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Emergy accounting of the Province of Siena: Towards a thermodynamic geography for regional studies

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Abstract

This research is part of the SPIn-Eco project for the Province of Siena, Italy, and applies an environmental accounting method to a region with reference to its population, human activities, natural cycles, infrastructures and other settings. This study asserts that the consumption of resources due to the human economy is a source of great concern because of the load it places on the biosphere. Environmental resources locally used, whether directly or indirectly, from both renewable energy fluxes and storage of materials and energies, are investigated.

In this paper *emergy analysis* is presented and applied to the Province of Siena and to each of its municipalities, in order to evaluate the main flows of energy and materials that supply the territorial system, including human subsystems, with reference to their actual environmental cost. Therefore, the behaviour of the whole system and the interactions between natural and human agents were studied; in other words, the attitudes of the territorial systems toward resource use as revealed by their patterns of emergy consumption were observed.

Once expressed in units of the same form of energy through the emergy evaluation, categories of resource consumption and systems of varying scales and organization are compared. Furthermore, indexes of environmental performance based on emergy are calculated. Flows of energy and materials are assessed, and their intensities, which vary throughout the area of the Province, are then visualized on maps.

Keywords: Emergy evaluation; Energy hierarchy; Sustainability indicators

1. An introduction to emergy

Systems within the biosphere are maintained by flows of energy that cycle materials and information. Without continuous inflows of energy that build order, systems degrade. Therefore, the emergy method for regional research evaluates flows of energy, material, and information to study human systems and their dynamics, from the relationships among constitutive components to the interactions with systems at a higher level; it concerns the interface of environment and human society. Quantitative understanding of the relationships between human-dominated systems and the biosphere is the realm of emergy analysis (Odum, 1988). The intrinsic value of ecosystems in biological terms is emphasized, whether human preference fully recognizes that value or not (Huang, 1998).

Human society feeds on quantities of energy and materials that flow through and within the boundaries of a region; it draws energy directly from the environment (whether they were daily flows such as sun–wind–rain or geothermal heat force; short-term storage flows such as wood, soil and water, or long-term storage flows of fossil fuels and minerals), or indirectly in the form of goods purchased from the global economy. Energy inputs with different forms and quality constantly supply local activities and transformation processes in order to provide products, services and profits. Man's ability to work depends on energy quality and quantity; this is measurable by the amount of energy of a lower quality or grade

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required to develop the higher grade. An energy hierarchy exists in the universe. According to Odum, for instance, ''the scale of energy goes from dilute sunlight up to plant matter, to coal, from coal to oil, to electricity and up to the high-quality work of computer and human information processing'' (Odum, 1973).

This concept of energy hierarchy is proposed by Odum (1996, 2001) as an energy law. In particular, the word ''hierarchy'' means that many units at one level contribute to a few units at a higher level. Because of the second law of thermodynamics, any energy transformation uses many calories of available energy of one kind to generate a few calories of available energy of another kind. An energy transformation is therefore a work process that converts one or more kinds of available energy into a different type of available energy (Brown et al., 2004).

The *emergy evaluation* is based on this theory. Emergy (spelled with an ''m'') is the available energy (exergy) of one kind required to be used up previously, directly and indirectly, to generate the inputs for an energy transformation (Odum, 1971, 1983, 1996; Brown et al., 2004). An approach for overcoming the diversity of metrics used for quantifying processes and activities is to normalize all products and services to a unit of measure that represents the quantity and quality of work being created and maintained by the system (Tilley and Swank, 2003). According to this definition, the *emergy method* uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy.

In the case of ecosystems, normalization should reflect the inherent system values that thousands of years of natural selection have created to organize the structure and function of ecosystems (Tilley and Swank, 2003). Odum suggested that sunlight is dilute energy, and the costs of concentrating it have already been optimized and yield maximized by the millions of years of natural selection taken for this maximization (Odum, 1972). Solar energy is the largest but most dispersed energy input to the earth (Brown and Ulgiati, 2004); it is used as the common denominator through which different types of resources, either energy or matter, can be measured and compared to each other. Forcing factors, state variables and other system attributes are therefore normalized to one metric unit, namely the *solar emergy joule* or *solar emjoule* (sej). Based on this unit, emergy is defined as the quantity of solar energy that has been used, whether directly or indirectly, in order to obtain a final product or service (Odum, 1988).

Emergy synthesis is a modelling tool that addresses the problem of normalizing system properties (Tilley and Swank, 2003); it is a measure of the global processes required to make something expressed in units of the same energy form, solar energy (solar irradiation). The more work done to produce something, or the more energy that is transformed, the higher the emergy content of that which is produced (Brown and Ulgiati, 1999).

In other words, emergy is the ''memory of energy'' (Scienceman, 1987, 1989) that was degraded in a transformation process; it accounts for all the natural resources that have been used throughout a sequence of different processes and steps towards a final product. To derive solar emergy from a product or service, it is necessary to trace back through all the resources and energy that have been used to produce it, and to express each in the amount of solar energy that went into their production. This memory goes back to the primary form of energy, which is solar energy. This has been done for a wide variety of resources and renewable energies driving the biogeochemical process of the Earth (Odum, 1996). Therefore, emergy is not a state function, because it takes into account the specific path from the initial to the present state.

How does the emergy method practically specify this theoretical framework through an operative procedure? When expressed as a ratio of the total emergy used to the energy of the product, a transformation coefficient results, namely solar transformity, in dimensions of sej/J. As its name implies, solar transformity can be used to ''transform'' a given product into emergy, by multiplying mass quantities (kg) or energy quantities (joule) by the transformity, which is defined as the emergy input per unit of product or service (Odum, 1971, 1983, 1996). This apparently circular procedure is made operative by the awareness that 1 emjoule is equivalent to 1 J of solar energy; it is obvious that the transformity of solar energy is 1 sej/J. Solar transformities represent the position that a forcing factor occupies in the hierarchical network of the earth's biosphere (Odum, 1996); it is the quantity of solar energy that has been used, directly or indirectly, in order to obtain one mass-energy unit (1 kg or 1 J) of a certain product. For example, if 80,000 solar emjoules are required to generate 20 J of wood, then the solar transformity of that wood is 4000 solar emjoules/J (80,000/20 sej/J). The higher the transformity of an item, the more available energy of another kind required to make it (Brown et al., 2004). Moreover, emergy is an extensive quantity, while transformity is an intensive quantity. Emergy can be considered as the *total energy cost*, given in sej, of a product. Transformity can be seen as the quality of the energy of a resource, expressed in sej/kg or sej/J. It is the *energy cost* per unit of product (or *environmental cost* per unit).

For convenience, in order not to have to calculate the emergy in products and services every time a process is evaluated, previously calculated transformities are used. There is no single transformity for most products, but, instead, a range. For instance, electricity has different transformities that depend on its production processes according to different power-sources (renewable–non-renewable) and different technologies (yield-efficiencies).

In other words, the Emergy method provides an appraisal of any resource's environmental cost based on its memory, back through a sequence or chain of effects, until arriving at the basic processes that supply any anthropic or natural system. In its most basic form, this primary source has the form of solar energy.

By definition, the solar emergy B_k of the flow k coming from a given process is

$$B_k = \sum_i \mathrm{Tr}_i E_i \quad i = 1, \ldots, n, \tag{1}$$

where E_i is the actual energy content of the ith independent input flow to the process and Tr_i the solar transformity of the ith input flow, defined as follows:

$$\mathrm{Tr}_i = B_i/E_i. \tag{2}$$

In Eq. (2), B_i is the total solar emergy driving the ith process. This circular definition is made operational by putting the solar transformity of direct solar energy Tr_s equal to 1.

Thus, when a process is directly driven by solar energy, the transformity clearly appears as a measure of the convergence of solar energy to originate the product flow. When a set of transformities Tr_i has been calculated for a certain number of flows or products originated by direct solar energy, it is possible to evaluate the indirect solar energy requirement of other processes where the input flows are known, according to Eq. (1). Finally, the solar transformity of a given process k can be calculated from Eqs. (1) and (2):

$$\mathrm{Tr}_k = B_k/E_k = \sum_i \mathrm{Tr}_i E_i/E_k, \tag{3}$$

where E_k is the actual energy content of product k.

Solar transformity is usually measured in solar emergy joules per joule of product (sej/J) (Ulgiati et al., 1995).

2. The emergy method for regional studies

The SPIn-Eco project provides an application of the emergy method to an appraisal of resource consumption in the territory of the Province of Siena (other examples of emergy evaluations at the territorial level are found in: Ulgiati et al., 1994; Campbell, 1998; Huang, 1998; Ortega et al., 1999; Pulselli et al., 2001; Kang and Park, 2002; Higgins, 2003; Tilley and Swank, 2003; Pulselli et al., 2004; Campbell et al., 2005). Specifically, this work aims to define and quantify the main fluxes, or exchanges of energy and matter, that flow through and within the boundaries of the Province. The region under study is therefore conceived as part of a much vaster territory in which processes have a wide range of action, or even, a global dimension (Tiezzi, 2006).

The inventory of the inputs that supply the territory of the Province of Siena comes from an observation of these multiple processes. Their visualization in a diagram gives a synthetic description of resource flows and transformation processes that take place in the territory; it works as a diagram in which relationships between the system and the outside and between its own parts have been decoded in the form of flows of energy and materials. This *energy systems diagram* is built according to the graphic directives given by H.T. Odum (1971, 1983, 1996) based on the use of *energy system symbols*.

In the diagram shown in Fig. 1, the large rectangle defines the boundaries of the system under study, the Province of Siena. In reference to these boundaries, the multiple relations among parts inside and outside the system are classified. Macro-sectors (right-smoothed rectangles and small rectangles) are subsystems with their own specific purposes. The primary transformation processes are agriculture, forests and cattle breeding. Secondary transformation processes are geothermal production of electricity, manufacturing industry, crafts, services and commerce (namely *tertiary*), waste treatment and disposal. Subsystems like *city and population,* including the amount of tourists attracted, are described as consumers (hexagons) that work as attractors for those fluxes that supply urban areas, whereas in general consumption is mostly localized.

Some inputs to the system come directly from the environment and natural cycles as solar radiation, rain, wind, the biogeochemical cycle and rivers (sources drawn on the left and upper side of the diagram). These flows supply local reservoirs (drawn in the form of storage) such as water, geothermal heat, soil and its organic content, and materials for quarrying (*minerals*). Wastes are also conceived as a local stock of resources. Other inputs come from outside the system in the form of purchased goods, energy, services, raw materials and fuels (sources drawn on the upper side of the diagram). Goods and services produced in the region are sold to markets represented by the circle outside the box on the right side of the diagram. Arrows are exchanges of energy and materials.

Resources are classified according to their origin, either from outside (environmental inputs, purchased energy and materials) or within the system (reservoirs of local resources). A second classification also occurs based on the nature of the sources, either renewable or non-renewable. Renewability is a relative concept, since it depends on how quickly a material or energy is used compared to the speed at which it is generated. Renewable materials and energies used directly by society are those flows of materials and energies that are used at rates slower than their generation rate: solar irradiation, rain, wind, and geothermal heat (this is assumed to be a spread flow all over the area of the Province) are assumed to be renewable resources (labelled R). Also geothermal heat for the local production of electricity is assessed because geothermal power stations exploit a very localized (concentrated—not spread) deep geothermal heat as power source that is renewable (75% with respect to the total emergy used for geothermal production of electricity). Non-renewable materials and energies used by society are flows coming from storage that are used at rates faster than their regeneration: water (it is assumed to be non renewable because of the risk of overexploitation due to intensive agriculture), soil, materials for quarrying (labelled N). Purchased fuels (labelled $F1$) for local transportation, industry, heating and cooling are

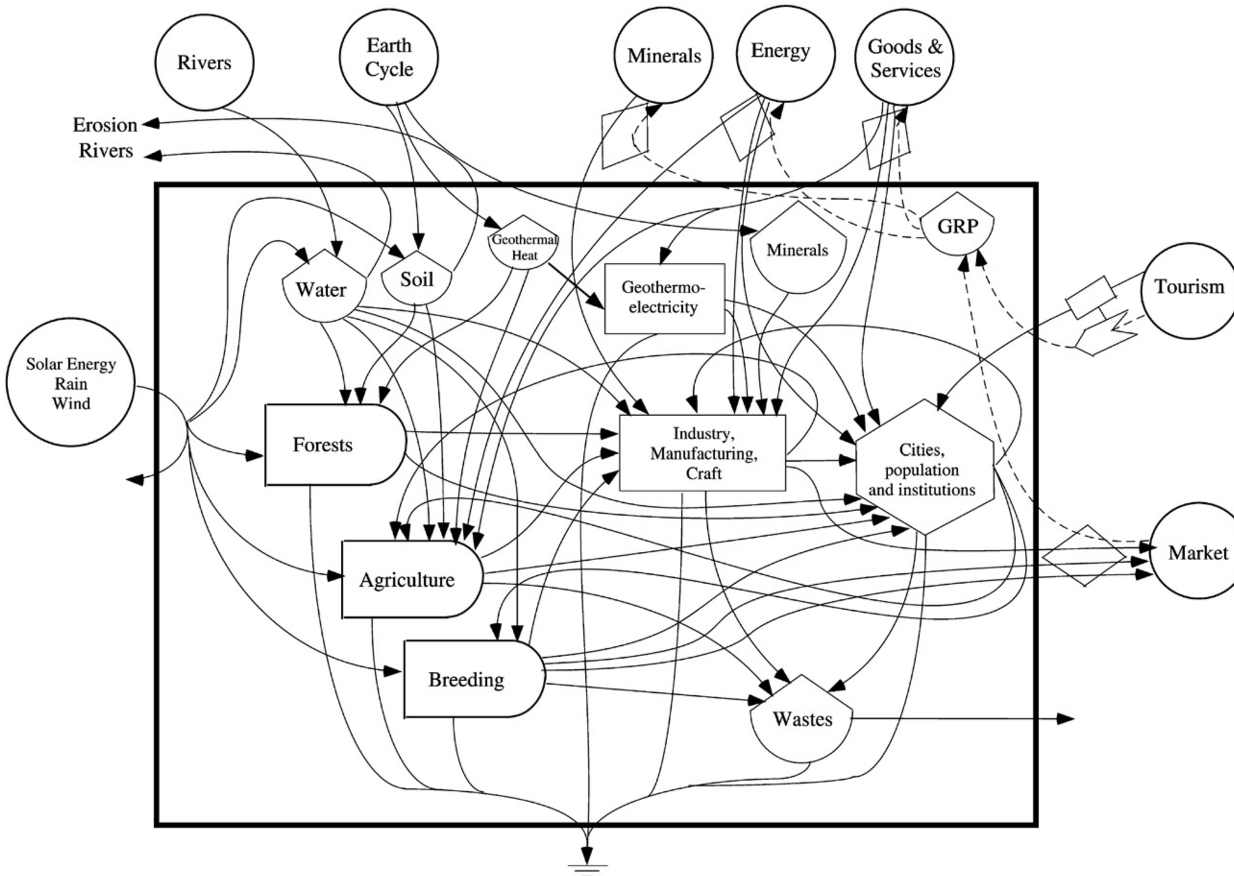

Fig. 1. Energy systems diagram of the Province of Siena—SPIn-Eco project.

also non-renewable. All other resources coming from the economy as purchased goods are transformed in some way, and fuels and other materials are typically used to transport them. The amount of non-renewable resources used for this treatment is relevant enough to presume that purchased goods (labelled $F2$) are non-renewable.

Statistical data is then collected, along with detailed information on local production and consumption, imports and exports, and the economy, as well as on local geomorphology (solar irradiation, rain, soil erosion, ore deposits, water, etc.). Data was collected during a year-long period (2000) and processed by transforming mass quantities (kg) and energy quantities (joule) into equivalent sej through multiplying by the appropriate transformities. Quantities and equivalent emergy values have been ordered into tables that distinguish different classes of resources. In particular, in Table 1, quantities of resource consumed and the equivalent amounts of emergy flow are gathered in groups as follows: local renewable R—local non-renewable N—imported fuels and energy $F1$. In Table 2, quantities of imports and the equivalent values of emergy flows in terms of purchased goods and materials are shown—imported goods $F2$. The transformities of each entry are reported on relative rows with the corresponding reference: (a) (Odum et al., 2000), (b) (Tiezzi, 2001), (c) (Bastianoni et al., 2005a, b), (d) (Ulgiati et al., 1993), (e) (Bastianoni et al., 1994), (f) (Brown and Arding, 1991), (g) (Tiezzi, 2000a), (h) (Ulgiati et al., 1994), (i) (Tiezzi, 2000b), (j) (Odum, 1992), (k) (Odum and Odum, 1987), (l) (Odum and Arding, 1991), (m) (Odum and Odum, 1983), (n) (Bjorklund et al., 2000), (o) (Odum, 1996), (p) (Bastianoni et al., 2001). Values are in scientific format (for example, 1.50E+2 means 1.50×10^2 that is equivalent to 150).

On this basis, some indicators are calculated:

- Environmental loading ratio (ELR): given by the ratio of non-renewable resources (both local and imported) to renewable ones ($N+F/R$);
- Emergy density (ED): given by the ratio of total emergy to the area of the system (U/area);
- Emergy per person (EpP): given by the ratio of total emergy to the population (U/population);
- Emergy investment ratio (EIR): given by the ratio of purchased inputs to local resources, both renewable and non-renewable (F/L).

Furthermore, the emergy method for regional research functions through a combination of both quantities (in terms of emjoules) and locations (in terms of given districts) and aims to generate maps in which the intensities of emergy values are shown. A kind of geography of resource flows is therefore decoded in order to locate areas

Table 1
Emergy flows of renewable *R*, non-renewable *N*, and imported energy and fuels *F*1—transformities are relative to the 15.83 baseline

No.	Item	Raw data	Unit	Transformity (sej/unit)	Ref.	Emergy (sej/yr)
1	Sunlight	1.64E+19	J/yr	1.00E+00	*a*	1.64E+19
2	Rain	3.13E+15	g/yr	1.45E+05	*a*	4.53E+20
3	Wind, kinetic energy	8.09E+15	J/yr	2.47E+03	*a*	2.00E+19
4	Geothermal heat	1.34E+16	J/yr	3.02E+04	*a*	4.05E+20
5	Soil erosion	9.26E+14	J/yr	1.24E+05	*a*	1.15E+20
6	Water, consumptions	2.06E+13	g/yr	1.95E+06	*b*	4.01E+19
7	Materials from mining					5.87E+21
	Clay and binders	1.16E+12	g/yr	1.68E+09	*a*	1.94E+21
	Inserts for buildings	1.65E+12	g/yr	1.68E+09	*a*	2.77E+21
	Ornamental (marble and other stones)	4.75E+11	g/yr	2.44E+09	*a*	1.16E+21
8	Electricity, local production	3.33E+15	J/yr	2.30E+05	*p*	7.66E+20
9	Electricity, import	3.70E+14	J/yr	2.07E+05	*p*	7.66E+19
10	Gasoline and diesel	9.18E+15	J/yr	1.11E+05	*o*	1.02E+21
11	Fuel oil, LPD and lubrificants	8.02E+14	J/yr	9.30E+04	*c*	7.46E+19
12	Natural gas	5.49E+15	J/yr	6.72E+04	*c*	3.69E+20
Renewable resources, *R* (sum of items 2%, 4% and 75% of 8)						1.43E+21
Non-renewable local resources, *N* (sum of items 5, 6 and 7)						6.03E+21
Imported resources (energy and fuel), *F*1 (sum of items 9, 10, 11%, 12% and 25% of 8)						1.73E+21

where resource flows achieve the lowest, medium and highest intensities.

For the Province of Siena, much statistical data has been collected on the scale of individual municipalities (36 municipalities) so that the location of consumption, referring to activities and land uses, achieves a satisfactory level of accuracy. In this way, an appraisal of sustainability may respond to any local area within the boundaries of the Province to provide information about the whole region and each of its parts. In particular, the emergy evaluation has been applied to 36 municipalities evenly aggregated into seven districts or neighbourhoods (Valdarbia, Valdichiana, Chianti Senese, Valdelsa, Valdimerse, Valdorcia, and Siena). A clear layout of the non-homogeneous intensity of the resources used within the Province and throughout the neighbourhoods and municipalities has been visualized (it is shown in Fig. 4).

3. Results and discussion

A synthetic report with some of the final outcomes for the Province of Siena is shown below. The main resource flows for the whole region have been quantified as follows:

1. The total emergy used in the Province of Siena is 1.12×10^{22} sej. This value corresponds to the sum of the emergy of all the flows that supply the whole region.
2. The total renewable emergy *R* is 1.43×10^{21} sej. It is approximately 12.8% of the total used emergy.
3. The total local non-renewable emergy *N* is 6.03×10^{21} sej. It is 53.9% of the total used emergy.
4. The total imported emergy *F* is 3.71×10^{21} sej, and is the sum of all the fluxes coming from the outside. It is 33.2% of the total emergy used. This value is given by the sum of the emergy amount due to purchased energy and fuels *F*1 (1.73×10^{21} sej) and the purchased goods and materials *F*2 (1.98×10^{21} sej).

The portion of renewable emergy in the entire region is not negligible, even if not apparently relevant; their assessment mainly depends on the local intensity of natural cycles, like solar irradiation, wind, rain and geothermal heat, despite their real exploitation, and on the physical configuration of the territory. These flows come directly from the environment and their transformities have very low values. For this reason, and according to the logic of emergy, high values of renewable resources relative to other flows are never expected in a developed area.

Even a fraction of the electricity consumed (almost 70% of the total consumption) can be considered renewable, because it is produced inside the Province from geothermal sources (75% of the total emergy used for geothermal production of electricity depends on a concentrated geothermal heat force that is renewable; most of the imported electricity is assumed to be thermoelectricity according to the national average) and is imputed to all 36 municipalities.

In terms of emergy, the region under study, with its population and local activities, depends on external sources for 33% of the total use. About 67% of resources used in the Province, whether renewable or non-renewable, are locally available, even if most of the local resource flows are non-renewable and generally involve materials from quarrying.

Extractive activity plays a significant role according to the emergy accounting of the Province, as shown in Fig. 2. The high amount of emergy contributed by extracted materials is due to their quantities and, especially, to the high values of their transformities. The work made by Nature, over long periods of time, to provide storages of

Table 2
Emergy flows of imported goods and materials F2—transformities are relative to the 15.83 baseline

No.	Item	Raw data	Unit	Transformity sej/unit	Ref.	Emergy sej/yr
	Agriculture					
1	Cereals	2.32E+14	J/yr	2.67E+05	*d*	6.20E+19
2	Legumes	3.56E+12	J/yr	1.39E+05	*e*	4.95E+17
3	Fruits	1.14E+11	J/yr	4.82E+05	*d*	5.48E+16
4	Vegetables	0.00E+00	J/yr	3.19E+06	*f*	0.00E+00
5	Seeds	1.57E+12	J/yr	1.33E+06	*d*	2.08E+18
6	Spices and tobacco	9.32E+12	J/yr	3.36E+05	*f*	3.13E+18
7	Plants and flowers	2.87E+09	g/yr	4.74E+09	*g*	1.36E+19
						8.13E+19
	Breeding, hunting and fishing					
8	Animals	3.37E+12	J/yr	5.33E+06	*h*	1.79E+19
9	Woods	3.54E+10	g/yr	1.68E+08	*f*	5.94E+18
10	Hunting and fishing	1.64E+09	g/yr	2.27E+08	*i*	3.71E+17
						2.42E+19
	Mining industry					
11	Metal minerals	3.79E+07	g/yr	5.81E+09	*h*	2.20E+17
12	Non-metal minerals	5.44E+09	g/yr	2.82E+09	*j*	1.54E+19
						1.56E+19
	Manufacturing industry					
13	Food industry	1.78E+14	J/yr	5.33E+06	*h*	9.50E+20
14	Tobacco industry	0.00E+00	J/yr	1.76E+05	*h*	0.00E+00
15	Leather industry	2.88E+12	J/yr	1.44E+07	*k*	4.16E+19
16	Textile industry	6.18E+12	J/yr	6.38E+06	*f*	3.94E+19
17	Furniture and clothing industry	2.26E+13	J/yr	6.38E+06	*f*	1.44E+20
18	Wood and cork industry	1.40E+15	J/yr	5.86E+04	*l*	8.23E+19
19	Paper industry	9.90E+13	J/yr	3.61E+05	*f*	3.58E+19
20	Graphic industry	1.65E+12	J/yr	3.61E+05	*f*	5.97E+17
21	Metallurgic industry	6.90E+09	g/yr	1.13E+10	*f*	7.77E+19
22	Mechanical industry	1.75E+10	g/yr	2.10E+10	*m*	3.67E+20
23	Mineral industry	2.45E+10	g/yr	3.09E+09	*n*	7.59E+19
24	Chemical industry	2.97E+10	g/yr	6.38E+08	*o*	1.89E+19
25	Rubber industry	7.66E+08	g/yr	7.22E+09	*f*	5.53E+18
26	Other manufacturing industries	3.95E+09	g/yr	5.81E+09	*h*	2.30E+19
						1.86E+21
Imported resources (goods and materials), *F*2 (sum of items 1–26)						1.98E+21

these materials is assessed in their transformities in order to enhance the environmental relevance and risk of any activity concerned with mining and quarrying.

Once all the inputs have been classified into categories, some indicators for the area are calculated (Brown and Ulgiati, 1997). Each municipality has been investigated, and the results of the analysis are shown in Table 3.

Fig. 3 shows a graph with classes of aggregated emery flows from the Province of Sienna.

The Province of Siena presents a low level of ELR = 6.80, which means that there is a certain equilibrium between the natural availability of renewable resources and the exploitation of non-renewable resources. However, the results at the municipal level are not homogeneous and show different conditions. The ELR achieves high values in areas such as Rapolano (28.03) of Valdarbia, Sinalunga (15.93) and Trequanda (31.46) of Valdichiana, Sovicille (27.47) of Valdimerse, San Quirico (11.30) of Valdorcia, especially due to the presence of industrial or quarrying activities. Not all the neighbourhoods of the Province have high ELR values and, in particular, the areas of Valdelsa and Valdorcia have lower values than the Province, 5.05 and 2.50, respectively. In some cases, the ELR is around 1, or even lower. This very special condition is found in San Giovanni d'Asso (0.91) of Valdarbia, Radicondoli (0.24) of Valdelsa, Chiusdino (0.59), Monticiano (0.33) and Murlo (0.93) of Valdimerse, Montalcino (1.40), Piancastagnaio (1.38) and Radicofani (0.77) of Valdorcia. These areas may be thought of as locations of storage of natural capital with very low impact in terms of resource use and extraction. Their importance for the sustainability of the entire region is strategic. In Fig. 3, a graph is shown with classes of aggregated emergy flows located in the neighbourhoods of the Province of Siena.

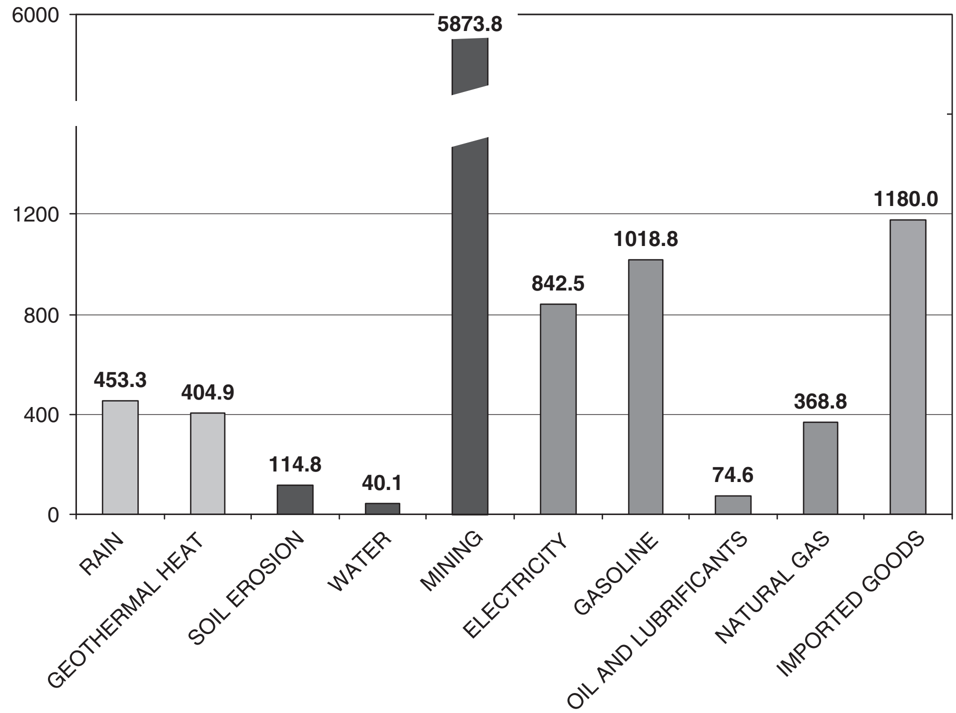

Fig. 2. Categories of resource consumptions and equivalent emergy values in the Province of Siena; unit: sej $\times 10^{18}$—SPIn-Eco project.

The ED analysis also reflects this situation. In particular, the intensity of emergy flows through the municipalities of the Province of Siena can indicate the areas where the low availability of land is a limiting factor for future development. This measure of spatial stress is lower in Chianti Senese (1.81×10^{12} sej/m^2), Valdelsa (2.78×10^{12} sej/m^2) and Valdorcia (1.30×10^{12} sej/m^2) than in the Province of Siena (2.92×10^{12} sej/m^2). Very low levels are found in Chiusdino (0.56×10^{12} sej/m^2), Monticiano (0.40×10^{12} sej/m^2) and Murlo (0.46×10^{12} sej/m^2) of Valdimerse.

The EpP shows how consumption is related to population and, in a certain sense, this index represents the responsibility of each inhabitant for the use of resources. However, it is important to consider the nature of the resources that are used. For example, the values of Monteriggioni (5.80×10^{16} sej per capita) and Radicondoli (6.68×10^{16} sej per capita) in Valdelsa are similar, but while 76% of the total emergy used in Radicondoli is renewable, 94% of the total use in Monteriggioni is not. The values for the municipality of Siena (2.03×10^{16} sej per capita) and Poggibonsi (2.07×10^{16} sej per capita) of Valdelsa show a certain equilibrium between local consumption and the presence of population; a high level of population density is compensated by a moderate amount of resources per capita. The high value in Valdimerse (12.90×10^{16} sej per capita) results from low population density and existence of a relevant level of exploitation of local non-renewable resources (namely a precious yellow marble).

The EIR is the emergy of the external purchased inputs supporting the system in relation to all local emergy, both renewable and non-renewable ($N+R$). A high level of the EIR represents a sort of fragility of the system because of its dependence on inputs from other economic systems. In the case of the Province of Siena, it was discovered a low level of purchased resources with respect to the local resource availability. The degree of dependence on other ecosystems shows a weakness in the competitive capacity (self-sufficiency and long-term sustainability) of a territorial system, because the availability of resources for development and maintenance is not under the system's control.

In Fig. 4, the outcomes are presented in the form of maps that show the total emergy used (U) and the environmental loading (ELR), in a grey scale, as distributed in the municipalities. Therefore, the result is an emergy geography that illustrates resource consumption via two parameters: the quantities consumed, according to their environmental costs, and the location of consumption into specific areas. Finally, the spatial organization of energy metabolism of the Province of Siena, that feeds on fluxes with different intensities instead of homogeneously, is presented in order to stimulate a scientific discussion on sustainability and economic competitiveness issues.

The map of total emergy used (U) shows areas with high, medium and low levels of emergy flows. The map of the ELR points out a few critical areas as well as those areas with optimal conditions of resource exploitation; the municipalities shown in white are those with values of ELR equal to or lower than 1 (renewable environmental resources exceed non-renewable). Both maps show, at a

Table 3
Emergy flows and indexes in Siena Province: neighbourhoods and municipalities—SPIn-Eco project

Area	*R* sej/yr $\times 10^{18}$	*N* sej/yr $\times 10^{18}$	*F* sej/yr $\times 10^{18}$	*U* sej/yr $\times 10^{18}$	ED *U*/area $\times 10^{12}$	EpP *U*/pop $\times 10^{16}$	ELR $N+F/R$ —	EIR F/L —
Province of Siena	1.43E+03	6.03+03	3.71E+03	1.12E+04	2.92	4.42	6.80	0.50
Valdarbia	153.29	1376.40	284.95	1814.65	3.39	8.18	10.84	0.19
Asciano	58.66	538.00	106.94	703.59	3.26	11.05	10.99	0.18
Buonconvento	19.01	27.01	26.95	72.97	1.13	2.31	2.84	0.59
Monteroni	31.46	40.01	74.71	146.18	1.38	2.09	3.65	1.05
Rapolano	29.77	768.55	66.15	864.48	10.41	18.16	28.03	0.08
San Giovanni d'Asso	14.39	2.84	10.19	27.42	0.41	3.06	0.91	0.59
Valdichiana	247.61	1477.85	896.48	2621.94	3.79	4.43	9.59	0.52
Cetona	15.67	2.36	37.89	55.92	1.05	1.95	2.57	2.10
Chianciano	25.68	3.65	79.79	109.12	2.99	1.51	3.25	2.72
Chiusi	29.02	50.25	124.98	204.26	3.52	2.34	6.04	1.58
Montepulciano	53.71	305.52	207.36	566.58	3.42	4.08	9.55	0.58
San Casciano dei Bagni	23.64	89.15	20.87	133.66	1.46	7.36	4.65	0.19
Sarteano	16.17	89.15	38.94	144.26	1.69	3.21	7.92	0.37
Sinalunga	40.91	435.13	216.71	692.75	8.81	5.93	15.93	0.46
Torrita	26.19	3.29	146.33	175.81	3.01	2.49	5.71	4.96
Trequanda	16.62	499.34	23.62	539.59	8.42	38.21	31.46	0.05
Chianti Senese	104.89	610.68	165.86	881.42	1.81	6.27	7.40	0.23
Castellina in Chianti	15.25	121.55	37.69	174.49	1.75	6.66	10.44	0.28
Castelnuovo Ber.	44.00	311.65	64.29	419.94	2.37	5.69	8.54	0.18
Gaiole in Chianti	27.88	173.67	33.16	234.72	1.82	9.80	7.42	0.16
Radda in Chianti	17.76	3.81	30.71	52.28	0.65	3.12	1.94	1.42
Valdelsa	313.86	440.76	1142.72	1897.34	2.78	2.92	5.05	1.51
Casole	41.33	14.43	83.49	139.24	0.94	4.98	2.37	1.50
Colle val d'Elsa	75.22	126.20	243.14	444.56	4.82	2.35	4.91	1.21
Monteriggioni	39.38	187.83	221.76	448.96	4.51	5.80	10.40	0.98
Poggibonsi	58.65	104.89	405.15	568.70	8.04	2.07	8.70	2.48
Radicondoli	52.46	2.90	9.81	65.17	0.49	6.68	0.24	0.18
San Gimignano	46.82	4.52	179.36	230.71	1.66	3.28	3.93	3.49
Valdimerse	165.77	1394.63	188.51	1748.91	3.43	12.90	9.55	0.12
Chiusdino	50.17	3.77	25.59	79.53	0.56	4.18	0.59	0.47
Monticiano	32.98	1.12	9.91	44.02	0.40	2.98	0.33	0.29
Murlo	27.36	2.62	22.79	52.77	0.46	2.76	0.93	0.76
Sovicille	55.25	1387.12	130.22	1572.59	10.94	19.03	27.47	0.09
Valdorcia	296.15	329.93	411.44	1037.52	1.30	4.17	2.50	0.66
Abbadia s. Salvatore	35.22	2.24	89.44	126.91	2.15	1.84	2.60	2.39
Castiglione d'Orcia	45.83	48.43	26.53	120.79	0.85	4.77	1.64	0.28
Montalcino	71.40	16.13	83.53	171.06	0.70	3.35	1.40	0.95
Piancastagnaio	41.64	2.02	55.31	98.97	1.42	2.23	1.38	1.27
Pienza	26.14	6.09	51.90	84.13	0.69	3.73	2.22	1.61
Radicofani	47.32	4.22	32.34	83.88	0.71	6.82	0.77	0.63
San Quirico d'Orcia	28.59	250.80	72.39	351.79	8.34	14.37	11.30	0.26
Siena	142.21	354.40	606.99	1103.60	9.30	2.03	6.76	1.22

glance, distinct areas with different behaviours in terms of the emergy fluxes (their intensity varies from the east side of the Province, with the highest values, to the west side, with the lowest). The layout obtained reflects the attitudes of the people living within the Province's municipalities (with their own environmental–social–economic aspects) in using resources.

Results from the emergy analysis of the Province of Siena also highlight another point: resource consumption in the Province of Siena is not very high, and is definitely lower than that of other provinces in Italy. These low levels of resource exploitation, in conjunction with the availability of natural resources, the absence of energy intensive industries, the production of electricity from geothermal power sources, the attitudes towards organic agriculture, sustainable tourism, the tradition of good practices of environmental management, the importance given by people to beautiful landscape and high-quality products like wine, enable Siena

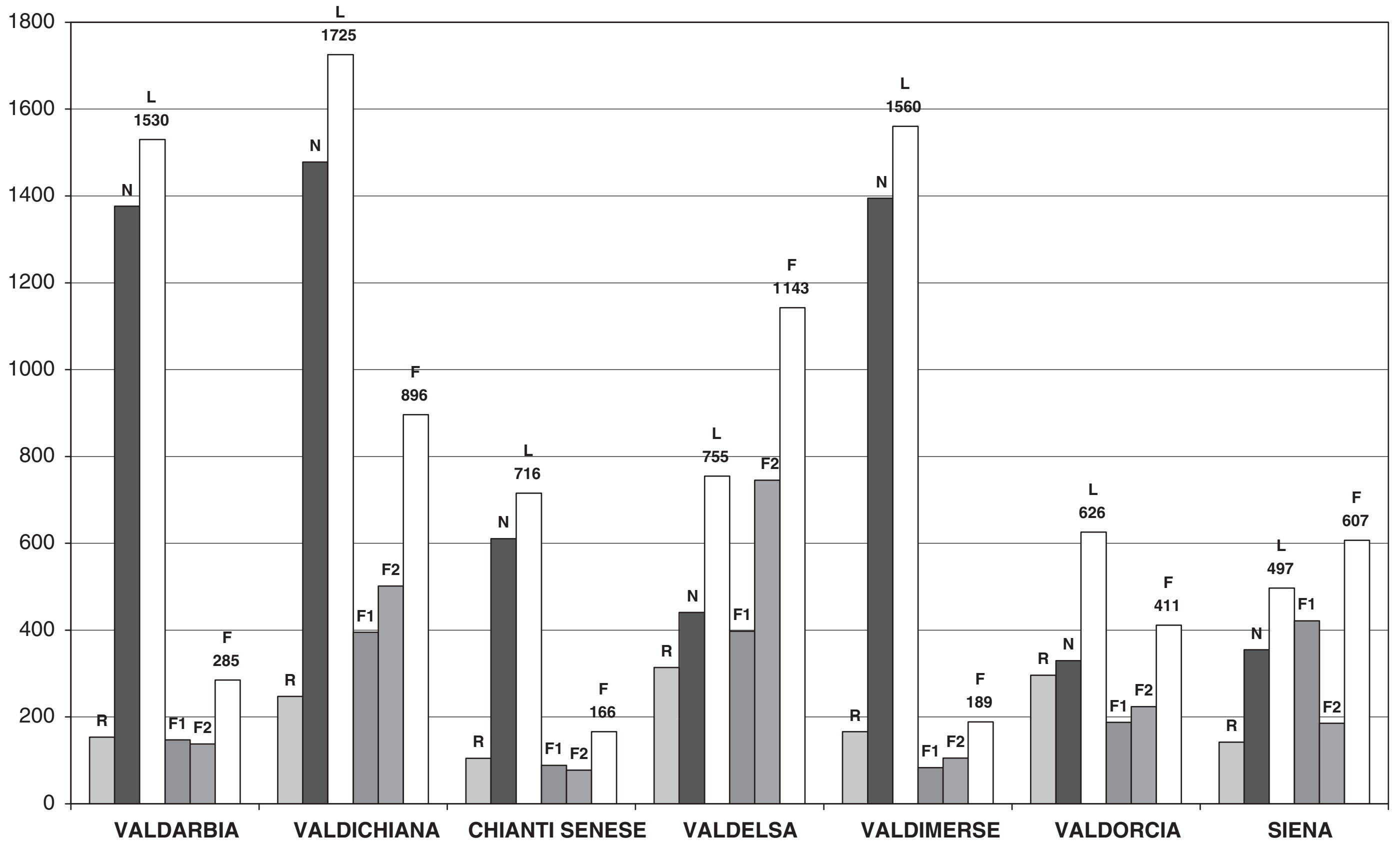

Fig. 3. Emergy flows classified as renewable *R*, non-renewable *N*, local *L* ($R+N$), imported energy *F*1, imported goods *F*2, total imports *F* ($F1+F2$) to Siena Province—SPIn-Eco project. Unit: sej $\times 10^{18}$.

to be considered a positive example of sustainability in human-dominated ecosystems and a potential reference for comparison in future regional studies.

4. Conclusion

4.1. Conclusions relative to methodology used

In order to evaluate the life-supporting functions of nature, an analysis of the flows of energy between ecological and economic systems has emerged in order to complement economic accounting (Odum, 1971, 1988; Odum and Odum, 1980, 1981). The goals of environmental management in achieving balance between the ecology and economy of integrated systems, including human settings and ecosystems with their transformation processes such as industrial and agricultural production, were assessed with emergy synthesis.

The high value of the emergy analysis is due to its ability to group different aspects of a territory and different sectors into a unique vision by referring to the following features:

- It identifies and quantifies the main inputs that allow a given system to achieve a certain level of organization and to maintain itself in a steady state.
- It focuses on the role of the environment in support of human-dominated processes, assuming solar energy as the basic primary source, directly or indirectly, of every product or process, and enabling any input to be translated in terms of equivalent solar energy, namely *emjoules*.
- It expands the time scale of the evaluation to include the memory of all the natural resources that have been used throughout a sequence of different processes and steps towards a final product.
- It assesses all the inputs that supply a system, especially those that are usually neglected by classic economic accounting methods, by means of a thermodynamics-based measure, giving an appraisal of the actual environmental cost of any class of resource which is not merely limited to its economic price or energetic content.
- It assesses different flows of both matter and energy in terms of sej, and allows them to be compared to each other and aggregated into classes according to their renewability or non-renewability, and to their local availability or external origin. Therefore, the importance of different sectors of activity can also be highlighted.
- It provides a comprehensive vision of urban and regional dynamics by decoding the geography of emergy flow intensities. These thermodynamic geographies show the

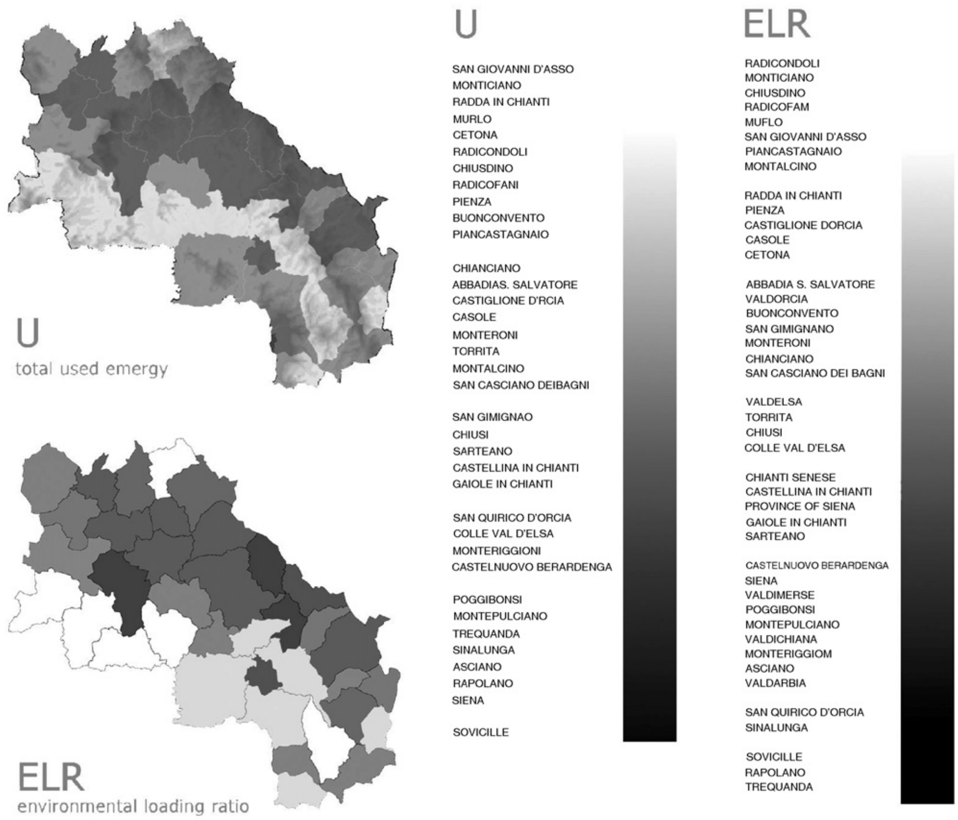

Fig. 4. The emergy geography in the municipalities of the Province of Siena: total used emergy (U) and environmental loading ratio (ELR)—SPIn-Eco project.

behaviour of the territorial system throughout the region in terms of resource availability and exploitation.

The emergy accounting for regional studies therefore provides information about a human system organization and its metabolism. Throughout the region under study, some areas function as nodes, with the highest intensities of resource fluxes and high levels of complexity and organization, such as cities and industrial districts, which have a high population density and many transformation processes. Other areas, with low levels of resource consumptions, function as reservoirs of natural resources and supply the existence of highly structured nodes; their role is strategic for the sustainability of the whole system.

4.2. Conclusions related to results obtained

Outcomes from the emergy accounting of the Province of Siena highlight a low level of local resource exploitation and the relative availability of natural resources. Results from each municipality enable increasing accuracy in our analysis of the Province, and point out those areas with an extreme use of resources and those with low levels of resource consumption and prevalence of renewable flows of emergy. The general equilibrium of emergy flows through the region, joined with the low consumption levels, suggest that Siena should be considered a positive example of sustainable management in human dominated ecosystems and a potential reference for comparison in future regional studies.

The emergy method has been applied in order to define geographies based on the environmental accounting of resource fluxes and their location within a territory. Different ecological and economic zones within an urban system have been shown in an attempt to understand how energy converges in the spatial context, and how multiple components interact and self-organize in a symbiotic manner during evolutionary processes. The energy characteristics of different land uses should have future implications in land use planning and management. This would involve, for example, the study of the spatial allocation and arrangement of land use activity in relation to patterns of energy flows (as proposed by Huang, 1998).

The accuracy of emergy evaluation and geographies could be further increased by improving methods and policies for data collection, resource consumption monitoring and location-based services. Geographic information systems (GIS) could be improved as well in order to display the spatial distribution of flows of energy and matter that supply human systems and inform design and planning practices. A comprehensive vision of regional complex dynamics is then expected in order to achieve synthetic and clear outcomes. This approach seeks to formulate areas of analysis, operative frameworks and strategic layers of action, visualizing possible key questions for future sustainable development; its focus on both spatial and temporal patterns refers to a new thermodynamic approach to regional studies.

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