ELSEVIER

Journal of Environmental Management 86 (2008) 419–426

Journal of Environmental Management

www.elsevier.com/locate/jenvman

Correlations and complementarities in data and methods through Principal Components Analysis (PCA) applied to the results of the SPIn-Eco Project

Simone Bastianoni[a,*], Federico M. Pulselli[a], Silvia Focardi[a], Elisa B.P. Tiezzi[b], Paola Gramatica[c,*]

[a]*Department of Chemical and Biosystems Sciences and Technologies—University of Siena, Via A. Moro, 2, 53100 Siena, Italy*
[b]*Department of Mathematical Sciences "Roberto Magari"—University of Siena, Italy Pian dei Mantellini 44, 53100 Siena, Italy*
[c]*Department of Structural and Functional Biology, QSAR and Environmental Chemistry Research Unit, University of Insubria, via Dunant 3, 21100 Varese, Italy*

Received 5 October 2005; received in revised form 2 February 2006; accepted 5 April 2006
Available online 13 November 2006

Abstract

This paper demonstrates how the results from different methods can be interpreted on the basis of a statistical approach that can help find new hints in the evaluation of sustainability at the territorial level. The SPIn-Eco Project for the Province of Siena (Italy) is an example of an environmental sustainability assessment of an area using methods that are suitable for a large system: Ecological Footprint, Greenhouse Gas Inventory, Extended Exergy Analysis, Emergy Evaluation, and Remote Sensing. The calculation of many indicators, derived from these methods, has prompted us to use a statistical method (Principal Components Analysis, PCA) to understand the degree of similarity/congruence of the indicators (here we have examined 26 of them) and the possibility of recognizing patterns or clusters in the description of the 36 municipalities that compose the Province of Siena. Among the results, unexpectedly, emergy flow and the Ecological Footprint resulted as being completely uncorrelated, apparently due to the importance that the non-renewable part of the emergy holds in the evaluation. The municipalities of the province are considerably spread out over the graphs, even though that of Siena is quite far from the rest along the first dimension. In addition, we were able to distinguish between more homogeneous districts (sets of municipalities), such as Val di Merse and Val d'Orcia, and very diverse ones, such as Val d'Elsa and Val di Chiana.
© 2006 Elsevier Ltd. All rights reserved.

Keywords: Integrated methods; PCA; SPIn-Eco project; Territorial system

1. Introduction

The SPIn-Eco Project is a multi-year research project (2001–2004) aiming to complete a sustainability assessment of the territory of the Province of Siena through the integration of different methods (see Pulselli et al., 2006a). The final outcome is composed of a huge data set that characterizes this very complex system, which must be organized into organic information. Since environmental sustainability is a multidimensional issue that involves the consistency of human behaviours with available natural resources and ecosystems' services, interactions and feedbacks incurring between human activity and the environmental dynamics must be monitored and represented from different points of view. These are the traditional environmental, social and economic aspects of sustainability, as well as the physical and political/institutional ones: the physical aspects are represented by the thermodynamic constraints that should limit human behaviour; the political/institutional ones are represented by the practical benefits in terms of normative compliance and environmental management for a public administration.

*Corresponding author. Tel.: +39 0577 234358; fax: +39 0577 232004.
E-mail addresses: bastianoni@unisi.it (S. Bastianoni), paola.gramatica@uninsubria.it (P. Gramatica).

0301-4797/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2006.04.018

In fact, several methods have been applied, each one providing different values and indicators for different territorial scales: the Province of Siena as a whole, the seven districts that compose it, and the 36 municipalities that compose each district and the province (Fig. 1 and Table 1).

Very often, only one method is utilized in the assessment of the level of sustainability of an area or of a production system. At times, the integration of two or three approaches has been presented (see for example Robèrt et al., 2002), but without the necessary amount of data in order to attempt an a posteriori comparison among them. Such an analysis is very important because it can highlight where the convergences are structural (i.e. built into the methods) or meaningful for the management of a system. Another product (if the data set is large enough) is a hint of how to optimize the choice of instruments (methods or indicators) to be used for the assessment, avoiding redundancies and eventually the waste of money for the projects: if two indicators for a population resulted as being structurally correlated, there would be no point in using both indicators; if we found that they are only linked in homogeneous areas, those indicators would explain and highlight the differences among non-homogeneous zones. The data set and the diversity of the approaches utilized make the SPIn-Eco Project a unique experimental test, in which an attempt is made to understand similarities and differences among various methods, even though within the 36 municipalities of the Province of Siena the lifestyle of the population might be considered to be quite homogeneous.

To both validate the methods adopted and investigate the coherence of numerical results with each other, statistical computations, according to well-known systems of analysis, are necessary. The Principal Component Analysis (PCA) is used in order to integrate the results of all the methods implemented for the territorial contexts. This enables multidimensional representations of the relationships between the results of different methods in the form of plots. The results of such a method demonstrate correlations, congruence, substitutability and interdependencies between raw data, aggregations of data and sustainability indicators. In particular, PCA is applied to the results of the following methods: Emergy Evaluation, Ecological Footprint Analysis, Greenhouse Gas Inventory, Remote Sensing Analysis, and other descriptive data. Each method provides a group of indicators as shown in Table 2. All the results that are computed in this paper are presented in other papers of this volume, and the methods are extensively explained (Pulselli et al., 2006b; Bagliani et al., 2006; Ridolfi et al., 2006; Focardi et al., 2006, respectively, for the four methods).

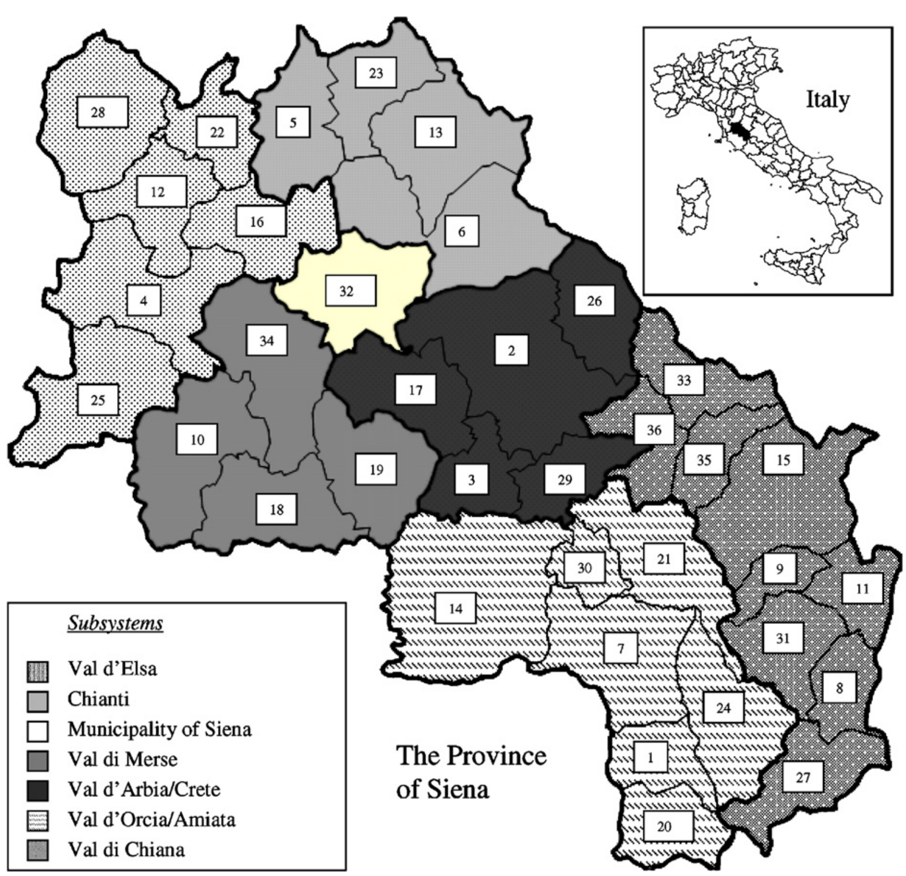

Fig. 1. The Province of Siena, its 7 districts and 36 municipalities and the national context.

Table 1
The 36 Municipalities within the Province of Siena and their corresponding districts. For each of them, the same research program has been designed and realized

No.	Municipality	District no.	District
1	Abbadia S. Salvatore	6	Val d'Orcia
2	Asciano	1	Val d'Arbia
3	Buonconvento	1	Val d'Arbia
4	Casole	4	Val d'Elsa
5	Castellina in Chianti	3	Chianti
6	Castelnuovo Berardenga	3	Chianti
7	Castiglione d'Orcia	6	Val d'Orcia
8	Cetona	2	Val di Chiana
9	Chianciano	2	Val di Chiana
10	Chiusdino	5	Val di Merse
11	Chiusi	2	Val di Chiana
12	Colle Val d'Elsa	4	Val d'Elsa
13	Gaiole in Chianti	3	Chianti
14	Montalcino	6	Val d'Orcia
15	Montepulciano	2	Val di Chiana
16	Monteriggioni	4	Val d'Elsa
17	Monteroni	1	Val d'Arbia
18	Monticiano	5	Val di Merse
19	Murlo	5	Val di Merse
20	Piancastagnaio	6	Val d'Orcia
21	Pienza	6	Val d'Orcia
22	Poggibonsi	4	Val d'Elsa
23	Radda in Chianti	3	Chianti
24	Radicofani	6	Val d'Orcia
25	Radicondoli	4	Val d'Elsa
26	Rapolano	1	Val d'Arbia
27	San Casciano dei Bagni	2	Val di Chiana
28	San Gimignano	4	Val d'Elsa
29	San Giovanni d'Asso	1	Val d'Arbia
30	San Quirico d'Orcia	6	Val d'Orcia
31	Sarteano	2	Val di Chiana
32	Siena	7	Municipality of Siena
33	Sinalunga	2	Val di Chiana
34	Sovicille	5	Val di Merse
35	Torrita	2	Val di Chiana
36	Trequanda	2	Val di Chiana

2. Methods

2.1. Sustainability indicators

Emergy Evaluation is an environmental accounting method of the use of resources in a given system on the basis of a common physical unit, equivalent solar energy. It provides data on the basis of classes of resources (renewable or non; local or imported) and indicators (see Table 2). For the results of Emergy Evaluation in the SPIn-Eco Project see Pulselli et al. (2006b), in this volume.

The Ecological Footprint Analysis estimates the amount of productive land that would be necessary to produce, in a sustainable manner, all goods and services necessary for a given population in order to support its consumption level as well as to absorb the relative wastes. See Table 2 for the indicators within the Ecological Footprint Analysis and the paper by Bagliani et al. (2006) in this volume.

The Greenhouse Gas (GHG) Inventory, according to the IPCC guidelines, compares the amount of anthropic emission of different GHGs from different sectors, such as energy, waste, agriculture and breeding, industry, etc., to the absorption capacity of the local forest and environment. Table 2 shows the elements of the inventory, and the paper by Ridolfi et al. (2006) illustrates the results of the SPIn-Eco Project.

Remote sensing is the observation and measurement of objects from a distance: instruments or recorders are not in direct contact with objects under investigation. Remote sensing focuses on the measurement of energy (at different wavelengths) that is emitted, transmitted, or reflected from an object in order to determine certain physical properties of the object. For the results of this method in the SPIn-Eco Project see Focardi et al. (2006), this volume.

In Table 2, a short description of the 26 indicators used in the PCA analysis is provided, together with the bibliography that can help the reader wishing more details. For the sake of conciseness we omit the complete description of the indicators in this part.

2.2. Principal components analysis

PCA is a mathematical transformation in which linear combinations of the input variables (here indicators) are created; the new variables, called principal components (PCs), explain as much of the variation as possible in the original data (Jackson, 1991; Krazanowski, 1988). The PCA decomposition algorithm ensures that the first PC explains the maximal amount of variance of the original data, the second PC explains the maximal remaining variance in the data subjected to being orthogonal (uncorrelated) to the first PC, and so on. PC's can be derived from either the raw data (via the covariance matrix) or from standardized data (via the correlation matrix, applied here). Standardized data treats all variables as equally important regardless of their scale of measurement. PCA performs two important tasks. First, it provides a way of reducing the dimensionality of the data. Second, it is a powerful visualization tool that enables graphic representation of intersample and intervariable relationships for exploratory data analysis. The plot of scores (coordinates of objects on the new variables) gives information about similarities among samples, while the plot of loadings (weights of original variables on the linear combination PCs are built from) shows correlations among the original variables. A combined plot of scores and loadings (biplot) gives further condensed information. In this paper, PCA of the data is performed by the package SCAN (1995).

3. Results and discussion

The preliminary analysis of the correlation of the input variables highlights the 100% correlation of two variables: BC and EFD (or EFS), which have singular similar

Table 2
All indicators (26) and their corresponding abbreviations used within the PCA

Methodology	Symbol	Indicator	Definition
	Area	*Area*	
	P	*Population*	
	PD	*Population density*	
	I	*Total income*	
	IpP	*Per-capita income*	
Emergy evaluation Odum (1988, 1996)	R	*Local renewable resources*	
	N	*Local non-renewable resources*	
	F	*Purchased non-local resources*	
	Em	*Total emergy flow*	$\mathrm{Em} = R+N+F$
	EYR	*Emergy yield ratio*	Ratio of the total amount of resources supporting the system to imported inputs (in emergy terms)
	ELR	*Environmental loading ratio*	Ratio of non-renewable to renewable resources (in emergy)
	EIR	*Emergy investment ratio*	Ratio of imported to local resources (in emergy)
	EmD	*Empower density*	Concentration of emergy flow in a given area
	EpP	*Emergy per person*	Per-capita emergy use of resources by a given population
Ecological footprint analysis Wackernagel and Rees (1996)	EF	*Ecological footprint*	The area necessary to support the standard of living of one person
	EF_{tot}	*Total ecological footprint*	The area necessary to support the standard of living of a population
	BC	*Biocapacity*	The actual productive land available for one person
	BC_{tot}	*Total biocapacity*	The actual productive land available for a population
	EFD or EFS	*Ecological deficit (or surplus)*	The positive (or negative) balance between EF and Biocapacity
Greenhouse Gas Inventory IPCC (1996)	Eq. CO_2	*Total emitted equivalent CO_2*	Emitted eq. CO_2, calculated on the basis of the Global Warming Potential for each sector.
	Abs CO_2	*Total absorbed equivalent CO_2*	Absorbed eq. CO_2, calculated on the basis of the forest areas and the types and ages of plants.
	Net CO_2	*Net equivalent CO_2*	Balance between Eq. CO_2 and Abs CO_2
Remote sensing analysis Focardi et al. (2006)	NDVI	*normalised vegetation index*	Difference of the corrected reflectance in red and the corrected reflectance in the near infrared.
	ESI	*Environmental stress indicator*	The classes from land cover classification are combined to create an indicator of environmental stress.
	RTI	*The radiant temperature index*	Normalization of the values of radiant temperature calculated from the thermal infrared waveband of the satellite sensor.
	ITS	*Indicator of territorial sustainability*	The resultant indicator can be applied on a pixel per pixel basis. $\mathrm{ITS} = \mathrm{NDVI} + 1/\mathrm{ESI} + 1/\mathrm{RTI}$

correlation with all the other indicators, thus one (EFD/EFS) was not included in the following PC Analysis. The input data and indicators considered useful for the multivariate analysis of the studied sites are 25.

There are 5 significant PCs with eigenvalues higher than 1 (see Table 3), for a total of explained variance (EV) of 84.5%. The most significant PCs are obviously the first two, with a cumulative explanation of 56.5% of data variability (EV of PC1 = 36.9%, EV of PC2 = 19.6%). The other PCs, with an EV of 12.5%, 10.9% and 4.6%, respectively, do not provide additional interesting information on the similarities among the studied sites, and therefore are not plotted here. In Table 4 all the eigenvectors for the 25 indicators are shown, according to the 5 PCs.

Table 3
Eigenvalues, proportion of the total variance covered by each component and the cumulative explanation of data variance in PCA (calculated from the Correlation Matrix)

Variable	PC1	PC2	PC3	PC4	PC5
Eigenvalue	9.2308	4.8973	3.1227	2.7309	1.1423
Proportion	0.369	0.196	0.125	0.109	0.046
Cumulative	0.369	0.565	0.690	0.799	0.845

In Fig. 2 the score plot of the sites studied is reported: the sites are plotted according to their similarity utilizing combined information of the applied indicators.

It is immediately evident that Siena (32) is a very particular city in the considered set of data, being completely isolated from the others. It is also interesting to note that Poggibonsi (22) is also significantly different from the other sites along the PC1 and that three sites, Rapolano (26), Sovicille (34) and Trequanda (36), must have some particularities as well, being isolated in the upper part of the graph by the PC2.

Table 4
Eigenvectors for all the indicators used in the PCA

Variable	PC1	PC2	PC3	PC4	PC5
Area	−0.006	0.044	**0.524**	0.137	0.172
P	**−0.321**	−0.029	−0.009	−0.079	−0.014
PD	**−0.298**	−0.064	−0.163	−0.010	0.024
I	**−0.315**	−0.036	−0.010	−0.128	−0.109
IpP	−0.127	−0.097	−0.119	**−0.314**	**−0.325**
R	**−0.262**	−0.006	**0.242**	−0.162	0.012
N	−0.093	**0.398**	0.049	0.031	0.147
F	**−0.319**	−0.023	−0.006	−0.016	0.066
Em	**−0.209**	**0.321**	0.055	0.009	0.146
EmD	−0.196	**0.317**	−0.153	0.061	0.036
EpP	0.041	**0.404**	−0.033	0.051	**−0.263**
ELR	−0.061	**0.419**	−0.100	0.098	0.036
EYR	0.054	**0.406**	−0.015	−0.009	**−0.245**
EIR	−0.073	**−0.237**	−0.199	0.122	**0.262**
BC	0.178	−0.036	**0.269**	−0.057	**−0.538**
BC_{tot}	−0.065	−0.118	−0.056	**−0.387**	−0.136
EF	**−0.319**	−0.033	−0.006	−0.110	−0.065
EF_{tot}	−0.068	0.032	**0.506**	−0.017	0.159
Eq. CO_2	**−0.318**	−0.021	0.017	−0.098	−0.088
Abs CO_2	0.087	0.064	0.257	**−0.405**	0.197
Net CO_2	**−0.317**	−0.037	−0.056	0.022	−0.136
NDVI	0.135	0.160	−0.116	**−0.424**	0.004
ESI	−0.084	−0.071	**0.220**	**0.297**	**−0.447**
RTI	−0.160	−0.027	**0.266**	**0.245**	0.023
ITS	0.124	0.076	−0.113	**−0.365**	0.020

The most significant components for each indicator are highlighted in bold.

The analysis of the loadings, reported in Fig. 3, is necessary in order to better understand which indicators are more relevant in determining the above separations.

Through a comparison of the two plots of Figs. 2 and 3 (or the view of Fig. 4: the biplot) it is possible to understand that the sites on the left side (negative score values for PC1) are characterized by a high value of indicators such as *P*, PD, *I*, CO_2 and *F*, thus they are the largest urban areas, and at the same time those where indicators on the right side (BC, ITS, NDVI and CO_2 absorbed) are less important. On the contrary, the municipalities on the right side are those characterized by agriculture, forests and low population density. The three sites isolated by the PC2 are characterized by the simultaneous highest values of *N*, EYR, ELR, EpP, EmD and Em and the lowest values of EIR. This is due to the fact that there is a very intense use of local, especially non-renewable, resources: marble in Sovicille, travertine in Rapolano and clay in Trequanda.

From the loading plot, the correlation and anti-correlation of the studied indicators in the set of data is also immediately evident. In fact, the angles of the lines reflect the correlation among the variables: at least for what concerns the first two PCs, the closer the direction of the line, the more the indicators are correlated within this data set; a 90° angle means total independency, a 180° angle anti-correlation.

We have found an interesting high level of correlation among CO_{2eq} emissions, EF_{tot}, *F* and *I*, typical expressions of human presence (*P*). Both CO_2 emissions and *I* are important data that are used to calculate EF, while we can expect that the higher the total income (*I*) the higher is the import of goods and services from outside the system (*F*). It is, instead, quite surprising to find this low level of correlation between EF and EpP, since both Emergy and Ecological Footprint methods aim to calculate the cost (in environmental terms) of the support of human consumptions, the former measuring it through the direct and

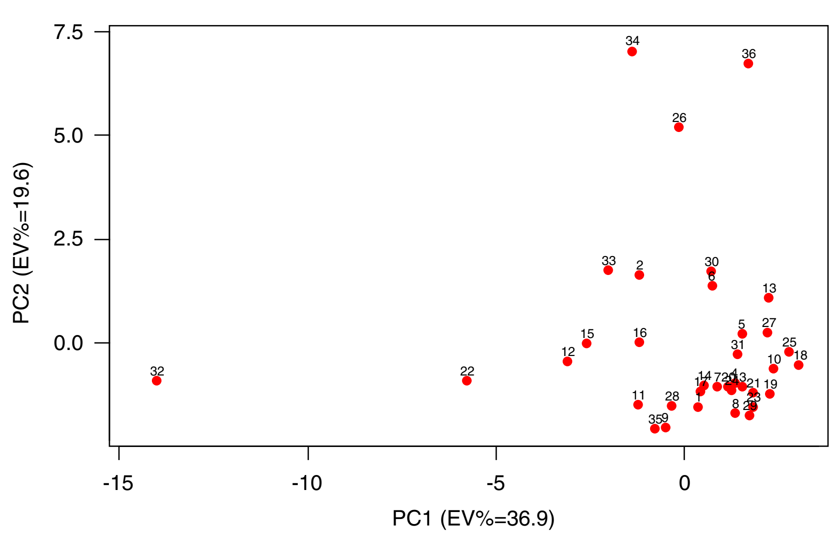

Fig. 2. Principal component score plot (Cumulative EV% = 56.5%).

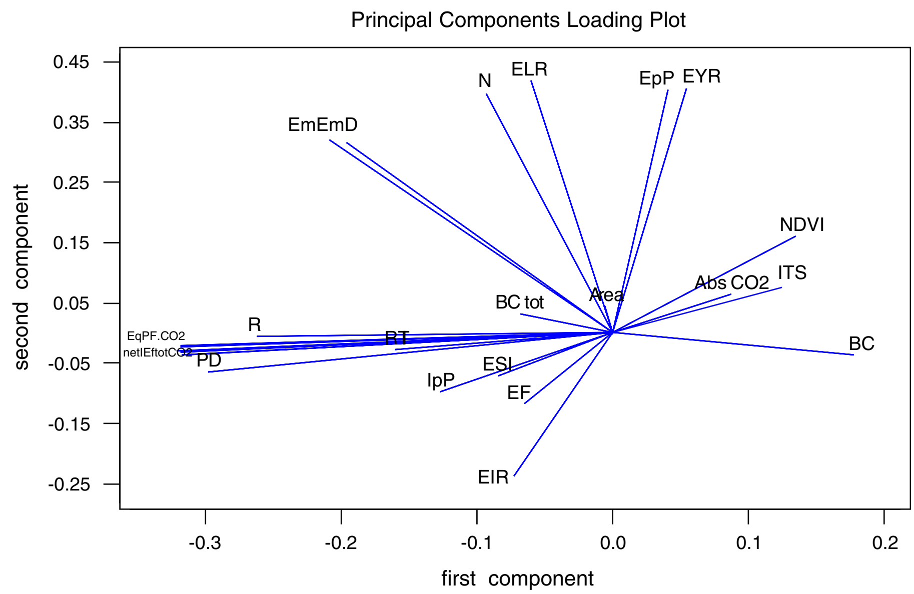

Fig. 3. Principal components loading plot. On the left side, where several lines and symbols overlap, we can find: Population (*P*), Population Density (PD), Total Income (*I*), Local Renewable Resources (*R*), Purchased non-local resources (*F*), Eq. CO_2, Net CO_2, Total Ecological Footprint (EF_{tot}).

indirect solar energy requirement, the latter through the amount of land needed. This low level of correlation may be explained by considering that, while emergy evaluation computes the non-renewable materials extracted locally (*N*), EF does not explicitly consider these types of materials in the balance sheet. *N* appears to be a very important indicator in this context, being uncorrelated with all the other indicators, except those that are directly influenced by *N* itself, such as ELR and Em. Another reason for the difference between the Emergy and Ecological Footprint analyses is the fact that while the former takes into account the total consumptions of goods within the area, the latter includes only the household consumptions, without considering industrial consumptions. Emergy evaluation and Ecological Footprint analysis are often considered as alternative approaches, basically highlighting the same problems. These results show that this is not true in general; on the contrary it seems helpful to compare their results to better understand the system under study.

Another aspect that is worth explaining, for its apparent contradiction of common sense, is the correlation of *R* (locally renewable emergy) with *F*, CO_2 emissions, *I*, etc.: the electricity obtained by geothermal energy has been included in *R* (for 75%) and distributed among the 36 municipalities according to the population of each and its energy demand; therefore, the higher the consumption of this energy, the higher the use of *R* (Pulselli et al., 2006b). Results would be different if electricity had been considered as coming completely from the national electricity network (Pulselli et al., 2006b).

An enlarged view of the sites without the bigger city of Siena is plotted in Fig. 5. In this figure, a closer inspection of the more similar sites is possible. Municipalities are grouped in districts (see Table 1 and Fig. 1), each one depicted with the same symbol. This analysis enables to evaluate the characteristics of homogeneity or diversity within each district. This has very important implications in the management of the provincial territory, since each municipality is not seen as an isolated system but within a larger territory, in which these characteristics can be optimized from a sustainability viewpoint.

The zones of Val d'Arbia, Val di Chiana and Val d'Elsa (1, 2 and 4, respectively) seem to be the most scattered. The Val d'Elsa municipalities, and to a lesser extent those of Val di Chiana, are separated mainly along the PC1, which means that in these zones there is the simultaneous presence of larger industrialized towns (such as Poggibonsi (22) in Val d'Elsa or Montepulciano (15) and Sinalunga (33) in Val di Chiana) and smaller towns surrounded by wild green areas (such as Radicondoli, (25) in Val d' Elsa or S. Casciano dei Bagni (27) in Val di Chiana). For Val di Chiana, as we have already noted, the biggest diversity along PC2 is for Trequanda (36). These two districts have very high diversity within their territories, which may be considered to be a point of strength, since this implies a lower fragility with respect, for example, to possible economic crises in one particular sector. However, these municipalities should consider an integrated policy for the system as a whole, as they do not have the homogeneity necessary to formulate a unique policy.

In Val d'Arbia the municipality of Asciano (2) is isolated from the others of the same zone, even if to a lesser extent than Rapolano (26), already highlighted before. The zone of Chianti (zone 3) is relatively homogeneous, for only a minor differentiation from the other Chianti villages can be observed for Radda (23).

The zones of Val di Merse (zone 5) and of Val d'Orcia (zone 6) are the most homogeneous, with the only great difference, already highlighted, of Sovicille (34) in Val di Merse and to a smaller measure that of S. Quirico

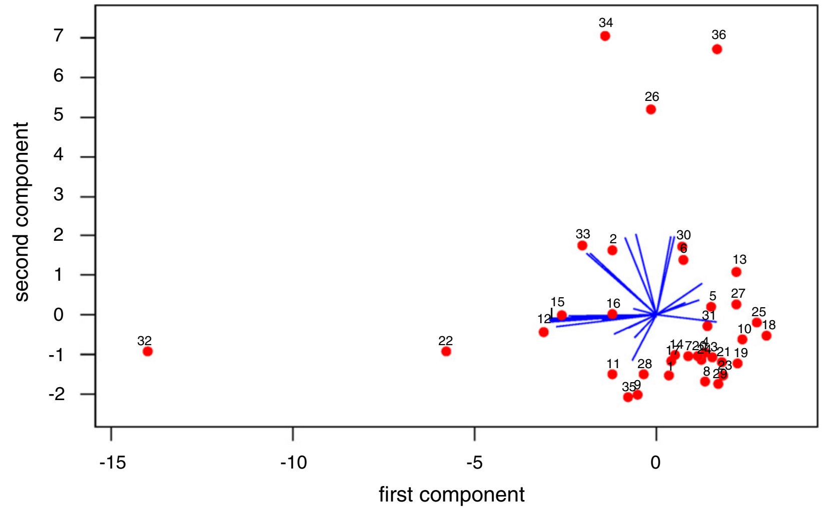

Fig. 4. Principal component biplot, obtained by the fusion of the information in Figs. 2 and 3.

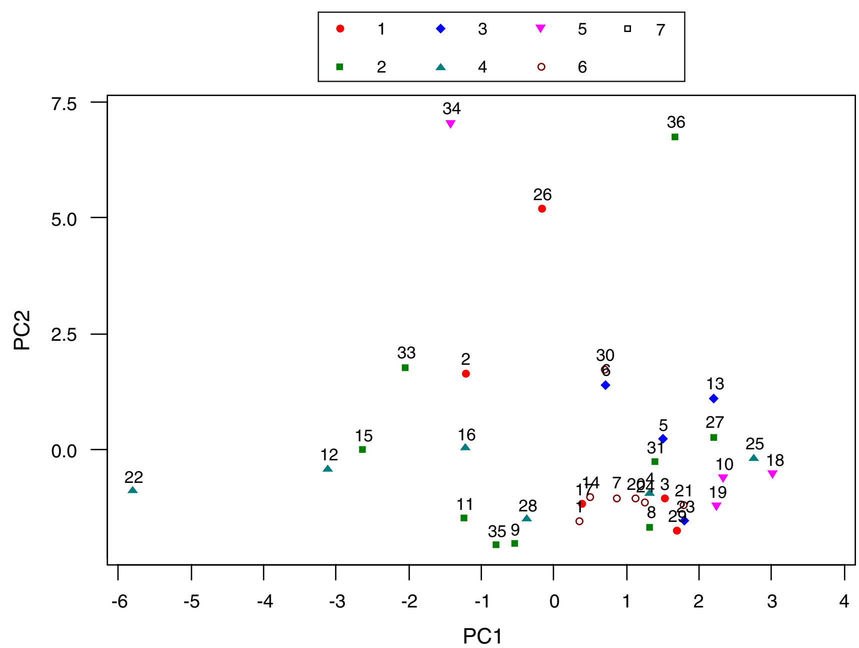

Fig. 5. Reduced Scatter plot of PC1 and PC2. The municipality of Siena (#32 in Fig. 2 and district 7) has been removed to highlight the distribution of the other municipalities in the plot. The municipalities are associated to their districts, labelled by equal symbols. In the legend 1 is Val d'Arbia, 2 is Val di Chiana, 3 is Chianti, 4 is Val d'Elsa, 5 is Val di Merse and 6 is Val d'Orcia.

d'Orcia (30), both isolated from the other villages of the corresponding zone by the emergy indicators, especially due to the role of the indicator *N*.

4. Conclusions

An amount of data such as that gathered and calculated during the SPIn-Eco Project necessitates a proper statistical treatment in order to discover more important indications than those resulting from the separate application of different methods. The treatment of the data by PCA has provided a multivariate view of the studied sites that would not be evident from a univariate analysis. The correlation among the indicators and their combined influence reveal 'hot spots' and/or similarities among sites that would be difficult to detect with simpler methods of data analysis. From the analysis of the PCA graphs, it is possible to highlight the sites of more concern from a sustainability viewpoint. On one side lies Siena, showing the highest Ecological Footprint and external emergy inputs (*F*), while on the other side lie Rapolano, Sovicille and Trequanda, which are depleting relatively quickly the non-renewable resources available in their territory. The rest are spread along the first component, without great differences along the second component of the PCA (these two components, together, are able to explain 56.5% of the total variability of data).

Districts within the Province of Siena can be very different from each other: some are quite homogeneous, and others vary greatly. From a sustainability viewpoint, diversity is a positive aspect that can give a system a higher level of resilience. However, problems may appear in realizing the importance of a policy that goes beyond the single municipality and involves the entire district as a system.

The PCA has also shown some unexpected results in the relations among indicators: the most striking one is the lack of congruence between Emergy (per person) and the Ecological Footprint. These two indicators aim to provide the same type of information, but the role of non-renewable materials, very highly considered in the Emergy evaluation and neglected in the Ecological Footprint, make them completely uncorrelated.

We hope that this project will be succeeded by many others of the same type in order to discover other implications regarding the similarities/differences among the indicators, and to optimize the quantity of data and information to be collected for an environmentally sustainable policy and management.

Acknowledgements

The authors would like to thank the Province of Siena Administration and the Monte dei Paschi Foundation for financially supporting this research.

References

Bagliani, M., Galli, A., Niccolucci, V., Marchettini, N., 2006. The ecological footprint analysis applied to a sub-national area: the case of the Province of Siena (Italy). Journal of Environmental Management, 2006, this volume. DOI:10.1016/j.jenvman.2006.04.015.

Focardi, S., Loiselle, S., Mazzuoli, S., Bracchini, L., Dattilo, A.M., Rossi, C., 2006. Satellite based indices in the analysis of land cover for municipalities in the Province of Siena. Journal of Environmental Management this volume. DOI:10.1016/j.jenvman.2006.08.011.

IPCC, Intergovernmental Panel on Climate Change, 1996. Greenhouse Gas Inventory. Reporting Instructions, (revised). vol. 1–3.

Jackson, J.E., 1991. A User's Guide to Principal Components. Wiley, NY, USA.

Krazanowski, W.J., 1988. Principles of Multivariate Analysis. A User's Perspective. Oxford Univ. Press, Oxford, UK.

Odum, H.T., 1988. Self organisation, transformity and information. Science 242, 1132–1139.

Odum, H.T., 1996. Environmental Accounting. Emergy and Environmental Decision Making. Wiley, New York.

Pulselli, F.M., Ciampalini, F., Leipert, C., Tiezzi, E., 2006a. Integrating methods for the environmental sustainability: the SPIn-Eco Project in the Province of Siena (Italy). Journal of Environmental Management this volume. DOI:10.1016/j.jenvman.2006.04.014.

Pulselli, R.M., Pulselli, F.M., Rustici, M., 2006b. The EMergy accounting of the Province of Siena: towards a thermodynamic geography for regional studies. Journal of Environmental Management this volume. DOI:10.1016/j.jenvman.2006.04.011.

Ridolfi, R., Kneller, M., Donati, A., Pulselli, R.M., 2006. The greenhouse gas balance of the Province of Siena. Journal of Environmental Management this volume. DOI:10.1016/j.jenvman.2006.04.012.

Robèrt, K.H., Schmidt-Bleek, B., Aloisi de Larderel, J., Basile, G., Jansen, J.L., Kuehr, R., Price Thomas, P., Suzuki, M., Hawken, P., Wackernagel, M., 2002. Strategic sustainable development—selection, design and synergies of applied tools. Journal of Cleaner Production 10 (3), 197–214.

SCAN—Software for Chemometric Analysis. Rel. 1.1 for Windows, 1995, Minitab, USA.

Wackernagel, M., Rees, W., 1996. The Ecological Footprint: reducing human impact on the Earth. New Society, Gabriola Island, BC, Canada.