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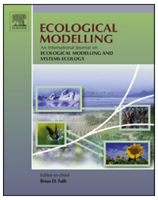

Short communication

# Effect of time scale on accounting for renewable emergy in ecosystems located in humid and arid climates

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ABSTRACT

Based on emergy accounting rules, only the greater number between emergy inputs from the same source, e.g., solar radiation and rainfall, should be accounted in emergy analysis to avoid double-counting. Using a year or a season as time scale, the rainfall emergy is usually larger than that of solar energy and thus taken as the renewable emergy input to the ecosystem. However, using a day as time scale, on sunny days with no rain only the solar energy would be counted as the renewable emergy. Therefore, different time scales may affect renewable emergy accounting. In this paper, we explored the effects of four time scales (year, season, month, and day) on renewable emergy accounting of forest ecosystems in Southeast China, a humid area, and the Minqin Oasis in Northwest China, an arid area. The results show that annual renewable emergy increased with the decrease of time scale but were close to each other in Southeast China (i.e., 2.5% difference at most), but were up to 30% different in arid Northwest China. However, the water which is actually used by forests for ecological productivity is evapotranspiration (ET), which can be less than precipitation in humid areas, but higher than rainfall in arid areas where groundwater compensates. Thus, it is ET rather than the available rainfall which should be counted as the renewable emergy input to ecological productivity. Otherwise the emergy contribution of renewable natural resources to ecosystems may be overestimated or underestimated, e.g., 0.33–7.33 times to the forests in Southeast China, and 0.36 times to the oasis system in Northwest China. Furthermore, despite whether or not it rains, ET emergy is often larger than solar emergy in most cases. Therefore, the use of ET emergy not only improves the estimate of emergy input, but also helps avoid the effect of time scale on renewable emergy accounting.

## 1. Introduction

Energy systems theory, developed by Odum (1983, 1994, 1996), provides the basis for using emergy synthesis as an environmental accounting tool that can measure real wealth independent of financial considerations (Odum, 1988, 1996; Brown and Ulgiati, 2004; Tilley, 2004; Campbell et al., 2005; Ortega et al., 2005; Bastianoni et al.,2007; Ulgiati et al., 2007; Rugani and Benetto, 2012; Geng et al., 2013; Zhang et al., 2013). Emergy was defined as the available energy previously used up directly and indirectly to make a product or service, usually expressed as solar emjoules (sej) (Odum, 1996). Emergy per unit values, i.e., transformity (sej/J), specific emergy (sej/g) and emergy/money ratio (sej/money), can be used to convert energy, material, and monetary flows to solar emjoules, respectively, allowing for direct comparison, addition, and subtraction (Lan et al., 2002; Odum, 2007; Li et al., 2011). Therefore, emergy analysis can properly evaluate environmental contributions that traditional economic evaluations usually overlook or underestimate (Campbell, 2001; Lu et al., 2010, 2012).

In semi-natural ecosystems such as agriculture, silviculture, aquaculture and fisheries, free environmental resources, such as solar radiation, water and wind, are combined with the purchased feedback inputs from the economy, such as fuels, materials, equipments and services, to produce a variety of products for humanity (Odum, 1996). Depending on the intensity of economic feedback,

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free environmental resources may contribute 5–95% of all emergy inputs of the products (Odum, 1996; Tilley, 1999; Lan et al., 2002; Ortega et al., 2005; Cohen et al., 2007; Felix and Tilley, 2009; Pereira and Ortega, 2010; Li et al., 2011, 2013). Thus, it is a fundamental requirement for environmental management and decision-making to properly measure the real value of free environmental resources such as solar energy, freshwater and wind.

When the standard emergy algebra rules are used to account for the environmental inputs to a system, only the largest environmental input is added to the sum because environmental resources are considered to be co-products of the same global sources of energy, i.e., solar energy, tide energy, and deep earth heat. Adding emergies derived from all of them would be "double counting" (Odum, 1996; Brown and Ulgiati, 2001). However, it needs to be noted that different time scales (year, season, month and day) may affect how much these environmental resources contribute to the total required solar emergy. Typically, the rain emergy is larger than the solar emergy on an annual or seasonal basis. However on a shorter time-scale, such as a day or a month, solar emergy can be greater than rain emergy because it does not rain in all days. Thus, it seems that different time scales can affect the renewable emergy accounting.

In contrast to emergy analyses that evaluate mean annual flows, Dynamic Emergy Accounting principles (Tilley and Brown, 2006; Tilley, 2014) can be and have been used to add solar and rain emergy on a daily basis to evaluate emergy flows in an entire watershed. That is, when simulating emergy flows, the choice of time-step in the model dictates whether solar and rain can be added. In general, the shorter the time-step, the easier and more appropriate it is to add renewable flows.

In addition, many emergy evaluations of ecological and agricultural systems use solar radiation or rainfall as the main renewable emergy input (Cavalett et al., 2006; Martin et al., 2006; La Rosa et al., 2008; Ju and Chen, 2011; Zhang et al., 2012). However, 100% of available natural resources, like rainfall and river water etc., are generally not used by the vegetation in ecological and agricultural systems, so it is an over simplification to use rain emergy rather than ET emergy. Ecosystems typically use a fraction of the rain emergy through the process of evapotranspiration (ET) (Thornton et al., 2002), with the extra portion leaving the system as runoff which is available for downstream systems. Thus, only the portion actually used (e.g., ET), rather than the entire available natural resource (e.g., rain and river water etc.), should be counted in the renewable emergy input to the ecosystem under study (Doherty, 1995; Tilley, 1999; Lefroy and Rydberg, 2003; Lu et al., 2006, 2007, 2011a; Felix and Tilley, 2009; Li et al., 2013). Further, regardless of whether or not it rains, ET can occur (Bowen, 1926; Monteith, 1965; Running and Hunt, 1993; Thornton et al., 2002; Savage et al., 2009) and has larger emergy than the solar energy, even at a day scale. Thus, taking ET emergy as the main estimate of renewable emergy input to an ecosystem's productivity is not only an improved refinement, but also alleviates the effect of time scale.

Besides time scale, it is noteworthy that the scaling problem may also occur in different spatial dimensions. When we take forest ecosystems for study sites, the ET emergy rather than the rain emergy should be considered as renewable emergy input to these forest ecosystems. However, when we extend the scale of forest ecosystems to the whole watershed, then the rain emergy should be accounted as the renewable emergy input, because it does some geological work for this watershed (Tilley and Brown, 2006).

In this paper, we selected three forest plantations in Southeast China, a subtropical monsoonal climate area with a mean annual precipitation of 1801 mm, and a desert-oasis ecotone known as Minqin Oasis in Northwest China, a temperate arid area with a mean annual precipitation of 110 mm, as study sites. We calculated the solar and rain emergy of these two ecosystems at four time scales (year, season, month and day). Then, based on emergy accounting rules, annual renewable emergy of these two ecosystems was determined for each time scale to explore its effect on renewable emergy accounting.

Finally, the ET was estimated as the renewable emergy input and compared with the solar emergy to determine whether it can alleviate the effect of time scale on environmental renewable emergy. This study aims to answer the following questions: (1) Does choice of time scale, like day, month, season and year, affect the emergy accounting of environmental renewable resources like solar energy and rain? (2) How much difference occurs among the results of renewable emergy accounting at these four time scales? (3) Can the use of ET alleviate the effect of time scale on renewable emergy accounting?

## 2. Materials and methods

We selected three forest plantations in Southeast China, a typical monsoonal climate area with abundant rainfall, and the Minqin Oasis in Northwest China, a typical desert-oasis ecotone, as study sites (Fig. 1). The three forest plantations—*Acacia mangium* (AM), *Schima superba* (SS), *Pinus elliottii* (PE)—are located at the Heshan National Field Research Station of Forest Ecosystems, Chinese Academy of Sciences (112°53′–112°54′E, 22°40′–22°41′N), Heshan City, Guangdong Province, Southeast China. This site receives an annual average net solar radiation of about 4.6E+09 $J/m^2$, has an annual average temperature of 21.7 °C and a mean annual rainfall of about 1800 mm (Lu et al., 2011b). The mean annual evapotranspiration may reach up to 1600 mm (Fu et al., 2009). Minqin Oasis, where the natural vegetation is dominated by a shrub (i.e., *Nitraria tangutorum*), is located at Northeast Hexi Corridor (103°02′–104°02′E, 38°05′–39°06′N), Gansu Province, Northwest China (Li, 2013). This site has a temperate continental arid climate, with a mean annual net solar radiation of about 5.7E+09 $J/m^2$, a mean annual temperature of about 7.8 °C and a mean annual rainfall of about 110 mm. Its mean annual evapotranspiration is about 165 mm, with the water deficiency being compensated by groundwater. The data of solar radiation and rain in two sites have been collected through regular observation (Fu et al., 2009; Li, 2013).

To compare and explain the effect of different time scales on renewable emergy accounting, we only take the solar emergy and the rain emergy into consideration in this paper. According to emergy accounting rules, only the larger one of the solar and rain

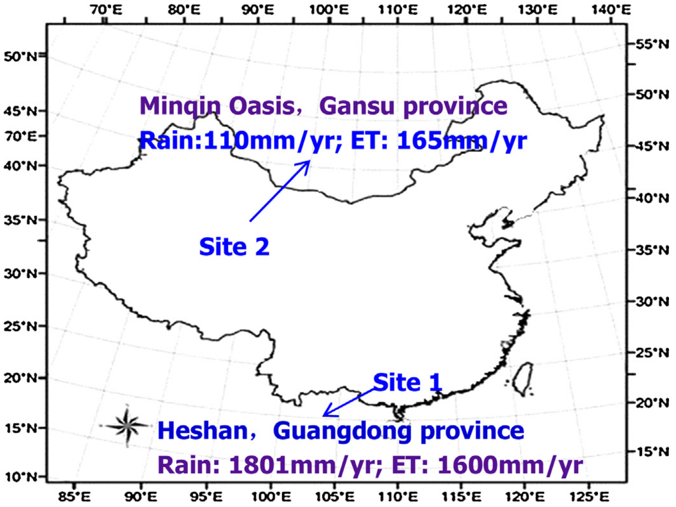

**Fig. 1.** The location of three forest plantations in Southeast China and the Minqin Oasis in Northwest China (Site 1: *Acacia mangium* (AM), *Schima superba* (SS), *Pinus elliottii* (PE); Site 2: *Nitraria tangutorum*).