Journal of Cleaner Production xxx (2013) 1–11

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluation of forest growth and carbon stock in forestry projects by system dynamics

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ARTICLE INFO

Article history:
Received 29 November 2012
Received in revised form
26 September 2013
Accepted 27 September 2013
Available online xxx

Keywords:
Forest
Carbon
System dynamics

ABSTRACT

Brazil is one of the largest producers of eucalyptus that is used for manufacturing pulp and paper; this contributes directly to the issue of carbon emissions. Reforestation of eucalyptus appears as a viable alternative for mitigating these carbon emissions, leveraging their high productivity to that of other leading countries in the market, such as Finland and Sweden. This study aims to develop a model for monitoring and evaluating forest growth and quantifying wood stocks and sequestered carbon. System dynamics was used to simulate forest growth. Forest growth was modeled from eight regions with dissimilar edaphoclimatic characteristics, in the state of Minas Gerais, in Brazil. The model was sensitive enough to the characteristics of the regions, where the difference in forest stocks was 45.1% at the end of 30 years in a harvest cycle of 7 years. It was found that the typical harvest cycle in practice by leading companies did not always yield a higher sequestered CO_2 accumulated stock. By shortening the harvest cycle, it was possible to obtain a gain of up to 21.0% in the sequestered CO_2 stock.

1. Introduction

The principal objective of the United Nations Framework Convention on Climate Change (UNFCCC) is to “stabilize [GHG] concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (Ellison et al., 2011). Mitigation of atmospheric CO_2 requires an approach that combines reducing CO_2 emission with increasing CO_2 storage (Sundquist et al., 2008). Forests and forest soils represent a major source of terrestrial carbon sequestration (Ellison et al., 2011). According to UNFCCC (2011), the Conference of the Parties (COP) 16/2010 deliberated policy approaches and positive incentives for emissions mitigation related to LULUCF (Land Use, Land-Use Change, and Forestry), that encourages developing country parties to contribute mitigation actions in the forest sector. Despite this, at COP 17/2011, the commitment period was extended from 2013 to 2020 or later, since doubts persist about the accounting rules on LULUCF (Ellison et al., 2011).

Forest management as a means to carbon sequestration has been suggested by Masera et al. (1995) who have demonstrated the potential of commercial plantations in Mexico for the same. Several studies have shown that forests and forest management play an important role in the active mitigation of atmospheric CO_2 through increased carbon (C) storage (Schlamadinger and Marland, 1996; Sedjo et al., 1997; Marland et al., 1997; Canadell and Raupach, 2008; Malmsheimer et al., 2008; Gonzalez-Benecke et al., 2010). The fixation of atmospheric CO_2 into plant tissue is one of the most effective mechanisms for offsetting C emissions (Sedjo, 1989; Sedjo et al., 1997; Nabuurs et al., 2007; Gonzalez-Benecke et al., 2010). Trees capture carbon dioxide from the atmosphere through the process of photosynthesis in which green leaves produce carbohydrate (Song and Woodcock, 2003). Numerous studies have demonstrated that growing trees sequester carbon that could provide relatively low-cost net emission reduction (Solberg, 1997; Van Kooten et al., 1997; Cannell, 1999; Newell and Stavins, 2000; Petersen and Solberg, 2004; Baskent and Keles, 2009). In this sense, the global balance of greenhouse gases can be measured or quantified using those forest management activities that increase forest biomass growth and reforestation (Hoen and Solberg, 1994; Plantinga and Birdsey, 1994; Van Kooten et al., 1995; Krcmar et al., 2001, 2005; Diaz-Balteiro and Romero, 2003; Backeus et al.,

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http://dx.doi.org/10.1016/j.jclepro.2013.09.049

2005, 2006; Raymer et al., 2005; Keles and Baskent, 2007; McCarney et al., 2008; Baskent et al., 2008; Baskent and Keles, 2009; Yousefpour and Hanewinkel, 2009; Keles, 2010). Hence, quantifying and controlling the structure or dynamics of the forest is critically important to the production and protection of the forest ecosystem.

According to Silva (2007), carbon sequestration can be quantified by estimating the plant biomass above and below the soil surface. Scarpinella (2002) asserts that to quantify the carbon of a forest is a complex problem, since it involves external factors such as climate change, soil profile, local temperature, and type of vegetation. The principal forest management technique used to mitigate atmospheric CO_2 involves increasing forest cover through afforestation or reforestation, resulting in increased average carbon density over time or increased carbon stock per unit area of land (Canadell and Raupach, 2008; U.S. EPA, 2005; Gonzalez-Benecke et al., 2010).

The emphasis is that, according to ABRAF (2012), Brazil was the 5th largest producer of pulp (softwood and hardwood) in the year 2000, only surpassed by the United States, Canada, Japan, and Finland. In 2011, the country was the 3rd largest producer of pulp among integrated producers and 1st among producers selling pulp in the market. ABRAF (2012) states that in Brazil, suitable agrarian conditions, historical policy of investment in research and development, verticalization of the pulp sector and quality of labor, provided the highest productivity per hectare and, consequently, the lowest harvest cycle for forest plantations. The productivity of eucalyptus in Brazil (35–55 m^3/ha year) has reached an index about ten times higher than the productivity of leaders and traditional countries in this market, such as Finland (4 m^3/ha year), Sweden (5.5 m^3/ha year), Spain (10 m^3/ha year), Portugal (12 m^3/ha year), South Africa (20 m^3/ha year), and Chile (30 m^3/ha year) (SBS, 2008).

The evaluation of forest growth and carbon stock in forestry projects can be seen as a social dilemma situation in which the search for higher profits may lead to sub-optimal usage, exploitation, and preservation of public goods, in this case, the forest. The public goods game (PGG) is often employed to study problems that arise due to the dissonance between individual and societal interests (Chen et al., 2012a). Companies may increase their profit by neglecting environmental metrics of sustainability, while the public goods, could be depreciated or lost due to individual patterns or economic interests. Although similar to the PGG, the collective-risk social dilemma can better capture some important features of social dilemma that arise frequently in realistic situations. One example is the climate change dilemma, where a region or nation may choose not to reduce the carbon emission in order to harvest short term economic benefits (Chen et al., 2012a,b).

Several research and theoretical models study and explain such unfavorable outcomes. For instance, the PGG is one of the models used for studying social dilemmas and cooperation in sizable groups (Chen et al., 2012b, 2012c; Szolnoki et al., 2012). In this sense, the original research of Chen et al. (2012a) have shown that stronger feedback between group performance and collective-risk social level is in general more favorable to the successful evolution of public cooperation, yet only if the collective targets to be reached are setup in a moderate level. Moreover, failure to reach the collective targets has dire consequences for all group members, independent of their strategies (Chen et al., 2012b).

Further detailed and comprehensive concepts and reviews regarding PGG, collective-risk social dilemma, co-evolutionary games and evolutionary dynamics of groups interactions on structured populations can be found in Santos et al. (2008), Perc and Szolnoki (2010) and Perc et al. (2013).

Industrial symbiosis is another model that can be used for studying industrial systems and the social dilemma situation. This model deals with the physical flows of materials and energy in local and regional industrial systems using a system approach. The key ideas that support industrial symbiosis are collaboration and synergism – both whose possibilities offered by geographic proximity bear a resemblance to natural ecosystems (Chertow, 2000, Veiga and Magrini, 2009; Sokka et al., 2011; Boons et al., 2011). Literature presents several methods that can be used to study industrial systems, i.e., those based on optimization and mathematical programming techniques (Diaz-Balteiro and Romero, 2003; Diaz-Balteiro and Rodriguez, 2006; Karlsson and Wolf, 2008), environmental process models (Gupta et al., 2002; Miehle et al., 2006; Pérez-Cruzado et al., 2011), business and economic models (Tsvetkova and Gustafsson, 2012; Mendes et al., 2012; Nghiem, 2013), physical principles and simulations (Baldwin et al., 2004; Huo and Chai, 2008), application of multi-criteria decision analysis (Khalili and Duecker, 2013; Giménez et al., 2013), environmental risk mapping (Gupta et al., 2002), and supply chain models (Hall, 2000; Seuring and Muller, 2008; Seuring, 2013).

1.1. System dynamics (SD)

Besides the methods and frameworks cited above, the dynamical system is a good method to evaluate forest growth and carbon stock in forestry projects. The dynamical system approach is closely related to agent-based modeling and it has been applied in several studies to simulate complex and realistic situations. One of the advantages of systems dynamics (SD) compared to the other methods cited above is that SD can model complex systems using a quantitative approach that leads to new insights that are not attainable thus far by traditional and established models. The SD allows managers to make decisions using a rich set of data generated from the simulation results. This enables better decision-making regarding the social, economic, and environmental aspects of sustainability.

In terms of simulation techniques, the SD is one that studies highly complex systems based on the foundation of feedback control theory (Kyung and Moosung, 2005). On the base of the structure model of the system SD analyzes, it analyzes the cause-and-effect relationship among the factors inside the system and depends on the computer simulation to quantitatively analyze the structure of the information feedback system and the dynamic relation between function and behavior (Wang, 1994; Liu et al., 2011). The application of simulation technology is intended to forecast the future trends according to certain parameters and levels, which are difficult to estimate (Xu and Li, 2011).

The SD has been tested in studies dealing with quantification of emissions and carbon sequestration in different activities. Purnomo and Mendonza (2011) have presented an SD embracing both social and biophysical factors affecting the problem of forest degradation in Indonesia. Olabisi (2010) used SD to compare causal loop diagrams of forest cover dynamics in Negros Island, Philippines. Anand et al. (2006) applied the SD approach in the evaluation and mitigation of CO_2 emissions from the cement industry in India. Sgouridis et al. (2011) used SD in the study of air transport and carbon emissions, for transitioning the air transport industry near an operating point of sustainability and environmental mobility. Trappey et al. (2012) evaluated the effects of green transport policy in Taiwan, proposed for the island of Penghu using SD. Hence, in the present study, the researchers opted to test the SD model for the complexity of quantifying forest carbon stocks. System dynamics can provide two kinds of benefits for public involvement regarding environmental decision: a structure for deliberation and education and a tool for incorporating technical analysis in the social and environmental process (Stave, 2002).