EMERGY SYNTHESIS 3:
Theory and Applications of the Emergy Methodology

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ABSTRACT

The natural park area of Roccamonfina (Central Italy) was investigated by means of the combined use of the emergy synthesis method and Geographical Information System (GIS), in order to evaluate the environmental and economic resources in the area, as well as the environmental support driving the sustainable development of the local economy and natural environment. Two and 3-dimensional maps of the investigated area were developed to assess geological and hydrological features, land use, natural park planning and management, and human settlements. Statistical data from local and regional databases were used to monitor the matter and energy flows, as well as the main economic activities and income sources. Forest production sectors in terms of wood and chestnuts have also been investigated. Natural and economic flows have been converted to emergy units and emergy-based indicators were calculated in order to evaluate the dynamics of the local system from a holistic point of view. Results suggest that compatibility between local economic activities and increasing environmental protection is possible, provided that the population density is relatively low and that local renewable sources are used to a significant extent.

INTRODUCTION

Several methods used for environmental analysis are characterized by a purely qualitative approach in determining the effects of human activities on ecosystems. Most of these approaches rely on an erroneous evaluation of the “natural capital”, which is considered to lack any market value. The natural capital is therefore underestimated, or even excluded, from conventional neo-classical economic assessments (IWAES, 1998; Herendeen, 2000). Ecological Economics, on the contrary, faces the challenges imposed by the bio-physical laws ruling the planet and considers economic systems as subsystems, “open” in thermodynamics terms and belonging to a broader ecological system (Ruth, 1993). Such an approach implies the awareness of limits to economic growth, for the economic system completely relies on resource inputs coming from the natural system. Some authors estimated the ecological and economic values of services supplied both by the environment and the natural capital, using merely economic approaches or more integrated economic and physical approaches (Costanza et al., 1997; Pimentel et al., 1997; Patterson, 2002; Tainter et al., 2003). In so doing, an assessment of the indirect “economic value” of services supplied by the environment has been made possible. For instance, a tree produces, during 50 years of life, $31,000 in terms of oxygen, $62,000 in terms of pollution mitigation, $31,000 in terms of erosion control and $37,000 in terms of recycling (Costanza et al., 1997). Its direct market value, as wood and wood pulp, is far less important. However, apart from a few monetary estimates, the indirect economic value of natural capital is generally ignored or undervalued in almost all the conventional and official accounting systems (as pointed out by Cialani and Giannantoni, 2001). It is of paramount importance to revise the models of
environmental analysis in order to include the natural capital, along with other productive factors, namely human capital and labour. In recent years, some new thermodynamics models have been applied to productive and territorial systems, including the emergy synthesis method. It deals with energy evaluation and environmental sustainability assessment outside of the neoclassical economic framework. Emergy analysis is a methodology rooted in thermodynamics and systems science, which is able to give a scientific framework to the evaluation of the organisation, complexity and sustainability characteristics of a specific system (Odum, 1988, 1996; Brown and Ulgiati, 2001, 2004). In particular, emergy analysis allows the quantitative assessment of economic, ecological and thermodynamics variables on a common basis, namely the environmental work provided directly and indirectly by the biosphere.

This work deals with the emergy analysis of Roccamonfina (Central Italy) municipal territory, located within the large crater of an extinct volcano and included within a Regional Natural Park. Such a district has important naturalistic, geological and archaeological features that appear to be putting severe constraints on several different strategies for regional economic development. The specific objective of this study is to integrate the survey of the district, carried out using Geographic Information System (GIS) tools, with a thermodynamics analysis of its environmental resources.

MATERIALS AND METHODS

GIS Analysis

A geographic information system named “GIS-Roccamonfina” was created using ArcView GIS software (http://www.esri.com/). “GIS-Roccamonfina” was used to highlight spatial resources, both natural and anthropogenic, characterizing the Roccamonfina Regional Park, with special reference to the Roccamonfina volcano and the Roccamonfina municipal territory. The GIS was used as a support tool for the emergy evaluation. The first step consisted of making cartographic and aerophotographic maps, from which some thematic layers have been vectorized (boundaries, roads, buildings, contour lines, etc.). In addition, raster maps were developed from four topographic maps and four aerial photographs of 1:25,000 scale, geo-referenced by affine transformation. The geometric elements belonging to each thematic layer (dots, curves, polygons) were linked to thematic databases. Afterwards, an urban and environmental characterization of the area was created by overlapping the raster background with vector layers. A map describing seven different land uses in the municipal territory of Roccamonfina and a geo-lithological map of the Roccamonfina volcano were also made. Contour lines and quoted points were vectorized and provided with an elevation value in order to make a three-dimensional map of the area by the triangular interpolation known as “Triangulated Irregular Network” (Burrough, 1998) as shown in Figure 1.

![Figure 1. Volcano of Roccamonfina: Digital Elevation Model (T.I.N.).](image)
Vector bi-dimensional themes (roads, buildings, etc.) were converted to vector three-dimensional files and merged with the digital elevation model (DEM). Finally, the two and three-dimensional maps and related databases were used for a quantitative spatial analysis of environmental resources.

**Emergy Analysis**

The main steps of the emergy analysis carried out during this study were:

1. Identification of the boundaries of the study area.
2. Modeling of the thermodynamic system by means of an energy flowchart (economic and natural resources).
3. Calculation of matter and energy flows.
4. Conversion of matter and energy flows into Solar Equivalent Energy (emergy) flows by means of suitable Transformities, updated to the new baseline for biosphere flows (total energy driving the biosphere: 15.83 E24 sej/year (Brown and Ulgiati, 2004).
5. Balance of the total emergy used by the system.
6. Calculation of new transformities and environmental sustainability indices.

The boundaries of the investigated area correspond to the administrative area of the municipality of Roccamonfina. The formal description of the energy and matter flows through the system is shown in Figure 2, using the symbolic energy language developed by Odum (1996).

The data used to implement the emergy analysis were obtained from: a) the annual handbooks of the Italian Institute of Statistics (ISTAT), b) a local database (ANCITEL), c) the analysis made through the “GIS-Roccamonfina” and finally, d) from direct evaluations of the study site. All data refer to the year 2000. The integration between GIS and emergy analyses allows us to understand the role of the environment in the economic dynamics of the investigated area. These aspects are usually not included in the official databases and statistics.

**RESULTS AND DISCUSSION**

The general framework of the area is consistent with a district characterized by agro-forestry activities with low chemical and mechanical input and lacking productive plants with high environmental impact. The investigated area does not experience water shortages, due to the presence of ground water and many springs that surround the volcanic caldera. Nevertheless, the area is almost totally dependent on external inputs such as electricity and fossil fuel, as well as machinery, food items and consumer goods. This dependence on external inputs results in a lack of complete sustainability, although the overall performance of the area is significantly better than the Italian average, primarily due to lower population density and low impact activities.

Tables 1, 2, and 3 show the main input and output flows respectively of the entire Roccamonfina area and for two main production sectors (chestnut and timber production), expressed both in raw units (J, g) and emergy units.

Locally available free environmental inputs (mainly the chemical potential of rain and the deep heat flow) account for about 9.7% of total emergy supporting the Roccamonfina economic and natural system (Table 1). An additional contribution of about 10.6% comes from local nonrenewable flows of topsoil used up and water from underground storages. The renewable and non-renewable flows combined represent about 20.3% of the total emergy use in the area. The local emergy contribution in this area is lower than the national average for the same year, which is about 25%. It reflects, however, a decreasing nationwide trend, from the 44% in the year 1984 to the 23% of the year 2002 (Cialani et al., 2004), which can be attributed to the increased use of emergy from imported fossil fuels in the last two decades. In fact, fossil fuels and electricity account for about 31.9% of the total
energy supporting the local economy of Roccamonfina, due to a substantial demand for transport, domestic uses, and agricultural machinery (mainly for forestry). The emergy of imported goods (including food items) is not very large (8.1%). Total imports (fuels and goods together) account for about 40% of total emergy use, the highest emergy flow to the system.

Services associated with the production and supply of fuels and goods account for about 28.8% (39.7% if services for governmental activities are included). The emergy flow associated with services was estimated globally, based on the cost of all imported items (including fuels), as well as on the amount of taxes paid to local and national governments for activities supporting the life of the local community (school, health services, governmental offices, etc.). Local labor was not included in this total in order to avoid double counting since it is supported by both the local environmental emergy flows and the imported flows of energy and goods, which were previously accounted for. The large flow of emergy supporting services (an amount practically equal to the amount of emergy for fuels and goods) seems to indicate a dependence of the local community on support from the larger national economy.

Chestnut production (Table 2) uses about 62% of the total area of Roccamonfina and is the largest economic activity based on local resources. Since chestnut harvesting is generally performed in the month of October, it is clearly a seasonal activity, to which a large fraction of labor is supplied by part-time workers. Workers invest about 15% of their yearly working time in this activity. Oak harvesting (Table 3) is less seasonal than chestnut harvesting, but it is also a part-time activity for several of the local people. Only 8.5% of the Park area is dedicated to oak production. Environmental emergy flows are, as expected, very important inputs to the local sub-sectors of chestnut and oak production, accounting for 56.1% and 43.4%, respectively. Labor and services, evaluated respectively
### Table 1. Emergy flows supporting the natural park of Roccamonfina in the year 2000.

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Unit</th>
<th>Amount (unit/yr)</th>
<th>Solar Transformity (sej/unit)</th>
<th>Ref. Transf</th>
<th>Solar Emergy (sej/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Sunlight</td>
<td>J/yr</td>
<td>1.31E+17</td>
<td>1.00E+00</td>
<td>[a]</td>
<td>1.31E+17</td>
</tr>
<tr>
<td>2</td>
<td>Wind (kinetic energy)</td>
<td>J/yr</td>
<td>2.72E+14</td>
<td>2.51E+03</td>
<td>[b]</td>
<td>6.84E+17</td>
</tr>
<tr>
<td>3</td>
<td>Earth cycle (thermal energy)</td>
<td>J/yr</td>
<td>5.29E+13</td>
<td>5.76E+04</td>
<td>[b]</td>
<td>3.05E+18</td>
</tr>
<tr>
<td>4</td>
<td>Rain (chemical potential energy)</td>
<td>J/yr</td>
<td>5.93E+13</td>
<td>3.05E+04</td>
<td>[b]</td>
<td>1.81E+18</td>
</tr>
<tr>
<td>5</td>
<td>Rain (geopotential energy)</td>
<td>J/yr</td>
<td>1.08E+14</td>
<td>1.76E+04</td>
<td>[b]</td>
<td>1.90E+18</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Renewable inputs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Net loss of topsoil</td>
<td>J/yr</td>
<td>2.47E+12</td>
<td>1.05E+05</td>
<td>[c]</td>
<td>2.58E+17</td>
</tr>
<tr>
<td>7</td>
<td>Water (from underground reservoirs)</td>
<td>J/yr</td>
<td>1.69E+12</td>
<td>3.05E+06</td>
<td>[f]</td>
<td>5.15E+18</td>
</tr>
<tr>
<td></td>
<td><strong>Nonrenewable inputs from within the area</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Gasoline for agriculture</td>
<td>J/yr</td>
<td>1.19E+11</td>
<td>1.11E+05</td>
<td>[b]</td>
<td>1.32E+16</td>
</tr>
<tr>
<td>9</td>
<td>Diesel for agriculture</td>
<td>J/yr</td>
<td>3.68E+12</td>
<td>9.39E+04</td>
<td>[d]</td>
<td>3.45E+17</td>
</tr>
<tr>
<td>10</td>
<td>Gasoline for transport</td>
<td>J/yr</td>
<td>3.09E+13</td>
<td>1.11E+05</td>
<td>[b]</td>
<td>3.42E+18</td>
</tr>
<tr>
<td>11</td>
<td>Diesel for transport</td>
<td>J/yr</td>
<td>1.53E+13</td>
<td>1.11E+05</td>
<td>[b]</td>
<td>1.69E+18</td>
</tr>
<tr>
<td>12</td>
<td>Natural gas</td>
<td>J/yr</td>
<td>4.34E+13</td>
<td>8.75E+04</td>
<td>[i]</td>
<td>3.80E+18</td>
</tr>
<tr>
<td>13</td>
<td>Electricity</td>
<td>J/yr</td>
<td>2.79E+13</td>
<td>2.51E+05</td>
<td>[f]</td>
<td>7.01E+18</td>
</tr>
<tr>
<td>14</td>
<td>Agricultural machinery (steel)</td>
<td>g/yr</td>
<td>8.26E+05</td>
<td>1.12E+10</td>
<td>[e]</td>
<td>9.28E+15</td>
</tr>
<tr>
<td>15</td>
<td>Agric. machinery (plastic and tires)</td>
<td>g/yr</td>
<td>9.18E+04</td>
<td>7.21E+09</td>
<td>[e]</td>
<td>6.62E+14</td>
</tr>
<tr>
<td>16</td>
<td>Transport machinery (steel)</td>
<td>g/yr</td>
<td>9.36E+05</td>
<td>1.12E+10</td>
<td>[e]</td>
<td>1.05E+16</td>
</tr>
<tr>
<td>17</td>
<td>Transport machinery (plastic and tires)</td>
<td>g/yr</td>
<td>1.04E+05</td>
<td>7.21E+09</td>
<td>[e]</td>
<td>7.50E+14</td>
</tr>
<tr>
<td>18</td>
<td>Textiles</td>
<td>J/yr</td>
<td>1.81E+11</td>
<td>6.37E+06</td>
<td>[h]</td>
<td>1.16E+18</td>
</tr>
<tr>
<td>19</td>
<td>Food items</td>
<td>J/yr</td>
<td>1.75E+13</td>
<td>1.68E+05</td>
<td>[d]</td>
<td>2.94E+18</td>
</tr>
<tr>
<td>20</td>
<td>Services associated to imports</td>
<td>€/yr</td>
<td>4.88E+06</td>
<td>3.01E+12</td>
<td>[g]</td>
<td>1.47E+19</td>
</tr>
<tr>
<td>21</td>
<td>Taxes paid to central government</td>
<td>€/yr</td>
<td>1.85E+06</td>
<td>3.01E+12</td>
<td>[g]</td>
<td>5.56E+18</td>
</tr>
<tr>
<td></td>
<td><strong>Different kinds of products, area level</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Gross economic product of area</td>
<td>€/yr</td>
<td>4.01E+07</td>
<td>1.27E+12</td>
<td>[l]</td>
<td>5.10E+19</td>
</tr>
<tr>
<td>23</td>
<td>People supported for one year</td>
<td>#</td>
<td>3.82E+03</td>
<td>1.33E+16</td>
<td>[m]</td>
<td>5.10E+19</td>
</tr>
</tbody>
</table>

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References for transformities

[a] By definition.
[d] Our estimate.
[e] Odum and Odum, 1983.
[g] Cialani et al., 2004; average for Italy last 10 years.
[i] Bargigli et al., 2003.
[l] Emergy per € of Gross Local Product; seJ/€; this study.
[m] Emergy per person per year; seJ/person/yr; this study.
as 33.0% and 49.8% of the total emergy used for chestnuts and oaks, also play a significant role in supporting the local economy. The larger importance of labor in oak production overshadows other smaller emergy inflows, making it difficult to compare the use of these minor flows between chestnut and oak production. Machinery, fuels and topsoil do not represent very significant emergy flows for both production activities.

Table 2. Emergy evaluation of chestnut forest production in the natural park of Roccamonfina, year 2000.

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Unit</th>
<th>Amount (unit/yr)</th>
<th>Solar Transformity (seJ/unit)</th>
<th>Ref. for Transf.</th>
<th>Solar Emergy (seJ/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sunlight</td>
<td>J/yr</td>
<td>8.15E+16</td>
<td>1.00E+00</td>
<td>[a]</td>
<td>8.15E+16</td>
</tr>
<tr>
<td>2</td>
<td>Wind (kinetic energy)</td>
<td>J/yr</td>
<td>1.70E+14</td>
<td>2.51E+03</td>
<td>[b]</td>
<td>4.27E+17</td>
</tr>
<tr>
<td>3</td>
<td>Earth cycle (thermal energy)</td>
<td>J/yr</td>
<td>3.30E+13</td>
<td>5.76E+04</td>
<td>[b]</td>
<td>1.90E+18</td>
</tr>
<tr>
<td>4</td>
<td>Rain (chemical potential energy)</td>
<td>J/yr</td>
<td>3.70E+13</td>
<td>3.05E+04</td>
<td>[b]</td>
<td>1.13E+18</td>
</tr>
<tr>
<td>5</td>
<td>Rain (geopotential energy)</td>
<td>J/yr</td>
<td>6.74E+13</td>
<td>1.76E+04</td>
<td>[b]</td>
<td>1.18E+18</td>
</tr>
</tbody>
</table>

(All flows are evaluated on a yearly basis. Numbers in the first column refer to calculation procedures in the Appendix II)

**Renewable inputs**

| 6   | Net loss of topsoil            | J/yr | 2.42E+12         | 1.05E+05                     | [c]             | 2.54E+17               |

**Imports and outside sources**

| 7   | Gasoline for agriculture       | J/yr | 1.13E+11         | 1.11E+05                     | [b]             | 1.24E+16               |
| 9   | Agricultural machinery (steel) | g/yr | 8.26E+05         | 1.12E+10                     | [e]             | 9.28E+15               |
| 10  | Agric. machinery (plastic and tires) | g/yr | 9.18E+04 | 7.21E+09 | [e]             | 6.62E+14               |
| 11.1| Human labour                   | work/yr | 1.41E+02 | 1.18E+16 | [f]             | 1.67E+18               |
| 11.2| Services for imports           | €/yr | 4.96E+04         | 3.01E+12                     | [i]             | 1.49E+17               |

**Total Production, chestnut**

| 12.1| Total production for outside market | g/yr | 5.35E+09 | 1.03E+09 | [g]             | 5.51E+18               |
| 12.2| Total production, Joules        | J/yr | 3.58E+13         | 1.54E+05                     | [h]             | 5.51E+18               |
| 12.3| Total market value of production | €/yr | 4.54E+06         | 1.21E+12                     | [i]             | 5.51E+18               |

References for Transformities

| [a]  | By definition.                  | [f]  | Emergy per person per year; seJ/person/yr; this study. |
| [b]  | Odum, 1996.                     | [g]  | Emergy per Kg of chestnut; seJ/Kg; this study.          |
| [d]  | Our estimate.                   | [i]  | Emergy per Euro of sold Product; seJ/€; this study.     |
Table 4 shows a comparison between the investigated area, mainly rural, and two selected areas with different environmental and economic characteristics: the Wine Spring Creek National Forest watershed, USA (Tilley and Swank, 2003) and the Italian economic and environmental system in the year 2000 (Cialani et al., 2004). The values of the emergy density (1.65E+12 sej m⁻² year⁻¹) and the emergy per person (1.33E+16 sej person⁻¹ year⁻¹) shown in Table 4 and compared to systems at different development levels help to estimate respectively the pressure of the economic activity on the area and the potential living standards of the municipality in terms of availability of resources and goods. The environmental loading ratio (ELR = 9.31) and the emergy indicator of sustainability (ESI = 0.13) reflect a larger use of local renewable resources in the investigated area, compared to Italian.

### Table 4. Emergy evaluation of wood production in the natural park of Roccamonfina, year 2000.

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Unit (unit/yr)</th>
<th>Solar (sej/unit)</th>
<th>Ref. Transf. (sej/yr)</th>
<th>Solar Emergy (sej/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sunlight</td>
<td>J/yr</td>
<td>1.11E+16</td>
<td></td>
<td>1.11E+16</td>
</tr>
<tr>
<td>2</td>
<td>Wind (kinetic energy)</td>
<td>J/yr</td>
<td>2.31E+13</td>
<td></td>
<td>5.82E+16</td>
</tr>
<tr>
<td>3</td>
<td>Earth cycle (thermal energy)</td>
<td>J/yr</td>
<td>4.50E+12</td>
<td></td>
<td>2.59E+17</td>
</tr>
<tr>
<td>4</td>
<td>Rain (chemical potential energy)</td>
<td>J/yr</td>
<td>5.04E+12</td>
<td></td>
<td>1.54E+17</td>
</tr>
<tr>
<td>5</td>
<td>Rain (geopotential energy)</td>
<td>J/yr</td>
<td>9.18E+12</td>
<td></td>
<td>1.61E+17</td>
</tr>
</tbody>
</table>

### Renewable inputs

- 1 Sunlight
- 2 Wind (kinetic energy)
- 3 Earth cycle (thermal energy)
- 4 Rain (chemical potential energy)
- 5 Rain (geopotential energy)

### Nonrenewable inputs from within the area

- 6 Net loss of topsoil
- 7 Gasoline for agriculture
- 8 Diesel for agriculture
- 9 Agricultural machinery (steel)
- 10 Agricultural machinery (plastic and tires)
- 11 Human labour
- 12 Services for imports

### Forest production, wood

- 12.1 Total production for outside market
- 12.2 Total production, Joules
- 12.3 Total market value of production

### References for transformities

- [a] By definition.
- [b] Odum, 1996.
- [d] Our estimate.
- [e] Odum and Odum, 1983.
- [f] Emergy per person per year; seJ/person/yr; this study.
- [g] Emergy per g of wood; seJ/g; this study.
- [h] Emergy per joule of wood; seJ/J; this study.
- [i] Emergy per € of sold Product; seJ/€; this study.
- [l] Cialani et al., 2004. Average value last 10 years.
averages. In fact, although Italy benefits from 25% indigenous resources, this figure mainly accounts for the nonrenewable emergy of minerals, which translates into a higher ELR. The area is still highly dependent on purchased inputs in terms of energy supply (electricity and fossil fuel).

The forestry economic value is exclusively based on chestnut and oak wood production, obtained by means of a low input traditional technique. Table 5 compares the local subsystems of wood and chestnut production with an industrialized corn production system in Italy (Ulgiati and Sciubba, 2003). Both production sectors do not require high-chemical input or intensive mechanization. In addition, the cover crop practice, widely used in the area, contributes to the reduction of soil erosion. Small soil surfaces are devoted to a low chemical input horticulture, mainly to meet family needs. The exploitation of the chestnut sector provides an annual income of 4.54E+06 € (Table 2). In addition, the wood sector provides a constant annual income of 1.84E+05 € (Table 3). The environmental loading ratio and emergy sustainability indicator values (Table 5) confirm the relatively good sustainability of chestnut and wood production in the park area and a notable difference compared to Italian industrialized corn production.

CONCLUSION

The combined use of emergy synthesis and geographical information systems (GIS) is capable of providing synergic information on the dynamics of human-dominated systems at any level. Environmental and landscape information from the GIS and economic and social information from

<table>
<thead>
<tr>
<th>Item</th>
<th>Item</th>
<th>Unit</th>
<th>Wine Spring Creek (North Carolina, USA)*</th>
<th>Roccamonfina (Italy)</th>
<th>Italy(^\text{§})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Characteristics of system</td>
<td>Fully environmental</td>
<td>Rural</td>
<td>National industrialized economy</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Area</td>
<td>m(^2)</td>
<td>1.13E+07</td>
<td>3.09E+07</td>
<td>3.01E+11</td>
</tr>
<tr>
<td>2</td>
<td>Population of area</td>
<td>people</td>
<td>0.00E+00</td>
<td>3.82E+03</td>
<td>5.70E+07</td>
</tr>
<tr>
<td>3</td>
<td>Wood produced</td>
<td>J</td>
<td>4.10E+09</td>
<td>2.77E+13</td>
<td>n.a.</td>
</tr>
<tr>
<td>4</td>
<td>Fraction derived from local sources, renewable and nonrenewable</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Loading Ratio (ELR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>0.93</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Ratio (ELR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Emergy density</td>
<td>seJ/m(^2)/yr</td>
<td>2.13E+08</td>
<td>1.65E+12</td>
<td>7.21E+12</td>
</tr>
<tr>
<td>7</td>
<td>Emergy use per person</td>
<td>seJ/person/yr</td>
<td>n.a.</td>
<td>1.33E+16</td>
<td>3.75E+16</td>
</tr>
<tr>
<td>8</td>
<td>Emergy Yield Ratio (EYR)</td>
<td></td>
<td>2.20</td>
<td>1.25</td>
<td>1.35</td>
</tr>
<tr>
<td>9</td>
<td>Emergy/GDP ratio</td>
<td>SeJ/€</td>
<td>n.a.</td>
<td>1.27E+12</td>
<td>1.94E+12</td>
</tr>
<tr>
<td>10</td>
<td>Sustainability index (ESI)</td>
<td></td>
<td>5.24</td>
<td>0.13</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\(^*\) Tilley and Swank, 2003
\(^\text{§}\) Cialani et al., 2004

-318-
Table 5. Comparison of selected photosynthetic production systems.

<table>
<thead>
<tr>
<th>Item</th>
<th>Name of the flow</th>
<th>Wood production (Roccamonfina, 2000)</th>
<th>Chestnut production (Roccamonfina, 2000)</th>
<th>Corn (Italy, 2000)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fraction derived from local sources</td>
<td>0.57</td>
<td>0.67</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>Environmental Loading Ratio (ELR)</td>
<td>0.87</td>
<td>0.60</td>
<td>7.42</td>
</tr>
<tr>
<td>3</td>
<td>EMpower density (seJ/m²/yr)</td>
<td>3.86E+11</td>
<td>2.94E+11</td>
<td>4.70E+11</td>
</tr>
<tr>
<td>4</td>
<td>Energy Yield Ratio (EYR)</td>
<td>1.98</td>
<td>2.63</td>
<td>1.20</td>
</tr>
<tr>
<td>5</td>
<td>Emergy/Money Value of Product (seJ/€)</td>
<td>5.26E+12</td>
<td>1.21E+12</td>
<td>5.85E+12</td>
</tr>
<tr>
<td>6</td>
<td>Sustainability index (EYR/ELR)</td>
<td>2.27</td>
<td>4.41</td>
<td>0.16</td>
</tr>
</tbody>
</table>


statistical databases can be fruitfully integrated within the conceptual framework of emergy synthesis, contributing to local policy making, as well as to understanding the relationship between the local and national economies. Results suggest that compatibility between some economic activities and increasing environmental protection is possible, provided that the population density is relatively low and that local renewable sources are used to a considerable extent. Sustainable economic activities can provide economic support to the local population, thus preventing people from abandoning the area for better living conditions. This relatively favorable situation could be further improved by starting the procedure for EMAS and ISO 14001 (Eco Management and Audit Scheme, International Organization for Standardization) certifications in the Roccamonfina area. As a consequence of this voluntary process for environmental certification the environmental protection level of the area could be increased and its natural capital reinforced.

REFERENCES


Campania Agro-Meteorological network, Personal communication


Municipality of Roccamonfina, Government of Italy, 2004, Personal communication


APPENDIX I: CALCULATIONS FOR TABLE 1

1. Solar energy
   - Land Area = 3.09E+07 m\(^2\) [Ancitel database]
   - Insolation = 1.26E+02 Kcal/cm\(^2\)/yr [Campania Agro-Meteorological network]
   - Albedo of land = 0.20 (fraction of solar energy reflected) [Henning, 1989]
   - Land Energy (J/yr) = (land area)(avg. insolation)(1-albedo) = 1.31E+17 J/yr

2. Wind kinetic energy
   - Wind energy on land = 8.80E+06 J/m\(^2\)/yr [Our estimate]
   - (Wind energy on land)(area) = 2.72E+14 J/yr

3. Earth cycle (steady state uplift balanced by erosion)
   - Heat flow per area = 1.71E+06 J/m\(^2\)/yr [Zito, 2003]
   - Land area = 3.09E+07 m\(^2\) [Ancitel database]
   - Energy (J/yr) = (land area)(heat flow per area) = 5.29E+13 J/yr

4. Rain chemical potential (evapotranspired water)
   - Land Area = 3.09E+07 m\(^2\) [Ancitel database]
   - Rain (average) = 0.97 m/yr [Campania Agro-Meteorological network]
   - Evapotranspiration rate from land = 0.400 (40% of total rainfall) [ISTAT, 1991]
   - Evapotranspired water = 0.39 m/yr = 1.20E+13 g/yr
   - Gibbs energy of water = 4.94 J/g [Odum, 1996]
   - Total energy input to photosynthesis on land, measured by Gibbs energy of evapotranspired water = 5.93E+13 J/yr

5. Rain, geopotential energy (runoff)
   - Area = 3.09E+07 m\(^2\) [Ancitel database]
   - Rainfall = 0.97 m/yr
   - Average Elevation = 612 m [Ancitel database]
   - Runoff rate = 0.600 (60% of total rainfall)
   - Total runoff water = 0.58 m/yr
   - Total mass of water = 1.80E+13 g/yr
   - Energy(J/yr) = (area)(runoff rate)(water density)(avg. elevation)(gravity) = 1.08E+14 J/yr

6. Loss of topsoil
   (areas with mature untouched vegetation are assumed to have little net gain or loss of topsoil)
   - Farmed area subject to erosion = 1.96E+07 m\(^2\) [Ancitel database]
   - Erosion rate of farmed area = 2.00E+02 g/m\(^2\)/yr
   - % organic in soil = 3.00% [Odum, 1996]
   - Ener. cont. per g organic = 5.00 kcal/g [Odum, 1996]
   - Net loss = (farmed area)(erosion rate) = 3.93E+09 g/yr
   - Energy of net loss (J/yr) = (net loss)(% org.in soil)(5.0 Kcal/g)(4186 J/kcal) = 2.47E+12 J/yr

7. Water from underground reservoirs
   - Total used = 3.42E+11 g/yr [Ancitel database]
Gibbs energy of water  = 4.94
Total free energy in water  = 1.69E+12 J/yr

8. Gasoline for agriculture
Total used  = 3.40E+03 liters/year
HHV of gasoline  = 3.51E+07 J/liter
Total energy from gasoline  = 1.19E+11 J/yr

9. Diesel for agriculture
Total used  = 1.03E+05 liters/year
HHV of gasoline  = 3.56E+07 J/liter
Total energy from gasoline  = 3.68E+12 J/yr

10. Gasoline for transport
Total used  = 8.80E+05 liters/year
HHV of gasoline  = 3.51E+07 J/liter
Total energy from gasoline  = 3.09E+13 J/yr

11. Diesel for transport
Total used  = 4.30E+05 liters/year
HHV of gasoline  = 3.56E+07 J/liter
Total energy from gasoline  = 1.53E+13 J/yr

12. Natural gas for domestic heating (70 % of demand met by means of local wood)
Total used  = 1.12E+06 m3 NG/yr
Mass of natural gas  = 7.84E+05 Kg/yr
Total energy  = 4.34E+13 J/yr

13. Electricity
Total used  = 7.75E+06 KWh/yr
Energy (J/yr)  = (Yearly Import)(3.6E+6 J/KWh)  = 2.79E+13 J/yr

14. Agricultural machinery (steel)
Number of tractors  = 62 units
Number of agric. Motorcycles  = 19 units
Average mass of tractors  = 9.00E+03 kg
Average mass of motorcycles  = 1.80E+02 kg
Fraction of machinery that is steel  = 0.90
Average lifetime  = 10.00 yrs
Total steel in machinery  = 8.26E+05 g/yr

15. Agricultural machinery (plastic material and tires)
Number of tractors  = 62 units
Number of agric. Motorcycles  = 19 units
Average mass of tractors  = 9.00E+03 kg
Average mass of motorcycles  = 1.80E+02 kg
Fraction of machinery that is plastic  = 0.10
Average lifetime  = 10.00 yrs
Total plastics in machinery  = 9.18E+04 g/yr
16. **Transport machinery** (steel)

Number of cars = 1843 units [Ancitel database]
Number of trucks and buses = 241 units [Ancitel database]
Average mass of cars = 4.00E+02 kg
Average mass of trucks & buses = 1.00E+04 kg
Fraction of machinery is steel = 0.90 [Our assumption]
Average lifetime = 10.00 yr [Our assumption]
Total steel in transport machinery = 9.36E+05 g/yr

17. **Transport machinery** (plastic material and tires)

Number of cars = 1843 units [Our assumption]
Number of trucks and buses = 241 units [Our assumption]
Average mass of cars = 4.00E+02 kg
Average mass of trucks & buses = 1.00E+04 kg
Fraction of machinery is plastics = 0.10 [Our assumption]
Average lifetime = 10.00 yrs [Our assumption]
Total steel in transport machinery = 1.04E+05 g/yr

18. **Textiles, clothes**

Total population = 3.82E+03 persons [Ancitel database]
Average textile items per person per year = 3.00E+03 g/person/yr [Our estimate]
Total textiles, whole population = 1.15E+07 g/yr
Energy content = 1.50E+07 BTU/t [Odum and Odum, 1987]
= (1.50E+7 BTU/t)(1055 J/BTU) = 1.58E+04 J/g
Total energy = 1.81E+11 J/yr

19. **Food items**

Total population = 3.82E+03 units [Ancitel database]
Average food per person per day = 6.00E+02 g/day [Our estimate]
Average food per person per year = 2.19E+05 g/yr [Our estimate]
Total import, whole population = 8.37E+08 g/yr [Our estimate]
Av. energy content of food items = 5 kcal/g
= 20930 J/g
Total energy in food items = 1.75E+13 J/yr

20. **Services associated to imports**

[globally estimated as 40% of the emergy of purchased inputs, based on the national average]
Fraction of purchased emergy input that is services = 0.30 [Est. on Italian average Cialani et al., 2004]

emergy of services = 8.74E+18 seJ/yr
Services = 4.88E+06 €/yr

21. **Taxes paid to Government** (services for central administration, schools, health services, etc)

Total paid = 1.85E+06 €/yr [Ministry of Finance]

22. **Total economic product of area**

Gross Area Product (GAP) = 4.01E+07 €/yr [Gross income available to local population]
APPENDIX II: CALCULATIONS FOR TABLE 2

1. Solar energy
   Land Area = 1.93E+07 m² [Ancitel database]
   Insolation = 1.26E+02 Kcal/cm²/yr [Campania Agro-Meteor. network]
   Albedo of land = 0.20 (fraction of solar energy reflected) [Henning, 1989]
   Land Energy (J/yr) = (land area)(avg. insolation)(1-albedo)
                       = 8.15E+16 J/yr

2. Wind kinetic energy
   Wind energy on land = 8.80E+06 J/m²/yr [ISTAT 1991]
                       = (Wind energy on land)(area)
                       = 1.70E+14 J/yr

3. Earth cycle (steady state uplift balanced by erosion)
   Heat flow per area = 1.71E+06 J/m²/yr [Zito, 2003]
   Land area = 1.93E+07 m² [Ancitel database]
   Energy (J/yr) = (land area)(heat flow per area)
                   = 3.30E+13 J/yr

4. Rain chemical potential (evapotranspired water)
   Land Area = 1.93E+07 m² [Ancitel database]
   Rain (average) = 0.97 m/yr [Campania Agro-Meteor. network]
   Evapotranspiration rate from land = 0.400 (40% of total rainfall) [ISTAT 1991]
   Evapotranspired water = 0.39 m/yr
                            = 7.49E+12 g/yr
   Gibbs energy of water = 4.94 J/g [Odum, 1996]
   Total energy input to photosynthesis on land, measured by Gibbs energy of evapotranspired water
                            = 3.70E+13 J/yr

5. Rain, geopotential energy (runoff)
   Area = 1.93E+07 m² [Ancitel database]
   Rainfall = 0.97 m/yr [Campania Agro-Meteor. network]
   Average Elevation = 612 m [Ancitel database]
   Runoff rate = 0.600 (60% of total rainfall) [ISTAT 1991]
   Total runoff water = 0.58 m/yr
   Total mass of water = 1.12E+13 g/yr
   Energy(J/yr) = (area)(runoff rate)(water density)(avg. elevation)(gravity)
                  = 6.74E+13 J/yr

6. Loss of topsoil
   (areas with mature untouched vegetation are assumed to have little net gain or loss of topsoil)
   Forest area subject to erosion = 1.93E+07 m² [Ancitel database]
   Erosion rate of forest area = 2.00E+02 g/m²/yr
   % organic in soil = 3.00% [Odum, 1996]
   Ener. cont. per g organic = 5.00 kcal/g [Odum, 1996]
   Net loss = (forest area)(erosion rate)
             = 3.86E+09 g/yr
Chapter 24. Combined Use of Energy Synthesis and GIS...

Energy of net loss (J/yr) 
\[ \text{Energy of net loss} = (\text{net loss})(\% \text{ org in soil})(5.0 \text{ Kcal/g})(4186 \text{ J/kcal}) \]
\[ = 2.42E+12 \text{ J/yr} \]

7. Gasoline for agriculture
Total used 
\[ = 3.20E+03 \text{ liters/year} \]  
[U.M.A. agency]
HHV of gasoline 
\[ = 3.51E+07 \text{ J/liter} \]  
[Ellington et al., 1993, p. 408]
Total energy from gasoline 
\[ = 1.13E+11 \]

8. Diesel for agriculture
Total used 
\[ = 9.74E+04 \text{ liters/year} \]  
[U.M.A. agency]
Higher Heating Value of gasoline 
\[ = 3.56E+07 \text{ J/liter} \]  
[Ellington et al, 1993, p. 408]
Total energy from gasoline 
\[ = 3.47E+12 \]

9. Agricultural machinery (steel)
Number of tractors 
\[ = 58 \text{ units} \]  
[U.M.A. agency]
Number of agriculture Motorcycles 
\[ = 18 \text{ units} \]  
[U.M.A. agency]
Average mass of tractors 
\[ = 9.00E+03 \text{ kg} \]
Average mass of motorcycles 
\[ = 1.80E+02 \text{ kg} \]
Fraction of machinery is steel 
\[ = 0.90 \]  
[Our assumption]
Average lifetime 
\[ = 10.00 \text{ yrs} \]  
[Our assumption]
Total steel in machinery 
\[ = 8.26E+05 \text{ g/yr} \]

10. Agricultural machinery (plastic material and tires)
Number of tractors 
\[ = 58 \text{ units} \]  
[U.M.A. agency]
Number of agriculture Motorcycles 
\[ = 18 \text{ units} \]  
[U.M.A. agency]
Average mass of tractors 
\[ = 9.00E+03 \text{ kg} \]
Average mass of motorcycles 
\[ = 1.80E+02 \text{ kg} \]
Fraction of machinery is plastics 
\[ = 0.10 \]  
[Our assumption]
Average lifetime 
\[ = 10.00 \text{ yrs} \]  
[Our assumption]
Total plastics in machinery 
\[ = 9.18E+04 \text{ g/yr} \]

11. Labor
11.1 Active in agriculture 
\[ = 939 \text{ persons} \]  
[based on statistical data, several sources]
Fraction of time spent for chestnuts 
\[ = 15\% \]  
[Our estimate]
Total labour for chestnuts 
\[ = 141 \text{ work-years} \]
11.2 Services for imports 
\[ = 8.89E+16 \text{ seJ} \]
Services 
\[ = 4.96E+04 \text{ €/yr} \]

12. Forest production, chestnut
Total production 
\[ = 5.94E+09 \text{ g/yr} \]  
[Municipality of Roccamonfina]
Caloric content of chestnut 
\[ = 1.60 \text{ Kcal/g} \]
Fraction exported to market 
\[ = 0.90 \]
Market value per Kg 
\[ = 0.85 \text{ €/Kg} \]  
[Municipality of Roccamonfina]
12.1 Production sold to outside market 
\[ = 5.35E+09 \text{ g/yr} \]
12.2 Energy of exported production 
\[ = 3.58E+13 \text{ J/yr} \]
12.3 Total market value 
\[ = 4.54E+06 \text{ €/yr} \]

APPENDIX III: CALCULATIONS FOR TABLE 3

1. Solar energy
Land Area 
\[ = 2.63E+06 \text{ m}^2 \]  
[Ancitel database]
Chapter 24. Combined Use of Energy Synthesis and GIS...

Insolation = 1.26E+02 Kcal/cm²/yr [Campania Agro-Meteo network]
Albedo of land = 0.20 (fraction of solar energy reflected) [Henning, 1989]
Land Energy (J/yr) = (land area)(avg. insolation)(1-albedo)
= 1.11E+16 J/yr

2. Wind kinetic energy
Wind energy on land = 8.80E+06 J/m²/yr [ISTAT 1991]
= (Wind energy on land)(area)
= 2.31E+13 J/yr

3. Earth cycle (steady state uplift balanced by erosion)
Heat flow per area = 1.71E+06 J/m²/yr [Zito, 2003]
Land area = 2.63E+06 m² [Ancitel database]
Energy (J/yr) = (land area)(heat flow per area)
= 4.50E+12 J/yr

4. Rain chemical potential (evapotranspired water)
Land Area = 2.63E+06 m² [Ancitel database]
Rain (average) = 0.97 m/yr [Campania Agro-Meteo network]
Evapotranspiration rate from land=0.400 (40% of total rainfall) [ISTAT 1991]
Evapotranspired water = 0.39 m/yr
= 1.02E+12 g/yr
Gibbs energy of water = 4.94 J/g [Odum, 1996]
Total energy input to photosynthesis on land, measured by Gibbs energy of evapotranspired water
= 5.04E+12 J/yr

5. Rain, geopotential energy (runoff)
Area = 2.63E+06 m² [Ancitel database]
Rainfall = 0.97 m/yr [Campania Agro-Meteo network]
Average Elevation = 612 m [Ancitel database]
Runoff rate = 0.600 (60% of total rainfall) [ISTAT 1991]
Total runoff water = 0.58 m/yr
Total mass of water = 1.53E+12 g/yr
Energy(J/yr) = (area)(runoff rate)(water density)(avg. elevation)(gravity)
= 9.18E+12 J/yr

6. Loss of topsoil
(areas with mature untouched vegetation are assumed to have little net gain or loss of topsoil)
Forest area subject to erosion = 2.63E+06 m² [Ancitel database]
Erosion rate of forest area = 2.00E+02 g/m²/yr
% organic in soil = 3.00% [Odum, 1996]
Ener. cont. per g organic = 5.00 kcal/g [Odum, 1996]
Net loss = (forest area)(erosion rate)
= 5.26E+08 g/yr
Energy of net loss (J/yr) = (net loss)(% org.in soil)(5.0 Kcal/g)(4186 J/kcal)
= 3.30E+11 J/yr

7. Gasoline for agriculture
Total used = 1.96E+02 liters/year [U.M.A. agency]
HHV of gasoline = 3.51E+07 J/liter [Ellington et al, 1993, p. 408]
Total energy from gasoline = 6.88E+09
Chapter 24. Combined Use of Energy Synthesis and GIS...

8. Diesel for agriculture

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total used</td>
<td>5.95E+03 liters/year</td>
<td>U.M.A. agency</td>
</tr>
<tr>
<td>HHV of gasolina</td>
<td>3.56E+07 J/liter</td>
<td>Ellington et al, 1993, p. 408</td>
</tr>
<tr>
<td>Total energy from gasolina</td>
<td>2.12E+11</td>
<td></td>
</tr>
</tbody>
</table>

9. Agricultural machinery (steel)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tractors</td>
<td>4 units</td>
<td>U.M.A. agency</td>
</tr>
<tr>
<td>Number of agricult. Motorcycles</td>
<td>1 units</td>
<td>U.M.A. agency</td>
</tr>
<tr>
<td>Average mass of tractors</td>
<td>9.00E+03 kg</td>
<td></td>
</tr>
<tr>
<td>Average mass of motorcycles</td>
<td>1.80E+02 kg</td>
<td></td>
</tr>
<tr>
<td>Fraction of machinery is steel</td>
<td>0.90</td>
<td>Our assumption</td>
</tr>
<tr>
<td>Average lifetime</td>
<td>10.00 yrs</td>
<td>Our assumption</td>
</tr>
<tr>
<td>Total steel in machinery</td>
<td>8.26E+05 g/yr</td>
<td></td>
</tr>
</tbody>
</table>

10. Agricultural machinery (plastic material and tires)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tractors</td>
<td>4 units</td>
<td>U.M.A. agency</td>
</tr>
<tr>
<td>Number of agricult. motorcycles</td>
<td>1 units</td>
<td>U.M.A. agency</td>
</tr>
<tr>
<td>Average mass of tractors</td>
<td>9.00E+03 kg</td>
<td></td>
</tr>
<tr>
<td>Average mass of motorcycles</td>
<td>1.80E+02 kg</td>
<td></td>
</tr>
<tr>
<td>Fraction of machinery is plastics</td>
<td>0.10</td>
<td>Our assumption</td>
</tr>
<tr>
<td>Average lifetime</td>
<td>10.00 yrs</td>
<td>Our assumption</td>
</tr>
<tr>
<td>Total plastics in machinery</td>
<td>9.18E+04 g/yr</td>
<td></td>
</tr>
</tbody>
</table>

11. Labor and services

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human labor (renewable for 9.5%)</td>
<td></td>
</tr>
<tr>
<td>Active in agriculture</td>
<td>200 persons</td>
</tr>
<tr>
<td>Fraction of time spent for wood harvest</td>
<td>20%</td>
</tr>
<tr>
<td>11.1 Total labour for wood</td>
<td>40 work-years</td>
</tr>
<tr>
<td>Services for imports</td>
<td>5.43E+15 seJ/yr</td>
</tr>
<tr>
<td>11.2 Services</td>
<td>3.03E+03 €/yr</td>
</tr>
</tbody>
</table>

12. Forest production, wood

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total production</td>
<td>2.63E+09 g/yr</td>
<td>Municipality of Roccamonfina</td>
</tr>
<tr>
<td>Caloric content of wood</td>
<td>3.60 Kcal/g</td>
<td></td>
</tr>
<tr>
<td>Fraction exported to market</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Market value per Kg</td>
<td>0.10 €/Kg</td>
<td>Municipality of Roccamonfina</td>
</tr>
<tr>
<td>12.1 Production sold to outside market</td>
<td>1.84E+09 g/yr</td>
<td></td>
</tr>
<tr>
<td>12.2 Energy of exported production</td>
<td>2.77E+13 J/yr</td>
<td></td>
</tr>
<tr>
<td>12.3 Total market value</td>
<td>1.84E+05 €/yr</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 24. Combined Use of Emergy Synthesis and GIS...