, 1993). Energy analyses of no-renewable source use is preferable when the reduction of the used energy has pursued in the agricultural systems. Up to now many authors focused their work on energy balance of both conventional and low energy input cropping systems considering both food and biomass crops (Sharma *et al*., 2011; Arvidsson, 2010; Deike *et al*., 2008; Gelfand *et al*., 2010; Boehmel *et al*., 2008; Rathke *et al*., 2007; Rathke and Diepenbrock, 2006; Monti and Venturi, 2003; Hülsbergen *et al*., 2001) and with reference to external energy inputs (Cruse *et al*., 2010; Wiens *et al*., 2008); nevertheless, an in depth study considering the presence of meadow in the cropping system is still missing.

In this paper we compare the productivity and energy balance of five forage crop systems which represent different models of forage production in Lombardy plain where low input farming systems are expected to be preferred to the current widespread high input farming systems using large amounts of agrochemicals and machinery: the present paper reports the results gathered in 22 years after the trial's establishment.

Materials and Methods

The experiment was carried out in Lodi, Italy (45°19' N, 9°30' E, 81 m asl), which is a location representative of the alluvial Po Valley. The used soil was a sandy-loam one of the mollic Hapludalf family, with sub acid pH (6.2), low in nitrogen, organic matter, and exchangeable potassium, and with good provision of assimilable phosphorus. The climate is typical of the lowlands of northwestern Italy: the average annual rainfall is about 800 mm (well distributed along the year) and the average annual daily temperature is 12.5°C with a minimum of 1.1°C in January and a maximum of 22.9°C in July.

Five cropping systems have been included in this investigation since 1984: i) one annually-repeated double crop (coded as R1) of autumn-sown Italian ryegrass + spring-sown maize both used for silage; ii) a three-year rotation (coded as R3) made of autumn-sown barley (*Hordeum vulgare* L.) + spring-sown maize both for silage purpose; Italian ryegrass + maize (both for silage)/grain maize; iii) a six-year rotation (R6): 3 years of Italian ryegrass + maize (both for silage) / 3 years of meadow (Ladino white clover, *Trifolium repens* L., + tall fescue, *Festuca arundinacea* Schreb.) for hay making; iv) a continuous grain maize cropping (CM); and v) a permanent meadow (PM) (Table 1). Each rotation underwent two kind of treatments corresponding to an high input level (H, mostly used in northern Italy lowlands) and low input level (L). The difference among these was "L" one was made of about 70% of the organic, chemical fertilisation and herbicide amounts given with the *H* one (Onofrii *et al*., 1993, 1996).

A further difference between H and L treatments concerned soil tillage before autumn-sown crops. In the H treatment, soil was ploughed to a depth of 30 cm and then rotary-cultivated, while in the *L* one it was rotary-cultivated to a depth of 15 cm only. In both treatments all maize crops, either for silage or grain production, were ploughed before sowing, and rotary-cultivated along the rows after plant emergence also to enhance the covering of the nitrogen fertiliser applied at post-emergence stage (half of total required amount). Every year, in both the treatments, four border irrigations of about 1000 m^3 ha^{-1} each were provided to the whole trial; for the sowing period and all the other cultural practices we referred to those typical for each considered crop in the region.

The experimental design on annual basis was a strip-plot with three replications in as many blocks; the main plots being represented by the input level and the sub-plots by the compared rotations. All the phases (crops) contemplated by the rotations, as indicated in Table 1, were present at the same time in each year, in each combination of block and input level, to avoid possible confounding effects of the factor year when comparing rotations made up of different phases in different years. In the experimental layout, two crops present in the same year in one rotation (e.g. Italian ryegrass and maize) were considered as just one crop. Altogether the trial included 72 plots (12 crop-phases × 3 blocks × 2 input levels), each measuring 60 m^2 (6×10 m).

The different cropping systems have been compared according to the energy balance sheet, using the gross energy method to determine the energy inputs of the cropping systems. This method takes into account only fossil energy sources without considering both renewable sources and human labour (Ceccon *et al*., 2002). It calculates the fossil energy directly used in crop production (e.g. oil, lubricants) as well as the energy embedded in agricultural requisites (e.g. machinery, seeds, agrochemicals, etc.). To this purpose, basic data on agricultural requisite use were regularly recorded from 1985 to 2006 taking into account the type of used machinery and its working times, the mass of applied fertilisers and agrochemicals, the seed rates and the irrigation depths. Table 2 summarises the energy conversion rates for agricultural requisites (Pimentel, 1980; Pellizzi, 1992, Jarach, 1985). Energy for machine depreciation was estimated combining mass conversion rate, reliable life and finding machinery val-

Table 1. List and sequence of the twelve crops in the five crop rotations under comparison.

Six-year rotation (R6)	Three-year rotation (R3)	Annual rotation (continuous double cropping) (R1)	Continuous grain maize cropping (CM)	Permanent meadow (PM)
IR–SM_1	SB–SM	IR–SM	GM	PM
IR–SM_2	IR–SM			
IR–SM_3	GM			
RM_1				
RM_2				
RM_3				

IR–SM, Italian ryegrass + maize (both for silage); RM, rotational meadow; SB–SM, barley + maize (both for silage); GM, grain maize.

Table 2. Energy (MJ=mega Joule) conversion rates for agricultural equisites/commodities.

Category	Agricultural practice/requisite	Size unit	Value	Reference
Machine (Depreciation=M×CR×V/RL×WT)	Agricultural practices	MJ×Hp×h^{-1}	7.68	Pimentel 1980
Contents	Tractors and combines	MJ kg^{-1}	92.00	Pimentel 1980
	Other equipment	MJ kg^{-1}	69.00	Pimentel 1980
Fertiliser	Nitrogen	MJ kg^{-1}	62.00	Pimentel 1980
	Phosphorous	MJ kg^{-1}	13.65	Pimentel 1980
	Potassium	MJ kg^{-1}	7.68	Pimentel 1980
Seeds		MJ kg^{-1}	15.00	Pimentel 1980
Agrochemicals	Herbicides	MJ kg-1	189.00	Pimentel 1980
	Geo-insecticides	MJ kg^{-1}	67.00	Pimentel 1980
	Plastic material	MJ kg^{-1}	100.80	Pimentel 1980
MFU		MJ	7.24	Chase 1981

M, mass of the machine; CR, conversion rate; V, unit value (dimensionless) at the end of the reliable life; RL, reliable life; WT, working time; MFU, milk feed unit.

ues and working times. Fuel consumption of machinery was set at 180 gr Hp^{-1} h^{-1}. The output energy content of the produced forage has been estimated with NIRS method (Chase, 1981) as net energy for milk cow production (Milk Feed Units=MFU=7.24 MJ).

The results were subjected to analysis of variance (ANOVA) performed with the SAS software.

Results and Discussion

Table 3 reports the milk feed units yield in the different crop systems at two different intensification levels over the twenty-two year period of the trial: on average, short rotation and level low of intensification (L) showed large yield oscillation among the years, as indicated by high values of the coefficient of variation (CV%) as compared to the other rotations.

On average, the higher yield stability was achieved in the R6 rotation while, on the contrary, PM and CM rotations at input L showed large yield oscillations as indicated CV values higher than 20%. This suggests that in the R6 treatment it occurs the establishment of satisfactory agricultural practices for these crop systems. Differences among mean values of milk feed units from each cropping systems are very high, ranging from 22,477 and 20,281 MFU ha^{-1} yr^{-1} (for R1, at H and L input levels) to 8587 and 7210 (for PM). At both input levels each rotation productivity is significantly different from the others according to the following rank: R1>R3>R6>CM>PM.

Table 4 depicts the overall energy use for crop growth (MJ ha^{-1} $year^{-1}$) in the 22-years trial under different crop systems by grouping homogeneous agricultural practices into four categories (machinery, irrigation, seed and agrochemicals included fertilisers) while cumulated values and share of the total energy use for single rotation are reported in Table 5. It comes out that great part of machinery energy (more than 50%) was spent for harvesting in the meadow (mowing, as well as hay raking, conditioning, baling and transporting) while in other crop systems the highest energy requirements were those for maize tillage and fertilisation. The maximum energy requirement (machinery, irrigation, seed and agrochemicals) is the one of maize grown in the R3 trial both at H and L energy level with 44,986 and 38,439 MJ ha^{-1} $year^{-1}$ respectively and with an incidence percentage of machinery ranging from 49.8% to 56.1%. Italian ryegrass and silage barley are the crops requiring the lowest energy (about 26,000 MJ ha^{-1} $year^{-1}$) while silage maize requires 39,789 and 33,641 MJ ha^{-1}

Table 3. Milk feed units yields ($ha^{-1}yr^{-1}$) in different cropping systems and coefficient of variation overall 22 years of the trial.

Rotation	Treatment H		Treatment L		Significance
	MFU	CV (%)	MFU	CV (%)	
R1	22,477[a]	14.8	20,281[a]	17.7	**
CM	11,921[d]	16.5	9932[d]	25.1	***
PM	8587[e]	21.2	7210[e]	23.2	***
R6	15,842[c]	12.8	14,234[c]	13.6	***
R3	18,826[b]	13.8	16,342[b]	14.3	***

MFU, milk feed unit; [a-e]means followed by same letter are not different for Duncan's test at P<0.01; **P<0.01; ***P<0.001; CV, coefficient of variation overall years (1985-2006).

Table 4. Energy content of agricultural practices/requisites (MJ ha^{-1} $year^{-1}$) for different crops and inputs treatment in the compared rotations.

Category	Agricultural practice/requisite	PM		Meadow 1st year		Meadow 2nd and 3rd year		Italian ryegrass R1-R3-R6		Grain maize CM		Grain maize R3		Silage maize (R1-R3-R6) After I. ryegrass		Silage maize (R1-R3-R6) After barley		Silage barley R3	
		H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
Machinery	Chopping/harwesting rapier	0	0	0	0	0	0	0	0	807	807	3226	3226	0	0	0	0	0	0
	Ploughing/chiselling	0	0	2489	2489	0	0	2489	1382	2489	2489	2489	2489	2489	2489	2489	2489	2489	1382
	Clod breaking	0	0	2305	2305	0	0	2305	1383	2305	2305	2305	2305	2305	2305	2305	2305	2305	2305
	Row weeding	0	0	0	0	0	0	0	0	768	768	768	768	768	768	768	768	0	0
	Roller paking	0	0	384	384	0	0	384	384	384	384	384	384	384	384	384	384	38	384
	Fertiliser application	883	883	883	883	883	883	845	845	461	461	461	461	461	461	461	461	845	845
	Manure application	2689	2258	2689	2258	0	0	0	0	0	0	0	0	2689	2258	2689	2358	0	0
	Sowing	0	0	576	576	0	0	576	576	499	499	499	499	499	499	499	499	576	576
	Spraying (herbicides)	0	0	0	0	0	0	0	0	307	307	307	307	307	307	307	307	307	307
	Mowing	2689	2689	2151	2151	2689	2689	0	0	0	0	0	0	0	0	0	0	0	0
	Harvesting	11.54	11.354	8681	8681	11.54	1.14	4610	4610	3572	3572	3572	3572	5070	5070	4563	4563	4424	4424
	Drying	0	0	0	0	0	0	0	0	6828	5989	6828	5989	0	0	0	0	0	0
Machine depreciation		2500	2400	3390	3287	2290	2200	2189	2086	1565	1565	1565	1565	2235	2235	2235	2235	2089	1886
	Subtotal	8772.54	8241.354	23,548	23,014	5873.54	5773.14	13,398	11,266	19,985	19,146	22,404	21,565	17,207	16,776	16,7	16,369	13,419	12,109
Irrigation		2151	2151	2420	2420	2151	2151	0	0	2823	2823	2823	2823	2823	2823	2420	2420	0	0
Seed		0	0	600	600	0	0	750	750	700	700	700	700	700	700	300	300	313	3136
Agrochemicals																			
	Fertiliser	10.714	7469	10.714	7469	10.714	7469	11,583	8108	17,633	12,344	17,633	12,344	17,633	12,344	17,633	12,344	9527	6809
	Herbicides	0	0	0	0	0	0	0	0	756	529	756	529	756	529	756	529	240	160
	Geo-insecticides	0	0	0	0	0	0	0	0	670	469	670	469	670	469	670	469	0	0
	Plastic material	2863	2419	564	564	2872	2419	0	0	0	0	0	0	0	0	0	0	0	0
	Subtotal	2873.714	9888	574.714	8033	2882.714	9888	11,583	8108	19,059	13,342	19,059	13,342	19,059	13,342	19,059	13,342	9767	6969

PM, permanent meadow; R1, 1-year continuous cereal double cropping; R3, 3-year rotation; R6, 6-year rotation; CM, continuous grain maize cropping;

Table 5. Energy content of agricultural practices/requisites (MJ ha^{-1} year^{-1}) groupped in 4 principal categories for different crops and input treatments in the compared farming systems and share of energy content (%).

Rotations\category		Machinery				Irrigation				Seed				Agrochemicals				Total	
	Crop\input treatments	H	%	L	%	H	%	L	%	H	%	L	%	H	%	L	%	H	L
R1		30,605	47	28,042	52	2823	4	2823	5	1450	2	1450	3	30,642	47	21,677	40	65,520	53,992
	Italian ryegrass	13,398	52	11,266	56	0	0	0	0	750	3	750	4	1,583	45	8108	40	25,731	20,124
	Silage maize	17,207	43	16,776	50	2823	7	2823	8	700	2	700	2	19,059	48	13,569	40	39,789	33,868
R3		27,709	47	26,028	53	2689	5	2689	5	1862	3	1862	4	26,176	45	18,368	38	58,436	48,947
	Italian ryegrass	13,398	52	11,266	56	0	0	0	0	750	3	750	4	11,583	45	8108	40	25,731	20,124
	Silage barley	13,419	51	12,109	55	0	0	0	0	3136	12	3136	14	9767	37	6969	31	26,322	22,214
	Silage maize a. It. ryegras	17,207	43	16,776	50	2823	7	2823	8	700	2	700	2	19,059	48	13,342	40 3	9789	33,641
	Silage maize a. barley	16,700	43	16369	50	2420	6	2420	7	300	1	300	1	19,059	0	13,342	41	38,479	32,431
	Grain maize	22,404	50	21565	56	2823	6	2823	7	700	2	700	2	19,059	42	13,342	35	44,986	38,430
R6		25,027	50	23,565	56	2532	5	2532	6	825	2	825	2	21,729	43	15,473	36	50,113	42,396
	Italian ryegrass	13,398	52	11,266	56	0	0	0	0	750	3	750	4	11,583	45	8108	40	25,731	20,124
	Silage maize a. It. ryegras	17,207	43	16,776	50	2823	7	2823	8	700	2	700	2	19,059	48	13,569	40	39,789	33,868
	Rotated meadow 1st year	23,548	62	23,014	68	2420	6	2420	7	600	2	600	2	11,278	30	8033	24	37,846	34,067
	Rotated meadow 2nd & 3rd yr	1,7400	53	17,126	59	2151	6	2151	7	0	0	0	0	13,586	41	9888	34	33,137	29,165
CM	Grain maize	19,985	47	19,146	53	2823	7	2823	8	700	2	700	2	19,059	45	13,342	37	42,567	36,011
PM	Permanent meadow	20,299	56	19,584	62	2151	6	2151	7	0	0	0	0	13,577	38	9888	31	36,027	31,623

R1, 1-year continuous cereal double cropping; R3, 3-year rotation; R6, 6-year rotation.

year-1 for treatment H and L respectively spending great part of energy for agrochemicals.

In all the studied rotational farming systems, energy required for fertilization and agrochemicals was on average the most relevant item whose cost of use exceeded the harvesting one in all the rotations at H input level with exception for the permanent meadow. With reference to the L input level, the most important energy input reduction is ascribable to the fertilization amount.

Table 6 summarises the main variables of the input/output balance sheet. On average, during the 22 years trial, rotations across input treatments produced different amounts of estimated energy for milk production: R1 showed the highest energy output with 162,733 MJ ha^{-1} year^{-1} (19% more than R3, 42% more than R6, 88% more than CM and 260% more than PM). This farming system output mainly depends on single crop output, with silage maize producing the highest amount of energy if compared to the other crops.

At low intensification level (L) inputs energy ranges from 53,992 (R1) to 31,623 MJ ha^{-1} year^{-1} (PM): the lack of meadow causes R1 and R3 to have the higher values of inputs. At high treatment level (H) there is an appreciable increase of energy required by rotations whose the mean values range from 65,520 (R1) to 36,027 MJ ha^{-1} year^{-1} (PM). On average, the amount of energy required by rotations was different for each input treatment level. The effect of rotations and input treatment on net energy is shown in Table 7. Here it can be pointed out how the net energy (energy output - energy input) was substantially different between rotations at the same level of input treatment, while comparing the two intensification levels at varying of the rotation shows that no difference in net energy can be seen for R1 and R6.

Therefore, net energy output from R1 is more than the triple than the one from PM. Mean outputs are lower for rotations including the meadow (R6 and PM), if compared with rotations without meadow (R1 and R3). In the same table, it can be noticed that also maize monoculture (CM) has a relatively low net energy but this can be ascribed to the fact that only grain has been transformed into energy for cow milk production.

Net/input energy ratios (or net energy production efficiency) are shown in the right part of the same table: here R1 is shown to be the most efficient cropping system in both H and L treatment, followed by R3 and R6 which do not show any significant difference between them, while the least efficient are CM an PM. These cropping systems can therefore ranked as follows: R1>R3=R6>CM>PM.

The results of the comparison between the two input treatment levels within the same rotation (Table 7) shows that R1, R3 and R6 are more efficient when the inputs are reduced because they show an higher out/in ratio under low (L) input treatment level.

Another consideration that can be done is that, according to the discussed results and under the pedological, climatic and agricultural conditions occurring during the trial, the most efficient rotations turned out to have the following features: i) shortness; ii) including maize; iii) including catch crops (e.g. Italian ryegrass – silage maize or silage barley).

Limiting factors to crop productivity (e.g. water, light and nitrogen)

Table 6. Energy input and output (MJ ha^{-1} year^{-1}) for different rotations.

Rotation/input treatment	Energy output H	Energy output L	Energy input H	Energy input L
	(MJ ha^{-1} year^{-1})			
R1	162,733	146,834	65,520	53,992
R3	136,300	118,316	58,436	48,947
R6	114,696	103,054	50,113	42,396
CM	86,308	71,908	42,567	36,011
PM	62,170	52,200	36,027	31,623

Table 7. Net Energy (MJ ha^{-1} year^{-1}) and energy efficiency for different rotations.

Rotation/input treatment	Net energy° H	Net energy° L	Energy efficiency° H	Energy efficiency° L
	(MJ ha^{-1} year^{-1})			
R1	97,213^{aA}	92,842^{aA}	1.48^{aB}	1.72^{aA}
R3	77,864^{bA}	69,369^{bB}	1.33^{bB}	1.42^{bA}
R6	64,583^{cA}	60,658^{bA}	1.29^{bB}	1.43^{bA}
CM	43,74^{dA}	35,897^{cB}	1.03^{cA}	1.00^{cA}
PM	26,143^{eA}	20,577^{dB}	0.73^{dA}	0.65^{dA}

°Means followed by same letter are not different for Duncan's test at P<0.05; $^{a-d}$valid between the rotations; ^{A,B}valid between the levels of intensification H.

are better used if rotations are more efficient: as a matter of fact, maize, belonging to C4 species, having a more efficient light use subsequently requires and uses higher amounts of water and nutrients. On the contrary, mixed cropping systems (meaning a main crop and followed by one catch crop within the same year: R1, R3 and R6 rotations) allow a better use of water and nutrients because of their prolonged soil coverage. On the contrary permanent meadow, despite having very high soil coverage, shows a low energy efficiency that can be due to its characteristic low yield potential. In case of low input level, the increase of the efficiency shown by R1, R3 and R6 rotations suggest that, to limit consumption of not renewable resources and environmental pollution by intensive agriculture, the chance of energy input reduction for these cropping systems should be seriously taken into account.

Conclusions

The data discussed in this paper can be considered representative of farming systems in the area of evaluation in as results of long-term experiments and some conclusions can be made.

- Energy analysis provides important information on fodder cropping systems properties.
- The overall productivity of the cropping systems was affected by the level of intensification and by the productivity of single crops especially maize.
- Farming systems mainly using external inputs seemed to induce higher crop yield stability than the more self-sufficient farming systems.
- Both net energy and energy efficiency evaluated on a cropping systems basis emphasise big differences among the compared types of agriculture and it seems that energy efficiency is mainly related to system outputs.

A final consideration suggested by our results concerns the level of intensiveness commonly applied to cropping systems in the region of evaluation. The fact that a 25-30% reduction of inputs, above all agrochemicals and fertilisers, involves a decrement of production less than proportional to the reduction of inputs and in the case of the net energy a no significant decrement in R1 and R6 should drive farmers to consider the chance of adopting less intensive agronomic practices, obtaining in exchange an increase of sustainability both under the economic and the environmental point of view.

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