EMERGY SYNTHESIS 6:
Theory and Applications of the Emergy Methodology

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Exploring Resource Use and Biophysical Constraints on Scottish Agriculture, at Regional and National Scales

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ABSTRACT

The resource use by and the biophysical constraints on the Scottish agricultural system are investigated at regional and national levels by means of the Emergy Synthesis method. The study focused on two case studies: the Cairngorms National Park (CNP) and the national agricultural sector as a whole, across time and spatial scales.

The evolution of the agricultural sector was explored over time (years 1991, 2001, 2007) accounting for locally renewable and nonrenewable resources, imported resources, labor and services, and performance indicators were calculated and compared. In the year 2007, the Emergy Yield Ratio (EYR) of the Scottish agricultural sector was about 46% lower than for CNP (2.65 versus 5.72, respectively). A higher Environmental Loading Ratio (ELR) was calculated for the national sector (1.25 versus 1.02, respectively). The Emergy Sustainability Index (ESI) was 2.12 for the national sector and 5.60 for CNP. Such figures were calculated without including the emergy flows supporting labor and services. If these latter are also accounted for, the ESI of the national level and CNP drop by 82% and 75% respectively. Such variation suggests that the large flows of non-renewable resources used by the Scottish agricultural sector heavily affect its global performance, making it dependent on the nonrenewable emergy sources that support the larger economic system in which the agricultural sector is embedded. Emergy synthesis indicators also capture the support provided for free by the environment to the process, as well as the environmental costs associated to the use of non-energy resources (topsoil, fertilizers, machinery, labor). Policies for improving the global sustainability of the agricultural sector are discussed in the paper.

INTRODUCTION

Agriculture needs to be investigated not only because it is a fundamental sector for the economic and social points of view but also and mainly for its direct links with natural systems in both supply and feedback aspects. Due to the increase of food demand all around the world, people are abandoning traditional agricultural techniques shifting towards an intensive agriculture. As widely discussed in the last decades (Brown and Ulgiati, 1999, 2001; MEA, 2005), intensive exploitation of photosynthesis may have negative effects on biodiversity, water supply, soil fertility among other aspects, very likely putting at risk the future carrying capacity and life support system of many areas of the planet. Agriculture is increasingly dependent on large amounts of fertilizers, pesticides, machinery. Abandoning traditional practices in favor of more intensive exploitation does not, in general, provide additional support to local populations and family farms. Instead, it determines the expulsion of farmers from their land and the concentration of land in the hands of fewer and fewer owners and big enterprises, practicing large-scale monocultures and shifting from traditional crops to cash and bioenergy crops. The risks associated to land use change and the related social impacts have been underlined by many researchers and international assessments (Pimentel et al., 1973; FAO, 2000;
Odum, 2007; IAASTD, 2009), that pointed out the need for using technology and science in order to prevent the decrease of rural population and to provide support to multifunctional agriculture, rural income and landscape protection.

A crucial step is implementing suitable evaluation methods to understand the relation between the agricultural process and the environment, to monitor the performance of agricultural systems, identify bottlenecks, and suggest improvements. The present paper analyzes the performance of the Scottish agricultural sector at national and regional scales by means of the emergy synthesis method, building on previous experiences by Ulgiati et al. (1993, 2008), Franzese et al. (2005, 2008, 2009), among others. Our research plan includes the evaluation of forestry, pulp & paper production, bioenergy production, food manufacturing and tourism.

MATERIALS AND METHODS

The resource use by and the biophysical constraints on the Scottish agricultural system are investigated at the regional level of the Cairngorms National Park (CNP) and at the national level of Scotland as a whole. Resource flows supporting such agricultural systems were evaluated in the years 1991, 2001, and 2007 in order to assess their environmental performance and sustainability over time. The study of the agricultural system in the CNP is part of a larger investigation about the multifunctional role of environmentally protected areas. In fact, while the Scottish agricultural system as such is not constrained by specific environmental protection policies, the activities in the CNP area are subject to regulations that at the same time aim at preserving both environmental integrity and a set of local economic activities, including agriculture, tourism, and small industrial enterprise.

The Area of Study

Scotland, located in the north of Britain, is very well known for its beautiful and mountainous landscape rich with forests, rivers and lakes, although its hilly nature make it difficult to carry out productive activities. As a result of such landscape-generate problems, 85% of Scotland’s land is considered a Less Favoured Area by the European Union which acknowledges the existence of natural and geographic disadvantages. Its climate is influenced by the Gulf Stream and also for this reason the wildlife and flora are very diverse. About 5,100,000 of people live in the country with a population density of 65.6 people per square kilometers. Out of this population, 65,000 people are directly employed in agriculture and it is estimated that more or less 250,000 jobs (1 in 10 of all Scottish jobs) derive from this sector. The smallest farms in terms of livestock and cropped areas are located in the north west of the country. Sheep farming is predominant in the north-west and south of Scotland. Larger cereal farms are concentrated in the eastern part. Beef farming takes place throughout the country, but it is particularly common in the south-west.

The Cairngorms National Park is the largest national park in the UK and was created as a result of the National Park (Scotland) Act in 2003. It covers 3,800 km² and supports approximately 16,000 resident people as well as significant protected habitats and species. National Parks in Scotland are explicitly required to achieve “sustainable development”, as illustrated by the four statutory duties set out in the Park Act: (1) to conserve and enhance the natural and cultural heritage of the area; (2) to promote sustainable use of the natural resources of the area; (3) to promote understanding and enjoyment of the special qualities of the area by the public; and (4) to promote sustainable economic and social development of the area’s communities. Therefore, they are not “wilderness reserves” but fit the International Union for Conservation of Nature (IUCN) category V (protected landscape). The National Park contains a variety of ecosystems from the sub-arctic Cairngorms plateau through managed moorlands, pastures and forestry to intensively farmed land in the river valleys. It is protected for both biodiversity and geodiversity. The mosaic of its habitats converge to create a unique and highly valued landscape. In 2006, 39% of the National Park was designated for nature conservation and 25% of the area was regarded as being of European or International importance for nature conservation. Furthermore, 25% of species in the UK conservation priority species list is found
within the National Park. Its geological features are of international importance and account for the Cairngorms’ inclusion in the Geological Conservation Review. The Cairngorms provide one of the best preserved examples of post glaciated landscape in the UK. The headwaters of Scotland’s three largest rivers (Tay, Dee, Spey) all rise within the National Park boundaries. Indeed, the water resources are very important for tourism, recreation, food and drink industries and as a resource for renewable energy. The Dee and the Spey are also protected under the Habitat’s Directive, for drinking water abstraction and safeguard of the economic salmonoid fishery resource. The Park contains a number of regionally important settlements that service its rural economy. The topography indicates that these communities have traditionally looked away from one another towards the major settlements on the coast or rivers (Aberdeen, Dundee, Perth or Inverness), as the major transport routes detour around the Cairngorms Massif. Therefore, the topography that gives the Park its special and unique features has traditionally divided, rather than united, the population living within its boundary.

The Emergy Synthesis Method

Emergy Synthesis is a biophysical accounting method based on the concept of energy quality and focused on the study of natural and human-dominated ecosystems from a “donor-side” point of view: the evaluation of the work done by the biosphere to generate goods and services (Odum, 1996). A more comprehensive explanation of the concepts, principles and applications of the emergy method can be found in Odum (1988, 1994, 1996), Brown and Ulgiati (2004 a,b) and Franzese et al. (2009).

A prerequisite for a sound emergy evaluation is that a careful inventory of mass and energy flows is accomplished, in order to provide a clear picture of the resources used locally by the system, including all those flows provided for free by the environment (sun, wind, rain, deep heat, etc) and never accounted for in conventional economic and energy accounting. Moreover, direct and indirect labor inputs are included. Once the inventory is performed, several data processing steps are needed to achieve the final emergy assessment of a system’s performance:

1. Identification of the spatial and temporal boundary of the investigated system. The same time boundaries were used for both investigated case studies. The local spatial scale is the area of the system, while the time scale is one year of time frame.
2. Modelling of the investigated system by means of a symbolic energy language. A systems diagram is drawn, including the main system’s components and their interactions to each other and with the surrounding environment.
3. Inventory of the input flows in terms of mass or energy.
4. Conversion of input flows emergy (seJ) units by means of appropriate conversion factors (so-called UEVs, Unit Emergy Values). Emergy Synthesis includes in its conversion coefficients.
also the resources provided for free by nature (sun, rain, wind, deep heat, topsoil, etc). This means that the time and spatial scales of indirect input flows are expanded from the local to the biosphere scale.

5. Calculation of the total emergy used by the system.

6. Calculation of the emergy intensities of the products, expressed as $seJ/kg$ (specific emergy), and other performance indicators, and interpretation of results.

**RESULTS AND DISCUSSION**

The system diagram of the Cairngorms National Park is shown in Figure 2. In this diagram the main different Park sub-systems are also shown. These sub-systems (wilderness, forestry and agriculture) directly and strongly supported by renewable sources are shown in an aggregated way on the left of the diagram. The renewable sources (sun, rain, wind, deep heat) are drawn as lumped together and shown as flowing into the system from the left side. These renewable sources support the investigated system directly (with specific focus on wilderness, forestry and agricultural production of the Park), and the other people’s activities indirectly through small industrial manufacture of agricultural and forestry products. In addition to renewable flows, further flows imported from the main economy (fossil fuels, fertilizers, electricity, goods, machinery and labor) support production patterns in the region. These inputs are shown as inflowing from the top of the diagram. The people living in the Park receive goods both from internal and external sectors, through commercial and transport infrastructures (assets). Tourists that come to Cairngorms National Park to visit the region interact with local assets and productive activities and enjoy local products, and environmental and recreation services. When they go away, they are also enriched with an information patrimony made up with increased understanding and enjoyment of environmental, social and artistic aspects of the area. The regional budget is mainly composed by the money that the region receives as an income of productive activities (goods exported) as well as contribution from external investments and subsidies. The money that tourists bring in adds up to the total budget, also indicated in the diagram, and is used to pay for the imported goods and raw resources. Money flows are shown as entering from the right side of the diagram and flowing out as payment of services associated to imports. It is important to note that the money paid for resources import only refers to the services associated to such resources. Services measure the indirect labor invested outside of the investigated system to extract and process the raw materials and make processed resources available to the production process (money does not pay nature for its free resources, but always pays direct and indirect labor). In a similar way it is possible to explain the diagram in Figure 3 that represents the agricultural sector of Scotland in the year 2007.

As shown in Figure 2, due to lack of disaggregated data for crop and livestock sub-systems, we had to make the assumption that all input flows are needed to generate at the same time the two products, livestock and crops. This is because a fraction of agricultural land is used as pasture, while another fraction is used to produce human food and animal feedstock with crop rotation. The total amount of emergy was divided by the amount of agricultural production, thus generating an average value of UEV for crops; then, the same amount of total emergy was divided by the livestock production to generate an average UEV for livestock.

Tables 1 and 2 list respectively the direct resource supply and generated products in the years 1991, 2001 and 2007 of both evaluated systems. From these data it clearly appears that both systems follow a similar trend: the direct labor applied to both agricultural processes, in terms of hours, decreases over time but becomes more expensive; at the same time, the use of agricultural machinery increases, but it is accompanied by a simultaneous decrease of electricity and fuel use, suggesting higher efficiency in machinery use. Fertilizers decrease from 1991 to 2007 having a peak in the year 2001, while pesticides and herbicides decline steadily. On the product side, the economic value grows in current price terms, while the total dry mass produced is more or less stable and so does the energy content.
Figure 2. Emergy system diagram of the Cairngorms National. Numbers in brackets are emergy flows ($x10^{18}$ seJ/yr) associated to each input in the year 2007.

Table 1. Direct supply and land use of the agricultural sectors of Scotland and CNP over time.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>g/yr</td>
<td>5.5E+16</td>
<td>5.1E+16</td>
<td>6.1E+16</td>
<td>1.6E+15</td>
<td>1.6E+15</td>
<td>1.6E+15</td>
</tr>
<tr>
<td>Total Cropped Land</td>
<td>ha/yr</td>
<td>3.9E+06</td>
<td>3.9E+06</td>
<td>4.2E+06</td>
<td>1.8E+05</td>
<td>1.8E+05</td>
<td>1.8E+05</td>
</tr>
<tr>
<td>Fertilizers (N+ PO4 +K2O)</td>
<td>g/yr</td>
<td>3.3E+11</td>
<td>4.0E+11</td>
<td>2.5E+11</td>
<td>4.4E+09</td>
<td>4.7E+09</td>
<td>3.5E+09</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>g/yr</td>
<td>2.0E+11</td>
<td>2.3E+11</td>
<td>1.4E+11</td>
<td>2.6E+09</td>
<td>2.8E+09</td>
<td>2.0E+09</td>
</tr>
<tr>
<td>Phosphate (PO4)</td>
<td>g/yr</td>
<td>6.1E+10</td>
<td>8.1E+10</td>
<td>4.9E+10</td>
<td>8.5E+08</td>
<td>8.7E+08</td>
<td>7.0E+08</td>
</tr>
<tr>
<td>Potassium (K2O)</td>
<td>g/yr</td>
<td>7.2E+10</td>
<td>9.4E+10</td>
<td>6.1E+10</td>
<td>9.8E+08</td>
<td>1.0E+09</td>
<td>8.1E+08</td>
</tr>
<tr>
<td>Fungicides</td>
<td>g/yr</td>
<td>1.1E+09</td>
<td>6.8E+08</td>
<td>7.5E+08</td>
<td>2.5E+06</td>
<td>1.4E+06</td>
<td>1.8E+06</td>
</tr>
<tr>
<td>Insecticides</td>
<td>g/yr</td>
<td>6.0E+06</td>
<td>3.7E+06</td>
<td>2.6E+06</td>
<td>3.4E+04</td>
<td>2.6E+04</td>
<td>2.1E+05</td>
</tr>
<tr>
<td>Herbicides</td>
<td>g/yr</td>
<td>9.8E+08</td>
<td>7.5E+08</td>
<td>6.8E+08</td>
<td>1.2E+07</td>
<td>5.5E+06</td>
<td>2.4E+06</td>
</tr>
<tr>
<td>Growth Regulators, Molluscicides and Others</td>
<td>g/yr</td>
<td>4.6E+08</td>
<td>4.6E+08</td>
<td>2.0E+08</td>
<td>9.6E+04</td>
<td>7.1E+04</td>
<td>7.3E+04</td>
</tr>
<tr>
<td>Electricity</td>
<td>J/yr</td>
<td>9.7E+14</td>
<td>5.4E+14</td>
<td>4.3E+14</td>
<td>8.2E+12</td>
<td>4.5E+12</td>
<td>3.6E+12</td>
</tr>
<tr>
<td>Water for Irrigation</td>
<td>g/yr</td>
<td>5.2E+12</td>
<td>5.2E+12</td>
<td>5.2E+12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Liquid Fuels</td>
<td>J/yr</td>
<td>1.2E+16</td>
<td>1.1E+16</td>
<td>9.9E+15</td>
<td>1.0E+14</td>
<td>9.4E+13</td>
<td>8.4E+13</td>
</tr>
<tr>
<td>Machinery</td>
<td>g/yr</td>
<td>3.3E+11</td>
<td>3.8E+11</td>
<td>7.2E+11</td>
<td>2.8E+09</td>
<td>3.2E+09</td>
<td>6.1E+09</td>
</tr>
<tr>
<td>Direct Labor</td>
<td>hrs/yr</td>
<td>9.2E+07</td>
<td>9.2E+07</td>
<td>8.5E+07</td>
<td>8.7E+05</td>
<td>8.7E+05</td>
<td>8.0E+05</td>
</tr>
<tr>
<td>Direct Labor</td>
<td>€/yr</td>
<td>6.1E+08</td>
<td>9.2E+08</td>
<td>9.4E+08</td>
<td>5.7E+06</td>
<td>8.7E+06</td>
<td>8.9E+06</td>
</tr>
<tr>
<td>Indirect Labor (Services)</td>
<td>€/yr</td>
<td>1.5E+09</td>
<td>1.5E+09</td>
<td>1.4E+09</td>
<td>7.2E+06</td>
<td>7.0E+06</td>
<td>9.5E+06</td>
</tr>
</tbody>
</table>
Figure 3. Emergy system diagram of the Scottish agricultural sector. Numbers in brackets are emergy flows \(x 10^{18} \text{ seJ/yr}\) associated to each input in the year 2007.

Table 2. Products generated by the agricultural sectors of Scotland and CNP over time.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Economic value of crop production</td>
<td>€/yr</td>
<td>6.0E+08</td>
<td>8.4E+08</td>
<td>1.1E+09</td>
<td>1.5E+06</td>
<td>2.4E+06</td>
<td>2.8E+06</td>
</tr>
<tr>
<td>Economic value of livestock production</td>
<td>€/yr</td>
<td>1.3E+09</td>
<td>1.3E+09</td>
<td>1.4E+09</td>
<td>9.7E+06</td>
<td>9.6E+06</td>
<td>1.1E+07</td>
</tr>
<tr>
<td>Total economic value</td>
<td>€/yr</td>
<td>1.9E+09</td>
<td>2.1E+09</td>
<td>2.5E+09</td>
<td>1.1E+07</td>
<td>1.2E+07</td>
<td>1.4E+07</td>
</tr>
<tr>
<td>Mass of crop production</td>
<td>g/yr</td>
<td>2.9E+12</td>
<td>2.9E+12</td>
<td>2.9E+12</td>
<td>7.5E+09</td>
<td>8.4E+09</td>
<td>7.6E+09</td>
</tr>
<tr>
<td>Mass of livestock production</td>
<td>g/yr</td>
<td>3.0E+11</td>
<td>2.9E+11</td>
<td>2.9E+11</td>
<td>1.2E+09</td>
<td>1.0E+09</td>
<td>1.1E+09</td>
</tr>
<tr>
<td>Total mass (dry matter)</td>
<td>g/yr</td>
<td>3.2E+12</td>
<td>3.1E+12</td>
<td>3.2E+12</td>
<td>8.7E+09</td>
<td>9.4E+09</td>
<td>8.7E+09</td>
</tr>
<tr>
<td>Energy content of crop</td>
<td>J/yr</td>
<td>3.7E+16</td>
<td>3.8E+16</td>
<td>3.8E+16</td>
<td>1.0E+14</td>
<td>1.2E+14</td>
<td>1.0E+14</td>
</tr>
<tr>
<td>Energy content of livestock</td>
<td>J/yr</td>
<td>7.8E+15</td>
<td>7.5E+15</td>
<td>7.7E+15</td>
<td>4.5E+13</td>
<td>3.9E+13</td>
<td>4.1E+13</td>
</tr>
<tr>
<td>Total energy content</td>
<td>J/yr</td>
<td>4.5E+16</td>
<td>4.5E+16</td>
<td>4.6E+16</td>
<td>1.5E+14</td>
<td>1.5E+14</td>
<td>1.4E+14</td>
</tr>
</tbody>
</table>

Table 3 shows a detailed calculation of the emergy flows supporting the Scottish agricultural sector in the year 2007. The same emergy evaluation at national level (Table 3) was implemented for the years 1991 and 2001 as well as for the agricultural sector of the Cairngorms National Park for the same years. Finally, performance and sustainability indicators were calculated for both systems.

Table 4 shows the extensive emergy-based indicators calculated for the two systems over time. The total emergy \(U\) was calculated with and without the emergy associated to labor \(L\) and services \(S\). The two values present a significant difference: at national level, labor and services represent about 50% of the total used emergy \(U\) while at the level of the National Park they are much lower (20-27%). These figures suggest a highly labor intensive agriculture but also, more likely, a highly subsidized system (money investment for Park protection more than for the value of agricultural products as such).
Tables 5 and 6 list the emergy based performance indicators for the two systems, over time (from 1991 to 2007). As previously underlined, indicators refer to the separate crop and livestock products as well as to the agricultural product as a whole (crop plus livestock), calculated with and without including the emergy associated to Labor and Services.

Indicators in Table 6 point out that: 1) the Emergy Yield Ratio (EYR) slightly increases in both systems (increased ability to exploit local resources); 2) the Environmental Loading Ratio (ELR) slightly decreases in both systems (higher reliance on renewable resources); 3) the Emergy Exchange Ratio (EER), i.e. the ratio of emergy exchanged in a trade or purchase (emergy received divided by emergy sent out) decreases for both systems; 4) the Emergy Sustainability Index (ESI) increases in both systems. The latter trend is very unusual and suggests the effectiveness of the governmental and local environmental and agricultural policies, apparently capable to decrease the use of imported and non-renewable resources and increase the reliance on local renewable resources.

### Table 3. Emergy evaluation of the agricultural sector of Scotland in the year 2007.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Raw amount</th>
<th>Emegy Intensity</th>
<th>Ref. for intensity*</th>
<th>Emegy (x10^18)seJ/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable Input (locally available)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun</td>
<td>J/yr</td>
<td>1.1E+20</td>
<td>1.0E+00</td>
<td>[a]</td>
<td>11.32</td>
</tr>
<tr>
<td>Wind (Kinetic Energy of Wind Used at the Surface)</td>
<td>J/yr</td>
<td>7.2E+17</td>
<td>2.5E+03</td>
<td>[b]</td>
<td>179.84</td>
</tr>
<tr>
<td>Rainfall (Chemical Potential)</td>
<td>J/yr</td>
<td>1.2E+17</td>
<td>3.1E+04</td>
<td>[b]</td>
<td>368.75</td>
</tr>
<tr>
<td>Deep Heat (Geothermal Heat)</td>
<td>J/yr</td>
<td>5.0E+16</td>
<td>1.2E+04</td>
<td>[b]</td>
<td>60.43</td>
</tr>
<tr>
<td><strong>Nonrenewable Input (locally available)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top soil (erosion, wheathering)</td>
<td>J/yr</td>
<td>1.2E+16</td>
<td>1.2E+05</td>
<td>[b]</td>
<td>149.02</td>
</tr>
<tr>
<td><strong>Imported Input</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>J/yr</td>
<td>9.8E+15</td>
<td>1.1E+05</td>
<td>[b]</td>
<td>108.07</td>
</tr>
<tr>
<td>Lubricants</td>
<td>J/yr</td>
<td>1.6E+14</td>
<td>1.1E+05</td>
<td>[b]</td>
<td>1.72</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>J/yr</td>
<td>1.0E+15</td>
<td>8.1E+04</td>
<td>[b]</td>
<td>8.23</td>
</tr>
<tr>
<td>Electricity</td>
<td>J/yr</td>
<td>4.3E+14</td>
<td>2.9E+05</td>
<td>[c]</td>
<td>12.29</td>
</tr>
<tr>
<td>Water for irrigation</td>
<td>g/yr</td>
<td>5.2E+12</td>
<td>7.6E+05</td>
<td>[d]</td>
<td>0.40</td>
</tr>
<tr>
<td>Fertilizers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>g/yr</td>
<td>1.4E+11</td>
<td>6.4E+09</td>
<td>[b]</td>
<td>87.89</td>
</tr>
<tr>
<td>Phosphate (PO4)</td>
<td>g/yr</td>
<td>4.9E+10</td>
<td>6.5E+09</td>
<td>[b]</td>
<td>32.03</td>
</tr>
<tr>
<td>Potassium (K2O)</td>
<td>g/yr</td>
<td>6.1E+10</td>
<td>1.8E+09</td>
<td>[b]</td>
<td>11.25</td>
</tr>
<tr>
<td>Fungicide</td>
<td>g/yr</td>
<td>7.5E+08</td>
<td>5.1E+09</td>
<td>[e]</td>
<td>0.38</td>
</tr>
<tr>
<td>Insecticides</td>
<td>g/yr</td>
<td>2.6E+06</td>
<td>4.8E+09</td>
<td>[e]</td>
<td>0.001</td>
</tr>
<tr>
<td>Herbicides</td>
<td>g/yr</td>
<td>6.8E+08</td>
<td>8.3E+09</td>
<td>[e]</td>
<td>0.56</td>
</tr>
<tr>
<td>Growth regulators, Molluscicides and Others</td>
<td>g/yr</td>
<td>2.0E+08</td>
<td>6.1E+09</td>
<td>[e]</td>
<td>0.12</td>
</tr>
<tr>
<td>Agricultural Machinery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel and Iron</td>
<td>g/yr</td>
<td>4.5E+10</td>
<td>5.3E+09</td>
<td>[f]</td>
<td>24.07</td>
</tr>
<tr>
<td>Aluminium</td>
<td>g/yr</td>
<td>7.7E+09</td>
<td>3.3E+10</td>
<td>[b]</td>
<td>25.17</td>
</tr>
<tr>
<td>Rubber and Plastic</td>
<td>g/yr</td>
<td>5.5E+08</td>
<td>3.7E+09</td>
<td>[b]</td>
<td>0.20</td>
</tr>
<tr>
<td>Copper</td>
<td>g/yr</td>
<td>1.7E+09</td>
<td>3.4E+09</td>
<td>[c]</td>
<td>0.56</td>
</tr>
<tr>
<td>Human Labor</td>
<td>€/yr</td>
<td>9.4E+08</td>
<td>3.9E+12</td>
<td>[g]</td>
<td>365.41</td>
</tr>
<tr>
<td>Annual Services in Agricultural Production</td>
<td>€/yr</td>
<td>1.4E+09</td>
<td>3.9E+12</td>
<td>[g]</td>
<td>556.80</td>
</tr>
</tbody>
</table>

*References for Transformity values: [a] [By definition]; [b] [After Odum, 2000]; [c] [Brown & Ulgiati, 2004b]; [d] [After Buenfill, A.A., 2000]; [e] [Estimated from Biondi et al., 1989]; [f] [Bargigli and Ulgiati, 2003]; [g] [Gasparatos et al., 2008]. Note: Values of specific emergies and transformities refer to the 15.83·10^24 seJ/yr biosphere baseline (Odum, 2000). All transformities calculated earlier, based on the 9.44·10^24 seJ/yr baseline, have been converted to the new baseline (multiplied by 1.68).
Table 4. Extensive emergy-based indicators of the agricultural sectors of Scotland and CNP over time.

<table>
<thead>
<tr>
<th>Extensive Indicators</th>
<th>Unit</th>
<th>Scotland</th>
<th></th>
<th></th>
<th>CNP</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Local renewable inputs, R</td>
<td>seJ/yr</td>
<td>3.3E+21</td>
<td>3.1E+21</td>
<td>3.7E+21</td>
<td>9.6E+19</td>
<td>9.9E+19</td>
<td>9.7E+19</td>
</tr>
<tr>
<td>Local non-renewable inputs, N</td>
<td>seJ/yr</td>
<td>1.4E+21</td>
<td>1.4E+21</td>
<td>1.5E+21</td>
<td>6.5E+19</td>
<td>6.5E+19</td>
<td>6.5E+19</td>
</tr>
<tr>
<td>Purchased inputs, F</td>
<td>seJ/yr</td>
<td>3.7E+21</td>
<td>3.9E+21</td>
<td>3.1E+21</td>
<td>4.0E+19</td>
<td>4.0E+19</td>
<td>3.4E+19</td>
</tr>
<tr>
<td>Direct Labor, L</td>
<td>seJ/yr</td>
<td>2.4E+21</td>
<td>3.6E+21</td>
<td>3.7E+21</td>
<td>2.2E+19</td>
<td>3.4E+19</td>
<td>3.5E+19</td>
</tr>
<tr>
<td>Services (indirect labor), S</td>
<td>seJ/yr</td>
<td>5.8E+21</td>
<td>6.0E+21</td>
<td>5.6E+21</td>
<td>2.8E+19</td>
<td>2.7E+19</td>
<td>3.7E+19</td>
</tr>
<tr>
<td>Total emergy inputs with L&amp;S; U = (R+N+F+L+S)</td>
<td>seJ/yr</td>
<td>1.7E+22</td>
<td>1.8E+22</td>
<td>1.8E+22</td>
<td>2.5E+20</td>
<td>2.7E+20</td>
<td>2.7E+20</td>
</tr>
<tr>
<td>Total emergy inputs without L&amp;S; U = (R+N+F)</td>
<td>seJ/yr</td>
<td>8.4E+21</td>
<td>8.4E+21</td>
<td>8.3E+21</td>
<td>2.0E+20</td>
<td>2.0E+20</td>
<td>2.0E+20</td>
</tr>
</tbody>
</table>

Table 5. Intensive emergy-based indicators of the agricultural sectors of Scotland and CNP (with Labor and Services).

<table>
<thead>
<tr>
<th>Intensive Indicators with Labor and Services</th>
<th>Unit</th>
<th>Scotland</th>
<th></th>
<th></th>
<th>CNP</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CROPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy per unit of economic value</td>
<td>seJ/€</td>
<td>2.8E+13</td>
<td>2.2E+13</td>
<td>1.6E+13</td>
<td>1.7E+14</td>
<td>1.1E+14</td>
<td>9.4E+13</td>
</tr>
<tr>
<td>Specific emergy per unit of dry matter</td>
<td>seJ/g</td>
<td>5.8E+09</td>
<td>6.3E+09</td>
<td>6.0E+09</td>
<td>3.3E+10</td>
<td>3.2E+10</td>
<td>3.5E+10</td>
</tr>
<tr>
<td>Solar Transformity</td>
<td>seJ/J</td>
<td>4.5E+05</td>
<td>4.8E+05</td>
<td>4.6E+05</td>
<td>2.5E+06</td>
<td>2.3E+06</td>
<td>2.6E+06</td>
</tr>
<tr>
<td>LIVESTOCK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy per unit of economic value</td>
<td>seJ/€</td>
<td>1.3E+13</td>
<td>1.4E+13</td>
<td>1.3E+13</td>
<td>2.6E+13</td>
<td>2.8E+13</td>
<td>2.4E+13</td>
</tr>
<tr>
<td>Specific emergy per unit of dry matter</td>
<td>seJ/g</td>
<td>5.4E+10</td>
<td>6.3E+10</td>
<td>6.1E+10</td>
<td>2.1E+11</td>
<td>2.6E+11</td>
<td>2.5E+11</td>
</tr>
<tr>
<td>Solar Transformity</td>
<td>seJ/J</td>
<td>2.1E+06</td>
<td>2.4E+06</td>
<td>2.3E+06</td>
<td>5.5E+06</td>
<td>6.9E+06</td>
<td>6.6E+06</td>
</tr>
<tr>
<td>WHOLE SYSTEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy per unit of economic value</td>
<td>seJ/€</td>
<td>8.9E+12</td>
<td>8.4E+12</td>
<td>7.2E+12</td>
<td>2.3E+13</td>
<td>2.2E+13</td>
<td>1.9E+13</td>
</tr>
<tr>
<td>Specific emergy per unit of dry matter</td>
<td>seJ/g</td>
<td>5.2E+09</td>
<td>5.7E+09</td>
<td>5.5E+09</td>
<td>2.9E+10</td>
<td>2.8E+10</td>
<td>3.1E+10</td>
</tr>
<tr>
<td>Solar Transformity</td>
<td>seJ/J</td>
<td>3.7E+05</td>
<td>4.0E+05</td>
<td>3.8E+05</td>
<td>1.7E+06</td>
<td>1.7E+06</td>
<td>1.9E+06</td>
</tr>
<tr>
<td>Empower density</td>
<td>seJ/ha</td>
<td>4.2E+15</td>
<td>4.6E+15</td>
<td>4.2E+15</td>
<td>1.4E+15</td>
<td>1.5E+15</td>
<td>1.5E+15</td>
</tr>
<tr>
<td>EYR = U/(F+L+S)</td>
<td></td>
<td>1.40</td>
<td>1.33</td>
<td>1.42</td>
<td>2.77</td>
<td>2.60</td>
<td>2.52</td>
</tr>
<tr>
<td>ELR = (N+F+L+S)/(R)</td>
<td></td>
<td>4.00</td>
<td>4.83</td>
<td>3.75</td>
<td>1.62</td>
<td>1.69</td>
<td>1.77</td>
</tr>
<tr>
<td>%REN = 1/(1+ELR)</td>
<td></td>
<td>0.20</td>
<td>0.17</td>
<td>0.21</td>
<td>0.38</td>
<td>0.37</td>
<td>0.36</td>
</tr>
<tr>
<td>ESI</td>
<td></td>
<td>0.35</td>
<td>0.28</td>
<td>0.38</td>
<td>1.71</td>
<td>1.54</td>
<td>1.43</td>
</tr>
<tr>
<td>EER</td>
<td></td>
<td>2.28</td>
<td>2.15</td>
<td>1.83</td>
<td>5.75</td>
<td>5.65</td>
<td>4.84</td>
</tr>
</tbody>
</table>

However, when labor and services are accounted for all indicators are affected negatively (Table 5), suggesting higher standard of living (from high UEV of labor) and highly subsidized processes (to afford costs of labor and purchased inputs).

Results are better understood in their globality if they are shown in a pictorial way, by means of radar diagrams. In order to diagram data with different orders of magnitude we applied two normalization procedures: (1) normalization with reference to the first year of investigation: all values are divided by the value of the first year of investigation (Figures 4 and 5); (2) normalization with reference to the total impact generated: for each indicator, the total impact is calculated by adding the values of the two systems, then, in order to calculate its fraction or percentage, the value of the indicator is divided by the sum of the two (Figure 5). The larger is the area identified by the diagram,
the more intensive is the global impact generated by the system. Figure 4 shows the emergy-based indicators calculated at the national agriculture level. Indicators show a good performance over time, from 1991 to 2007, but for a negative performance in the year 2001. Instead, the same indicators calculated for the CNP and shown in Figure 5 have a more stable trend. In the year 2007, the Emergy Yield Ratio (EYR) of the Scottish agricultural sector was about 46% than for the CNP (2.65 versus 5.72, respectively). A higher Environmental Loading Ratio (ELR) was calculated for the national sector than for CNP (1.25 versus 1.02, respectively). The Emergy Sustainability Index (ESI) was 2.12 for the national sector and 5.60 for CNP (Table 6). Such figures were calculated without including the emergy flows supporting labor and services. If these latter are also accounted for, the ESI of the national level and CNP drop by 82% and 75%, respectively.

The comparison of emergy based indicators between the two investigated systems, shown in Figure 6, points out a lower productivity of the agriculture in the Park than at national scale. Such a lower productivity affects the UEVs calculated (seJ/€, seJ/g, seJ/J) that are higher for the National Park than for the whole Scotland; instead, the other calculated indicators, Empower Density (seJ/ha), Emergy Yield Ratio, Emergy Investment Ratio Environmental Loading Ratio, Environmental Sustainability Index, are higher for the national scale showing a bigger impact of this system.

Finally, Figure 7 (the so called emergy signature of the system) highlights how the share of the different resources driving the Scottish National agriculture changes over time.

Much to our surprise, the environmental sources still have a much higher role than the imported nonrenewables (fuels, machinery, fertilizers), unlike other agricultural systems worldwide. Labor and services also have a huge emergy cost associated: this is due however, to the actual number of labor hours applied (that is steadily declining), but instead to the standard of living (labor cost, i.e. emergy cost of resources supporting direct and indirect labor). Efforts to decrease the total emergy use of the country and make it more reliant on renewables would translate into less emergy-intensive and more renewable labor and services, in so also improving the performance of agricultural and other productive sectors. Results converge to pointing out that the whole agricultural sector of Scotland, although performing relatively well compared to other agricultural systems worldwide, is more environmental impacting than the agriculture of the CNP.

Table 6. Intensive emergy indicators of the agricultural sectors of Scotland and CNP (without Labor and Services).

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>CROPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy per unit of economic value</td>
<td>seJ/€</td>
<td>1.4E+13 1.0E+13 7.8E+12</td>
<td>1.4E+14 8.6E+13 6.9E+13</td>
<td>2.1E+13 2.1E+13 1.7E+13</td>
<td>2.1E+14 8.6E+13 6.9E+13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific emergy per unit of dry matter</td>
<td>seJ/g</td>
<td>2.9E+09 2.9E+09 2.8E+09</td>
<td>2.7E+10 2.4E+10 2.6E+10</td>
<td>2.7E+10 2.4E+10 2.6E+10</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Solar Transformity</td>
<td>seJ/J</td>
<td>2.3E+05 2.2E+05 2.2E+05</td>
<td>2.0E+06 1.8E+06 1.9E+06</td>
<td>2.0E+06 1.8E+06 1.9E+06</td>
<td>2.0E+06 1.8E+06 1.9E+06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIVESTOCK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy per unit of economic value</td>
<td>seJ/€</td>
<td>6.7E+12 6.4E+12 6.0E+12</td>
<td>2.1E+13 2.1E+13 1.7E+13</td>
<td>2.1E+13 2.1E+13 1.7E+13</td>
<td>2.1E+13 2.1E+13 1.7E+13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific emergy per unit of dry matter</td>
<td>seJ/g</td>
<td>2.8E+10 2.9E+10 2.9E+10</td>
<td>1.7E+11 2.0E+11 1.9E+11</td>
<td>1.7E+11 2.0E+11 1.9E+11</td>
<td>1.7E+11 2.0E+11 1.9E+11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Transformity</td>
<td>seJ/J</td>
<td>1.1E+06 1.1E+06 1.1E+06</td>
<td>4.4E+06 5.3E+06 4.8E+06</td>
<td>4.4E+06 5.3E+06 4.8E+06</td>
<td>4.4E+06 5.3E+06 4.8E+06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL (CROPS + LIVESTOCK)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy per unit of economic value</td>
<td>seJ/€</td>
<td>4.5E+12 3.9E+12 3.4E+12</td>
<td>1.8E+13 1.7E+13 1.4E+13</td>
<td>1.8E+13 1.7E+13 1.4E+13</td>
<td>1.8E+13 1.7E+13 1.4E+13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific emergy per unit of dry matter</td>
<td>seJ/g</td>
<td>2.7E+09 2.7E+09 2.6E+09</td>
<td>2.3E+10 2.2E+10 2.3E+10</td>
<td>2.3E+10 2.2E+10 2.3E+10</td>
<td>2.3E+10 2.2E+10 2.3E+10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Transformity</td>
<td>seJ/J</td>
<td>1.9E+05 1.9E+05 1.8E+05</td>
<td>1.4E+06 1.3E+06 1.4E+06</td>
<td>1.4E+06 1.3E+06 1.4E+06</td>
<td>1.4E+06 1.3E+06 1.4E+06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empower density</td>
<td>seJ/ha</td>
<td>2.1E+15 2.1E+15 2.0E+15</td>
<td>1.1E+15 1.1E+15 1.1E+15</td>
<td>1.1E+15 1.1E+15 1.1E+15</td>
<td>1.1E+15 1.1E+15 1.1E+15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EYR = U/(F+L+S)</td>
<td></td>
<td>2.29 2.15 2.65</td>
<td>5.03 5.04 5.72</td>
<td>2.29 2.15 2.65</td>
<td>5.03 5.04 5.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELR = (N+F+L+S)/(R)</td>
<td></td>
<td>1.53 1.72 1.25</td>
<td>1.09 1.06 1.02</td>
<td>1.53 1.72 1.25</td>
<td>1.09 1.06 1.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>%REN = 1/(1+ELR)</td>
<td></td>
<td>0.40 0.37 0.44</td>
<td>0.48 0.48 0.49</td>
<td>0.40 0.37 0.44</td>
<td>0.48 0.48 0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESI</td>
<td></td>
<td>1.50 1.25 2.12</td>
<td>4.61 4.74 5.60</td>
<td>1.50 1.25 2.12</td>
<td>4.61 4.74 5.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EER</td>
<td></td>
<td>1.16 1.00 0.87</td>
<td>4.58 4.33 3.53</td>
<td>1.16 1.00 0.87</td>
<td>4.58 4.33 3.53</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4. Emergy-based indicators of the agricultural sector of Scotland over time. Values normalized from Table 5.

Figure 5. Emergy-based indicators of the agricultural sector of the Cairngorms National Park over time. Values normalized from Table 5.
Figure 6. Comparison of emergy-based indicators referring to the agricultural sectors of Scotland and CNP in the year 2007. Values normalized from Table 5.

Figure 7. Emergy signature of the agricultural sector of Scotland over time.
The radar diagram allows the analyst to identify at a glance where each system performs better or worse. In summary, the CNP has a low productivity, while the national sector uses too much of nonrenewables and therefore loads more on the environment. It is a good sign that the emergy indicators calculated at national level slightly improve over time, and that the same indicators calculated for the CNP remain stable at the already good level achieved thanks to the implementation of strict conservation policies. Results raise an important aspect that is related to the interplay between the need for high productivity in support of a large population (Scotland, 65.6 persons/km²) traded for higher environmental load, or enforced environmental protection in a system that is hardly capable of supporting 4 persons/km². Policies that are concerned about both standard of life and environmental protection need to address efficient and effective use of resources (doing more with less) and decreased use of nonrenewables and imported ones (increased reliance on local sources). The latter aspect requires that local resources are both conserved (clean environment, traditions, food quality) and usefully exploited within a multifunctional framework similar to the scheme shown in Figure 1 (additional income from diversification of activities as well as increased use and reuse of residues). It is not a given that such strategies are feasible to the extent that is required to keep the same standard of living and improve environmental care. It is also not a given that Scottish population accepts a lower standard of living (in terms of resource use) in order to allow for the same standard of environmental protection enjoyed by CNP. Finally, it is still to be understood if an optimum share of economic development and environmental protection can be identified and, if so, implemented through top-down policies. This is why policy enforcement and performance monitoring must both be implemented as the two sides of the same coin, in order to allow deeper understanding and sound actions.

CONCLUSION

Results point out a global environmentally sound performance of Scottish agriculture and an even better performance of agricultural activities in the Cairngorms National Park. However, the comparison between the two systems identifies a tradeoff between increased economic production and environmental protection. Reliance on locally renewable resources is unlikely to allow high yields as energy intensive production still does. On the other hand, increased population and standard of living call for production activities much beyond the renewable carrying capacity of a region or country. Policies that improve the multi-functionality of production activities, and support doing more with less can help, but they seem far from being able to fill the existing gap between expectations for economic improvement and awareness of the need for environmental integrity.

Moreover, the large fraction of emergy provided as labor and services in both the investigated systems (but specially in the CNP) suggests that the global performance of the Scottish economy, based on large flows of nonrenewable resources, heavily affects the dynamics of the agricultural sector (and very likely all other sectors). In fact, labor and services rely on the nonrenewable emergy sources that support the main economy. Such a finding points out the need for an accurate exploration of the context in which the investigated process is embedded and suggests that efforts for the improvement of the performance of a productive sector are unlikely to be successful without a simultaneous effort for the improvement of the larger surrounding economic system. Saving resources in a given sector in the hope that they can be reinvested somewhere else to keep pushing the standard of living to a even higher level of resource consumption may translate into a crude awakening. When the lifestyle goes up, it affects the economic and emergy cost of labor, in so making the individual productive sectors less effective and sustainable. Some investors decide to outsource the production, others may decide to decrease labor by increasing machinery (until oil price allows), others simply may go out of business. Instead, if the standard of living is reoriented to less consumery habits and more community values, then all the sectorial performance indicators may benefit from the lower large-scale resource use.

The application of the emergy synthesis approach allows monitoring the use of resources over time, by also including their quality in the accounting. In so doing, aspects that are most often disregarded in conventional economic and energy analyses are highlighted and become the basis of
more environmentally sound policies. In particular, it becomes possible to identify tradeoffs between intensity of resource use, standard of living, and environmental integrity that are linked to each other by internal loops and synergies, and would otherwise remain hidden and unaccounted for.

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