A methodology for designing and evaluating alternative cropping systems: Application on dairy and arable farms

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abstract

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To improve the sustainability of agricultural systems of the Lombardia region (northern Italy), a mixed indicator-model-expert approach was used. Starting from the results of a previous assessment of cur- rent management (ACT) in dairy and arable farms, alternative management scenarios at field level were designed in order to reduce nitrogen (N) losses whilst maintaining or improving the environmental and economic sustainability at the farming system level. By working with a group of experts supported by a mechanisation model and a cropping system model, two alternative N management scenarios were defined following a step-by-step decision procedure. The first scenario (FERT) is an improvement of the current fertiliser management scheme, applied at the same crops as in ACT and aimed at maintaining the same yields. The second scenario (ROT) is based on changes in crop rotations by introducing new crops to reduce N losses and to maintain economic profitability. The sustainability of the two scenarios was assessed and compared with agro-ecological and economic indicators. The results of FERT, indicate that the application of adequate N management plans tuned to the production target and the promotion of best management practices may help to reduce N surplus and consequently to save fossil energy and to decrease the costs of production. In the ROT scenario, the introduction of alfalfa cultivation reduces N surplus on maize, whereas intensive double cropping systems (two crops harvested in 12 months) increase N surplus and require higher energy consumptions and production costs compared to cultivat- ing a summer crop only. However, in rotational systems more favourable weed population dynamics are expected compared to ACT. Both alternative scenarios were not implemented in practice, but they are realistic and are consistent with results of experiments where management options similar to those introduced in FERT and ROT were tested.

This work indicates that the rational integration between scientific tools (indicators and models) and expert knowledge is adequate to deal with complex farming and cropping systems, which require a multidisciplinary approach.

1. Introduction

The sustainability of farming and cropping systems is evalu- ated by adopting various approaches, including agro-ecological indicators and models (Acutis et al., 2000; Padovani et al., 2004; Meul et al., 2008; Bechini and Castoldi, 2009; Castoldi et al., 2009; Bassanino et al., 2011). These applications represent the first step towards the achievement of sustainable agriculture. The second step requires to develop and analyse alternative man- agement options with low environmental impact. Alternative management practices can be evaluated only if their expected pro- ductive and environmental performances can be reliably estimated. Strong interconnections occurring amongst different sub-systems (soil, crops, animals, feeding, housing, manure management and machinery; Børsting et al., 2003) result in a high level of complex- ity of the farm system. In a whole farm perspective, this complexity should be considered, as changes in one sub-system may impact one or more of the others. Starting from the field level, hypothet- ical alternative cropping systems can be defined and their effects on other farm components evaluated through the prediction of a set of variables related to crop yield, animal diet, labour organi- sation and economic profitability. These effects can be estimated using whole-farm models describing all the interactions within a farm. However, these models are complex and require many input data, thus they are normally applied to focus on a specific domain (e.g. nitrogen cycle, greenhouse gas emissions, labour, economic performance, weed management). Alternatively, indicators can be used, even though indicators alone do not allow the prediction of variables under the new conditions. For this reason, the use of indicators should be complemented by expert advice (Clavel et al., 2011).

This situation is typical of many agricultural and environmental problems, whose solutions can be searched through the so-called Systems thinking (ST) methods, as suggested by some relatively recent operational research approaches (Checkland, 1983; Holt and Schoorl, 1989; Mingers and Rosenhead, 2004; Mingers and White, 2010). In particular, ST can be applied to integrate several spa- tial and temporal levels through the combination of extensive data collected on real systems or already available in the literature, sim- ulation models, appreciative knowledge from experts and eventual knowledge from local stakeholders.

The use of the ST is often ideal to analyse cropping systems, and the literature presents several cases where this approach has been applied more or less explicitly. Published research works deal with the scale of single crop, field, or farm. Some authors rely more on experts than on models. For example, to define improved crop man- agement practices Debaeke et al. (2009) have presented a method for prototyping and testing cropping systems in field experiments, using decision rules to reach defined objectives under constraints. Lançon et al. (2007) have integrated the proposals of different experts through workshops. A different approach is proposed by Bergez et al. (2010), who used model simulation in an iterative pro- cedure to evaluate candidate management plans proposed either by the software or by the user. An example dealing with the devel- opment of improved management at a more complex scale than the single crop is that of Bachinger and Zander (2007), who have developed a software to generate and evaluate the sustainability of crop rotations, by defining the management scheme of each sin- gle crop in rotation. At the more complex farm scale, Van Calker et al. (2004) have optimised the sustainability of a dairy farm under several constraints, using linear programming to describe the com- plex relationships internal to the farm. Del Prado et al. (2011) have developed a complete mechanistic dynamic simulation model of a dairy farm that is used to evaluate management scenarios provided by the user.

The application context considered here is the plain area of the Lombardia region (northern Italy), characterised by an intensively managed agriculture, a livestock density almost four times higher than Italian average (1.12 livestock units ha−1 of total regional area; ISTAT, 2008), a high average milk production (9268 kg cow−1 year−1; AIA, 2008), and a relevant use of produc- tion factors. After having assessed the current state of the farming systems in the region (Fumagalli et al., 2011) we have designed and evaluated alternative cropping systems by using an innovative approach that combines agro-ecological and economic indicators, expert knowledge and dynamic simulation models, according to ST methods. The approach presented in this paper was adopted to describe the sustainability of cropping systems in the current situa- tion, identify alternative management scenarios, and evaluate their sustainability in comparison with the current state.

2. Materials and methods

2.1. *Systems thinking and the indicator-model-expert approach*

The basic scheme of our ST approach applied for evaluating alternative management options in various farming systems is shown in Fig. 1. These systems are always affected by multiple actors and perspectives generating several economic, environ- mental and operational impacts on the farm management. Thus, there are several evaluation viewpoints, usually characterised by many uncertainties. Systems thinking methods offer support through modelling and group facilitation to stimulate dialogues and decisions, and to reach shared understanding and joint agree- ments about the domain. The domain here consists of a set of selected representative farms that are monitored and then eval- uated with respect to their sustainability at the cropping system level using agro-ecological and economic indicators. Based on the results of this evaluation and on the identification of the least sustainable aspects of current management, alternative manage- ment scenarios are designed. Farm data are defined and structured according to the farm configuration view proposed by Mazzetto and Sacco (2011), which represents a farm as a collection of goods (resources and materials to be consumed or produced) and actions (all the planned or executed decisions that lead to the farm behaviour). Each scenario is described by the combi- nation of several management practices that are determined by

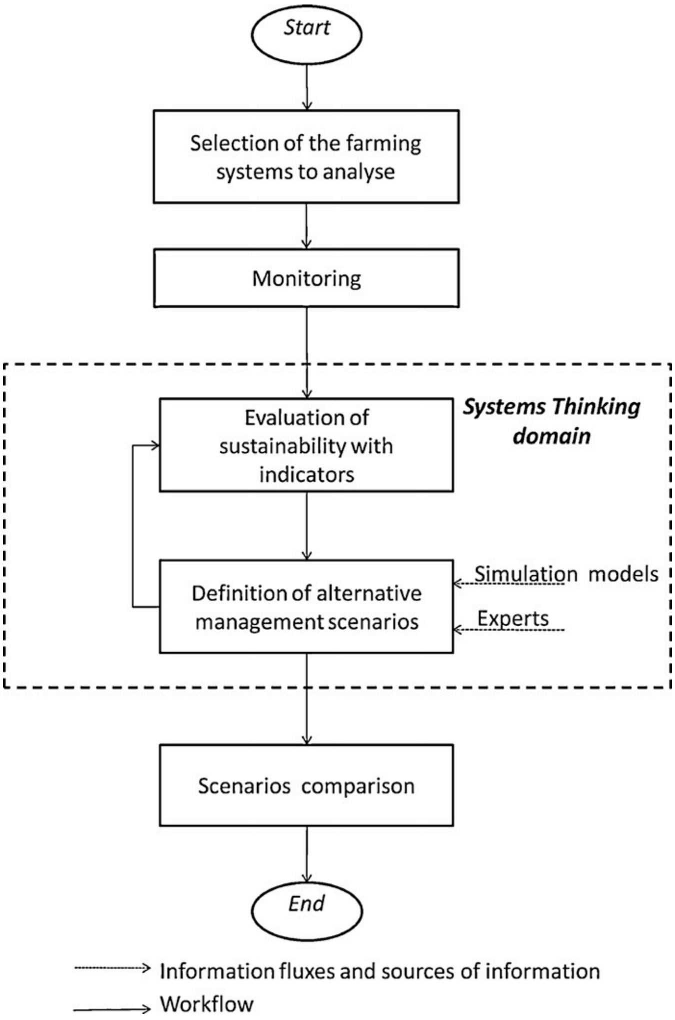

Fig. 1. Flow chart describing the Systems Thinking approach based on indicators, models and expert knowledge to analyse and improve farming systems.

planned actions (crop rotation, sowing dates, cultivars used, tillage operations, fertilisations, irrigations, harvest, and so on). Each man- agement scenario is defined without changing farm resources, i.e. without new investments in land, buildings, machines or labour. Scenarios are designed using the data provided by experts and the results of dynamic simulation models. Agro-ecological and eco- nomic indicators are finally calculated to compare each alternative scenario.

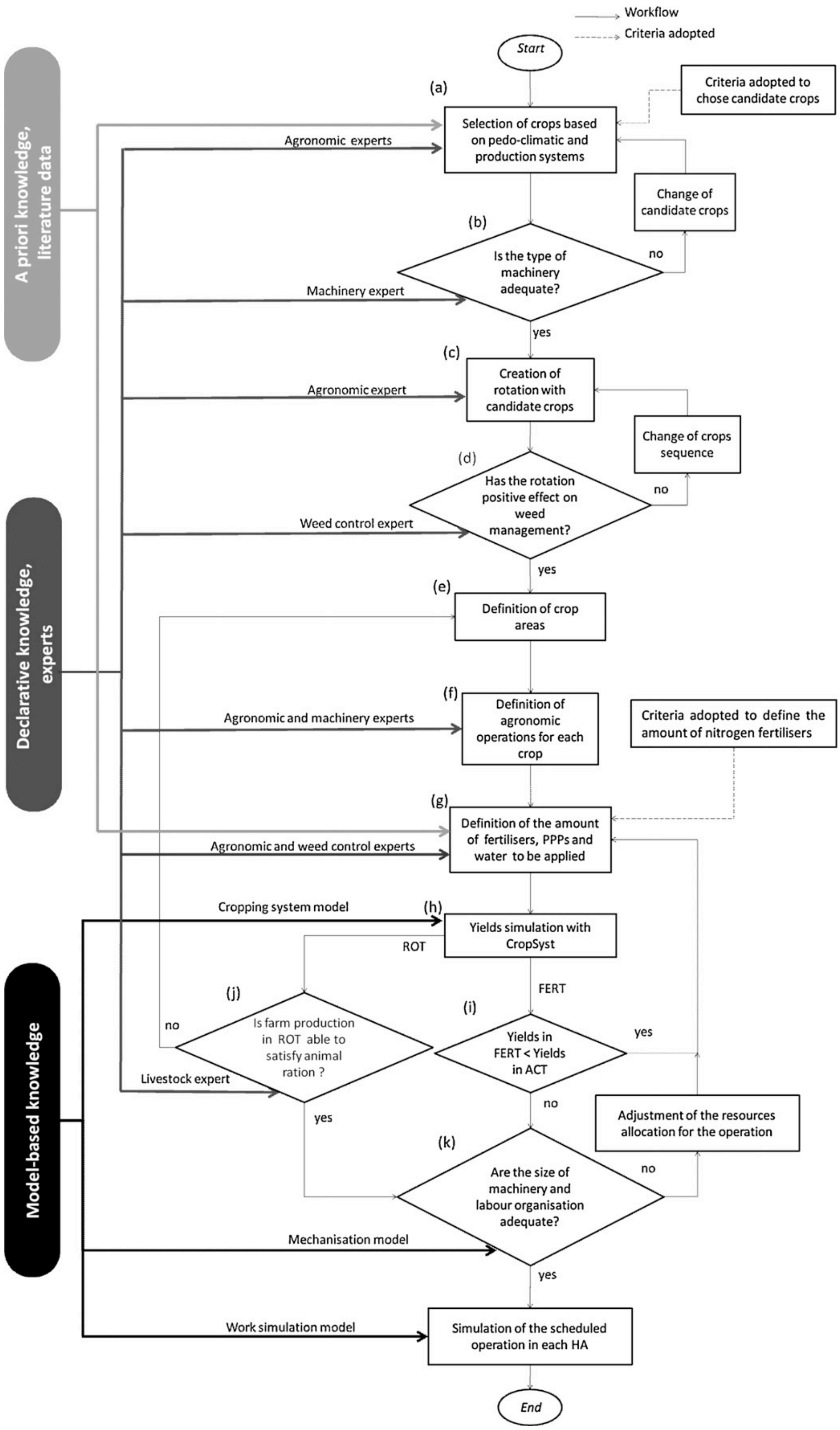
Workflow
Criteria adopted
Start
A priori knowledge, literature data
Declarative knowledge, experts
Model-based knowledge
(a)
Selection of crops based on pedo-climatic and production systems
Criteria adopted to chose candidate crops
Agronomic experts
Change of candidate crops
(b)
Is the type of machinery adequate?
no
Machinery expert
yes
(c)
Creation of rotation with candidate crops
Agronomic expert
Change of crops sequence
(d)
Has the rotation positive effect on weed management?
no
Weed control expert
yes
(e)
Definition of crop areas
(f)
Definition of agronomic operations for each crop
Agronomic and machinery experts
Criteria adopted to define the amount of nitrogen fertilisers
(g)
Definition of the amount of fertilisers, PPPs and water to be applied
Agronomic and weed control experts
Cropping system model
(h)
Yields simulation with CropSyst
ROT
FERT
(j)
Is farm production in ROT able to satisfy animal ration ?
no
Livestock expert
yes
(i)
Yields in FERT < Yields in ACT
yes
no
Adjustment of the resources allocation for the operation
(k)
Are the size of machinery and labour organisation adequate?
no
Mechanisation model
yes
Work simulation model
Simulation of the scheduled operation in each HA
End

Fig. 2. Flow chart describing the step-by step procedure used to generate alternative management scenarios at field level. The workflow starts in (g) for FERT and in (a) for ROT. See Section 2.5 for details.

2.2. *Work overview*

The indicator-model-expert approach was applied, following the workflow of Fig. 1, at seven farms. Based on the results of their sustainability assessment (Fumagalli et al., 2011), alternative management scenarios at the field level were designed to reduce N losses by working with a group of experts supported by the use of a mechanisation model and a cropping system model (Fig. 2). Alternative scenarios were analysed from a planning perspective only, and their agro-environmental and economic sustainability was subsequently assessed and compared using indicators.

Our study focused on the cropping system level, and the related indicators depended only on the fluxes of matter and energy at the field level. The study of livestock was limited to its contribution to the flux of nutrients and indirect energy, entering the field as manure.

2.3. *Study area*

The study area (around 700,000 ha) is the agricultural plain of Lombardia (between 44◦50 N and 45◦50 N and 8◦40 E and 11◦80 E) located in the Po valley. The area is characterised by a large pedoclimatic variability (Fumagalli et al., 2011). Sixty-two percent of the area is defined as vulnerable to nitrates (Regione Lombardia, 2006). Maize (*Zea mays* L.), used for grain and silage, is the main cultivated crop; permanent meadows, winter wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), soybean [*Glycine max* (L.) Merr.], and Italian ryegrass (*Lolium multiflorum* Lam.) are also widely cultivated.

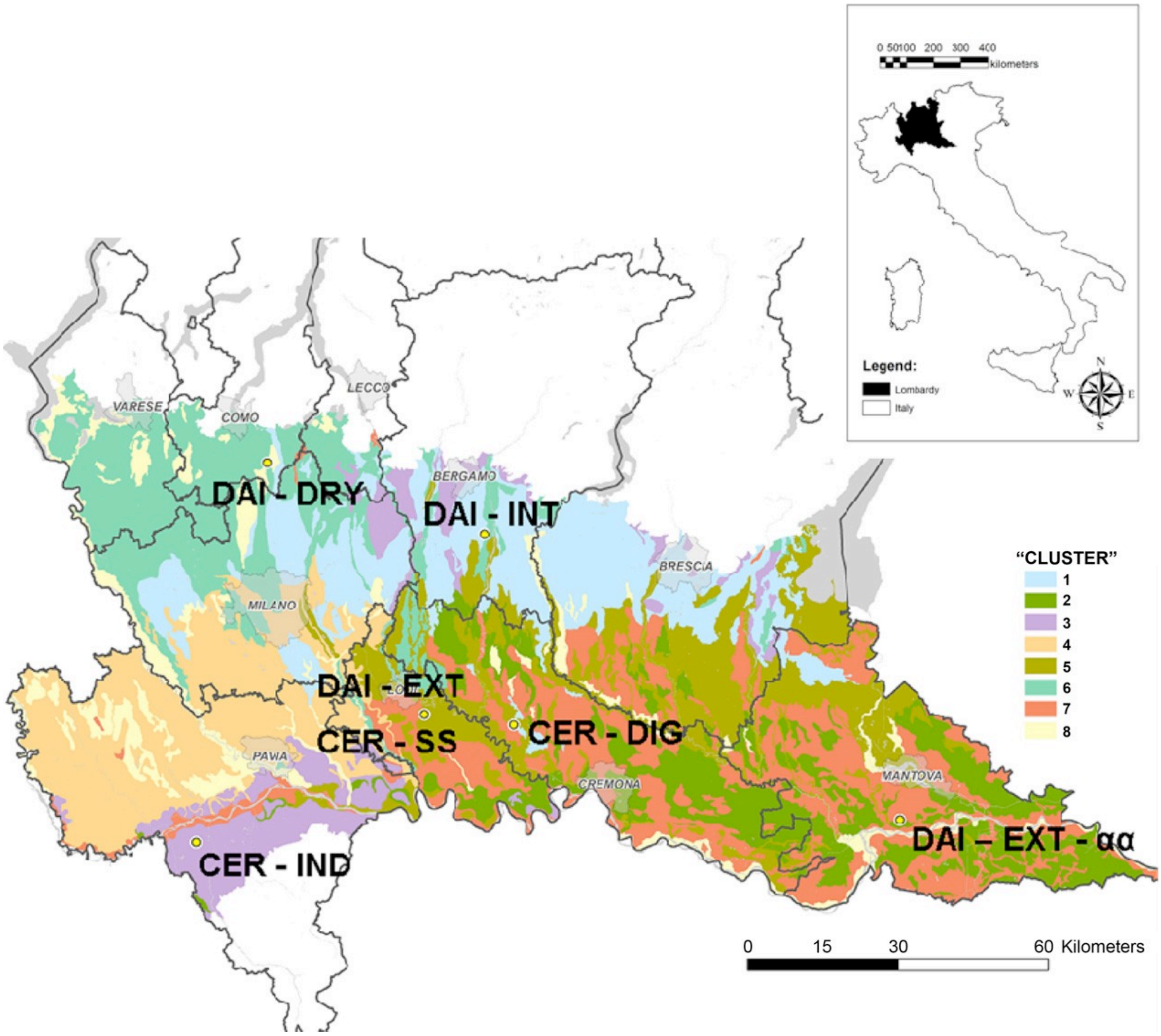

Fig. 3. Studied area: pedo-climatic areas and location of farms in the agricultural plain of Lombardia region. The geographical location of DAI-EXT and CER-SS farms is identified on the map with the same point. From Fumagalli et al. (2011).

Animal production involves keeping the animals in stables all year round. Irrigation is commonly applied with surface and sprinkler methods. Tillage is mostly carried out by ploughing and harrowing; minimum and no tillage are adopted rarely.

2.4. *Survey of farming and cropping systems*

The seven farms (Table 1; Fig. 3) are four dairy farms (DAI- EXT- : dairy extensive with alfalfa, DAI-DRY: dairy non-irrigated, DAI-INT: dairy intensive, DAI-EXT: dairy extensive) and three cereal farms (CER-SS: cereal with use of sewage sludge, CER-DIG: cereal with use of digested manure, CER-IND: cereal and industrial crops). The farms differ for climate, soil type, land capability, type of production, crop share, landscape and spatial configuration. Each farm was monitored (Fumagalli et al., 2011) by collecting information that corresponds to the average farmer's behaviour over several years. We recorded the farm-gate annual input and output fluxes of N, the crop management for each single field, the list of machin- ery available on farm, the tractor–implement combination for each individual crop operation, and the livestock management. To simplify data management, the fields in each farm were aggregated into homogeneous areas (HA). Soil type and crop management were equal within each HA. The farm configuration recorded during this survey was labelled as “actual scenario” (ACT).

The sustainability of ACT at the cropping system level was evalu- ated by using the indicators listed in Table 2 (Fumagalli et al., 2011). The data (Figs. 4–7) shows that there is frequent excess of N use, high consumption of fossil energy, consistent use of plant protec- tion products (PPPs) and a diffuse risk of occurrence of unfavourable weed community dynamics.

2.5. *Definition and evaluation of alternative scenarios*

The alternative scenarios had to satisfy these requirements:

(i) maintain for each farm the current type of livestock products;

(ii) maintain the farm resources (herd composition, buildings and machinery); (iii) guarantee the production of an adequate amount of feed to maintain, together with the purchased concentrates, the animal ration as in the ACT scenario.

According to these constraints, we designed two alternative N management scenarios. The first scenario (FERT) included the same crops as in ACT, but N management was improved. We did not develop FERT in farms where N management was considered appropriate in ACT (i.e. low *S*NB for all the HAs of the farm). The second scenario (ROT) was based on changes in crop rotation, which included new crops able to reduce N losses and to maintain eco- nomic profitability. To design the alternative scenarios we used a step-by-step decision procedure (Fig. 2).

The first step for defining ROT (Fig. 2a) was the choice of can- didate crops, using these criteria: (i) increase the area devoted to autumn–winter crops in a double cropping system (two crops harvested in 12 months) in order to increase N uptake during the period when most leaching occurs; (ii) introduce alfalfa meadows to ensure high N uptake and guarantee residual fertility to the following crop; and (iii) introduce bio-energy cash crops and/or industrial crops. The selection of the crops was based on the pedo-climatic and current cropping and livestock systems charac- teristics. For example, alfalfa was excluded in sub-acid soils, whilst autumn–winter crops (harvested for silage or ploughed in the soil as catch crop before reaching full maturity) were introduced in farms where a continuous maize cultivation system was common and when soil type allowed it. The introduction of bio-energy or industrial crops was considered only in farms without livestock.

The second step (Fig. 2b) was to check the suitability of the farm machinery for the new crops. The expert verified if the machinery available on farm was qualitatively adequate to carry out the new agronomic operations. In few cases this adequacy did not occur, thus we assumed that an external custom service provider carried out the operation.

The selected crops were then organised in rotations (Fig. 2c), designed considering the positive relationship between crop types (e.g. maize should preferentially follow leguminous crops to take advantage from N residual effect) and the potential long-term impact on weed dynamics (Fig. 2d: the alternation between autumn–winter and spring crops and between monocotyledonous and dicotyledonous crops contributes to the development of a diversified weed community compared to monocropping). To each crop, an area (Fig. 2e) and a set of agronomic operations (Fig. 2f: tillage, fertilisation, sowing, irrigation, PPPs application and har- vest) were assigned, together with the amount of production factors applied (Fig. 2g). The amount of N fertilisers to maximise N use efficiency was calculated for FERT and ROT by compiling a nutrient management plan (NMP) which is a mass balance based on target yield, soil N mineralisation, estimated recovery of applied N and manure N content. When preparing the NMP we acted accord- ing to the following rules: (i) the manure produced on-farm was completely used on farm fields; (ii) the manure was redistributed amongst crops N uptake; (iii) the manure was preferably applied in spring and not in autumn if the soil type allowed it; and (iv) the use of chemical N fertilisers was reduced compared to ACT. In the few cases where crops were poorly fertilised in ACT, an integration with mineral N was defined through the NMP.

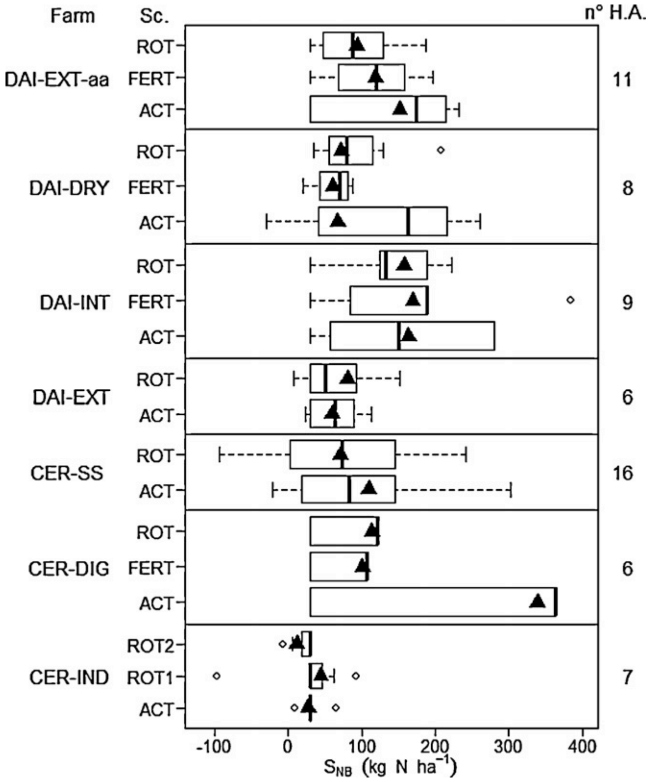

Fig. 4. Box plots of soil surface balance (*S*NB) calculated for each homogenous area (HA) in seven farms of Lombardia, subdivided by management scenario (Sc. = ACT, FERT and ROT). The boxes indicate the 1st and 3rd quartiles of the distribution, the bold line is the median, the bars are the maximum and minimum, the points represent the outliers and the filled triangles represent the weighted average (based on crop area) at farm scale.

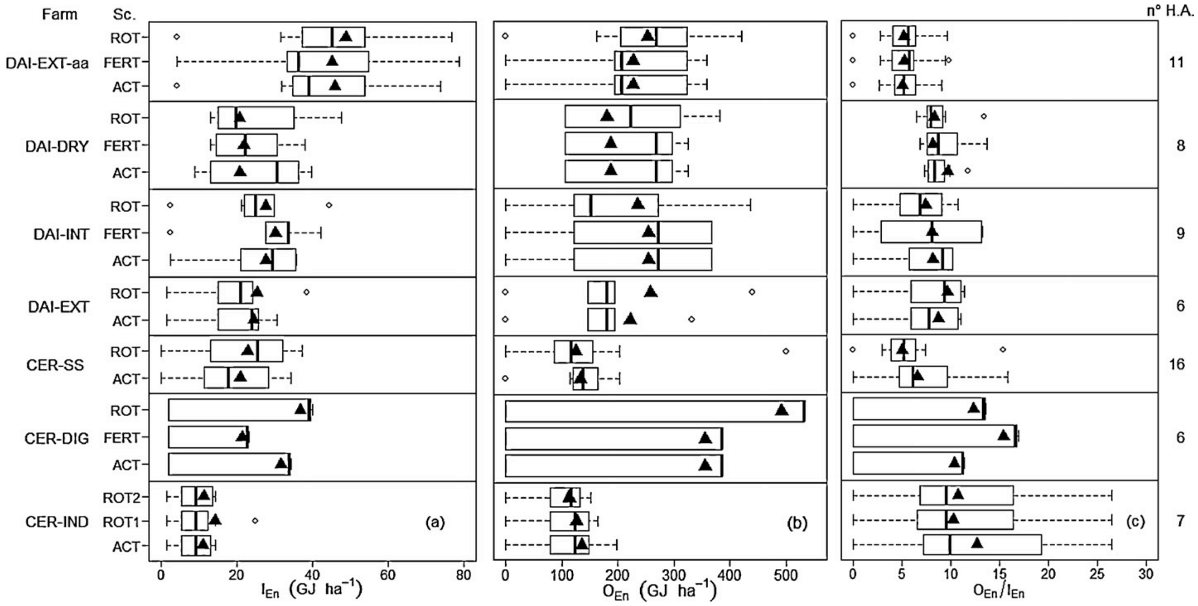

Fig. 5. Box plots of energy indicators calculated for each homogenous area (HA) in seven farms of Lombardia, subdivided by management scenario (Sc. = ACT, FERT and ROT):
(a) energy inputs (*I*En); (b) energy outputs (*O*En); (c) energy efficiency (*O*En/*I*En).

Crop yields according to the new fertilisation scheme were predicted (Fig. 2h) by using the cropping system simulation model CropSyst (Stöckle et al., 2003), already tested in northern Italy (Donatelli et al., 1997; Confalonieri and Bechini, 2004; Bechini et al., 2006, 2008). CropSyst was run for a period of 18 years using a set of daily meteorological data (1990–2007) of the weather station closest to each farm. If the yield predicted by the model for FERT was lower than in ACT, the amount of N previously defined with the NMP was adjusted until the yield in FERT was the same as in ACT (Fig. 2i). In ROT the simulated yields were used to calculate the feed produced on-farm. This feed, together with concentrates and forage purchased, had to satisfy the animal ration. According to the new

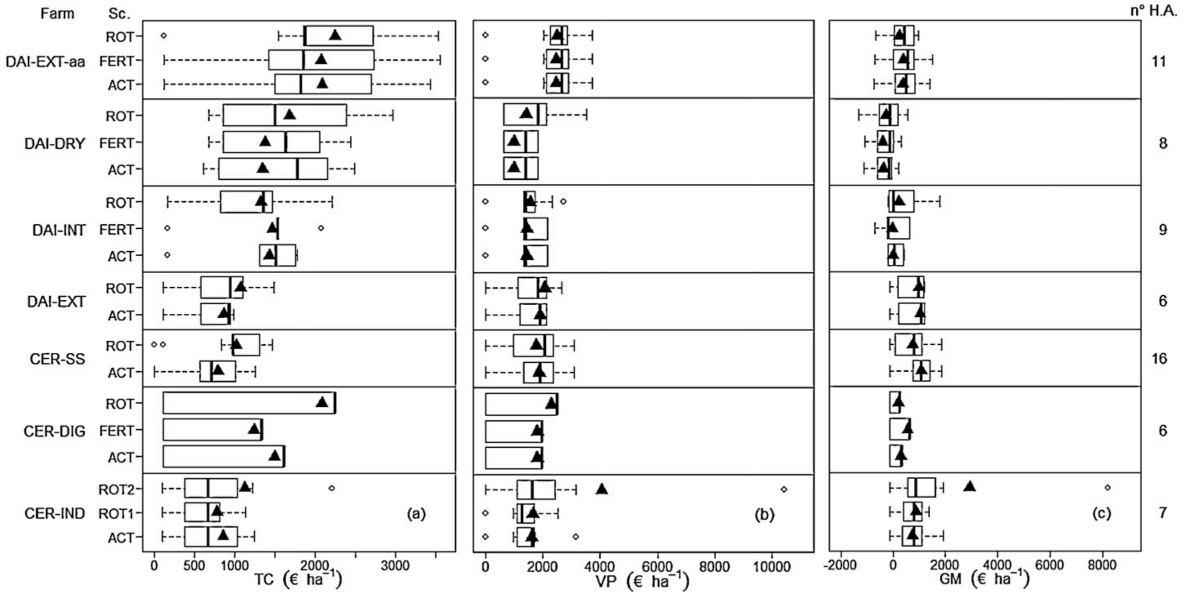

Fig. 6. Box plots of economic indicators calculated for each homogenous area (HA) in seven farms of Lombardia, and subdivided by management scenario (Sc. = ACT, FERT and ROT): (a) total costs (TC); (b) value of production (VP); (c) gross margin (GM).

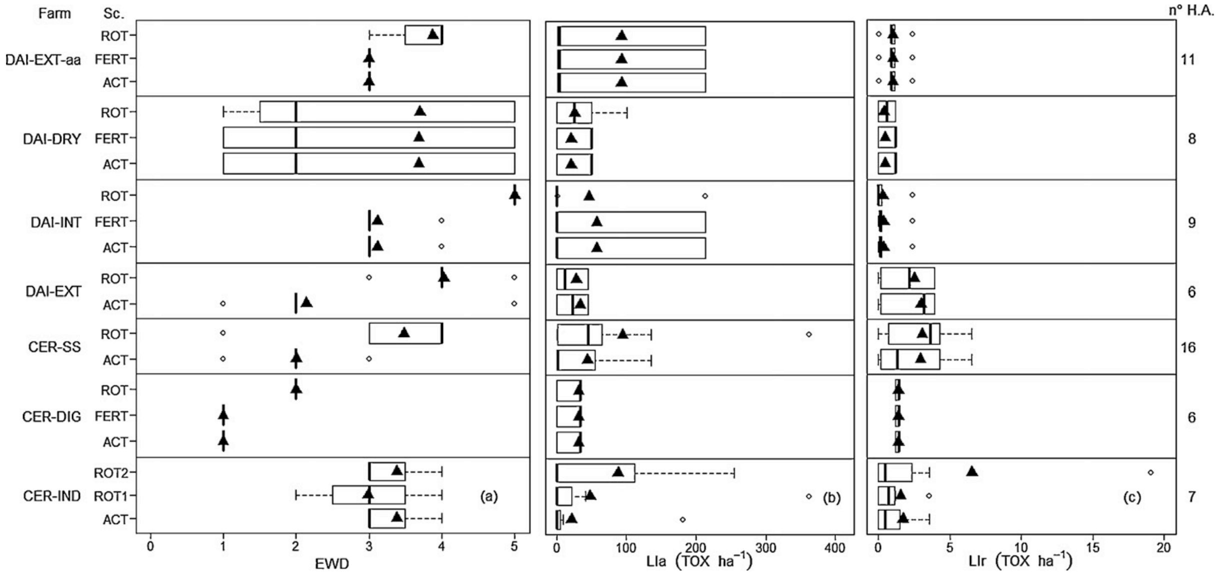

Fig. 7. Box plots of expected weed community dynamic indicator (EWD, 1 = worst case; 5 = best case) (a) and of potential eco-toxicological impact indicators: (b) Load Index algae (LIa); (c) Load Index rats (LIr), calculated for each homogenous area (HA) in seven farms of Lombardia and subdivided by management scenario (Sc. = ACT, FERT and ROT).

availability of feed, the ration of heifers, dry cows and lactating cows was revised by an expert (Fig. 2j) using Sistema Plurimix software (Anonymous, 2009) with the aim to maintain dry matter, crude pro- tein, fat, non-structural carbohydrate and neutral detergent fibre equal to ACT.

The consistency of the tractor–implement combinations adopted for each agronomic operation was verified mainly accord- ing to the power requirements of the implements, which depend on the type of machine, on the operating prescriptions, and on the environmental context (Fig. 2k), using a mechanisation model (Lazzari and Mazzetto, 1996; Fumagalli et al., 2011). If these requirements were not satisfied, we selected the most suitable trac- tor amongst those previously declared available at the farm. If none of them was adequate, we assumed that an external custom service provider carried out the operation. The same model was used to simulate the temporal distribution during the year of the agronomic operations, with a time step of 10 days. For each 10-day period the cumulative time assigned to operations was compared with the potential availability of working hours. These were estimated based on the workability of each period (which in turn depends on day length, climatic conditions and soil characteristics) and the contractual duration of the daily work. This comparison made it possible to verify if potential peaks of activities could affect labour organisation. Peaks were managed through work overtime or using additional external temporary labour (Fig. 2k). The mechanisa- tion model finally simulated the work of each tractor–implement combination on each HA for each scenario, thus providing the final expected performances (field efficiency indices and hours of work, fuel and oil consumptions, and materials consumed or produced).

The indicators of Table 2 were calculated for each farm and each scenario using the sources of information listed in Table 3, and, for each HA, the information resulting from a typical year of activities (excepting the EWD score, which was referred to the crop sequence). The calculations were carried out at the level of HA and are presented as the weighted average (based on crop area) for the whole farm.

3. Results

3.1. *Definition of scenarios*

The actual and alternative scenarios are described in Table 4. The FERT scenario was proposed for four farms (DAI-INT, DAI-EXT-

, DAI-DRY and CER-DIG). The reduction of mineral-N application on maize was considered in all these farms, whilst the redistribu- tion of manure-N amongst the crops was preferred in farms with alfalfa meadows. N applied with chemical fertilisers was increased in DAI-INT on silage barley (*Hordeum vulgare* L.) and in DAI-DRY on permanent meadows. The ROT scenario was proposed for all farms. In all dairy farms and in one cereal farm (CER-DIG) the main changes were the increase of area devoted to alfalfa and the introduction of the double cropping system represented by an autumn–winter crop [Italian ryegrass, silage wheat or triticale for silage (*x Triticosecale* Wittmack)] followed by maize. Bio-energy crops [winter oilseed rape (*Brassica napus* L.) and sunflower (*Helianthus annuus* L.)] and industrial crops as onion (*Allium cepa* L.) were introduced only in cereal farms (CER-SS and CER-IND) to replace grain or industrial crops that in ACT were sold outside the farm. In CER-IND farm, two alternative ROT scenarios (ROT1 and ROT2) were evaluated.

3.2. *Sustainability of FERT vs. ACT*

In FERT, *S*NB was generally lower than in ACT (Fig. 4) with the exception of DAI-INT. The greatest reduction of *S*NB in FERT with respect to ACT was obtained in CER-DIG and in DAI-EXT- , where an excessive amount of inorganic N fertiliser was applied on maize. In DAI-EXT- the redistribution of manure amongst crops increased the apparent N recovery of organic fertilisers applied on farm. The small reduction of *S*NB in DAI-DRY was due to the increase of mineral N on grass (poorly fertilised in ACT and culti- vated on 60% of the total farm area). In DAI-INT, *S*NB was slightly increased: the low apparent N recovery of organic fertilisers applied on silage barley (poorly fertilised in ACT) has forced the integration with chemical fertilisers to guarantee an adequate amount of N forgrowing; this has nullified the effect of reducing inorganic N fertil- isation on maize. The improvement of N management contributed to reduce *I*En, but only in CER-DIG and in DAI-EXT- (Fig. 5a). In DAI-EXT- the reduction of *I*En was relatively small because part of *I*En is due to energy consumed for alfalfa drying, which could not be decreased. In DAI-DRY and DAI-INT the energy consumed for N application on grass and on silage barley, respectively, has nullified the reduction of *I*En obtained in maize. Given that the *O*En (Fig. 5b) remained unchanged due to equal crop yields, the energy efficiency (*O*En/*I*En) improved only in CER-DIG and in DAI-EXT- (Fig. 5c). Similar findings occurred for the economic indicators. In CER-DIG and DAI-EXT- the reduction of TC (Fig. 6a) determined an increase of GM of 15 and 258 D ha−1 (Fig. 6c), respectively. A small increase of TC, associated with negative effects on GM, was observed in DAI-DRY and DAI-INT. In all farms LI and EWD (Fig. 7) did not differ because the use of PPPs and the crop rotation did not change.

3.3. *Sustainability of ROT vs. FERT*

The changes introduced with ROT had contrasting effects on farm-average *S*NB (Fig. 4) compared to FERT. In DAI-DRY and CER- DIG, *S*NB slightly increased due to the low apparent N recovery of organic fertilisers applied on autumn–winter crops, that required an additional application of mineral N. *S*NB decreased in DAI- INT and DAI-EXT- . Alfalfa meadow in DAI-INT contributed to improve the use of manure-N, whilst in DAI-EXT- the maize crop, cultivated in a double cropping system with Italian ryegrass, received organic fertilisers in spring (applied in autumn both in ACT and FERT), thus increasing the apparent N recovery.

In farms where the sole change was the introduction of the double cropping system (CER-DIG and DAI-EXT-), the additional crop management operations increased *I*En (Fig. 5a). However, the increase of total crop production and consequently of *O*En (Fig. 5b), was insufficient to improve energy efficiency (*O*En/*I*En) (Fig. 5c). On the opposite, *I*En decreased in farms (DAI-DRY and DAI-INT) where, in addition to the double cropping system, we also introduced crops such as grain barley or alfalfa, characterised by lower energy requirements.

In general, the labour requirements of the double cropping systems have increased TC (Fig. 6a), except for DAI-INT, where the high costs of the double cropping system were compensated by the lower costs of alfalfa cultivation. The double cropping systems and alfalfa increased VP (Fig. 6b), but only in DAI-INT and DAI-DRY this contributed to enhance GM (Fig. 6c). They also contributed to increase EWD. Because they did not require additional use of PPPs, variations of LI were not substantial (Fig. 7).

3.4. *Sustainability of ROT vs. ACT (for farms without a FERT scenario)*

In CER-SS and CER-IND (ROT1), where bio-energy crops were introduced, contrasting effects on farm-average *S*NB were observed (Fig. 4). In CER-SS, where oilseed rape and sunflower replaced winter wheat, *S*NB decreased. In CER-IND (ROT1) grain maize was also introduced; its higher N requirements increased *S*NB. In CER-IND (ROT2) onion replaced sugar beet and *S*NB decreased. In DAI-EXT, the introduction of alfalfa and the double cropping system with maize silage and winter forage crops (low apparent N recovery) determined higher *S*NB in ROT vs. ACT.

With the exception of CER-IND (ROT2), *I*En was higher (Fig. 5a).

Total DM production and *O*En (Fig. 5b) decreased in CER-IND and CER-SS, whilst they increased in DAI-EXT, due to high biomass production of alfalfa and double cropping system.

TC in CER-SS and DAI-EXT increased (Fig. 6a). In CER-IND(ROT1) the cost of the external custom service for harvesting bio-energy crops was half compared to sugar beet and pea cultivated in ACT, whilst this cost for onion CER-IND(ROT2) was the double (Fig. 6a). GM (Fig. 6c) increased only in CER-IND(ROT2) due to high VP of onion.

The more complex rotations in CER-SS and DAI-EXT received a higher EWD score (Fig. 7a) compared with the previous maize–wheat system in ACT. In CER-IND there were no important variations of EWD in ROT1 and ROT2 vs. ACT.

In DAI-EXT, alfalfa did not require the use of PPPs and con- sequently the potential eco-toxicological impacts was slightly decreased (Fig. 7b and c). Maize and oil crops in CER-SS and onion in CER-IND (ROT2) required more PPPs and therefore LI increased (Fig. 7b and c).

4. Discussion

4.1. *Evaluation of the methodology*

Our work stems from a growing field of research focused on ST approaches, that combine indicators, models and expert knowl- edge to propose and eventually implement in practice alternative cropping and farming systems. Our methodology to develop the ROT scenario uses the same tools employed in other ST exam- ples. We used expert knowledge to establish decision rules and constraints, and to resolve conflicting objectives; we used models to predict some features of the system under the new conditions occurring after the identification of the improved management; and we used indicators to describe the state of the system. Com- pared to other approaches at the farm scale, we combined these tools in a rather original way, thus giving several interesting properties to the method.

First of all, our procedure allows the definition and the eval- uation of improved management scenarios for the farm, whilst the works cited above for the farm scale assume that the scenar- ios are provided by the user. This difference is important because the definition of the scenario is complex and needs to take into consideration the relationships internal to the farm, and a clear methodological support is needed.

Moreover, our step-by-step procedure contains several control points for the definition of the ROT scenario (Fig. 2), and therefore we did not need an iterative procedure.

Another important characteristic is that our procedure does not rely only on simulation models. This choice was made to avoid the complications generated by the risk of lack of model robustness, time needed to complete and validate the simulations, number of inputs required and domains where models are not yet sufficiently developed (e.g. weeds). The methodology proposed in this paper allowed us to define and evaluate three scenarios for seven farms, by dealing with a total of 63 HAs (187 fields), thus demonstrating the applicability at a relatively large number of cases. Should we have relied only on models, this result could have been difficult to achieve.

And finally, the relatively simple evaluation of scenarios made it possible to deal with a number of issues which is rarely addressed simultaneously in most research: in none of the examples cited before the energy indicators and the fate of pesticides were con- sidered.

The choice of building a methodology that is not fully auto- mated, but requires instead a continuous interaction amongst team members, model outputs and indicators, has of course a drawback, which is the lack of codified and standardised operations. There- fore, the results are prone to human errors during the application of the methodology, and are not repeatable, whilst for example the results by Van Calker et al. (2004) should always be the same under a given set of relationships, constraints and objectives.

4.2. *Evaluation of alternative management scenarios*

The application here presented is based on real data describ- ing the ACT scenario. Unfortunately, we did not have the resources to implement in practice the alternative scenarios. The literature provides examples of practical implementation of improved farm- ing systems: Verloop et al. (2006) describe the reduction of farm N surplus that was achieved at the “De Marke” prototype farm in the Netherlands (Aarts et al., 2000), without increasing land or exporting manure. The implementation, however, is expensive and requires also resources other than money: interest of the persons involved, technical skills and instrumentations.

The lack of a practical test of our alternative scenarios does not hinder to evaluate if they are realistic. A wide amount of literature that compares conventional with alternative management options at the cropping system level is available. In this paragraph we will therefore use this body of information to evaluate the effectiveness of FERT and ROT.

4.3. *Nitrogen management*

At most of the farms we found consistent *S*NB. The results of FERT suggest that the application of NMPs at the current cropping systems in Lombardia can reduce N surplus in several cases. In an 11-year field experiment in highly productive maize-based sys- tems of northern Italy, Grignani et al. (2007) found that an increase of the N applied with slurry and chemical fertilisers from 215 to 385 kg N ha−1 did not significantly affect crop yields, but increased N surplus. Similar results were obtained by Zavattaro et al. (2012) in the same site. In a similar pedo-climatic environment, Perego et al. (2012) confirmed the important role of NMP in reducing nitrate leaching.

A change in rotation, however, as exemplified in the ROT sce- nario, did not substantially reduce the surplus at all farms and HAs, but only in some of them. The addition of autumn–winter crops was a solution proposed in maize-based systems because they are able to uptake the residual mineral N after maize and, as demonstrated in field experiments (Heggenstaller et al., 2008; Trindade et al., 2008), to reduce potential nitrate leaching. The dou- ble cropping system was considered in ROT for 10 HAs. Compared with single cropping of maize, it did not contribute to reduce N surplus, on average. However, when considering HAs with Ital- ian ryegrass, the N surplus was reduced (as confirmed also by Perego et al., 2012) due to its lower N requirements compared to other autumn–winter crops, such as winter wheat and triticale for silage.

Alfalfa cultivation was introduced or extended in livestock farms where excess manure application may lead to high N availability in the soil. The presence of alfalfa allowed increasing the area available for spreading, thus reducing N surplus on maize, due to the sub- stantial N uptake of alfalfa. Results from Spallacci et al. (1996) and from Ceotto and Spallacci (2006) indicate that increasing the dose of manure-N applied on alfalfa increases the crop N uptake with- out accumulation of nitrate in the soil. Moreover, N-fertilised alfalfa had significantly higher dry matter yields compared to unfertilised alfalfa, due to lower photosyntates consumption for symbiotic N- fixation (Ceotto and Spallacci, 2006).

4.4. *Fossil energy use*

As a direct consequence of adjusting the use of inorganic N fertilisers in the FERT scenario, *I*En decreased and *O*En/*I*En increased in several HAs but not in all of them: *I*En increased in HAs where a supplement of inorganic N fertilisers was considered appropriate. An increased *O*En/*I*En and a reduced *I*En were obtained experi- mentally by Nassi o Di Nasso et al. (2011) for a low input vs. a conventional six-year crop rotation that included sugar beet, durum wheat, sorghum, and sunflower, compared over 12 years in the field. Similar results were obtained for a 22-year experiment by Tomasoni et al. (2011) and by Angelini et al. (2005), when reducing the inputs to five fodder cropping systems and the N input to giant reed (*Arundo donax* L.), respectively. In our study the new rotations proposed in ROT left the *I*En unchanged or even increased it, due to the introduction of the double cropping system. In fact, it required on average an addition of 12 GJ ha−1 of *I*En, and caused a slight decrease of *O*En/*I*En. Tomasoni et al. (2011) and Ceccon et al. (2002) confirmed that the double cropping system requires more fossil energy when compared to more simplified (monocropping of maize and permanent meadows) or diversified (alternation between autumn–winter and spring crops and between mono- cotyledon and dicotyledonous crops and presence of meadows) rotations. However, in both studies, this system showed a higher *O*En/*I*En due to its characteristic high yield potential.

4.4.1. *Economic performance*

In ACT the cost of chemical fertilisers accounted, on average for all farms where a FERT scenario was proposed, for 33% of the cost of production factors, with a maximum of 44% in the farm CER-DIG where most of the area is devoted to maize (Fumagalli et al., 2011). Thus, the improved use of inorganic N fertilisers based on NMPs decreased TC and increased GM in several HAs, but not in all of them (as for *I*En). In the farms where the FERT scenario was devel- oped, GM increased on average by 52 D ha−1. Focusing on the 14 HAs cultivated with maize, GM increased on average by 183 D ha−1. A reduction of TC was also obtained experimentally by Pampana et al. (2002) for a low input compared to a conventional irrigated continuous maize. The intensification and diversification of crop- ping systems proposed in ROT contributed to increase the costs of production. Analysing the 10 HAs where the double cropping system was introduced, TC increased by 682 D ha−1 (on average), and GM decreased. The average and maximum reduction of GM corresponded to 346 D ha−1 and 537 D ha−1, respectively. Similar findings were also found by Zentner et al. (2002) and by De Haan (2001).

The ROT scenario can be discussed also with respect to the Common Agricultural Policy (CAP). In fact, the new proposals to reform the CAP give large emphasis in the first pillar to sustainable management practices: the implementation of diversified crop- ping systems proposed in ROT could become determinant in the future for farmers in order to receive the direct payments. Con- sidering instead the current CAP (2007–2013) it is reasonable to compare the economic results of the ROT scenario with the aids provided by the agro-environmental sub-measure 214A of the cur- rent Rural Development Program (RDP) as applied in the Lombardia Region. The sub-measure 214A implies that the voluntary partici- pation of the farmers to “Balanced fertilization and crop rotation” action gives rise to a payment of 169 D ha−1 that further increases to 251 D ha−1 with the additional implementation of the “Cover crops” action. These actions can be considered similar to the management options proposed in our ROT scenario and therefore the subsidy provided by the RDP as an economic return for the envi- ronmental services provided could offset by 50–72% the loss of GM due to the implementation of ROT.

The higher economic costs of ROT should not hide the potential advantages of this cultivation scenario. Indeed, from a soil sustain- ability perspective, the cropping systems proposed in ROT can have positive long-term effects on the content of soil organic carbon due to the addition of organic matter from crop residues. Grignani et al. (2007) showed that, in maize-based cultivation systems similar to those studied here, the highest SOC (12.7 g C/kg) was achieved with maize grain (a cultivation system where only the grain is removed from the field, whilst the residues are returned to the soil). On thecontrary, maize silage had lower SOC (11.4 g C/kg), due to removal from the field of the entire above ground biomass. The double cropping system (maize silage + autumn–winter crop) was inter- mediate (12.1 g C/kg), thus confirming the importance of returning crop residues to soil (in this case the below-ground residues of both crops).

Moreover, the diversification of crops proposed in ROT, con- firmed by the increase of the crop diversity indicator in six farms (Table 1), can contribute to improve the landscape structure and its quality. As discussed by BIOIS (2010), a crops mosaic more fragmented both in space and time compared to monoculture determines an abundant farmland biodiversity and could further favour the development of various green corridors with an elevated ecological functionality.

4.4.2. *Weed population dynamics and potential environmental impact of PPPs*

In the seven farms the weighted average EWD in ACT ranged from 1 (CER-DIG) to about 3.7 (DAI-DRY). There were no changes of this indicator in the FERT scenario, which was developed using the same crops and the same crop sequence used in ACT (Fig. 7a). Nevertheless, minor effects on weed dynamics could be expected in the mid and long-term in response to variations in N management, either as a direct effect on weed growth, or indirectly, promoting or depressing crop competition and weed soil seed bank depletion (De Cauwer et al., 2011).

The EWD score was generally higher in ROT. A more diversified crop sequence may increase the variability of selection pressure towards weeds, thus favouring the development of more balanced weed communities, which usually require less efforts to be success- fully managed (Blackshaw et al., 2001; Derksen et al., 2002). This effect, however, cannot be easily quantified and therefore in ROT we considered the adoption of conventional weed management, which mainly relies upon the use of herbicides. As a consequence, LI in ROT was very similar to ACT (Fig. 7b and c).

5. Conclusions

The core of our approach is the step-by-step procedure (based on decision rules) and the integration of models and experts aimed at designing the alternative cropping systems. Our integrated method has proven to be adequate to deal with complex and different farming and cropping systems, which require a multidisciplinary approach and where a relatively complete and detailed dataset is available.

Our results suggest that improved N use can be reached adopting adequate N management plans, and that this may in turn increase the energy and the economic performance. Some of the changes in crop rotations (in particular the introduction of double crop- ping systems to increase soil cover) have increased energy inputs and economic costs. However, diversified crop rotations can have positive effects on weed management.

Finally, we want to highlight the relevant consistency of our integrated ST-indicators approach with the possibility of applying a multi-criteria decision method to find a suitable solution. This aspect will be surely taken into account in future analyses. In addi- tion, the cropping systems that with this approach have shown to be most interesting should be tested in real farms.

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