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Emergy accounting for regional studies: Case study of Canada and its provinces

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ABSTRACT

Sustainable regional management (development) requires an understanding of interactions between the social, economic, and ecological systems within the boundaries of a region. In this paper, application of emergy (an environmental accounting method) for regional planning is discussed through a case study. Emergy (spelled with an "m") methodology is an environmental accounting technique that evaluates the energy system for the thermodynamics of an open system. Major renewable and non-renewable resource fluxes to a region, including energy, matter, human activities, and money can be converted to emergy by using corresponding transformity functions.

As a case study, this paper discusses the emergy accounting of Canada and its provinces with various emergy-based indicators. Moreover, emergy maps were generated in a form of emergy geography. These maps are multi-dimensional illustrations that show resource consumption, emergy per person, and emergy density across Canada under two parameters: (1) the quantities of resources consumed and (2) the location of consumption. Emergy analysis also highlights concentrations of renewable and natural resources in Canada and distinguishes the provinces with the highest resource consumption. Analysis of emergy indicator for Canadian provinces shows that Alberta with the highest EYR (7.35) provides energy to the economy of Canada. However, ELR value of Alberta (8.5) indicates that the province's current economic approach is not sustainable as it relies mainly on non-renewable emergy inputs (mainly from fossil fuels). ELR of British Columbia and Manitoba indicates that these two provinces created a firm balance between emergy use of renewable and non-renewable resources. The characterizations of regions provided in this paper can be used for future land planning and management both in federal and provincial levels.

1. Frameworks for regional studies

Sustainable regional management (development) requires an understanding of interactions between the social, economic, and ecological systems within the boundaries of a region. Combining information about type, location, and amount of resource consumption within a region is crucial for large-scale regional planning. Flow of resource fluxes to a region, including energy, matter, human activities, and money need to be quantified. Human–environment interactions in regions can be illustrated, showing that human activities using resources, the variable intensity of which creates spatial patterns (Pulselli et al., 2007). In this paper, the 'emergy' methodology, an environmental accounting method, is used to conduct a large-scale regional study.

2. Introduction to emergy evaluation of regions

Emergy (spelled with an "m") evaluation is an environmental accounting technique that considers an energy system for the thermodynamics of an open system (Odum and Odum, 1981; Odum, 1996). Considering a region as an open system, emergy assessment helps to identify the role of ecosystems in the local and global economy by quantifying the natural resources in the region and work done by people living in the region. Emergy assessment also focuses on processes such as extraction, production, transformation, and trade. Emergy evaluation can be applied to a region to study relations between humans and the environment through flows of energy and matter since human activities are shaped not only by economic rules but also by ecosystem constraints (Pulselli et al., 2007).

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Odum (1996) proposed the concept of 'energy hierarchy' as an energy law. In any hierarchy, many units at one level contribute to a few units at the level above them. According to the second law of thermodynamics, any energy transformation consumes many calories of available energy, of one kind, to generate fewer calories of available energy of another kind. Therefore, an energy transformation works as a process that converts one or more kinds of available energy into a different type of available energy (Brown et al., 2004). By definition, emergy is the available energy of one kind that has been used up directly and indirectly to make a product or service (Odum, 1971, 1983, 1996). Emergy uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy (Pulselli et al., 2008). Emergy assessment considers systems as a network of energy fluxes. It assigns a value to natural and economic products and services by converting them into equivalents of one form of energy, with reference to the theory of energy hierarchy in systems ecology (Pulselli et al., 2007). The most common method is transforming all resources, including energy and matter, to solar energy (called solar emergy joule, solar emjoule or 'seJ') since solar energy is the earth's largest but most dispersed energy input (Brown and Ulgiati, 2004). en referred to as energy memory.

Emergy is also referred to as the "memory of energy" (Scienceman, 1987). When a system is evaluated in solar emergy, the quantities represented are the 'memory' of the solar energy used to make it. Thus, the quantities are not energy and do not behave like energy (Brown and Herendeen, 1996). The emergy of different products was calculated by multiplying mass (g) or energy quantities (J) by transformity, also referred to as Unit Emergy Value (UEV), which is a transformation coefficient. Transformity is the solar emergy required, directly or indirectly, to make 1 J or 1 g of a product or service. In other words, transformity is the emergy input per unit of product or service (Odum, 1971, 1983, 1996).

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

$$B_k = \sum_i \mathrm{Tr}_i E_i \quad i = 1, 2, \ldots n \tag{1}$$

where, E_i is the actual energy content of the ith independent input flow to the process and Tr_i is the solar transformity of the ith input flow (Pulselli et al., 2007). It is common to measure solar transformity in solar emergy joules per joule of product (seJ/J) with a base that 1 emjoule is equivalent to 1 J of solar energy and transformity of solar energy is 1 seJ/J (Ulgiati et al., 1995).

Solar transformities represent the position of any product or service in the hierarchical network of the earth's biosphere (Odum, 1996). For instance, if 6000 solar emjoules are required to generate 30 J of natural gasoline, then the solar transformity of that gasoline is 200 solar emjoules/J (6000/30 seJ/J). The higher the transformity of an item, the more available energy of another kind is required to make it (Brown et al., 2004). For convenience, it is very common to use transformity values derived from other studies. It is assumed that transformity values are still valid under minor different conditions such as place and/or time (Meillaud et al., 2005). Moreover, most products have a range of transformities depending on their production process (Pulselli et al., 2008).

3. Emergy evaluation of Canada and its provinces

The aim of this paper is to perform the emergy evaluation of Canada and its ten provinces: Alberta, British Columbia, Manitoba, New Brunswick, Newfoundland and Labrador, Nova Scotia, Ontario, Prince Edward Island, Quebec and Saskatchewan for the year 2011. Canadian territories are excluded form the analysis due to unavailability of data.

An emergy evaluation of regions and their resources provides a large scale perspective for an assessment of environmental areas, and assists in informed decision making for the public benefit (Odum, 1996). Specifically, the objective of this paper is to identify and quantify the main flows of energy, matter, and money that go in and out of the boundaries of Canada and its provinces. Other examples of emergy evaluations of states and nations can be found in the literature with reference to Odum and Odum (1983), Pillet and Odum (1984), Huang and Odum (1991), Ulgiati et al. (1994), Campbell (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), Pulselli et al. (2007, 2008), and Brown et al. (2009).

3.1. Flows considered in the analysis and the source of raw data

Emergy evaluations of energy resources, transformation processes, and regional systems involve calculation of all energy and material flows in and out of the system studied. This paper follows the "standard" synthesis table that is provided as a template for regional system evaluation based on an emergy evaluation of the United States, conducted by Stachetti (Emergy Systems, 2011a). The raw input data to the system (E_i) are gathered from the most recent data available in reliable databases, such as Statistics Canada, Natural Resources Canada, and the Food and Agricultural Organization (FAO) of the United Nations (UN). Fig. 1 illustrates a synthetic description of the resource flows and transformation processes that occur within the system boundary. This diagram shows both the external relationships between the system and its outside sources as well as between its own parts (in the form of arrows that represent flows of energy, matter, and money). The energy system diagram is drawn based on the symbols of the energy systems language – brought up by H.T. Odum (1971, 1983, 1996), as shown in Table 1.

3.2. Energy system diagram (Odum, 1996)

In the diagram shown in Fig. 1, the large rounded rectangle defines the boundaries of Canada, as the system under study. It covers different flows, including matter and energy, that contribute to the emergy system. It also demonstrates the circulation of money in the system and shows the gross domestic product of Canada. Resources are categorized based on their origin that is either from outside the system, such as environmental inputs and purchased energy and goods or within the system. Also, sources are classified as either renewable or non-renewable.

Environmental resource inputs and renewable resources (R) such as sun, rain, and wind enter the system from the left. Non-renewable resources that are created within the system boundaries are (N_0, N_1 and N_2). (N_0) represents rural resources, such as soil and forest biomass, if – within the system consumption rate is more than their regeneration. The reserves of fuels and minerals that are renewed over longer periods of geologic time is designated by (N_1). Export pathway (N_2) shows flow of resources that pass through the system without significant transformation. Examples include minerals that are mined and exported abroad without further processing. Imports to the system are shown on the top and right of Fig. 1. Imports include the emergy of fuels and minerals (F), goods (G), and the total imported service emergy (P_2I), that is the product of the dollars of imports (I) and the average emergy to money ratio (P_2) of the world. The emergy of import services account for the money spend to purchase and import goods to the system. The flow of money is shown with a dashed-line and ($) in the system diagram. The exports to the markets on the lower right have pathways for fuels, goods, and services similar to those discussed for imports. Emergy of goods (B) and emergy of non-