Biomass and Bioenergy xxx (2017) 1–12

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Impact of ecosystem carbon stock change on greenhouse gas emissions and carbon payback periods of cassava-based ethanol in Vietnam

Trung H. Nguyen [a, c, *], Stephen Williams [b], Keith Paustian [a, b]

[a] Department of Soil and Crop Sciences, Colorado State University, USA
[b] Natural Resource Ecology Lab, Colorado State University, USA
[c] Hue University of Agriculture and Forestry, Vietnam

ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form
5 February 2017
Accepted 10 February 2017
Available online xxx

Keywords:
Life cycle assessment
Carbon stock change
Greenhouse gas emission
Payback period
Cassava-based ethanol
CENTURY

ABSTRACT

Cassava-based ethanol has been promoted in China and Southeast Asia as an effective means to reduce greenhouse gas (GHG) emissions and promote energy security. However, existing life cycle assessments of the environmental impacts of cassava ethanol have used highly-aggregated empirical methods to estimate ecosystem C stock changes, which do not capture finer-scale characteristics of different cassava growing regions within a country. We investigated carbon debts, GHG emissions, and payback periods for cassava-based ethanol in Vietnam using a life cycle assessment approach coupled with the widely-used ecosystem biogeochemical CENTURY model. The model simulated regionally-specific carbon stock changes associated with cassava cultivation for biofuel feedstock under different land use change, cassava yield and fertilization scenarios. We found that switching land use to cassava production for biofuel substantially reduced soil organic carbon in all major cassava growing regions in Vietnam. GHG emissions, carbon debts, and payback periods of Vietnam's cassava ethanol were strongly dependent on cassava yield. The mean carbon debt due to direct land use change to cassava production for ethanol ranged from 66 to 97 Mg of CO_2 per hectare, and the net carbon dioxide equivalent emission of cassava-based ethanol ranged from 36 to 95 g MJ^{-1}, depending on the range of cassava fresh weight yield (from 18 to 60 Mg ha^{-1}). To repay a carbon debt from direct land use change within 25 years, the average fresh weight yield of cassava used as feedstock for ethanol production must be above 33 Mg ha^{-1}.

1. Introduction

Cassava (*Manihot esculenta* Crantz) has recently been promoted as a potential feedstock for ethanol production in Vietnam and many other parts of Asia, including China and Thailand, due to its high yield and low input requirements [1] [2] [3]. Cassava can attain reasonably high yields with minimal irrigation and fertilization, with average fresh weight cassava yields in the region ranging from 17.2 to 60.0 Mg ha^{-1} [4] [5]. The Vietnamese government has set a clear strategy for the development of biofuel through 2015 with a broad vision toward 2025. Pursuant to Decision No. 177/2007/QD-TTg of 2007, the biofuel output target for 2025 is 1.8 Mt $year^{-1}$, equivalent to 5% of projected total fuel demand, with 0.6 Mt $year^{-1}$ coming from cassava-based ethanol [6].

However, questions remain about the overall benefits of cassava-based ethanol on greenhouse gas (GHG) reduction and potential negative impacts of cassava production on soil productivity due to soil erosion and high nutrient demand [7] [8] [9]. Although GHG mitigation is not currently the main driving force for development of biofuels in Asia, the GHG footprint of cassava-ethanol and potential negative impacts of cassava as a biofuel feedstock are a concern to policymakers in developing countries and should be a consideration when implementing national biofuel expansion plans. Consequently, there have been a handful of life cycle assessment (LCA) studies carried out to assess the environmental performance of cassava-based ethanol in China, Thailand, and Vietnam. LCA is defined by the International Organization for Standardization (ISO) as an analysis of the environmental impacts throughout the entire life cycle of a product, from raw material

* Corresponding author. Present address: Department of Soil and Crop Sciences, Colorado State University, 307 University Ave., Bldg.: Plant Sciences C127, Fort Collins, CO 80523-1170, USA.
E-mail address: nguyentrung1710@gmail.com (T.H. Nguyen).

http://dx.doi.org/10.1016/j.biombioe.2017.02.009
0961-9534/

extraction and acquisition, to energy and material production and manufacturing, to use and end of life treatment and final disposal [10]. Since LCA in the context of biofuels is still a relatively recent tool that requires further improvements and standardizations [11] [12] [13], the LCA results for cassava-based ethanol in the region vary dramatically between studies (Table 1).

Le et al. [4] indicated that this variation mainly stemmed from the differences in LCA assumptions, and the insufficiency in accounting for direct and indirect land use change (LUC) emissions, i.e., the emissions associated with changes in land use due to the cultivation of cassava for biofuel feedstock. Indirect land use change (iLUC) is the displacement of existing food production systems to new areas as a consequence of the land use change due to biofuel feedstock production. The quantification of iLUC is very complicated as it normally requires the linkage between the global economic equilibrium projections and the thorough analysis of land use change [18]. Therefore, it is often ignored in attributional LCAs like those conducted for cassava-based ethanol. Direct land use change (dLUC) deals with changes in carbon stock (C stock) including vegetation carbon (Cveg) and soil organic carbon (SOC) due to the introduction of a new cropping system for biofuel feedstock production that replaces the existing land use at a specific site. Direct land use change becomes a problem when carbon-rich ecosystems, such as forests and grasslands, are converted to produce feedstock for biofuels. These conversions release a significant amount of the carbon that had previously been stored in these ecosystems into the atmosphere, creating a "carbon debt" that subsequent biofuel production will have to offset.

The LUC effects are induced by the production of biofuels and thus must be carefully factored into the accounting of biofuel GHG emissions. Changes in Cveg (aboveground and belowground live carbon) are easier to measure or estimate while SOC change is more difficult and more expensive to quantify [19]. Therefore, SOC has often been ignored in many early LCA studies of cassava ethanol [2] [5] [15] [16].

More recent studies have attempted to address this problem by using simple (Tier 1) empirical models developed for the Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories to estimate SOC change due to changes in generic land use types [4] [17] [20]. Tier 1 soil C methodology uses broad averages for nine globally-defined climatic regions and six classes of soils [20], and was designed to support basic national inventory accounting in countries with minimal data and scientific resources. Thus this approach is poorly-suited for quantifying more locally-specific impacts on C stock change associated with local weather conditions, soil properties, cropping practices, and land use history of a specific location. In addition, the rates of SOC change are typically high following land use conversion, and then gradually decrease as SOC approaches a new stable state. This dynamic transition affects how GHG emissions associated with feedstock production are analyzed. The Tier 1 method has a fixed time horizon of 20 years, over which a constant rate of change is assumed, and thus the method does not capture the more dynamic and longer-term changes in soil C stocks that are of interest for computing soil carbon debts related to land use change.

An alternative solution for estimating soil C stock changes is to employ process-based models, such as CENTURY [21], DAYCENT [22], DNDC [23], or RothC [24]. Although these biogeochemical models were originally developed for research purposes at field-scale, many of them have been used effectively for soil C or GHG estimation at regional to national scales [25] [26]. Compared to aggregated empirical models like the IPCC Tier 1 methods, these process-based models can better represent site-specific conditions by integrating non-discrete variables, such as temperature and moisture, and the interactions of biophysical characteristics (e.g., climate and soil characteristics). In addition, these models can capture the historical influence of land use and management practices on potential future changes in soil C stocks [27].

We investigated GHG emissions from the production stage, carbon debts, and carbon payback periods of cassava-based ethanol in Vietnam with an emphasis on soil C stock changes due to dLUC. A process-based model (CENTURY) was used to simulate these changes. The model takes into account more site-specific factors including climate, soils, cropping practices, land use history, and dLUC and produces time series of C stock changes based on dynamic simulation of carbon and nitrogen cycling processes in the soil–plant system.

2. Methods

2.1. Modeling the emissions from C stock changes caused by dLUC to cassava cultivation

The data on dLUC to cassava cultivation for biofuel feedstock in Vietnam were obtained from the survey conducted by Le et al. [4] in 2013, and then aggregated into percentages of dLUC to cassava by main growing region (North Central, South Central, Central Highlands, and Southeast) and by baseline land use type within each region (annuals, perennials, forest, and grassland) (Table 2). Annuals are defined as land used for crops with a less than one-year growing cycle and which must be newly sown or planted for further production after the harvest (e.g., rice, maize, wheat, millet, sugarcane, reed, and jute). Perennials are defined as land cultivated with long-term crops which do not have to be replanted for several years (e.g., tea, coffee, rubber, and citrus). Forests are land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds in situ, and grassland are land covered with herbaceous plants with less than 10% tree and shrub cover [28]. The barren land, and denuded hills were also included in the grassland. The CENTURY model [21] was used to model the C stock changes to cassava for the four baseline land use types in the four cassava growing regions. The results were then used to compute the mean carbon debts and annualized emissions from C stock changes caused by dLUC to cassava production for biofuel feedstock in Vietnam. The main steps of the modeling process included: (1) model inputs and parameterization; (2) model simulation; and (3) calculation of carbon debts and annualized emissions from C stock changes caused by dLUC (Fig. 1).

2.1.1. Model descriptions

The CENTURY model is a general ecosystem biogeochemical model that is widely used to simulate ecosystem carbon and

Table 1
GHG balance for cassava-based ethanol in Vietnam: a comparison.

Criteria	Gasoline [14]	Hu et al. [15]	Liu et al. [5]	Leng et al. [16]	Nguyen et al. [2]	Silalertruksa and Gheewala [17]	Le et al. [4]
Country		China	Guangxi, China	China	Thailand	Thailand	Vietnam
LUC emission (g MJ^{-1})						36–222	33
GHG balance (g MJ^{-1})	94	73	20–74	734	46	63–313	35
% of GHG reduction (vs. gasoline)		23	79–22	−681	51	33–(−233)	63

Please cite this article in press as: T.H. Nguyen, et al., Impact of ecosystem carbon stock change on greenhouse gas emissions and carbon payback periods of cassava-based ethanol in Vietnam, Biomass and Bioenergy (2017), http://dx.doi.org/10.1016/j.biombioe.2017.02.009