New Induced Land Use Change (ILUC) emissions assessment: Updates from IPCC guidelines and new estimates of soil carbon from the Harmonized World Soil Database (HWSD)

Lauren Benavidez, Shuo Chen, Ye Yuan, and Qianlai Zhuang

1 Introduction

In the past decade, GTAP-BIO has been frequently used to evaluate land use changes due to biofuel pathways, an ongoing option to substitute petroleum products (Hertel et al., 2010; Taheripour and Tyner, 2013; Taheripour et al., 2017, Zhao et al., 2021). Given the relevance of biofuel production, assessing the resulting emissions due to land use changes associated with each biofuel is imperative. These emissions are known as induced land use change (ILUC) emissions. In previous studies, the land-use change simulations from GTAP-BIO have been complemented with an emissions calculator tool that allows for the estimation of ILUC values. This tool is the AEZ-EF model (Plevin et al., 2014).

The use of biofuels is a relevant bioenergy policy that tries to decarbonize the energy system and minimize the environmental impacts of this sector. A correct estimation of ILUC values is an important policy tool since major bioenergy-focused organizations such as the EU Renewable Energy Directive (EU-RED II) and the US Renewable Energy Standard (US-RFS) consider indirect land-use change as a parameter to assign limits in the use of biofuels.

The AEZ-EF model (Plevin et al., 2014) contains a variety of emission factors that are relevant in calculating land use emissions. Most of this data is built from the first inventory guidelines from The Intergovernmental Panel on Climate Change (IPCC) in 2006. Additionally, it relies heavily on soil and vegetation carbon estimates by region and agroecological zones (AEZ).

The AEZ-EF model's corresponding data items have not been updated since its development in 2014. This paper aims to update the soil carbon data of the AEZ-EF model. This paper also updates the AEZ-EF model to follow the IPCC 2019 guideline for calculating land use emissions. This paper provides a more accurate and updated tool to estimate induced land-use change emissions to assess the potential environmental effects not only for biofuel pathways but for other potential land-use change policies.

The updates of inventory guidelines require the simple substitution of the newly reported emission factors and the complementation of new mappings to the GTAP-BIO regional and AEZs classification. The updates on the soil carbon data were made leveraging the recently released Harmonized World Soil Database (HWSD) version 2.0, released in 2023. A soil organic carbon (SOC) estimation was made across soil mapping units. After this step, a series of land-use filtering maps were used to reduce the bias of the soil carbon estimates that were to be introduced in the model. Finally, the maps were classified into the main three agricultural land-cover types: forest, cropland, and grassland, leveraging highly accurate satellite data, to be later classified into the 18 agroecological zones to be consistent with the AEZ-EF model and GTAP-Bio.

The results show an overall decrease in ILUC values due to the update of the IPCC-related emission factors. These ILUC values will further change when the new soil carbon estimates are updated.

2 Methodology

2.1 IPCC Guidelines updates

As a first step, updates were made to the data integrated into the AEZ-EF module. Most of these changes stem from the revised inventory guidelines provided by the IPCC in 2019, which update the original guidelines released in 2006. The IPCC's fifth assessment report, published in 2014, also contributed to the updated data.

Five categories of data were updated according to new estimates provided by IPCC: Global Warming Potentials, litter data, soil stock change factors, forest combustion factors, and deadwood data. Four of these five categories were initially sourced from the IPCC and incorporated into the AEZ-EF module. However, the data pertaining to the deadwood was originally derived from an estimate in a research paper by Pan et al. (2011) due to the lack of available data in the 2006 IPCC guidelines. The IPCC 2019 refinement now includes this category in their reported data; therefore, the AEZ-EF module was modified to use this data instead of the reported paper, as the IPCC is considered a reliable data source regarding these factors. The rest of the emission factors were mapped and updated into the AEZ-EF model.[1]

2.2 Estimates of soil carbon from HWSD

The second step of this paper estimates and updates the soil carbon data embedded in the AEZ-EF model. This model utilizes soil carbon estimates from Gibbs et al. (2014) to assess emissions factors for the three land cover types: Forest, pasture, and cropland. Gibbs et al. (2014) have used estimates of soil carbon content for each main agricultural land type from the Harmonized World Soil Database (HWSD) version 1.1. However, significant changes have been made to this data source. For example, the implementation of the WISE30sec database that includes new soil mapping units.

This paper intends to provide insights into soil carbon relevance on ILUC emissions by leveraging a new soil carbon dataset. To obtain the new estimates of soil carbon, freshly released data from HWSD version 2.0 published in 2023 was used, utilizing the soil attributes database containing organic carbon data, bulk density, and depth, among other elements necessary to study

[1] Detailed explanation about the update is available upon request.

soil properties. The data for soil attributes is derived from the HWSD by their soil mapping unit coding and at the layer level. At the layer level, the estimation for soil organic carbon was performed using a formulae similar to the one used by Gibbs et al. (2014) but modified according to Kochy et al. (2015), who made adjustments for coarse fragments (Co), at the same time, Gibbs et al. (2014) utilize organic matter and a coefficient of adjustment in their formulae to estimate organic carbon content in soils; however, organic matter data is not present in the last two versions of the HWSD. Therefore, we directly took the organic carbon content proportion into the formulae as Kochy et al. (2015). The final formulation is:

$$SOC_{l,SMU} = \frac{(100 - Co_{l,SMU})}{100} * \frac{OC_{l,SMU}}{100} * BD_{l,SMU} * (D1 - D2)$$

Where the soil organic carbon (*SOC*) is estimated at the layer (*l*) and soil mapping unit (*SMU*) levels. In the formulation above, *OC* represents the organic carbon content, *BD* refers to the bulk density, and *D1* and *D2* refer to the bottom and top depth, respectively. After this formulation, the estimated SOC by layers was aggregated to the soil mapping unit level by leveraging from the share of each layer in a single soil mapping unit *SH*:

$$SOC_{SMU} = SOC_{l,SMU} * \frac{SH_{l,SMU}}{100}$$

The above formulae give, as a result, the soil organic carbon at the soil mapping unit expressed in g/cm^2, which was later transformed to *T/Ha* for final estimation. However, these results are not sufficient to be introduced in the AEZ-EF model. These results need to be classified by land use type: cropland, pasture land, and forest land.

After obtaining soil organic carbon estimates at the world level, it is necessary to map those quantities according to the land type and the regional division by country and agroecological zones. However, before drawing up the map for land use types, it is necessary to filter out lands that are not destined for production or conservation in terms of cropland, pasture, and forest. Gibbs et al., 2014 leveraged Ramankutty's (2009) cropland and pastureland maps, which represent these two global land uses for 2000. In the case of forests, these were taken from data derived from MODIS land cover.

Leveraging Gibbs et al.'s 2014 methodology, we filtered two types of lands before mapping out our SOC estimates: wetlands and deserts. In the case of wetlands, two maps were utilized to filter areas corresponding to wetlands. The first one was obtained from the Global Lakes and Wetlands database. The second map was obtained from Reich (1997). This map is another filter for wetland areas at the global level developed by the USDA-NRCS. Finally, the Food and Agricultural Organization (FAO) eco-floristic zones map was used to filter out deserts.

For this paper, the base of our land cover maps is different, and we provide data that, first, has more updated values than the Ramankutty maps provided for 2000. Second, it provides a more precise grid-cell level definition of the land covers that is backed by international organizations, and it has the feature that this data is updated every year. This paper proposes to represent the three agricultural lands leveraging Modis satellite data for 2020.

The MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data contains 13 land cover classifications according to the vegetation and humidity characteristics. In order to have a consistent classification of land, we utilized the FAO mapping equations to convert the MODIS classification into the FAO-reported land covers. Specifically, we matched the grassland, natural, herbaceous, woody croplands, and tree-covered FAO areas to represent pastureland, cropland, and forests. The estimation of these land covers revolves around the following three equations:

$$Grassland = Class_{30} + 0.20(Class_{35}) \tag{1}$$

$$Cropland = Class_{36} + 0.60(Class_{25} + Class_{35}) \tag{2}$$

$$Forest = Class_{10} + Class_{20} + 0.40(Class_{25}) \tag{3}$$

All the filtered maps and land cover areas were estimated at the grid-cell level. Each soil mapping unit was mapped into the geometries presented in the wetlands, FAO ecofloristic zones, and MODIS databases. At the end of these procedures, we mapped the estimations by land cover into the 18 agroecological zones (AEZ) that are contained in GTAP-BIO. The tree's main databases thus contained data for soil organic carbon at the AEZ level and for each grid cell (geometry). To obtain the total estimates by country and AEZ, the area of each grid cell was estimated to later perform an area-weighted average aggregation of the soil organic carbon data.

3 **Data**

This section explains some of the most relevant characteristics of the data utilized to obtain the new soil organic carbon estimates at the AEZ and region levels. Data for the update on emissions factors used for the first stage of this project is not explained, as it is better detailed in the supplementary material. Two main datasets were used for this estimation. The first is the newly released harmonized world soil database version 2.0, compiled by the FAO and the International Institute for Applied Systems Analysis (IIASA).

The second database is the compilation of land cover maps, which are divided into two main categories: land cover filter maps and land cover agricultural maps. The land cover maps for wetlands and deserts were used as filters since these land types are often less likely to be converted to agricultural or forest use, as Gibbs et al. (2014) indicated. The second category is the MODIS data, which estimates the coverage of the three main agricultural lands.

3.1 Soil Attributes data - HWSDV2

The harmonized world soil database is a compilation of different soil mapping units coded in which there is a set of specific soil attributes that are contained at the layer level within a soil mapping unit.[2] Figure 1 represents the codification of soil mapping units for the world where the same color indicates a same mapping unit with similar attributes.

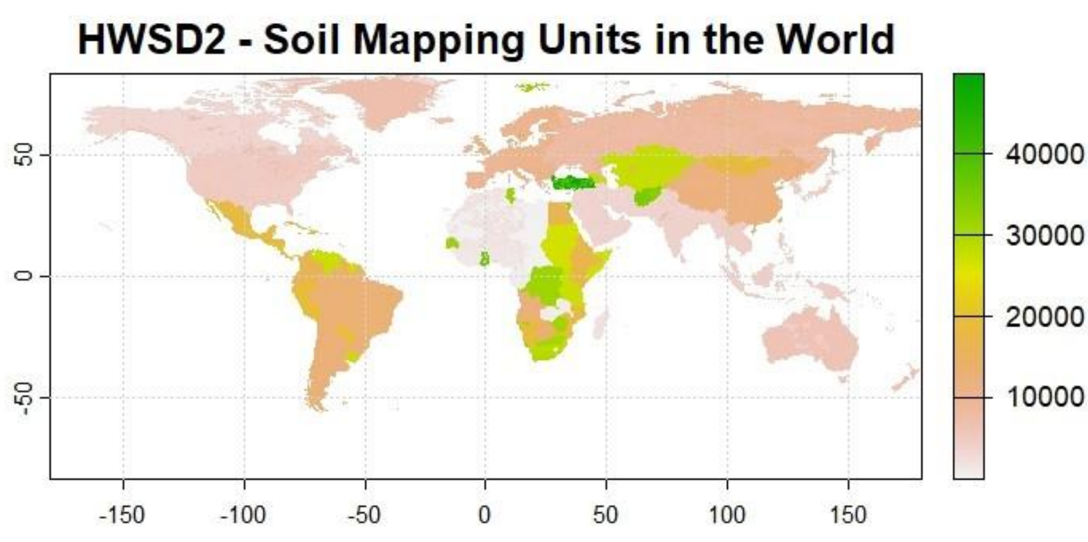

Figure 1: World Soil Mapping units classification - HWSD2

[2] For more information about the HWSD version 2.0, see the technical documentation at: https://www.fao.org/3/cc3823en/cc3823en.pdf

3.2 Land Cover/Use maps

This section presents the maps used to filter areas that do not enter into the estimation of the soil organic carbon stocks: wetlands and deserts. As mentioned before, this procedure follows the methodology used by Gibbs et al. (2014), and we utilize the same filter maps as that study, as the referenced maps have not been updated. This section also briefly explains the land cover maps used in the division of land between forest, cropland, and pasture and why these updated maps are a relevant contribution in terms of soil organic carbon estimation and emission factors due to induced land use change.

3.2.1 Filter Maps

Figures 2 and 3 represent the wetland filters used for area calculation. For clearer reference, only one country was plotted to represent wetlands distributions, in this case, the USA. In Figure 3, the area we are keeping is the area marked in white as these areas don't have any wetland classification. In Figure 4, the area preserved is the area code with zero. The similitude between both wetland databases is clear, especially in the Alaska area. However, it is important to use both databases to take wetlands out of the estimation with greater efficacy.

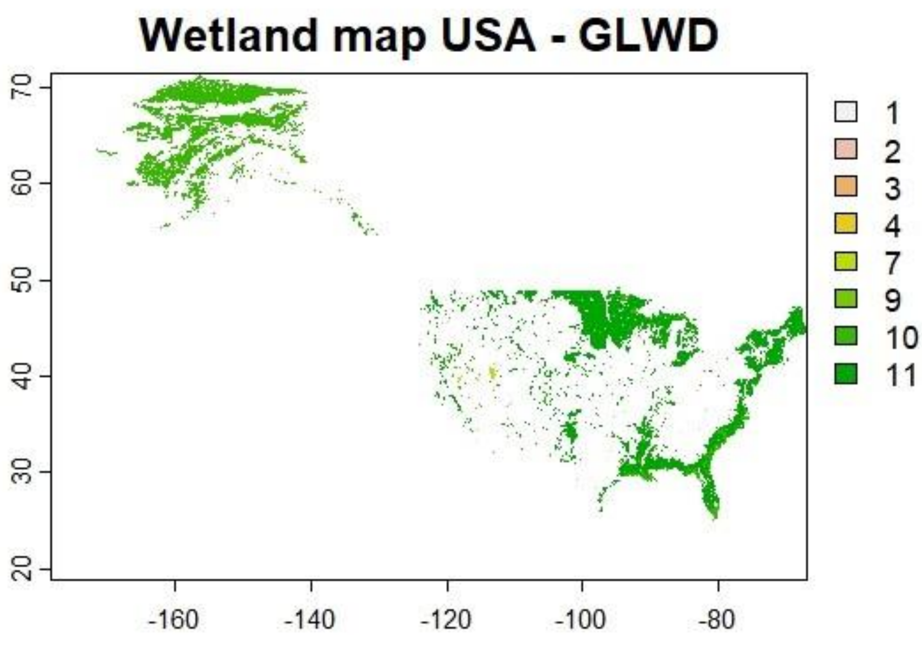

Figure 2: Global Lakes and Wetlands map (GLWD) - USA

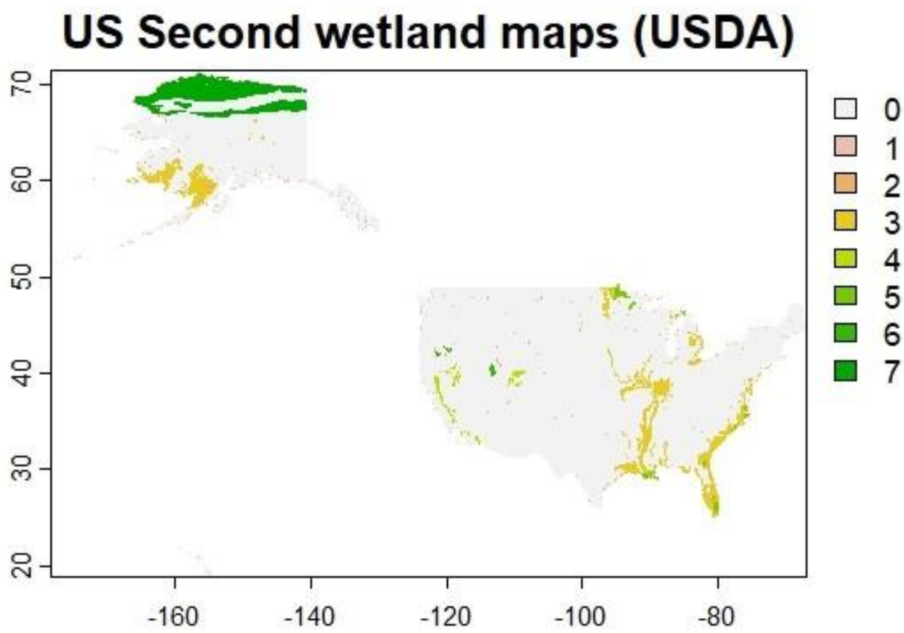

Figure 3: USDA Global wetlands map - USA

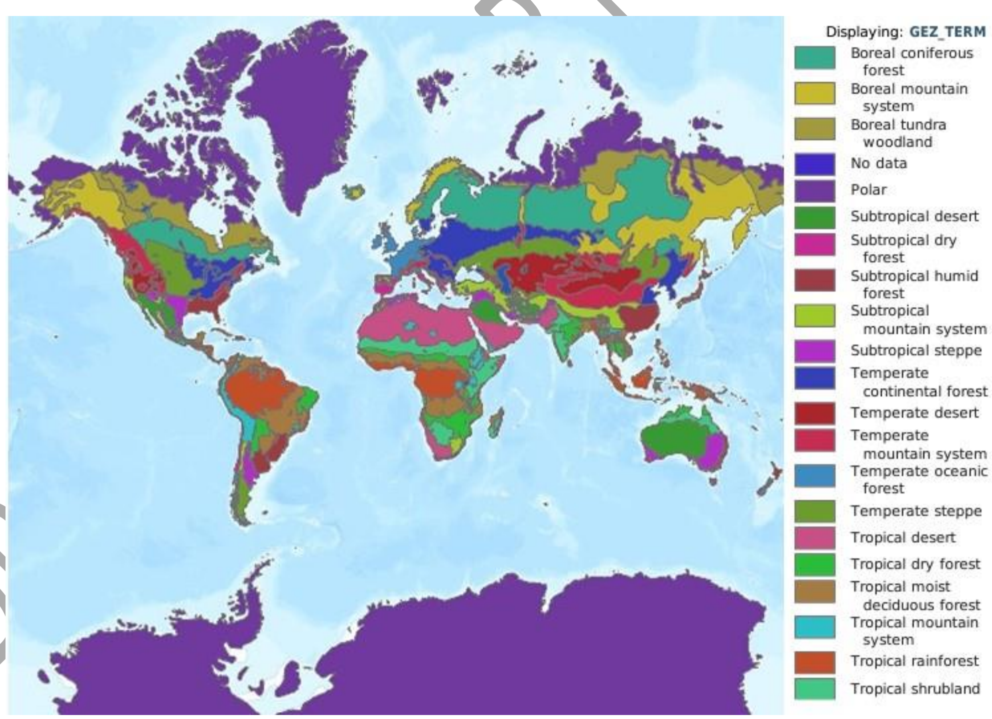

Figure 4: FAO - Ecofloristic zones

Figure 4 represents the FAO ecofloristic zone. These capture different weather and humidity regimes across the world. For this paper's purposes, we filtered out three regions: subtropical deserts, temperate deserts, and tropical deserts.

3.2.2 Modis - Land Cover

The MODIS land cover data divides a territory into 12 categories according to vegetation content and some climate regimes. Figure 5 plots the 12 categories for the USA and is a representation of the land cover in this country for 2020. For the representation of agricultural land: forest, cropland, and pasture, we are interested in six categories, as discussed in the methodology section. We can notice that the majority of the mainland US is covered by categories within the 25 and 40.

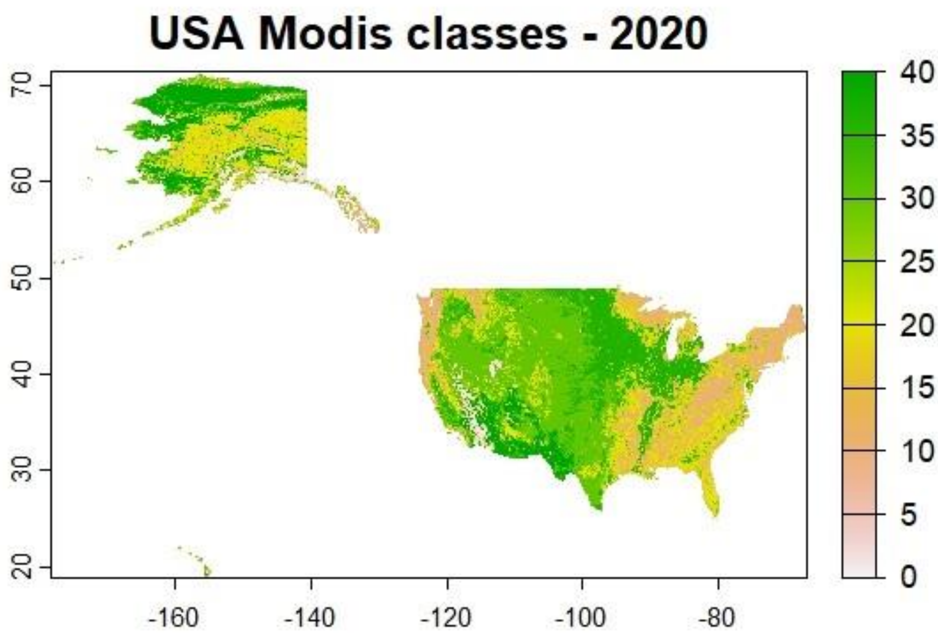

Figure 5: MODIS Land Cover data - USA (2020)

4 Preliminary Results

4.1 Emissions factors update.

The first phase of this research included updating the model to include the reviewed IPCC inventory guidelines. After the carbon data update, the ILUC emissions for different biofuel pathways were estimated and compared to the previous AEZ-EF results.

The estimation of the updated emission factors using current IPCC inventory guidelines data has indicated that the ILUC values had been reduced compared with the original AEZ-EF emissions across most of the biofuel's pathways, especially for those in the USA and Brazil. However, updates in soil organic carbon by land cover would change the ILUC values further.

5 References

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