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Dynamic emergy accounting of water and carbon ecosystem services: A model to simulate the impacts of land-use change

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ABSTRACT

Expansion of agriculture over ecosystem areas is widely recognized as one of the most significant human alterations to the global environment over the last century. Although food and fiber production are essential ecosystem services (ES) to humankind, the clearing of forests for agricultural use is associated with changes in land cover which affect a wide range of ES at local, regional and global scales. Considering the importance of climate change, freshwater scarcity, soil erosion and other environmental issues, this paper aims to simulate the impact of land-use change on the ecosystem services related to water and carbon biogeochemical processes. The system under study is the Taquarizinho river basin, located in the eastern region of Mato Grosso do Sul State, Brazil, inserted in the upland borders of one of the largest wetland systems of the world, the Pantanal. Formerly occupied by Brazilian savannah (*Cerrado*), more than half of Taquarizinho watershed was converted both to agriculture and pasture lands since the 1960s. In order to quantify the impact of land-use change on ES provided by Taquarizinho over the years, this paper introduces the hydro-carbon model, which dynamically represents ecosystem services related to water and carbon cycles, such as canal discharge, groundwater recharge, evapotranspiration, biomass carbon sequestration, litter carbon sequestration, and soil carbon sequestration. The hydro-carbon model uses emergy for estimating the monetary value of ecosystem services provided by the river basin under different land-use scenarios. In this paper, extreme scenarios represent typical land-use types in Taquarizinho basin: native savanna (NS), agroforestry systems (AF), conventional tillage agriculture (CT), no-tillage multiple cropping agriculture (NT), degraded pastures (DP), and pastures under improved management (IP). Results in this paper reveal a hierarchy related to water and carbon ES provision, in descending order: native savanna (247 EM\$ ha^{-1} y^{-1}), agroforestry system (204 EM\$ ha^{-1} y^{-1}), pastures under improved management (180 EM\$ ha^{-1} y^{-1}), no-tillage multiple cropping agriculture (160 EM\$ ha^{-1} y^{-1}), degraded pastures (104 EM\$ ha^{-1} y^{-1}) and conventional tillage agriculture (75 EM\$ ha^{-1} y^{-1}).

1. Introduction

A doubling in global food demand is projected for 2050. If past impacts of agriculture on human population and consumption continue, a billion hectares of natural ecosystems would be converted to agriculture in this period, predominately in Latin America and sub-Saharan central Africa (Tilman et al., 2001). In Brazil, about 16.8 million ha of additional land will be required to accommodate the expansion of all economic activities over the 2006–2030 period. Considering business-as-usual deforestation rates, agricultural production and livestock activities would be responsible to eliminate an additional 13.8 million of hectares of forest in Northern Amazon, 1.2 million hectares of *Cerrado* (the Brazilian savannah) in Brazilian Center-West and other 2 million hectares of native vegetation in Maranhão, Piauí, Tocantins and Bahia states in this period (World Bank, 2010).

Land-use changes are cumulatively a major drive of global environmental change. In extent, the most important form of land use conversion is the expansion of crop and grazing land over natural ecosystems (Lambin and Meyfroidt, 2011), which affect ecosystem services (ES) provision since it simplifies the ecosystem (Altieri, 1999) and changes the local environmental properties (Matson et al., 1997). Although modern conventional agriculture maximizes ES of food and raw material production, some agricultural management practices can lead to reduction in other ES, fundamental to human life support (Tilman et al., 2002).

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Agricultural and grazing activities have dual consequences for human welfare because they involve services obtained from food and fiber production and disservices derived from losses of ES (Zhang et al., 2007) such as soil erosion and loss of biodiversity. Although benefit from food production is economically measured by parameters such as food market prices, there is a gap of information related to economic losses caused by the depletion of ES (Watanabe and Ortega, 2011). Therefore, ES depletion is partially related to a weakness in most human decision-making processes of not attributing monetary values to the benefits provided by the environment (MEA, 2005).

Considering that most ecosystem managers do not have technical and financial resources to estimate present value of ecosystem services in monetary terms (Prato, 2007), this paper introduces a model which allows calculations of daily monetary flows of carbon and water processes based on the concept of emergy (Odum, 1996). It aims to simulate the impact of land-use and land cover change (LUCC) on the provision of ecosystem services at river basin scale, such as evapotranspiration, canal discharge, groundwater recharge, carbon sequestration in net primary production (NPP), carbon sequestration in soils, carbon sequestration in litter and net carbon exchange in the basin. Model outputs are presented in terms of mass, emergy and monetary flows on a daily basis.

2. Emergy accounting, biogeochemical processes and ecosystem services

Emergy is defined as the available energy of one kind required directly and indirectly to make a product or provide a service (Odum, 1996). Using the principles of thermodynamics, general systems theory, ecology and other sciences, the emergy synthesis is able to measure the energy and mass flows of any system on a common basis, usually in terms of a solar equivalent Joule or 'seJ' (Odum and Odum, 2000). Thus, emergy accounting is a biophysical approach to estimating the contribution of nature to economic activity, as opposed to other methods that rely on a population's perceived value of nature's contribution (Tilley and Brown, 2006). According to Odum and Odum (2000), emergy-based valuation would avoid neoclassical approaches that "would not capture real contributions of ecosystems and could delay the organization of a sustainable pattern of environment and people". Conventional approaches related to ecological economics, such as willingness-to-pay based on the contingent valuation method, usually capture the value of ecosystem entities narrowly and anthropocentrically, while in contrast emergy tries to estimate their ecocentric value (Hau and Bakshi, 2004).

According to Watanabe and Ortega (2011), biogeochemical flows are coherent entities to be assessed by the emergy-based approach primarily because such flows can be decoded in terms of mass and energy. Ecosystems services, such as soil formation, could be related to a superposition of two or more biogeochemical flows (carbon sequestration, nitrogen biological fixation and water percolation, for instance) which are unitary ecosystem processes that directly or indirectly affect the human perception of welfare. Therefore, biogeochemical processes would have an effect on a wide range of ecosystem services, including climate regulation, food and raw material production, soil formation, water supply and flood control. Depending on the level of depletion caused by human intervention on the ecosystem, biogeochemical inputs and outputs can become unbalanced and then the damaged ecosystems could potentially generate environmental disservices such as soil erosion, flooding, water scarcity and other undesirable events. An example would be land-use change processes such as the substitution of native forests by agricultural activities without management practices, which have the ability to harm the regulatory properties of natural systems and decrease their capability of providing ecosystem services (Watanabe and Ortega, 2011).

An ecosystem service that contributes to the economy of a given region can be expressed in terms as Emdollars. According to Odum (1996, p. 57), "if a flow of emergy is responsible for a portion of the real wealth of an economic system, we can infer that this proportion of the system's buying power is due to this emergy flow. Therefore, the emdollars (EM$) are the appropriate measure for discussing large-scale considerations of an economy, including environment and information, as well as human goods and services". Quantitatively, EM$ indicate how much an ecosystem service or product contributes to the economy and allows environmental contributions to be compared to more traditional macroeconomic measures (Tilley and Brown, 2006).

In this paper, emergy flows of ecosystem services were converted to money (emdollar) by using the ratio calculated by dividing the total emergy use in the Brazilian economy by the Brazilian Gross Domestic Product (GDP) in 2006, which corresponded to 10.52×10^{12} seJ USD^{-1}, according to a previous study of Brazilian Emdollar (Pereira, 2012).

3. Description of study area

The selected study area is within the Taquarizinho watershed which comprises the cities of São Gabriel do Oeste and Rio Verde de Mato Grosso, located at northern region of the State of Mato Grosso do Sul, Brazil. The climate of Taquarizinho watershed is hot and humid with a mean annual temperature of 25 °C and average rainfall of 1300 mm y^{-1}. The annual rainfall pattern is seasonal with wet season from October to March and dry season from April to September (Oliveira, 2007).

The main river is named Taquarizinho whose distance from source (720 m above sea level) to mouth (280 m above sea level) is approximately 55,000 m (Flores, 2007). It flows toward Coxim river and then to Taquari river which, in turn, flows to the Pantanal, the largest Brazilian wetland. The eastern Pantanal floodplains have been affected by upstream land-use changes related to the expansion of agricultural and grazing activities during the last five decades. The Taquarizinho watershed, for instance, was originally covered by 100% of Cerrado, the Brazilian savannah, however has been modified since the 1960s. In 1966, Taquarizinho land use was of 82% native forest, 16% pasture and 2% cropland, mostly for soybean production. After three decades of agricultural expansion, these figures have changed to 34%, 46% and 21%, respectively, according to Brazilian Agricultural Research Corporation (Embrapa, 2011) (Fig. 1).

4. Hydro-carbon model development

The hydro-carbon model was initially based on Tilley and Brown (2006) that have assessed wetland stormwater management systems (WSMS) in Black Creek (C-1) basin in Florida State, United States. They have simulated the temporal variability of solar transformity and also eco-hydrological value of WSMS in terms of emergy and equivalent money, based on dynamic emergy accounting.

In the hydro-carbon model described in this paper, hydrological processes and storages are based on the system boundary conditions, state variables and driving functions, as they appear in the upland watershed model developed by Tilley and Brown (2006). However, a group of new forcing functions, state variables, storages, interactions and pathways have been included in the model in order to simulate LUCC effects on ecosystem services related to water and carbon at the river basin scale. The development of an