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

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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 CO₂ 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.

Keywords: Life cycle assessment, carbon stock change, greenhouse gas emission, payback period, cassava-based ethanol, CENTURY.

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 – 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 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).

(Table 1. Here)

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 (C_{veg}) 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 C_{veg} (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 Modelling 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 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ, and grassland are land covered with herbaceous plants with less than 10 percent tree and shrub cover [28]. The barren land, and denuded hills were also included in the grassland. The CENTURY model [21] was then 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 modelling 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).

(Table 2. Here)

(Fig. 1. Here)

2.1.1 Model descriptions

The CENTURY model is a general ecosystem biogeochemical model that is widely used to simulate ecosystem carbon and nitrogen dynamics [29]. It is a multi-compartmental model composed of a soil organic matter/decomposition submodel, a water budget model, a grassland/crop submodel, a forest production submodel, and routines to simulate a large suite of land management practices (e.g., plant species, planting, harvest, tillage, fertilization, irrigation, grazing, etc.) and disturbance events (e.g., land clearing, fire). CENTURY uses relatively coarse time steps (monthly for soil organic C and N processes; weekly for plant growth and water balance calculations) and thus is intended for simulating medium- to long-term (annual to centuries) changes in SOC and other ecosystem parameters in response to changes in climate, land use, and management [19]. CENTURY and DAYCENT (the daily time-step version of CENTURY [30]) have been successfully applied to various ecosystems in various locations throughout the world [31][32][33][34]. Relatively few data inputs are required for CENTURY, including monthly maximum/minimum air temperature and precipitation, surface soil texture class, and land cover/use data (e.g., vegetation type, cultivation/planting schedules, amount and timing of nutrient amendments), which suited the conditions of our study (e.g., limited daily weather data for the research locations and study regions).

2.1.2 Model inputs and parameterization

Averaged monthly precipitation, maximum, and minimum temperatures observed at stations in Vietnam were obtained from the Statistics and Food Security Database [35] for 12 years (2001 - 2013) and then transformed into appropriate formats for CENTURY. We used data from five provincial weather stations to represent the four geographical regions (Fig. 2). There are two weather stations in the North Central region due to its location in a transitional zone between two distinct regional weather patterns.

(Fig. 2. Here)

Major soil types and their properties were obtained from literature (Table 3) and were coupled with weather data to parameterize the site conditions in CENTURY. We assumed these soil characteristics as typical for all cassava growing regions.

(Table 3. Here)

To model the C stock of the baseline land use types before dLUC to cassava cultivation, specific sets of soils were assigned to the different land use types for each cassava growing region (Table 4) [41]. We modeled broad classes of land use such as annuals, perennials, forest, and grassland and assume that each land use type could be represented by the dominant crop/tree species.

Maize, peanut, sugarcane, cassava, and rice were selected to represent annuals. Their cropping proportions in each region (Table 4) were calculated based on the planted area data obtained from the General Statistics Office of Vietnam [42]. Mixed fruit tree, secondary tropical forest, and mixed grass were used to represent perennials, forest, and grassland, respectively. Due to the unavailability of soil area proportions for the annuals land use type, modeled crops were

assumed to be evenly distributed across the corresponding soil types. The SOC of the annuals was averaged based on the cropping proportions of the representing species.

(Table 4. Here)

Management practices for various crops used in our model simulation, such as planting and harvest dates, fertilization, and irrigation, were obtained from Vietnam's National Center for Agricultural Extension databases [43], as summarized in Table 5.

(Table 5. Here)

We mainly used CENTURY default parameters [44] for each of the ecosystems and crop types in our analysis. Because of the significant impacts of vegetation growth processes on the prediction of SOC dynamics and GHG emissions [45], we calibrated the CENTURY's growth submodels against the reported values from literature for the studied vegetation types. PRDX is a parameter used for calculating potential aboveground monthly production as a function of solar radiation, thus representing the genetic potential production of different vegetation types or crop varieties. We adjusted the PRDX for each vegetation type and simulated growth under different regional climate, soil conditions, and standard management practices. Modeled yield or Cveg of each species at national-scale were calculated by averaging the regional values, and compared with the literature reported data [46][47] to choose the best values for PRDX. Due to the lack of field experiments measuring SOC as a function of land management practices in Vietnam, we were not able to directly validate model predictions of SOC changes for the various crop and land use types.

2.1.3 Scenarios for the analysis of expanded cassava production

For a baseline scenario, we used Vietnam's average cassava yield reported by FAO in 2013 (18 Mg ha⁻¹) [46], and a fertilizer/pesticide application rate (per ha) of 58 kg of N, 53 kg of P₂O₅, 47 kg of K₂O, and 0.23 kg of pesticide [4]. Cassava fields were moderately irrigated at 75% field capacity using auto-irrigation function in CENTURY at the time of planting. The corresponding baseline Fertilizer-to-Yield ratios (FTY_{baseline}) were 3.22 kg Mg⁻¹, 2.94 kg Mg⁻¹, 2.61 kg Mg⁻¹, and 0.013 kg Mg⁻¹ for N, P₂O₅, K₂O, and pesticide, respectively.

To represent the relation between yield increase and fertilization rates, we used a simple linear equation:

$$F_i = (\Delta Y) * FTY_i + F_{i_baseline}, \quad \text{Eq. 1}$$

where F_i , FTY_i , $F_{i_baseline}$ are the application rate (kg ha⁻¹), Fertilizer-to-Yield ratio (kg Mg⁻¹), and the baseline application rate (kg ha⁻¹) of the fertilizer (or pesticide) i , respectively; ΔY (Mg ha⁻¹) is the difference between the modeled and the baseline yield.

We then performed an analysis using a range of the reported cassava yield (from 18 to 60 Mg ha⁻¹) and a range of FTY (from 50 to 150% of the FTY_{baseline}) to examine the effects of cassava yield improvements and changes in the corresponding fertilizer application on GHG emissions, carbon debts, and carbon payback periods. The scenarios with reduced FTY represent the effects of future cassava breeding advances and/or improved N management that enhance the yield response to nitrogen, while the scenario with the highest FTY represents potentially less efficient N utilization as yields increase. The simulated yield and fertilization ranges are specified in Table 6. Since most of cassava production area in Vietnam is rain-fed, we did not consider the variation in the irrigation rate. Instead, irrigation (irrigated at 75% field capacity) and other

management practices used in this study such as farmyard manure application (5 Mg ha^{-1}) were kept constant throughout the sensitivity analysis. In addition, we assumed that these management practices were at average levels and were applied uniformly for all cassava growing regions in Vietnam.

(Table 6. Here)

2.1.4 Model simulations

Prior to modeling SOC under the cassava system, we set up the baseline SOC for all land use types in all cassava growing regions with CENTURY. Baseline SOC reflects the SOC level under the current management practice, and is used to evaluate the magnitude and direction of SOC change due to dLUC to cassava production for ethanol. The baseline simulation is comprised of two stages: an initial model spin-up followed by a simulation of historical land use. The spin-up simulation sets the equilibrium for SOC under natural systems with little or no disturbance from human activities, with tropical forest used as the native vegetation. To run the model to equilibrium SOC, we simulated tropical forest with default CENTURY parameters for 10,000 years under locally specific soils and climate data for each region. Subsequently, the model was run from this equilibrium condition for each specific historical land use, including annuals, perennials, forest, and grassland for each region. A period of 68 years (1945 to 2013) was used for the historic and current land use period. The year 1945 was selected because it marked the beginning of broad-scale forestland conversion to agricultural use, brought on by numerous agricultural policies. The SOC stocks at the end of the historic/current period were used as a baseline for comparison with the future projection scenarios of conversion to cassava production. In all cases, the baseline SOC reached new stable states before 2013. The

experimental simulation started in 2014 when cassava was grown as a replacement for each land use type. We then modeled the changes in SOC over time to identify new SOC stable states under the cassava growing system. The net changes between baseline and cassava SOC stable states, in addition to changes in Cveg between the two systems, were used to calculate the carbon debts and annualized GHG emissions due to dLUC to cassava production.

2.1.5 Calculation of carbon debts and annualized emissions from C stock changes caused by dLUC

The time frame (in years) chosen for our study was the longest transition time for a new SOC stable state after converting from a baseline land use to cassava land use. This provides a common time frame, beyond which there are no significant net changes in ecosystem C stocks, i.e., emissions from dLUC for all land use change scenarios are accounted for within the time frame. Since changes towards a new steady-state soil C stock (under constant climate and management conditions) are asymptotic, we defined SOC as reaching an approximate new equilibrium after land use conversion (at $t=0$) once a 5-year period SOC change under the new land use was less than 1%, i.e.,

$$\frac{| \text{SOC}(t-5) - \text{SOC}(t) | * 100}{\text{SOC}(t-5)} < 1\%, \quad \text{Eq. 2}$$

where $\text{SOC}(t-5)$ and $\text{SOC}(t)$ are SOC at time $t-5$ and t , respectively. The time (t) in years for the longest time interval to a new approximate steady-state as defined in Eq. 2 (for any of the land use conversions to cassava) was chosen as the LCA accounting time frame (T).

The carbon debt due to dLUC from a specific land use to cassava is the difference in C stock between that land use and the cassava system at their SOC stable states. Our study reported

carbon debts in the unit of Mg of carbon dioxide per hectare. The annualized emissions from C stock changes caused by dLUC (i.e., the annualized dLUC emissions) were calculated by dividing the mean carbon debts by the accounting time frame (T). We separately calculated the carbon debt for each baseline land use in each region, and then computed the regionally-averaged carbon debts based on these individual values, weighted by the percentages of dLUC to cassava in each growing region (Table 2). Finally, we calculated the mean carbon debt from the regionally-averaged values weighted by the percentages of dLUC to cassava by growing region (Table 2).

2.2 Calculation of net GHG emissions and payback periods for cassava-based ethanol in Vietnam.

2.2.1. Calculation of net GHG emissions.

Our study used a standard life cycle assessment approach [48] to calculate the net GHG emissions for cassava-based ethanol in Vietnam. We considered three GHGs including carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄), and reported the GHG emissions in CO₂ equivalent (CO₂eq) by aggregating the individual GHG using their 100-year global warming potential values (GWP₁₀₀) [20]. The functional unit used to compare the environmental performance of ethanol and conventional gasoline (CG) was one megajoule (MJ). The CO₂eq emission of CG used in our study was 94 g MJ⁻¹ [14]. Our analysis employed the cassava-based ethanol production system and associated life cycle inventory values described in [4] (Fig.3).

(Fig. 3. Here)

Net GHG emissions (E) from production and utilization of cassava-based ethanol were comprised of three components, stemming from: a) cassava cultivation (E_{cp}), b) ethanol conversion (E_c), and c) transport and distribution (E_{td}). Since determining the emissions from processing and transport (E_c and E_{td}) was not the focus of our study, we used the results reported in [4]. The authors employed the guidelines from the IPCC [20], the Harmonized Calculations of Biofuel Greenhouse Gas Emissions in Europe (BioGrace) [49], and Renewable Energy Directive (RED) [50] to calculate net CO₂eq emissions of 129 g L⁻¹ for the conversion process and 31 g L⁻¹ for the distribution and blending process of cassava-based ethanol in Vietnam.

We estimated GHG emissions from the cassava cultivation stage (E_{cp}) according to equation (3).

$$E_{cp} = E_{fertilizer} + E_{pesticide} + E_{diesel} + E_{burning} + E_{N_2O} + E_{dluc}, \quad \text{Eq. 3}$$

where $E_{fertilizer}$ is the CO₂eq emission from fertilizer use (g L⁻¹), $E_{pesticide}$ the CO₂eq emission from pesticide use (g L⁻¹), E_{diesel} the CO₂eq emission from diesel consumption (g L⁻¹), $E_{burning}$ the CO₂eq emission from burning of cassava residue (g L⁻¹), E_{N_2O} the CO₂eq emission of N₂O from managed soils (g L⁻¹), and E_{dluc} the annualized CO₂eq emission from C stock changes caused by dLUC (g L⁻¹).

For $E_{fertilizer}$, $E_{pesticide}$, E_{diesel} , and $E_{burning}$ we used emission factors (EFs) reported in the IPCC [20] and BioGrace guidelines [49]. E_{dluc} calculations were described above (section 2.1.5). Direct N₂O emissions from managed soils were calculated from the amount of organic and synthetic N applied as fertilizers, the N in crop residues returned to soils, and any additional mineralized N associated with net decreases in total soil organic N stocks [20]. Indirect N₂O emissions were computed from both fractions of volatilized N and leaching and runoff of N estimated in the

CENTURY simulations. Direct and indirect N₂O emissions were computed using emission factors in the BioGrace GHG calculation excel tool (version 4c) [49].

We allocated total GHG emissions between the main product (ethanol) and coproducts and calculated the GHG offset credits (if any) from the utilization of the coproducts. The coproducts of the cassava-based ethanol production are distiller's dried grains with solubles (DDGS), biogas, cassava processing residues, and CO₂ [2][4][17][16]. According to Leng et al. [16], 18% of total GHG emissions from the production of cassava-based ethanol can be allocated to DDGS. The biogas from the ethanol conversion process is utilized for combustion as a supplemental input energy source [4]. Due to the high moisture content (86%) of the cassava processing residues, the energy and emission credits of this coproduct used for the replacement of a farm fertilizer application was offset by the emissions generated during the transportation of this bulky material from ethanol plants to farms [51]. Le et al. [4] reported that a CO₂eq emission of 490 g L⁻¹ are being collected from the fermentation process for further use in other industries, such as those for food and beverage. We argue that this is not a real GHG emission offset because CO₂ is only temporarily captured and will be released back into the atmosphere as soon as the food and beverage products are consumed. Furthermore, there is no information regarding the compression and transportation of the collected CO₂ to other industries. We, therefore, did not consider any GHG offset credit for the CO₂ coproduct.

2.2.2 Calculation of carbon payback period

Carbon payback period for cassava-based ethanol represents the number of years it takes for the carbon savings from avoided fossil fuel combustion (if any) to offset the losses in ecosystem

carbon from clearing land to grow cassava for biofuel feedstock [52]. Carbon payback period (R) was computed according to equation (4):

$$R = \frac{D}{S * P * LHVe} , \quad \text{Eq. 4}$$

where D is the mean carbon debt (Mg ha^{-1}) calculated in section 2.1.5, S is the avoided CO_2eq emission due to replacing conventional gasoline (CG) with ethanol (Mg MJ^{-1}), P is the annual ethanol productivity ($\text{L ha}^{-1} \text{ year}^{-1}$), and LHVe is the low heat value of ethanol (21.1 MJ L^{-1}). S is calculated as the difference between GHG emission of CG and that of ethanol, and must be greater than zero for carbon payback period to be realized. $S * P * LHVe$ is the annual emission reductions by production and utilization of ethanol. The conversion ratio of fresh cassava root (kg) to ethanol (L) used in our study was 6:1 [53].

3. RESULTS

3.1 Calibration of CENTURY'S predicted yield and biomass production

Table 7 shows the CENTURY modeled yields and Cveg together with reported yields from literature (in Mg of carbon per hectare) that were used for model calibration. The average modeled yields of maize, peanut, rice, cassava, and sugarcane were compared with the average yields reported by FAO (2013) for Vietnam [46]. FAO reports crop yields in the marketed forms of the crops in each country, which are clean and dry weight for cereals (e.g. rice, maize) and oil-bearing crops (e.g. peanut), and clean weight with relative high moisture contents for roots and tubers (e.g. cassava) and sugar crops (e.g. sugarcane). We reported yields in term of carbon fraction (yield-C) by assuming the carbon content of 40%, and the moisture contents of 65%,

70% and 15% for cassava root, sugarcane stalk, and other annual crops (including maize, peanut, and rice), respectively [53][54]. The modeled Cveg of mixed fruit tree (representing perennials), secondary tropical forest (representing forest), and mixed grass (representing grassland) were compared with those of mixed fruit tree, grazed secondary forest, and perennial grass (*Chromolaena odorata* L.) reported by Zemek [47] for the Chieng Khoi watershed in Vietnam. The results showed that CENTURY was able to adequately represent plant productivity of the chosen species.

(Table 7. Here)

3.2 Changes in C stock due to cassava production for ethanol in Vietnam

Simulated trends in SOC changes for a 40-year time period following conversion to cassava are presented in Fig. 4. The SOC before conversion to cassava varied by different growing regions and baseline land use types. In general, the SOC levels were highest in the southeast and lowest in the north central region for all the baseline land uses. For the different land use types, baseline SOC stocks generally differed in the order forest $\approx$ perennials > grassland > annuals. Difference between the forest and grassland vs annual crop baseline values were least for the central highlands region.

The conversion of land use to cassava for ethanol decreased SOC for most baseline land uses in all regions (Fig. 4). The main driving factor is the low carbon inputs from cassava biomass residuals (annual crop residuals are often burned onsite), particularly for the conversions from non-annual crops where the decrease in C inputs, along with higher decomposition rates with

tillage, caused the greatest decline in SOC. Only the conversion from other annual crops to cassava slightly increased SOC at cassava yields of 57 Mg ha⁻¹ and above.

(Fig. 4. Here)

The predicted rates and magnitudes of SOC changes due to dLUC varied by different cassava growing regions and varied according to baseline land uses, due to a number of factors including cassava yield, management practices, soil type, and weather. The rates of SOC change tended to be highest in forest, followed by grassland and perennial systems. Most SOC losses occurred during the first 5 - 10 years after conversion to cassava. Forest, grassland, and perennials require more time than annuals to approach a new SOC stable state after land clearing for cassava cultivation. In all scenarios, SOC tended to reach new approximate stable states within the maximum of 25 years. We, therefore, selected 25 years as the time frame for our analysis. This time frame is also appropriate for the discussion of biofuels policy or budget planning. The difference in SOC between the baseline land uses and cassava cultivation at 25 years after conversion ranged from 7 – 20 Mg ha⁻¹ at cassava yields of 18 Mg ha⁻¹, and (-2) to 12 Mg ha⁻¹ at the maximum considered yield of 60 Mg ha⁻¹ (Fig. 5). In most regions (except the Southeast), the highest carbon loss occurred when clearing forest to grow cassava, followed by perennials, grass, and annuals. SOC stocks under cassava tended to increase as projected yields (hence also plant residues) of cassava increased. The difference in SOC stocks between minimum and maximum considered cassava yields ranged from 8 – 11 Mg ha⁻¹.

(Fig. 5. Here)

The mean carbon debt of cassava-based ethanol in Vietnam strongly depended on cassava yield (Fig. 6). Higher yields reduced the carbon debts due to decreases in SOC loss. The mean carbon debt due to dLUC to cassava production for ethanol declined linearly from 97 to 66 Mg ha⁻¹ corresponding to the increase in cassava yield from 18 to 60 Mg ha⁻¹.

(Fig. 6. Here)

3.3 Greenhouse gas emission of cassava-based ethanol in Vietnam

Annualized dLUC GHG emissions of cassava-based ethanol in Vietnam ranged from 10 to 50 g MJ⁻¹, and constitutes about 23 - 53% of total net GHG emissions, depending on cassava yield and fertilizer application (Fig. 7). The net GHG emission of cassava-based ethanol decreased in conjunction with an increase in cassava yield and a decrease in fertilization. At the cassava yield level of 18 Mg ha⁻¹, the net GHG emission was 95 g MJ⁻¹, indicating no avoided GHG emission when replacing CG with ethanol. In fact, the displacement of CG by cassava-based ethanol increased the total emission by 1 g MJ⁻¹ at this yield level. With the least fertilizer addition (50% FTY_{baseline}), increasing yield from 18 to 60 Mg ha⁻¹ decreased the net GHG emission from 95 to 33 g MJ⁻¹, and increased the avoided GHG emission from (-1) to 61 g MJ⁻¹. The GHG emission difference between 50% FTY_{baseline} and 150% FTY_{baseline} was higher at higher cassava yield levels and reached a maximum at 13 g CO₂eq MJ⁻¹. The annual avoided GHG emissions per hectare of cassava production for ethanol ranges between (-0.1) – 13.0 Mg ha⁻¹ year⁻¹ at 50% FTY_{baseline} and (-0.1) – 10.3 Mg ha⁻¹ year⁻¹ at 150% FTY_{baseline}.

(Fig. 7. Here)

3.3. Carbon payback period for cassava-based ethanol in Vietnam

Our results showed that payback period declined significantly as cassava yield increased (Fig. 8). This was because of lower carbon debts and greater fossil fuel offset at higher yields. The vertical asymptote of payback period is the yield level where the net GHG emission of ethanol is equal to that of CG (i.e., payback period reaches infinity). The vertical asymptote of payback period for cassava-based ethanol in Vietnam was 18.3 Mg ha^{-1} . There was no payback period below this yield level because replacing CG with ethanol increases net GHG emissions. The GHG mitigation benefit of cassava-based ethanol starts to be realized above this yield level. Payback period was equal to the study time frame (25 years) at the cassava yield of 31 Mg ha^{-1} and 33 Mg ha^{-1} for 50% $\text{FTY}_{\text{baseline}}$ and 150% $\text{FTY}_{\text{baseline}}$, respectively. The most optimistic scenario with the highest considered cassava yield (60 Mg ha^{-1}) and 50% $\text{FTY}_{\text{baseline}}$ resulted in the lowest payback period of 5 years. The effect of fertilization on payback period was substantial at lower cassava yields and decreased as yield increased. The difference in payback period between 50% $\text{FTY}_{\text{baseline}}$ and 150% $\text{FTY}_{\text{baseline}}$ ranged from 95 years to 1 year as yield varied from 19 to 60 Mg ha^{-1} .

(Fig. 8. Here)

4. DISCUSSION

The carbon debt, net GHG emission, and payback period of cassava-based ethanol in Vietnam computed based on CENTURY's modeled dLUC were compared with those calculated based on the results from Le et al. [4] at the same yield level. Using Tier 1 IPCC's guideline, Le et al. [4] reported an annualized dLUC CO_2 emission of 3.89 Mg ha^{-1} corresponding to a carbon debt of 77.84 Mg ha^{-1} over a 20-year period. To compare the results between the two approaches, we recalculated the net GHG emission and payback period using the method presented in section

2.2.1 and 2.2.2 with the annualized dLUC emission obtained from [4] at the cassava yield of 33 Mg ha⁻¹. The comparison revealed that using Tier 1 IPCC's guidelines to estimate the annualized dLUC emissions for cassava-based ethanol resulted in a reduction of 10.5 Mg ha⁻¹ in mean carbon debt, but an increase of 2.56 g MJ⁻¹ in the net GHG emission due to higher annualized dLUC emission caused by shorter time frame (20 years). This combination yielded a slight reduction in the payback period of 1 year (assuming 150% FTY_{baseline}) and 1.1 year (assuming 50% FTY_{baseline}).

Cassava-based ethanol has been internalized in Vietnam's energy policy for partial replacement of conventional fossil fuels, and increased environmental protection [6]. However, as shown in our results, the GHG mitigation effects of cassava-based ethanol depended strongly on the average cassava feedstock yield. Higher yields significantly reduced carbon debts and payback periods. The mean carbon debt was paid off within the study time frame of 25 years only at the cassava yields above 33 Mg ha⁻¹ (Fig. 8). This yield level is only attained on farm trials using practices that currently have low adoption rates (<10%) [55]. To maximize the environmental benefit of cassava-based ethanol, research and policies should be implemented to improve the average cassava yield used for ethanol production.

Additional factors that affect the estimation for carbon debts and LUC emissions of cassava-based ethanol include soil erosion and iLUC. Although they were beyond the scope of our study, it is worthwhile to discuss their potential impacts on the environmental performance of cassava-based ethanol. Studies have shown that growing cassava can severely erode the soils, especially those planted on hilly terrain [9]. The average soil erosion rate under cassava cultivation in the region is 50 Mg ha⁻¹ year⁻¹ [9][56][57]. While erosion could potentially impact crop productivity,

and thus lower C inputs from residues, its impact as a net source or sink of C with respect to the atmosphere at large scales (landscape, region, globe) is a topic of active debate [58][59]. Soil erosion results in the removal of SOC from one site and its subsequent deposition at other sites. The mineralization during transport and landscape deposition of eroded SOC were previously thought to be a source of CO₂ to the atmosphere [60]. However, the burial of eroded SOC in some depositional environments like lakes, rivers, or oceans may also result in a long-term C sequestration due to inhibited C decomposition. The fundamental controls on the magnitude of the erosion-induced sink or source are the extremely complex and combined effects of erosion and deposition, changes in the rates of SOC decomposition and C inputs in eroded or deposited soil [61]. Thus, erosion impacts of cassava production are highly site-specific and require a more detailed analysis to account for the net impact on C stock change.

Indirect LUC could occur when existing agricultural land is converted to cassava production for ethanol, causing new land conversions elsewhere to displace the food and feed production. These conversions could produce large GHG emissions if carbon-rich ecosystem such as forests are converted. In the case of cassava production for biofuel in Vietnam, the conversion of annuals and perennials to cassava could potentially induce partial conversion of other land uses such as forest and grassland to annuals and perennials, intensification of existing crop production systems, increase in import, and demand adjustments by price regulation in agricultural commodity market to make up for the reduced supply of annual and perennial products. The proportion of each factor and its associated emissions contributing to iLUC effects are highly uncertain. Our simulations showed that land conversion from forest to annuals resulted in an average SOC loss of 11 Mg ha⁻¹ and an average C_{veg} loss of 58 Mg ha⁻¹, yet conversion from forest to perennials resulted in no change in SOC and a C_{veg} loss of 44 Mg ha⁻¹. In the worst

case scenario, if 100% of the conversion from annuals and perennials to cassava was replaced by forestland conversion, iLUC could add a significant amount of 116 Mg ha⁻¹ to the carbon debt, and shift the asymptote for payback period to between 31 Mg ha⁻¹ (assuming 50% FTY_{baseline}) and 35 Mg ha⁻¹ (assuming 150% FTY_{baseline}) (Fig. 9)

Fig. 9. Here.

5. CONCLUSION

We investigated carbon debts, GHG emissions, and carbon payback periods for cassava-based ethanol in Vietnam under different yield and fertilization scenarios for a time frame of 25 years. The employment of a biogeochemical model enabled us to do a more spatially-explicit qualification of C stock changes due to dLUC to cassava production that accounted for regional differences in climate, soil, and baseline management conditions. The fresh weight yield range used in our analysis (18 – 60 Mg ha⁻¹) is the realistic yield levels reported in literature. Our results showed that the mean carbon debt due to dLUC to cassava production ranged from 66 to 97 Mg ha⁻¹. The net GHG emission of cassava-based ethanol with the inclusion of dLUC emissions ranged from 33 to 95 g MJ⁻¹, varying as a function of cassava yield (from 18 to 60 Mg ha⁻¹) and fertilizer inputs. The cassava yield level above which the GHG mitigation benefit of cassava-based ethanol is realized was 18.3 Mg ha⁻¹. To repay the carbon debt from direct land use change within 25 years, the average cassava yield used as feedstock for ethanol production must be above 33 Mg ha⁻¹. It is recommended that research and policies be implemented to increase average feedstock yield to improve the environmental performance of cassava-based ethanol.

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FIGURE CAPTIONS

Fig. 1. Overview of model inputs and simulation process.

Fig. 2. Average monthly climate data of five weather stations in Vietnam.

Fig. 3. Cassava-based ethanol production system in Vietnam.

Figure adopted from Le et al. [4]

Fig. 4. Changes in SOC due to dLUC to cassava cultivation for bioethanol in Vietnam.

The filled areas are the SOC difference between the cassava fresh wt. yield of 18 Mg ha⁻¹ and 60 Mg ha⁻¹.

Fig. 5. Difference in SOC between baseline land use and cassava at 25 years after conversion.

Negative values of Δ SOC indicate soil carbon increases.

Fig. 6. Mean carbon debt as a function of yield for cassava-based ethanol in Vietnam.

Fig. 7. Greenhouse gas emissions of cassava-based ethanol in Vietnam under different cassava yield and fertilization scenarios. The filled areas are the difference between 50% FTY_{baseline} and 150% FTY_{baseline}

Fig. 8. Carbon payback period of cassava-based ethanol in Vietnam under different cassava yield and fertilization scenarios.

Fig. 9. Carbon payback period of cassava-based ethanol in Vietnam with iLUC (assuming 100% of the conversion from annuals and perennials to cassava was replaced by forestland conversion).

Key:

TABLES

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

Table 2: Percentages of dLUC to cassava cultivation for bioethanol production in Vietnam [4]

Region	Percentage of dLUC to cassava by growing region	Percentage of dLUC to cassava by land use type in each growing region			
		Annuals	Perennials	Forest	Grassland
North Central	8	40.0	12.5	2.5	45.0
South Central	26	32.0	24.0	10.0	34.0
Central Highlands	39	16.3	17.5	20.0	46.3
Southeast	27	36.7	50.0	5.0	8.3

Table 3: Properties of major soil types in Vietnam used to parameter CENTURY

Soil types	Taxonomy	pH	%Sand	%Silt	%Clay	Bulk density	Drainage	Average %OC	Source
Sandy	Arenosols	5.3	77	12	11	1.51	0.9	0.7	[36]
Alluvial	Fluvisols	4.6	23	40	37	1.31	0.8	2.2	[37]
Red	Ferralsols	4.0	20	27	53	0.85	0.6	5.0	[37][38]
Grey Degraded	Haplic Acrisol	4.3	64	15	21	1.34	0.8	1.0	[39]
Ferralitic	Other Acrisol	3.9	40	22	38	0.85	0.7	2.3	[40]

Table 4: Modeled species with their cropping proportions by region

Region	Land use type	Soil type	Simulated species	Cropping proportion
Northern Central	Annuals	Sandy, Alluvial Grey degraded, Ferrallitic	Maize	0.12
			Peanut	0.06
			Sugarcane	0.06
			Cassava	0.07
		Alluvial	Rice*	0.69
Southern Central	Annuals	Sandy, Alluvial, Grey degraded, Ferrallitic	Maize	0.1
			Peanut	0.04
			Sugarcane	0.07
			Cassava	0.13
		Alluvial	Rice	0.66
Central Highlands	Annuals	Red, Grey degraded Ferrallitic, Alluvial	Maize	0.36
			Peanut	0.03
			Sugarcane	0.07
			Cassava	0.21
		Alluvial	Rice	0.33
South East	Annuals	Alluvial, Grey degraded, Red, Ferrallitic	Maize	0.15
			Peanut	0.04
			Sugarcane	0.07
			Cassava	0.18
		Alluvial	Rice	0.56
All regions	Perennials	Ferrallitic/Red**	Mixed fruit tree	1.00
	Forest	Ferrallitic	Secondary tropical forest	1.00
	Grassland	Ferrallitic	Mixed grass	1.00

Note: * Rice is only modeled on alluvial soil

** Perennials are modeled on both ferrallitic and red soils in Central Highlands.

Table 5: Management practices of the modeled species

Species	Management				
	Growing season ^a	Manure addition (Mg ha ⁻¹)	Fertilization (kg N ha ⁻¹)	Irrigation (%) ^c	Residue removal (%)
Maize	2	5	100	90	75
Peanut	2	3	30	90	25
Sugarcane	8-year rotation	8	100	95	95
Cassava	1	5	58	75	79
Rice	2	5	100	100	75
Mixed fruit tree	8-year rotation	5	120	95	5 ^b

Note: ^a Number of growing seasons per year unless specified

^b Mixed fruit tree is pruned annually and clearcut at the end of the rotation.

^c Percent of field capacity irrigated

Table 6: Modelling scenarios

	FTY ^a range	Fertilizer type	Lower bound	Upper bound	Fertilization rate equation ^b
Yield (Mg ha ⁻¹)			18	60	
Fertilizer inputs (kg ha ⁻¹)	50% FTY _{baseline}	N	58	126	$F_N = \Delta Y * 1.61 + 58$
		P	53	115	$F_P = \Delta Y * 1.47 + 53$
		K	47	102	$F_K = \Delta Y * 1.31 + 47$
		Pesticide	0.23	0.50	$F_{\text{pesticide}} = \Delta Y * 0.0065 + 0.23$
	150% FTY _{baseline}	N	58	261	$F_N = \Delta Y * 4.83 + 58$
		P	53	239	$F_P = \Delta Y * 4.41 + 53$
		K	47	212	$F_K = \Delta Y * 3.92 + 47$
		Pesticide	0.23	1.04	$F_{\text{pesticide}} = \Delta Y * 0.02 + 0.23$

Note: ^a Fertilizer-to-Yield ratio

^b See Eq.1

Table 7: Comparison between modeled yield-C and Cveg with calibrating literature data

Species	CENTURY's modeled outputs (Mg ha ⁻¹) [*]				Calibrating data (Mg ha ⁻¹)	
	North Central	South Central	Central Highlands	Southeast	FAO (2013) [46]	Zemek (2009) [47]
Maize	1.3	1.2	1.8	1.6	1.5	
Peanut	0.5	0.3	1.2	1.3	0.7	
Rice	1.5	1.1	2.6	2.5	1.9	
Cassava	2.4	2.1	2.7	2.9	2.5	
Sugarcane	7.5	7.8	7.6	7.5	7.8	
Mixed grass	5.1	4.4	5.7	4.4		4.6
Mixed fruit tree	12.4	11.6	16.9	16.0		13.0
Secondary tropical forest	59.4	58.2	62.4	53.1		60.0

Note: ^{*}All the unit are reported in term of Mg of carbon per hectare.