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Emergy-based sustainability assessment of a loblolly pine (*Pinus taeda*) production system in southern Brazil

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ABSTRACT

The world's wood demand from planted forests is expected to drastically increase in the following decades. Brazil displays very high levels of forest productivity for *Pinus* and *Eucalyptus* planted forests. Loblolly pine (*Pinus taeda*) is the most important species in terms of planted forest area in southern Brazil. There, it is mainly used for paper and pulpwood production, but also allows for multi-purpose and high quality wood production. Of particular interest is whether loblolly pine management in southern Brazil comprises a sustainable alternative to world's wood demand. A promising tool to assess forest sustainability is named *emergy synthesis* (or emergy accounting). It is a top-down environmental accounting approach set out to assess holistically nature and society's contributions toward a production process. It converts all forms of energy, materials, and human services into equivalents of one form of energy: Emergy, expressed in solar emjoules (seJ). This study aimed to assess the emergy-based sustainability of a loblolly pine wood production system practiced by a private forest company in southern Brazil (municipality of Rio Negrinho, Santa Catarina State). Data on society's input (materials, fuels and labor) were provided by the company itself and subsequently checked through field measurements and personal communication with the forestry staff. Nature's input was segregated into renewable and non-renewable resources, with their estimates being derived from literature information. *Renewable natural resources* in the form of rainfall comprised 82.4% of total emergy. The organic fraction of soil loss represented the emergy flow of *non-renewable natural resources* and accounted for 0.85% of total emergy. The remaining 16.75% of total emergy comprised society's contribution. The loblolly pine system outperformed large-scale, intensively managed agriculture and eucalyptus production systems in Brazil as regards the emergy index of *renewability*. In relation to planted forests worldwide, this loblolly pine system displayed the lowest *transformity*, indicating that it was the most efficient system at producing a joule of wood per emergy investment. From the perspective of emergy synthesis, this loblolly pine production system is a feasible alternative to world's wood demand and to sustainable land use in southern Brazil. While we perceived emergy synthesis to be an important tool to assess forest sustainability, we strongly argue that it should be complemented by other assessment approaches in order to consider, inter alia, short-term adverse impacts on soils and the socioeconomic benefits of providing job opportunities and ecosystem services.

1. Introduction

Burgeoning populations and growing economies can be expected to substantially increase the world's wood demand in the following decades (FAO, 2010, 2015). Nevertheless, wood harvesting from natural forests might decline in the future as natural forests are increasingly being designated for conservation of water, soil and biodiversity, or other uses that preclude or limit wood production (FAO, 2010, 2015). Moreover, natural forest conversion to other land uses and unsustainable forest management practices pose major threats to the global wood supply from natural forests (Warman, 2014). Therefore, planted forests should play an increasingly greater role in the global wood supply (ABARE, 1999; FAO, 2000; Carle and Holmgren, 2008), a projection that raises concerns about how to assess and improve planted forest

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sustainability.

In Brazil, planted forests play a much more important role than its area might suggest. They currently account for less than 1.5 percent of forest lands (SFB, 2013), but 90.5 percent of industrial roundwood production (IBGE, 2014). Planted forest management is realized under a farm-level landscape approach. Privately owned forest farms are characterized by the co-existence of nature reserves and planted forests. This is because Brazil's Forest Code requires that landowners conserve native vegetation by setting aside a Legal Reserve (LR), which occupies 80% of the property area in the Amazon and 20% in other biomes. Additionally, landowners are required to set aside Areas of Permanent Preservation (APPs) for the purpose of soil and water conservation. Roughly, half of Brazil's native vegetation area is estimated to reside on private properties (Soares-Filho et al., 2014).

The tremendous productivity of Brazilian planted forests is due in no small part to genetic improvement programs (Aguiar et al., 2011). Loblolly pine (*Pinus taeda*) is the most used species for planted forests in southern Brazil. It's growth is not restricted by climate in most part of this region, nonetheless productivity varies considerably in relation to soil, climate and management practices (Higa et al., 2008).

Loblolly pine planted forests in southern Brazil are mostly managed by large-scale forest companies to supply raw material for paper, pulp and wood-based composite industries. These production systems are mainly characterized by large-scale plantations, genetically improved seeds, initial spacing of 1600–1800 seedlings/ha, short rotations (15–20 years), and absence of pruning and thinning treatments (Dobner, 2013). Nonetheless, silvicultural interventions show great potential for improving loblolly pine wood quality in this region (Dobner, 2013). Moreover, loblolly pine multi-purpose wood production in southern Brazil displays a set of economic advantages. Namely, low input costs (Dobner, 2013; Oliveira, 2013), which is partially explained by its low nutritional requirements (Reissmann and Wisniewski, 2004); low market risks, which is possible trough output diversification; and a consolidated domestic demand for solid wood products (Dobner, 2013; Ibá, 2015). Overall, loblolly pine planted forests is a promising land use to improving the livelihood of small to mid-size landowners in southern Brazil. Of particular interest is whether it also comprises a sustainable land use.

Emergy synthesis (or emergy accounting) has become a prominent sustainability assessment approach (Hau and Bakshi, 2004; Ness et al., 2007; Gasparatos et al., 2008). Emergy (spelled with "m") is a measure of nature and society's contribution in generating products and services (Brown and Ulgiati, 1999; Odum et al., 2000). Emergy synthesis provides a biophysical basis to converting inputs and outputs flows for a system into a common unit of measure, so that they can be aggregated to provide a holistic understanding of system's functioning and to assess important sustainability attributes, such as efficiency and renewability (Ulgiati et al., 1995; Brown and Ulgiati, 2001; Ulgiati et al., 2011).

Emergy synthesis has been employed to the sustainability assessment of a broad range of agriculture and agroforest production systems worldwide (e.g. Lefroy and Rydberg, 2003; Diemont et al., 2006; Martin et al., 2006; Cuadra and Bjorklund, 2007; Agostinho et al., 2010). However, there have been only few emergy studies dealing exclusively with intensively managed, single species planted forests (Doherty, 1995; Odum et al., 2000; Doherty et al., 2002; Romanelli et al., 2008; Pedroso et al., 2010).

This study aimed to assess the emergy-based sustainability of a loblolly pine wood production system practiced by a private forest company in southern Brazil (municipality of Rio Negrinho, Santa Catarina State). Furthermore, it attempted to advance on the use of emergy synthesis as tool to assess forest sustainability.

2. Materials and methods

2.1. Pine production system

This study was conducted at a forestry company in southern Brazil. At that time, the company owned a total area of 35,350 ha, distributed in different land properties within the states of Parana and Santa Catarina. Over half of this area contemplated natural forests aimed at nature conservation and ecosystem services delivery. Planted forests, mostly loblolly pine stands, comprised 41.9% of total forest area.

Most of the company's pine plantation area was covered by native forest back in the seventies. The conversion of native forest into pine plantations came in response to the creation of federal subsidies for forest plantation establishment. First generations of pine stands were mostly managed on a 25-year rotation schedule. But to shorten the return period on final harvest revenue, the rotations of the following generations were gradually reduced to 17 years.

The loblolly pine production system was managed for multi-purpose wood production, especially wood for furniture making, and the management regime typically comprised two pruning and one thinning treatments. Average standing woody biomass productivity was $30\,m^3\,ha^{-1}\,year^{-1}$.

For this study, we select a forest farm that displayed a close-to-average forest yield and that the different phases of the forest production cycle were spatially represented.

The forest farm was located in the municipality of Rio Negrinho, which lies on a plateau in the northern part of the state of Santa Catarina. The Agroecological Zone of Rio Negrinho is characterized by subtropical climate (classified as Cfa according to Köppen climate classification) and by the following mean annual values: temperature between 15.5 °C and 17.0 °C, precipitation between $1360.0\,mm\,year^{-1}$ and $1670.0\,mm\,year^{-1}$, and relative humidity between 80.0 and 86.2% (EPAGRI/CIRAM, 2012). Rio Negrinho is located in Atlantic Forest biome, more precisely in a transitional zone between the ecoregions formed by coniferous forests (Araucaria Moist Forest) and by montane tropical moist forests (Serra do Mar Coastal Forests). The soil type is classified as cambisol. It is a very acid and moderately deep soil, the parent material being predominantly Paleozoic sedimentary rocks.

2.1.1. Data

System characterization contemplated a forest production cycle that began with soil preparation and ended with log loading onto trucks at the landing. Rainfall and the organic matter of soil loss represented nature's input to system. Their estimates were based on literature information. Data on society's contribution were provided by the forest company itself and subsequently checked through field measurements and personal communication with the forestry staff.. Fieldwork was carried out between 2011 and 2012. Society's contribution was addressed in terms of management activity and input item. The first comprised the activities of soil preparation, planting and infilling, weed chemical control, weed physical control, ant chemical control, pruning, thinning, and clear felling. The input items encompassed human services (labor), fuel, seedlings, herbicide, formicide, plastic depreciation, steel depreciation, and iron depreciation. Depreciation rate estimates for machines, equipment and tools were provided by the forestry staff.

2.1.2. System description

Mechanical soil preparation consists of forest floor windrowing and subsoiling to 50 cm depth along planting lines. Both activities were accomplished with a bulldozer. Planting comprises a manual activity. Seedlings are planted at an initial growing spacing of 2.5 × 2.0 m. Replanting (infilling) occurs thirty days later if seedling survival rate is lower than 98%.

Leaf-cutting ants control consists of applying granulated baits fifteen days after mechanical soil preparation. Five-gram granulated baits, with sulfluramid as the core active ingredient, are applied at a