Trade-off analysis for agro-ecological indicators: application of Sustainable Solution Space to maize cropping systems in northern Italy

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Abstract: *The sustainability of cropping systems is usually evaluated by considering each aspect separately, without considering the trade-offs within or among aspects. We applied Sustainability Solution Space approach (SSP) to analyse the trade-offs among ecological and economic indicators for 125 maize "crops" (crop × field × year combinations) in seven farms monitored during 2005-2006 in northern Italy. Nine indicators were selected to describe the economic and energetic management characteristics, the nutrient surpluses, and pesticides potential impacts. In a first step, an initial sustainability range was defined for each indicator. This led to a Sustainability Space, a nine-dimensions hyper-volume, including all possible combination of indicators. In a second step, the correlation between the indicators was determined. The strongest correlations were used in the SSP algorithm to shrink the hyper-volume, defining the SSP that includes all the realistic sustainable combinations of crop management. Our results showed that only seven crops were very close to SSP, while 23 had all indicators within the initial sustainable hyper-volume, but not in the final SSP. The crucial aspects when calculating the SSP are: i) the definition of the initial sustainability ranges and ii) the number of interactions considered. Therefore, a sensitivity analysis was carried out in order to analyse the robustness of the SSP approach. The weak correlations had a low effect in the SSP; hence at least the application of strongest correlation is enough. In addition, the application of different initial sustainable ranges produced different SSPs, but the differences obtained for each indicator were not large.*

Keywords: *Agro-ecological indicators; crop management; cropping systems; sensitivity analysis; sustainability assessment; trade-off.*

Introduction

Pursuing sustainability for agricultural systems is considered essential for fostering better life and working conditions throughout the world. In the last decade, the demand for an integrated evaluation of agricultural systems has increased and several evaluation tools have been developed (Rosnoblet et al., 2006; Binder et al., 2010). To deal with agriculture, decision makers need tools able to summarize the characteristics of real agricultural systems into simple quantities. Environmental impacts of agricultural systems can be analyzed using different methods: i) direct measurements, ii) simulation models, and iii) simple or composite indicators, each having different levels of applicability and different potential explanations of the system (Bockstaller and Girardin, 2003). The use of indicators is suggested for a preliminary evaluation of sustainability, because they are based on data already available or easy to collect, while direct measurements and simulation models are more expensive and time consuming.

The indicator frameworks usually applied to describe the sustainability of agricultural systems (e.g. Vereijken, 1995; Meul et al., 2008; Bechini and Castoldi, 2009) do not normally consider interactions and trade-offs among different indicators. In the examples cited and in many other cases, every indicator is considered individually, while a system assessment requires an integration of information into a unique analysis. Interactions among crop management practices themselves also can influence their impacts. When evaluating agricultural assessment methods, Binder et al. (2010) found that these methods tended to neglect trade-offs and interactions among indicators. To overcome these shortcomings, they suggested applying tools that have a systemic perspective. One approach with these characteristics is the Sustainable Solution Space, SSP (Wiek and Binder, 2005), a systemic and multidisciplinary approach for assessing the sustainability of a wide range of systems. The method uses sustainability ranges rather than thresholds and considers the interactions among the indicators. The SSP has been applied to analyze the sustainability of cities (Speerli, 2004) and of the milk value added chain (Binder et al., 2008; Binder et al., 2009). So far, it has not been applied to analyze cropping systems. The objective of this work was to test the SSP approach in order to define the sustainable space, for a case study related to maize cultivation in northern Italy, described by nine economic and agro-ecological indicators.

Materials and methods

Table 1 depicts how each step of the SSP was performed for the case of arable cropping systems in northern Italy.

Table 1. Steps of the application of SSP adapted to sustainability assessment.

Step	Description	Data source or Method
Step 1	Characterization of the region to be assessed	Bechini and Castoldi, 2009
Step 2	Problem oriented derivation of indicators (e.g., ecological, economic and social)	Bechini and Castoldi, 2009
Step 3	Analysis of the relationships among the indicators	Regression model
Step 4	Specification of the sustainability ranges for the indicators	Ranges (see Table 4)
Step 5	Definition of the solution space for decision-making	SusSpaceWrapper program
Step 6	Analysis of the trade-offs	

Step 1 – Characterization of the region

The Sud Milano Agricultural Park (PASM; 45°N, 9°E; 47,000 ha, of which 35,000 are agricultural) is a regional metropolitan agricultural Park embracing the city of Milan (northern Italy). The Park is located in a plain area (altitude from 80–160 asl) with prevalence of loam, sandy-loam, silt-loam soils. The climate is sub-humid; the average annual rainfall is about 950 mm. Temperatures increase from January (average minimum: –1.2°C and maximum: 4.9°C) to July (average minimum: 17.7°C, and maximum: 29.2°C). The agricultural systems are intensive with moderate to high yields. The most important crops are maize (*Zea mays* L.), rice (*Oryza sativa* L.), permanent meadows, barley (*Hordeum* spp.), and winter wheat (*Triticum aestivum* L.). The high intensive swine and dairy farms, strongly influence the cropping systems: in order to produce the foodstuff, grain and silage maize are largely cultivated in continuous crop, with high nutrient and herbicide inputs. The large amount of manure produced by animals is spread at high rates per unit area on maize and meadows, producing high nutrient surpluses (Bechini and Castoldi, 2006; Castoldi et al., 2009a).

Step 2 – Derivation of indicators

In order to describe the most important agro-environmental issues of the PASM, a set of 15 indicators was selected from literature (Castoldi and Bechini, 2006; Castoldi et al., 2007), The indicators were grouped in four classes, describing the management of:

i) economic resources: variable costs (VC), gross income, and gross margin (GM);
ii) nutrients: N (NS) and P (PS) soil surface balances (Parris, 1998);
iii) energy: energy inputs (EnIN) for gasoline, lubricants, pesticides, fertilisers, seeds, and machinery; energy output (EnOUT), and the dependency of food and feed production on non-renewable energy (EnOI = EnOUT/EnIN);
iv) pesticides: Load Index (OECD, 2005), calculated for several non target organisms, i.e. algae (LIa), crustaceans, fish, and rats (LIr); Environmental Exposure to Pesticides (Vereijken, 1995) for three different environmental compartments, i.e. air, soil (EEPs), and groundwater; the LIa and LIr were defined as the sum of the ratios between dose and acute toxicity (for algae and

rat, respectively) calculated for each active ingredients (a.i.) applied, while EEPs was defined as the sum of the products between dose and half life of the chemical in soil for each a.i. applied.

Table 2. Indicators calculated for the 131 fields monitored in the period 2004-2006 and selected for the definition of SSP for arable cropping systems in northern Italy.

Indicator	Indicator acronym	Unit
Economic indicators		
Variable costs	VC	(€ ha^{-1})
Gross margin	GM	(€ ha^{-1})
Nutrient management indicators		
Nitrogen soil surface balance	NS	(kg N ha^{-1})
Phosphorus soil surface balance	PS	(kg P_2O_5 ha^{-1})
Energy management indicators		
Fossil energy input	EnIN	(GJ ha^{-1})
Dependency of food and feed production on non-renewable energy (EnOUT/EnIN)	EnOI	(GJ GJ^{-1})
Pesticide indicators		
Load Index algae	LIa	(10^6 L water ha^{-1})
Load Index rats	LIr	(10^6 kg rat ha^{-1})
Environmental Exposure to Pesticides (soil)	EEPs	(kg a.i. day ha^{-1})

The use of 15 indicators for the SSP calculation would have made this approach onerous, because numerous relations among indicators (i.e. 105) would have been calculated and analysed. In order to facilitate the application of the SSP approach, a sub set of 9 indicators (Table 2) was used. The nine indicators selected were able to describe the main issues of the Park: the two economic indicators (VC and GM) provided information about the cost and profit of cropping systems; the two nutrient indicators (NS and PS) described the management of the two nutrient (N and P) that have had the most important environmental impact; the two energy indicators provided information about the fossil energy consumed (EnIN) and the energetic performance of the system (EnOI). Load Index analyzed the potential impact of the toxicity of a.i. against two levels of the trophic chain (LIa for the lower level of primary producers, and LIr for the higher level of mammals). Moreover, EEPs evaluated the potential exposure in one of the most important and sensible agricultural compartments, the soil.

We relied on a data set of crop management on seven farms in the PASM (Bechini and Castoldi, 2009). These were two dairy farms with different livestock density (DAI-INT and DAI-EXT), two swine farms with different livestock density (SWI-INT and SWI-EXT), two rice farms (one with poultry livestock [RIC-POU] and the other without livestock [RIC-CER]), and a mixed farm (MIX). These farms were visited periodically from October 2004 to October 2006. The data on crop management were collected by face-to-face interviews. The nine indicators selected (Table 2) were calculated for 266 "crops" (i.e. for 266 crop × field × year combinations), of which 125 were maize. All the procedures used for the calculation of the indicators and the complete results were already reported by Bechini and Castoldi (2009).

Step 3 – Analysis of the relationships among the indicators

Linear regressions among indicators were calculated to determine the relationship among different aspects of the cropping system. The squared original sustainability space described by these two indicators was defined by the two sustainability ranges (yellow area delimited by I_{1min}, I_{1max}, and I_{2min}, I_{2max}; Fig. 1). The functional relations (i.e. correlation between indicators) then might reduce this original sustainability space as shown in Fig. 1. This means that e.g. if yields would increase beyond a certain level, the environmental impact would be higher than the defined sustainable value. Alternatively, very low environmental contamination might lead to yields well below what farmers might consider sustainable. That was, the area in which the system of these two indicators can develop sustainably was the green area depicted with oblique dash in Fig. 1. In the case studied, each regression was estimated in a bi-directional way; i.e. Indicator 1 was regressed against Indicator 2, and *vice-versa*. The goodness of fit (R^2 of the regression) was used to decide the inclusion (or the exclusion) of each regression in SSP calculations. To test the sensitivity to various R^2 thresholds, the calculations were performed by selecting a set of interactions, including equations with R^2 either higher than 0.35, or 0.25, or 0.15.

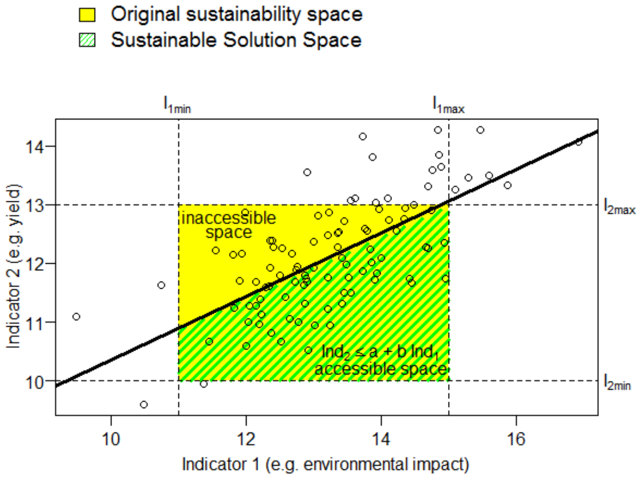

Figure 1. Trade-off between pairs of indicators, e.g. yield and environmental impact. Vertical and horizontal dashed lines: original sustainability ranges for indicator 1 (I_{1min} and I_{1max}) and 2 (I_{2min} and I_{2max}), respectively; solid oblique line: regression line.

Step 4 – Definition of the original sustainability ranges of the indicators

Original sustainability ranges were defined separately for each indicator. These ranges were reduced by the application of the SSP algorithm (step 5) using the relationships among indicators (step 3). The sustainability ranges of indicators were either calculated using the statistical distribution of indicator values obtained from a sufficiently high number of cases (Castoldi and Bechini, 2010). The application of values based on indicator distribution produced unusual original sustainability ranges, but on the other hand let it possible to define ranges not influenced by the subjective choice based on expert knowledge.

In this study, two sets of original sustainability ranges were defined: the first set, named "MR" (more restrictive) was defined by the 1^{st} and 3^{rd} quartile of the statistical distributions of indicators, while for the second set "LR" (less restrictive) the 10^{th} and 90^{th} percentiles were used. Three situations occurred in the definition of the ranges: i) for indicators having a lower and upper limit (NS, PS), both thresholds were used; ii) for indicators with a lower limit only (GM, EnOI) the 1^{st} quartile or the 10^{th} percentile were applied and no upper limit was set; iii) for indicators with a upper limit only (VC, EnIN, LIa, LIr, and EEPs) only the 3^{rd} quartile or the 90^{th} percentile were applied and the lower limit was set equal to zero (no economic and energy inputs, and no pesticide applications). The calculation of the sustainable space based on the original sustainability ranges of each indicator without considering their interactions led to an N-dimensional hyper-space (N was the number of indicators) which was obtained with traditional assessment methods that do not consider the trade-off among indicators.

Step 5 – Calculation of the SSP

The SSP was calculated with the computer program SusSpaceWrapper (Steinberger and Binder, 2008), a geometric computer program based in the Matlab language. It uses the N-dimensional space of indicators, ranges and relations between indicators, and finds the SSP corresponding to the intersection of the ranges and relations. The software requires as first input values the indicators, along with their sustainability ranges (see step 4). We estimated the SSP with six different procedures (Table 3). These procedures were adopted to analyse how sensitive the SSP was to potential changes in each of the mentioned parameters (ranges: MR, LR; number of relations considered).

The SSP model used the original sustainability ranges (set in step 4) to define the N-dimensional hyper-space that describes the original sustainability space. Consequently it used the relationships among the indicators (step 3) to reduce this original sustainability space, providing the final SSPs, where a sustainable situation was technically obtainable: the SSP model excluded all the N-dimensional situations that cannot be reached because the value of one indicator excluded values of other indicators.

Table 3. Procedures followed for the calculation of SSP for arable cropping systems.

Proc.	Use of regressions with R^2 >	Number of regressions used	Original sustainability range
A	0.35	8	MR
B	0.35	8	LR
C	0.25	18	MR
D[1]	0.25	16	MR
E	0.15	26	MR
F[2]	0.15	18	MR

MR: more restrictive original sustainability range; LR: less restrictive original sustainability range.
[1] As C, but without considering the relation between NS *vs*. EnOI; [2] As E, but without considering the indicator EnOI

Original sustainability space, namely the N-dimensional hyper-space was determined and relations among indicators calculated. The SSP is then found in two steps. The first step determined the intersections (points in N-space) between the new functional boundaries (i.e. regression line) and the sustainability ranges. This is done by solving the equations for planar intersections described by the functional relations between indicators. The second step consisted in identifying which of these points lied at the vertices (corners) of the sustainability space: by finding the points which were consistent with all the sustainability ranges and functional boundaries, and excluding those which were outside. The final SSP is defined by these vertices (Binder et al., 2009).

Step 6 – Analysis of trade-offs

The possible resulting SSPs are the following: i) empty; ii) a unique point; iii) a line; iv) a 2-dimensional area; vi) a 3 to N-dimensional volume defined by its corner point coordinates. Given the functional relationships among the indicators, trade-offs can be analyzed. This analysis is of particular interest if policy measures or strategies have to be evaluated: if one indicator is outside the SSP and measures are developed so that it will be inside the SSP, the main question is whether these changes will affect other indicators negatively and just shift the burden of “unsustainability” to another part of the system.

Results

Linear relations and original sustainability ranges

The linear relations among the nine indicators used in this study are usually poor (low R^2). The strongest relation is obtained between NS and PS (R^2 = 0.63). This is mostly due to the large use of animal manure that contains both nutrients: unlike mineral fertilizers, that can be separately used for different nutrients, the application of manure containing a high dose of N corresponds to a high dose of P as well. Moreover, NS and PS are related to nutrient inputs that in a good agronomic practice are dependent on the expected yield; therefore NS and PS are related to the same factor (crop yield). Nitrogen surplus is also correlated with EnIN (R^2 = 0.46) due to the high energy content of fertilizer-N. The VC is correlated to EnIN (R^2 = 0.39) because both indicators depend on the input flow of materials consumed during cultivation. Also GM and EnOI are well correlated (R^2 = 0.52), because both depend on the relation between outputs and inputs. Nineteen pairs of indicators have R^2 lower that 0.10, in particular VC *vs.* PS, GM *vs.* EnIN, LIa *vs.* LIr, and EnOI *vs.* EEPs (all pairs with R^2 = 0.00). The original sustainability ranges for each indicator are based on the 1st and 3rd quartiles (used to define MR) and the 10th and 90th percentiles (LR) of the statistical distribution of the indicators (Table 4). The original sustainability ranges are rather large, including indicator values that in some cases could represent unsustainable conditions.

Sustainable Solution Space

The original sustainability ranges defined by MR and LR, and the SSP obtained with procedures A and B, are shown in Fig. 2. The comparison of results obtained with procedures A and B (Table 5) shows that the application of larger original sustainability ranges (procedure B compared to A; Fig. 2) does not produce a substantial increase of SSP (Fig. 2 and Table 5). In procedure B, the ranges for VC, NS, PS, and EnIN are lower compared to procedure A; the ranges for GM and EnOI are the same in procedures A and B, while for the pesticide indicators the ranges are higher in B compared to A.

The increase of the number of relationships among indicators (procedure C) provides an empty SSP, because the conditions imposed are too many. When the relation NS *vs.* EnOI is not considered (procedure D), the SSP is similar to that obtained with procedure A, with smaller ranges for pesticides indicators (Table 5). Like in procedure C, also in procedure E the SSP is an empty space; when EnOI is excluded from analysis (procedure F), SSP is not empty anymore (Table 5); the differences between SSP obtained in procedures A and F are substantial only for the lower limit of GM, that decreases from 968 to 735 € ha^{-1}, providing larger SSP.

Table 4. Two sets of original sustainability ranges used for the calculation of SSP.

Indicator[1]		Original sustainability ranges			
		MR[2]		LR[3]	
		Lower	Upper	Lower	Upper
VC	(€ ha^{-1})	0	658	0	733
GM	(€ ha^{-1})	735	∞	550	∞
NS	(kg N ha^{-1})	79	226	45	316
PS	(kg P_2O_5 ha^{-1})	-28	168	-69	288
EnIN	(GJ ha^{-1})	0.0	30.1	0.0	34.4
EnOI	(GJ GJ^{-1})	11.1	∞	10.0	∞
LIa	(10^6 L water ha^{-1})	0.0	204.2	0.0	233.7
LIr	(10^6 kg rat ha^{-1})	0.0	1.8	0.0	2.1
EEPs	(kg a.i. day ha^{-1})	0.0	60.5	0.0	75.2

[1] For acronyms and units see Table 2.
[2] more restrictive ranges defined by the 1st and 3rd quartiles of the statistical distributions of indicators.
[3] less restrictive ranges defined by the 10th and 90th quartiles of the statistical distributions of indicators.

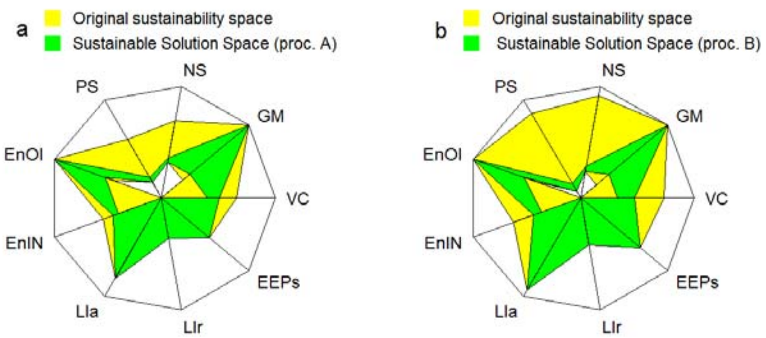

Figure 2. Original sustainability space and Sustainable Solution Space, calculated for 131 maize crops, with (a) procedure A and (b) procedure B. Each axis of the radar graphs represents an indicator; each axis has different scales: 0 - 1000 € ha^{-1} for VC, 0 - 3000 € ha^{-1} for GM, -50 - 350 kg N ha^{-1} for NS, -100-350 kg P_2O_5 ha^{-1} for PS, 0 - 25 GJ GJ^{-1} for EnOI, 0 - 55 GJ ha^{-1} for EnIN, 0 - 250 · 10^6 L water ha^{-1} for LIa, 0 – 5 · 10^6 kg rat ha^{-1} for LIr, 0 - 110 kg a.i. day ha^{-1} for EEPs. For acronyms see Tables 2 and 3.

Table 5. Sustainable Solution Space obtained with different procedures for the maize cultivation.

Indicat. [1]	Sustainable Solution Space: Proc. A[2]		Proc. B[2]		Proc. C		Proc. D[2]		Proc. E		Proc. F[2]	
	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper
VC	398.2	507.0	323.7	477.8			398.2	507.0			398.2	507.0
GM	968.3	∞	968.3	∞			968.3	∞			*734.7*	∞
NS	*79.1*	93.7	*45.0*	63.9	No solution		*79.1*	93.7	No solution		*79.1*	94
PS	*-27.6*	-5.1	*-69.0*	-34.7			*-27.6*	-1.4			*-27.6*	-1.4
EnIN	22.2	25.0	20.1	24.0			22.2	25.0	No solution		22.2	25.0
EnOI	13.2	*1211.5*	13.2	*1211.5*	No solution		13.2	*1211.5*	No solution		–	–
LIa	*0.0*	*204.2*	*0.0*	*233.7*			*0.0*	122.2			*0.0*	*204.2*
LIr	*0.0*	*1.8*	*0.0*	*2.1*			*0.0*	1.5			*0.0*	*1.8*
EEPs	*0.0*	*60.5*	*0.0*	*75.2*			14.3	53.2			*0.0*	*60.5*

The procedures are described in Table 3 and in the text.
[1] For acronyms and units see Table 2.
[2] In italics the ranges not modified by SSP: these are the same value of the original sust. ranges (see Table 4).

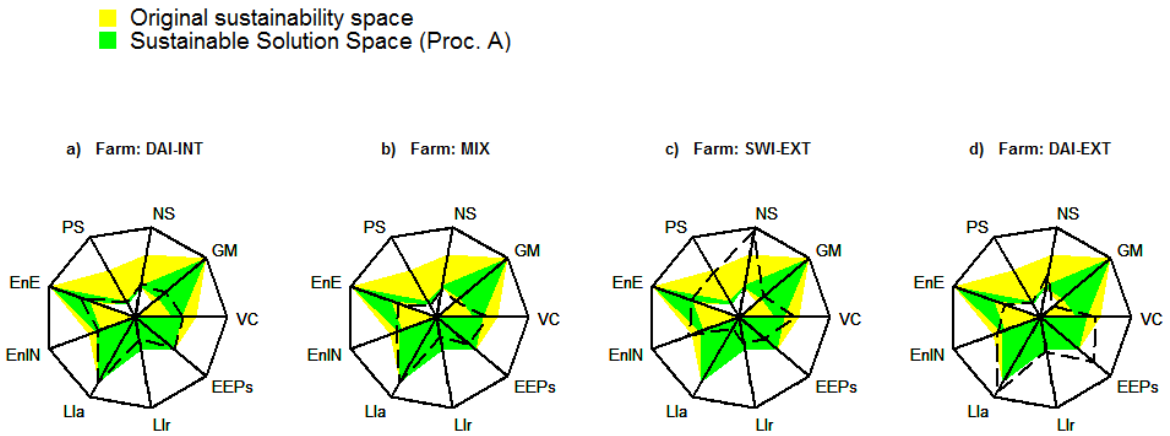

Figure 3. Examples of original sustainability space and indicator values obtained for six fields on different farms (dashed line) and relation with the original sustainability space and final SSP obtained with procedure A. Each axis of the radar graphs represents an indicator; each axis has a different scale: see Fig. 2. For their acronyms see Table 2. DAI-INT: dairy intensive farms; MIX: mixed farm; SWI-EXT: swine extensive farm; DAI-EXT: dairy extensive farm.

From an agronomical point of view, the SSP of procedure A provides an economically feasible solution (i.e. VC between 398 and 507 € ha^{-1} and GM higher than 968 € ha^{-1}). The NS is lower compared to the original sustainability range, but relevant surpluses (from 79 to 94 kg N ha^{-1}) are the compromise needed in order to reach a good sustainability for other indicators (i.e. PS and EnIN). Negative PS values are imposed by the algorithm to reach the sustainability for NS; this would be possible only until the soil would contain excessive concentration of extractable soil P. A considerable consumption of fossil energy (EnIN > 22.2 GJ ha^{-1}) is needed to reach the sustainability also for other indicators (i.e. NS and VC); the need to reduce input flows (by constraining PS, NS, and EnIN) provides a narrow window for EnIN (upper range of 25.0 GJ ha^{-1}). The ranges for potential impact related to pesticide use are not reduced by the application of SusSpaceWrapper in procedure A, and therefore these impacts, according to the methodology adopted, do not influence the other aspects of cropping systems monitored. No crop, among the 125 monitored, has all the indicator values within the SSP in procedure A; only seven crops are very close to this space (e.g. Fig. 3a); 23 crops have all indicators within the original sustainability space, but not in the SSP obtained in procedure A (e.g. Fig. 3b); 95 crops show at least one indicator out of the original sustainability space (e.g. Fig. 3c–d).

Discussion

Optimal agricultural management

According to SSP methodology, the best management was carried out by DAI-INT. In this farm, a conventional crop management was carried out. During 2006, seven silage maize crops obtained high yields (on average 20.3 Mg DM ha^{-1}), and this had a relevant effect on GM (on average 1231 € ha^{-1})

and EnOI (16.0 GJ GJ^{-1}). These high yields were possible because of the good meteorological conditions in 2006, the good quality of the soils, and a correct crop management. Two to three irrigations (depending on the crop considered) were necessary: this increased the fossil energy inputs necessary for the cultivation. The farmer made good use of the slurry produced by livestock (96 m^3 ha^{-1} corresponding to 211 kg N ha^{-1} and 87.6 kg P_2O_5 ha^{-1}), thus obtaining a relatively low VC (on average 527 € ha^{-1}) and EnIN (23.7 GJ ha^{-1}). Moreover, the mineral fertilizations were reduced compared to traditional practices for KCl (270 kg ha^{-1}), and suspended for P_2O_5 (the soil were rich in extractable soil P; Castoldi et al., 2009b), saving money and energy. The main energy inputs were represented by top-dress N-urea fertilization (227 kg ha^{-1}). The NS and PS were acceptable: on average 99 and -16 kg ha^{-1}. Other components of the costs and energy inputs were represented by seeds, ploughing, harrowing, and ensilage. Insecticides and fungicides were not used during the growing season, while two weeding treatments were carried out, after sowing, and during post-emergence; the pesticide indicators were high but fell inside the SSP (204.2, 1.2, and 60.1 for LIa, LIr, and EEPs, respectively).

Other farmers did not reach a good management, as testified by the values of one or more indicators. For example CER-RIC did not use animal manure, and the NS and PS were usually satisfactory, but the VC and EnIN were elevated due to the high price and energy content of fertilizers, in particular N-fertilizers. The lack of irrigation during the year 2006 in MIX reduced significantly maize yields and therefore GM and EnOI, and increased correspondingly the nutrient surpluses. In other cases unsustainable managements could be made more accurate: for example, the excessive application of manure in RIC-POU and SWI-EXT could be reduced, or at least less or no mineral fertilizers could be used after manure applications, thus improving the nutrient balances, VC, and EnIN.

Methodological aspects of the SSP approach

When indicators are used to assess ecosystems sustainability, it is necessary to reach a compromise between data requirement and the possibility to evaluate a large number of issues. Evaluating many issues requires a large data set that is not easy to obtain. When the relations among indicators are strong (i.e. $R^2 = 1$), the trade-offs among indicators are easy to find, and SusSpaceWrapper program will reduce the original sustainability ranges of each indicator according to these relations. In this situation two indicators that are highly correlated ($R^2 > 0.8$) describe the same aspect of the cropping system studied, and therefore the information provided by the two indicators is redundant. In the opposite situation (when R^2 is close to zero), there is no correlation among the two indicators, and SusSpaceWrapper cannot reduce the original sustainability ranges (e.g. for the pesticide indicators in procedure A). In this situation change in crop management can improve the sustainability of a specific issue (described by an indicator), independently from other issues; therefore there are no consequences on other issues described by other indicators. In real cropping systems, as those monitored in this study, the R^2 are variable in the range 0 - 1; in our case, some relations had low R^2, and the SSP approach might support the management towards a more sustainable situation, by considering the most relevant relations among indicators. Moreover, in the application of SSP, a large set of indicators can create problems in data management (too many relations would be considered) and in the interpretation of results. The most relevant problem is related to the possibility that SusSpaceWrapper might provide an empty space when a large number of original sustainability ranges and correlations are used. The definition of the original sustainability range for each indicator is an other crucial aspect when calculating the SSP, because it could modify the final SSP.

Sensitivity to changes in the number of interactions considered

A limitation of this study is that, compared to mechanistic simulation models, which provide a detailed description of the ecosystems studied, the simpler empirical approach used here, that is based on the distributions of indicators selected and their most significant correlations, provides a more limited explanatory power. The interactions among indicators used in this study were usually low, and the correlations with very low R^2 (lower than 0.15) were not considered for the calculation of SSP. For example, in procedures A and B (Table 3) the interactions with pesticide indicators were not considered because their R^2 were lower than 0.35; hence, the original sustainability ranges were not influenced by trade-offs with the indicators with which the R^2 was low. Therefore, the SSP obtained with SusSpaceWrapper was not reduced compared to original sustainability ranges (values in italics Table 5). On the other hand, when also the correlations with pesticide indicators were considered (procedures D and F), the original sustainability ranges (MR) were reduced only in procedure D (Table 5).

In order to test the sensitivity of SSP, the number of interactions considered for the calculation was increased (from 8 in procedure A to 18 in procedure C; Table 3). In this case an empty SSP was obtained which means that an SSP does not exist. For this reason, it would not be advisable to use the entire set of 15 indicators calculated by Bechini and Castoldi (2009). Moreover, in the six procedures a different number of regressions were used in order to test the sensitivity of the SSP to different original sustainability ranges, to various R^2 thresholds, in order to find an equilibrium among the number of relations considered and the result obtained, without producing an empty SSP. A change in the R^2 from 0.35 to 0.25 or 0.15 (i.e. the inclusion of more equations in the modelling procedure) resulted in no solution if both original sustainability ranges (MR and LR) were selected. This suggests a high sensitivity of the model to additional equations and relationships.

Sensitivity to changes in the original sustainability ranges

The percentage of change of the ranges from MR to LR is presented in the left part of the Table 6, while the effect on the corresponding results from the SSP in procedure A and B is shown in the right part. The sustainability ranges of the pesticide related indicators and the EnOI were not affected by a change in the thresholds of the other indicators. This implies that these indicators are quite independent from the others. The application of different original sustainability ranges produced different SSPs, but the differences obtained in the procedures A and B for each indicator were not large (Table 5). The VC and EnIN, however, and moreover NS and PS were the most sensitive indicators: their lower and upper values were highly influenced by the change of the original sustainability ranges of the other indicators and more so than by the changes of their own thresholds (when changing from MR to LR). This implies that these are four indicators for which trade-offs might become relevant. Our solution to obtain an objective definition of the original sustainability ranges was based on the percentages of the real statistical distributions. In spite of, the original sustainability ranges (Table 4) are questionable; these original ranges did not affect substantially the calculation of SSP, because in several cases the interactions among indicators reduced these ranges (Table 5).

Table 6. Sensitivity analysis for the changes of original sustainability ranges and corresponding Sustainable Solution Space (SSP) obtained in procedure A and procedure B[1].

	% change proc. A *vs.* proc. B			
Indicator[2]	Original ranges		SSP	
	lower value	upper value	lower value	upper value
VC	0.0	-10.2	-23.0	6.1
GM	-33.6	0.0	0.0	0.0
NS	73.8	-28.6	75.7	46.7
PS	-60.1	-41.7	-60.0	-85.3
EnIN	0.0	-12.6	10.4	4.0
EnOI	11.2	0.0	0.0	0.0
LIa	0.0	-12.6	0.0	-12.6
LIr	0.0	-14.3	0.0	-14.3
OCI	0.0	-19.6	0.0	-19.6

[1] definition of procedures in Table 3; [2] For acronyms and units see Table 2.

Conclusions

Sustainable Solution Space methodology was able to discriminate the performance of different cropping systems, evaluating whether their management was sustainable or not. Contrary to the traditional approaches that evaluate separately the different aspects of sustainability, SSP considers also their relations and trade-offs, excluding the ranges of indicator that are considered sustainable, but that are related to unsustainable values for other indicators. This approach was applied to 125 maize crop monitored in northern Italy during 2004–2006. According to the methodology proposed, a large number of cropping systems monitored were not sustainable. In many cases one or two indicators were out of the sustainability space; therefore, a completely sustainable management is not easy to reach, due to trade-offs among indicators. The results of sensitivity analysis suggest that: i) the definition of each original sustainability ranges is essential for the SSP and also affects the SSP results for the other indicators; ii) relations with R^2 greater than 0.35 are sufficient to select the most sensitive relations among indicators. That is, we suggest that the analysis should start from the most restrictive definition of sustainability, including, however only the most relevant interactions between indicators (i.e. procedure A), since these will drive the results of the analysis. If no solution is found, the relations which are restricting the SSP should be analyzed in depth and the trade-offs between indicators involved in these relations explored. In a later step the effect of loosening the sustainability criteria on the SSP should be analyzed. When finding a solution the sensitivity of the results to the changes in the original threshold values should be explored to identify the key indicators of the system, namely those mostly affected by changes or restrictions in the other ones. This knowledge will support the planning of intervention in taking these specific indicators.

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