AEZ-EF Cellulosic Model

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1. Introduction

This document describes changes made to the Python version of the Agro-ecological zone Emission Factor (AEZ-EF) model (Plevin, Gibbs et al. 2014) to add the capacity to estimate land-use change (LUC) carbon intensity (CI) of biofuels produced from switchgrass, Miscanthus, and poplar. Modeling of other, previously supported feedstocks should produce the same results as those from the unmodified model. See the original model documentation for a complete description of the published version; this document describes only changes made to support cellulosic feedstocks.

The primary challenge in updating the model was to characterize changes in soil organic carbon (SOC) after conversion to cellulosic crops, as these crops can sequester substantial quantities of carbon, particularly in depleted soil.

A review of the literature on SOC changes under cellulosic crops yielded two papers deemed most relevant: a model-based study (Qin, Dunn et al. 2016a) and a meta-analysis of empirical data by the same authors (Qin, Dunn et al. 2016b). The latter has been used to parameterize Argonne National Lab's CCLUB model with GTAP for the same purpose as the present work.

The main challenges with using empirical data to estimate changes under cellulosic crops are:

1. SOC changes vary widely by soil type, land-use history, climate, and crop management.
2. Studies vary in methods, e.g., in sampling depth, duration, method of comparison (repeated sampling, paired-site, or chronosequence approaches.)
3. SOC changes depend on input levels (of biomass) so a study of SOC after conversion to grasses *without* harvesting may overstate the SOC gains for a bioenergy production scenario with an assumed harvest index of 0.9.

Another issue with the meta-analysis data is that pasture and native grassland were both classified as grassland, yet GTAP represents only pasture. It's unclear whether SOC sequestion is higher or lower under natural grassland given differences in soil exposure, biomass removal and manure inputs.

The data used to characterize SOC changes in the model update were taken from the modeling study (Qin, Dunn et al. 2016a), and are presented in Table 2.

2. Land-use Transitions

SOC changes depend, *inter alia*, on the SOC status of land prior to conversion, for which the pre-transition land-use is used as a proxy, and the land use post-conversion. GTAP, however, reports only the final area in individual crops, forestry, and livestock production: it doesn't indicate which prior land uses were converted to which new ones. To allocate GTAP's area changes to specific land-use transitions, the reported changes are assigned to a series of transition in an order assumed to represent ease of transition.

The revised model relies on the original code for all previously-modeled transitions, with the exception that sugarcane and oil palm have been separated out rather than combined as "perennial" crops in some calculations. Eliminating this special case allows all conversion sequences to be handled uniformly.

Three new crops were added to the model: Miscanthus, switchgrass, and poplar. Given the different rates of soil organic carbon (SOC) change under these crops when transitioning from forest, pasture, cropland-pasture, and annual cropland, adding these three crops resulted in an expansion of possible transition sequences.

The model first computes the total change to oil palm in peatland regions (presently only Malaysia/Indonesia) assuming that one-third of this occurs on peatland, and assigns this first to transitions from forestry (FOR) to "oil palm on peat" (OPP) and then pasture (PAS) to OPP. The amounts allocated are subtracted from the changes reported by GTAP. Reported land changes are then allocated where possible to other land-use transitions in the order shown in Table 1. Note that in a sensitivity analysis in which we randomized the order of transitions, the minimum and maximum CI results for each feedstock differed by 1.5 g CO_2e MJ^{-1}.

Table 1. Order of assigning GTAP-reported LUC to specific land-use transitions. Transitions are identifed in pairs as (prior land use, subsequent land use). ANN=annual crops, FOR=forestry, PAS=pasture, CP=cropland pasture, SUG=sugarcane, SWG=switchgrass, MSC=Miscanthus, POP=poplar, PLM=oil palm, OPP=oil palm on peat.

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Special case of transitions to oil palm on peat
(FOR, OPP)
(PAS, OPP)

Transitions to/from cropland-pasture.
(ANN, CP)
(SUG, CP)
(SWG, CP)
(MSC, CP)
(POP, CP)
(PLM, CP)
(CP, ANN)
(CP, SUG)
(CP, SWG)
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(CP, MSC)
(CP, POP)
(CP, PLM)

Transitions among grasses and poplar
(SWG, MSC)
(MSC, SWG)
(SWG, POP)
(MSC, POP)
(POP, SWG)
(POP, MSC)

Transitions among annual, perennials, and grasses.
Assume no transitions between palm & sugar and cellulosics.
(ANN, SUG)
(ANN, PLM)
(ANN, SWG)
(ANN, MSC)
(ANN, POP)

(SUG, ANN)
(PLM, ANN)
(SWG, ANN)
(MSC, ANN)
(POP, ANN)

Changes between perennials
(SUG, PLM)
(PLM, SUG)

Transitions between crops and pasture
(SWG, PAS)
(MSC, PAS)
(POP, PAS)
(PAS, SWG)
(PAS, MSC)
(PAS, POP)

(ANN, PAS)
(SUG, PAS)
(PLM, PAS)
(PAS, ANN)
(PAS, SUG)
(PAS, PLM)    (PAS, OPP) handled separately

Transitions between pasture and forestry
(FOR, PAS)
(PAS, FOR)

Transitions between forestry and tree crops
(FOR, POP)
(FOR, PLM)    (FOR, OPP) handled separately
(POP, FOR)
(PLM, FOR)

Transitions between forestry and the rest
(FOR, ANN)
(FOR, SUG)
(FOR, SWG)
(FOR, MSC)
(ANN, FOR)
(SUG, FOR)
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(SWG, FOR)
(MSC, FOR)
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The CARB AEZ-EF model did not consider transitions between cropland-pasture and pasture, in either direction. For consistency, the current version of AEZ-EF treats these transitions as causing zero emissions or sequestration.

3. Soil carbon changes

Changes in SOC for transitions to cellulosic feedstocks were derived from Qin, Dunn et al. (2016a) using a software tool to extract numerical values from graphical presentations, based on figures 4 and S6. For Miscanthus and switchgrass, we used the median value for conversion by AEZ. Information for poplar was not available by AEZ, so the overall average value was used. The values from these US-based data were applied globally (by AEZ for the grasses.) These values are the total changes in SOC over 30 years, divided by 30 years; the model recovers the total by multiplying these by 30 years. The SOC data used are presented in Table 2. Note that positive values indicate sequestration; negative values indicate emissions.

Table 2. Annual per-hectare soil carbon changes, by transition and AEZ.

AEZ	old	new	Mg C /ha / y
7	ANN	SWG	0.361
7	ANN	MSC	0.571
7	CP	SWG	0.34
7	CP	MSC	0.554
7	PAS	SWG	0.056
7	PAS	MSC	0.309
7	FOR	SWG	-0.234
7	FOR	MSC	0.053
8	ANN	SWG	0.304
8	ANN	MSC	0.857
8	CP	SWG	0.265
8	CP	MSC	0.841
8	PAS	SWG	-0.044
8	PAS	MSC	0.521
8	FOR	SWG	-0.467
8	FOR	MSC	0.147
9	ANN	SWG	0.297
9	ANN	MSC	0.924
9	CP	SWG	0.256
9	CP	MSC	0.919
9	PAS	SWG	-0.179
9	PAS	MSC	0.467
9	FOR	SWG	-0.698
9	FOR	MSC	0.01
10	ANN	SWG	0.495
10	ANN	MSC	1.26
10	CP	SWG	0.432
10	CP	MSC	1.24
10	PAS	SWG	-0.158
10	PAS	MSC	0.66

10	FOR	SWG	-0.471
10	FOR	MSC	0.338
11	ANN	SWG	0.844
11	ANN	MSC	1.093
11	CP	SWG	0.776
11	CP	MSC	1.06
11	PAS	SWG	-0.012
11	PAS	MSC	0.28
11	FOR	SWG	0.221
11	FOR	MSC	0.508
12	ANN	SWG	0.894
12	ANN	MSC	0.804
12	CP	SWG	0.82
12	CP	MSC	0.756
12	PAS	SWG	-0.098
12	PAS	MSC	-0.168
12	FOR	SWG	-0.122
12	FOR	MSC	-0.025
13	ANN	SWG	0.21
13	ANN	MSC	0.805
13	CP	SWG	0.19
13	CP	MSC	0.771
13	PAS	SWG	-0.035
13	PAS	MSC	0.471
13	FOR	SWG	-0.17
13	FOR	MSC	0.397
14	ANN	SWG	0.239
14	ANN	MSC	1
14	CP	SWG	0.146
14	CP	MSC	0.966
14	PAS	SWG	-0.409
14	PAS	MSC	0.454
14	FOR	SWG	-0.356
14	FOR	MSC	0.519
7	ANN	POP	0.233
8	ANN	POP	0.233
9	ANN	POP	0.233
10	ANN	POP	0.233
11	ANN	POP	0.233
12	ANN	POP	0.233
13	ANN	POP	0.233
14	ANN	POP	0.233
7	CP	POP	0.177
8	CP	POP	0.177
9	CP	POP	0.177
10	CP	POP	0.177
11	CP	POP	0.177
12	CP	POP	0.177
13	CP	POP	0.177
14	CP	POP	0.177
all	PAS	POP	-0.465
all	FOR	POP	-0.408

4. Cropland pasture

The implicit definition of “cropland pasture” in AEZ-EF differs from that underlying the Qin et al. modeling study. In the latter, a specific land-use history is assumed for all cropland pasture that results in nearly identical sequestration rates upon conversion to cellulosic crops whether from CP or annual crops. That is, the cropland pasture is assumed to be very similar to cropland in SOC.

In contrast, the AEZ-EF model assumed that emissions related to conversions of CP were half of those from converting pasture to the same final land use, since the actual state of any parcel of CP can be anywhere from quite recently in cropland (low carbon) to years in pasture (high carbon).

As a result, the emissions for various transitions as modeled in AEZ-EF are not entirely consistent. For example, in US AEZ10, the emission factor for a transition from annual crops to CP is -114 Mg C/ha, and from CP to Miscanthus is -62 Mg C/ha, for a total of -176 Mg C/ha, while the emission factor for a transition directly from annuals to Miscanthus is only -137 Mg C/ha.

Note however, that while the direct conversion of CP to cellulosic feedstocks relies on the data from Qin et al., other conversions of CP in response to cellulosic feedstock shocks rely on the prior assumption of half the emissions of the corresponding transition from pasture.

5. Other assumptions

We assume that only one cellulosic feedstock is grown in each fuel shock scenario. There is, however, a small non-zero amount of production for all three feedstocks in the baseline: shocks are implemented as a percent increase in production, so there cannot be zero production before the shock. We treat all transitions from the cellulosic feedstocks that are not shocked in the current experiment as transitions from cropland-pasture, since this is the dominant conversion source for all three feedstocks.

The biomass lost when converting cropland-pasture to other land uses is assumed to be the same as when converting pasture land. This is a small quantity relative to other carbon pools, so changing this assumption has relatively little effect.

We assume that 20% of the above-ground herbaceous crops is lost post-harvest due weathering or in transportation. The values used in GTAP for switchgrass and Miscanthus yield are expressed in bone-dry tons per hectare, net of lossage; to estimate average annual above-ground biomass carbon stock, the GTAP yield values are divided by (1 - 0.20) or 0.80 to, which is then combined with harvest index, moisture fraction (assumed 1.0 for cellulosics), and carbon fraction to compute total crop biomass.

The values added to the file *cropspec.har* for the three cellulosic crops are shown in Table 3.

Table 3. Parameters used to compute crop carbon for the three cellulosic feedstocks. % C = carbon fraction of dry matter; % lost = fraction lost post-harvest in weathering/transport; % dry = fraction of harvested biomass that is dry matter (i.e., not moisture); HI = harvest index, i.e., the fraction of total plant biomass removed in harvest; R:S = root:shoot ratio, i.e., the ratio of root biomass to above-ground biomass.

	% C	% lost	% dry	HI	R:S
Miscanthus	0.45	0.2	1.0	0.9	0.41
Switchgrass	0.45	0.2	1.0	0.9	0.72
Poplar	0.45	0.0	1.0	0.9	0.4

6. Uncertainty

The modeled Qin, Dunn et al. (2016a) SOC data have substantial error bars, yet we have extracted median values for use in this analysis. Given the strong dominance of CP-to-cellulosic crop conversions, the CI results are quite sensitive to the assumed rates of SOC change associated with conversions of cropland-pasture to cellulosic crops.

Table 4 shows the CI values for 6 runs for each feedstock, using 20 and 30-year time horizons (for both analytic horizon and foregone sequestration period) and different values for a "SOC factor" that is multiplied by the median values from Qin, Dunn et al. (2016a) for SOC changes when transitioning from CP to the three cellulosic crops. **Note that Table 4 presents results for test data and is not representative of final results, which were not available when this documentation was prepared.** These results serve only to show the sensitivity of CI values to the assumptions of SOC change rate and time horizon.

Table 4. Results of simple sensitivity analysis based on test data, not final data. (Values in g CO_2e MJ^{-1}). The "SOC factor" is multiplied by the values from Qin et al. (2016) shown above to decrease or increase the values in tandem. The "Time horizon" indicates whether effects were considered over 20 or 30 years.

SOC factor	**0.5**		**1.0**		**1.5**	
Time horizon	**20**	**30**	**20**	**30**	**20**	**30**
MSC	4.0	3.1	-11.3	-7.1	-26.6	-17.3
POP	-2.1	-1.0	-14.1	-9.0	-26.1	-17.0
SWG	-1.7	-0.7	-15.3	-9.7	-28.8	-18.8

References

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