**Supplemental Material for**

**Exploring a United States Maize Cellulose Biofuel Scenario Using an Integrated Energy and Agricultural Markets Solution Approach**

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**There are 3 parts to this Supplementary Material:**

*I*. Simulated crops

*II*. Reallocation method and example calculations

*III*. EPIC model description and general simulation design

**PART *I***

**Table SI I.1:** Crop varieties that are simulated by EPIC, whose cropland undergoes reallocation and which have Markets solution projections of crop yield trend from 2002 to 2022.

|  |  |  |
| --- | --- | --- |
| **Simulated Crop** | **Reallocation (yes/no)** | **Markets Solution Yield****Change (%)** |
| Maize for grain, rainfed | Yes | 30.4 |
| Maize for grain, irrigated | Yes | 30.4 |
| Maize for silage, rainfed | No | - |
| Maize for silage, irrigated | No | - |
| Soybean, rainfed | Yes | 16.7 |
| Soybean, irrigated | Yes | 16.7 |
| Sorghum for grain, rainfed | Yes | 12.7 |
| Sorghum for grain, irrigated | Yes | 12.7 |
| Sorghum for silage, rainfed | No | - |
| Sorghum for silage, irrigated | No | - |
| Cotton, rainfed | Yes | 34.9 |
| Cotton, irrigated | Yes | 34.9 |
| Winter Wheat, rainfed | Yes | 20.1 |
| Winter Wheat, irrigated | Yes | 20.1 |
| Spring Wheat, rainfed | Yes | 20.1 |
| Spring Wheat, irrigated | Yes | 20.1 |
| Barley, rainfed | Yes | 22.2 |
| Barley, irrigated | Yes | 22.2 |
| Oats, rainfed | Yes | 8.5 |
| Oats, irrigated | Yes | 8.5 |
| Peanuts, rainfed | Yes | - |
| Peanuts, irrigated | Yes | - |
| Potatoes, rainfed | No | - |
| Potatoes, irrigated | No | - |
| Rye, rainfed | No | - |
| Rye, irrigated | No | - |
| Rice | No | 20.1 |
| Edible and dry beans, rainfed | No | - |
| Edible and dry beans, irrigated | No | - |
| Canola, rainfed | No | - |
| Canola, irrigated | No | - |
| \*Other Crop, rainfed | No | - |
| \*Other Crop, irrigated | No | - |
| Bermuda and Fescue Hay, rainfed | Yes | 4.5 |
| Bermuda and Fescue Hay, irrigated | Yes | 4.5 |
| Alfalfa, rainfed | No | 4.5 |
| Alfalfa, irrigated | No | 4.5 |
| \*Other grass hay, rainfed | Yes | - |

\*Other crop includes crops that are not explicitly modeled. All other crop area is simulated as if it were cultivated to maize. Other grass represents tame pasture grasses that are not explicitly modeled. All other grass area is simulated as if it were coastal Bermuda (southern US) or fescue (northern US) hay.

**Part *II*:** **Cropland Reallocation Methodology**

***II*. A The reallocation hierarchy:**

The Markets model estimate of planted maize cropland refers to grain maize only. Changes in wheat land area include both spring and winter wheat, while changes in hay cropland include both grass hay and alfalfa. Crop area changes are reported as total state level change, with no distinction between rain fed and irrigated crops.

The crop reallocation hierarchy (Table SI *II*.1) reflects best professional judgment based on existing rotation systems (*i.e.*, presence of alternative infrastructure), crop price, and overall cost of production, and is in general agreement with criteria employed by the CARD/FAPRI agricultural markets model (personnel communication Dr. Pat Westhoff, Professor and Director, Food and Agricultural Policy Research Institute (FAPRI), University of Missouri, Columbia, MO). Maize and soybeans are often grown in rotation and so infrastructure for either crop is already in place. Grain sorghum is grown in the same geographic area are grain maize and equipment can easily be modified to handle shifts from sorghum to maize or soybean. Cotton is geographically separate from the main maize and soybean areas, but is grown in rotation with grain sorghum. Winter wheat is occasionally used in rotation with maize in the United States Midwest, but can also be harvested for biomass. “Other Crops” are broken out to sunflower and canola because of their importance for pressed oil markets. They are low in the hierarchy because they are high value crops that are unlikely to be shifted. Land under Conservation Reserve Program (CRP) contract in 2002 is assumed to support a mix of grass-cover species (Other grass), and because of the CRP contract structure and generally less productive soils – are less likely to be shifted. It is also assumed that “Other grass” in never irrigated.

Table SI II.2 summarizes National scale cropland area re-allocation results. Note that the simulated crop-specific land area increases match exactly those projected by the CARD model. The crop-specific land area decreases are generally smaller than those projected by CARD. This is because of a fundamental disagreement between the CARD and NLCD data layers regarding the overall amount of agricultural land. CARD total agricultural land area is 4.98 million acres greater than the NLCD. After levels 1-15 of the hierarchy (Table SI II.1) have been completed, if there is an area shortfall in a state, the hay crop class is re-visited. If the shortfall cannot be made up with additional hay/alfalfa allocations, then NLCD Class 72 (grassland) land area is re-allocated to Class 81 (hay and pasture). This reflects acknowledgment that there are classification errors in NLCD.

|  |  |
| --- | --- |
| **Hierarchy position** | **Crop Name** |
| 1 | Grain Maize |
| 2 | Soybean |
| 3 | Grain Sorghum |
| 4 | Cotton |
| 5 | Winter Wheat |
| 6 | Spring Wheat |
| 7 | Hay - grass |
| 8 | Hay - alfalfa |
| 9 | Peanuts |
| 10 | Oats |
| 11 | Barley |
| 12 | Other Crop – sunflower |
| 13 | Rice |
| 14 | Other Crop- canola |
| 15 | Other Grass (CRP) |
| 16 | Re-allocate hay and alfalfa |
| 17 | NLCD Grassland |

**Table SI II.1:** Cropland re-allocation hierarchy.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **A****2002 Markets****model Crop****Area** | **B****2002 Simulated****Crop Area** | **C****Market 2002 to 2022****Re-allocation** | **D****EPIC 2002 to 2022CROP****Re-allocation** |
| **Increase** | **decrease** | **Increase** | **decrease** |
| Maize | 75.70 | 61.80 | 19.44 | 0.12 | 19.44 | 0.12 |
| Soybean | 74.08 | 65.25 | 6.55 | 6.19 | 6.55 | 6.09 |
| Sorghum | 10.25 | 5.68 | 0.12 | 2.96 | 0.12 | 2.81 |
| Cotton | 15.5 | 12.10 | 0.03 | 6.77 | 0.03 | 6.53 |
| Wheat | 59.43 | 37.75 | 2.66 | 3.53 | 2.66 | 2.90 |
| Barley | 4.95 | 3.36 | 0.01 | 1.12 | 0.01 | 0.57 |
| Oats | 4.40 | 1.63 | 0.06 | 1.43 | 0.06 | 0.86 |
| Peanuts | 1.54 | 1.22 | 0.21 | 0.36 | 0.21 | 0.16 |
| Rice | 3.33 | 3.31 | 0.07 | 0.39 | 0.07 | 0.18 |
| All hay | 63.52 | 109.11 | 2.61 | 5.11 | 2.61 | 5.27 |
| \*OtherCrop |  |  | 0.06 | 0.52 | 0.01 | 0.33 |
| Other Grass(CRP) |  |  | 0.47 | 3.94 | 0.47 | 1.45 |
| Grassland |  |  |  |  |  | 4.98 |

**Table SI II.2:** A) 2002 Markets model, B) 2002 simulated (BELD) cropland area, C) Markets model 2022, and D) 2022CROP scenario (million acres) area increases and decreases. The simulated “Other Crop” and “Other Grass” includes agricultural crops in addition to those addressed directly by CARD and so initial 2002 values for these classes are not included in this summary.

**II.B Example Calculations for Cropland Reallocation**

**II.B.1 Example 1: State-level re-allocation for Illinois**

Begin by computing the CARD state level cropland differences (Table SI II.3, Column A). There are 3 crops whose areas increase; maize, wheat and CRP. For iteration 1 (maize), arrange all the crop differences in (Table SI II.1) hierarchical order with maize at the top. Move through the crop difference list until you find the first available area (crop with a decreasing area, *i.e.*, soybean). Use the available area. If it is equal to or greater than the maize increase, then re-allocation for maize is complete. If not, move to the next available crop (negative difference, *i.e.*, grain sorghum) and use this available area. Repeat until all the maize demand is met.

Move to the second iteration by placing wheat at the top of the allocation list. Move through the hierarchy as before, using remaining available area. Note that after all the available cropland has been allocated, there is still 0.2016 mill ac of wheat area demand that has not been met. Re-visit our hay re-allocation (Table SI II.1, step 16) recognizing that miss-classification errors are particularly prevalent in the original land use data layer. If sufficient 2002 area remains (Table SI II.3, Column B), add the remaining wheat area demand (0.2016 mill ac) to the previous Hayland allocation (0.2100 mill ac), resulting in a state level hayland decrease of 0.4116 mill ac. Proceed to the third allocation iteration.

There is no cropland area remaining for the third reallocation step and so we move directly to reallocation of hayland. Add the CRP land increase (0.0817) to the previous total Hayland reduction for a total of 0.4933 million acres hayland reduction in Illinois (Table SI II.3, Column C).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Crop Name** | **Markets****model****change****(A)** | **Simulation****available****crop****(B)** | **Iteration 1****(Maize)****available****area****remaining****(crop area****still****needed)** | **Step 2****Wheat-****available****area****allocation** | **Step 3****CRP****available****area****allocation** | **Final****simulated****change****(C)** |
| 1 | Grain Maize | +2.2505 |  |  | 0 | 0 | +2.2505 |
| 2 | Soybean | -2.0495 | 9.491 | 0 (0.201) | 0 | 0 | -2.0495 |
| 3 | GrainSorghum | -0.0211 | 0.0425 | 0 (0.1799) | 0 | 0 | -0.0211 |
| 4 | Cotton | 0 | 0 | 0 (0.1799) | 0 | 0 | 0 |
| 5 | Winter Wheat | +0.2653 | 0.4549 |  |  | 0 | +0.2653 |
| 6 | Spring Wheat | - | - | - | 0 | 0 | - |
| 7 | Hay - grass | -0.2100 | 3.046 | -.0301 (0) | 0 (0.2352) | 0 | -0.2100 |
| 8 | Hay - alfalfa | - | - | - | - | - | - |
| 9 | Peanuts | 0 | 0 |  | 0 | 0 | 0 |
| 10 | Oats | -0.0336 | .0373 |  | 0 (0.2016) | 0 | -0.0336 |
| 11 | Barley | 0 | .0005 |  | 0 | 0 | 0 |
| 12 | Other Crop –sunflower | 0 | 1.384 |  | 0 | 0 | 0 |
| 13 | Rice | 0 | 0 |  | 0 | 0 | 0 |
| 14 | Other Crop-canola | 0 | - |  | 0 | 0 | 0 |
| 15 | Other Grass(CRP) | +0.0817 | 0.191 |  | 0 |  | +0.0817 |
| 16 | Re-allocatehay and alfalfa |  |  |  | -0.4116 | - 0.4933 | -0.4933 |
| 17 | NLCDGrassland |  | 0.246 |  |  |  |  |

**Table SI II.3.** State-level Crop area allocation procedure for Illinois (million acres). Column B is the2002 estimated BELD cropland and column C is the simulated 2022CROP.

**II.B.2 Example 2:** **State-level re-allocation for North Dakota**

The most notable Example 2 difference from Example 1 is that even before iteration 1 reallocation is complete, there is no available cropland remaining. This can arise from at least two sources. First, it is well-known that there are classification errors in the NLCD data among wheat, hay or pastureland and grassland classes. It has been noted previously that the Markets model assumes there are 4.98 million acres more agricultural land than does NLCD (the sum of classes 81 and 82). In addition, there are potential shortfalls in simulated CRP area estimates. For instance, the Markets models indicates that cropland in CRP increases from 33.92 mill acres in 2002 to 36.80 mill acres in 2008 before falling to 30.00 mill acres in 2013. This value was then extrapolated forward assuming no change and so there are 2.9 mill acres that were allocated from cropland to CRP that the Markets solution reallocates in intervening years to other crop species, that is unaccounted for in our 2002 simulated cropland allocation. In the absence of more detailed information, we reallocate area from the NLCD grassland Class (81) to soybean, hay and other crops with state-level increases.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Crop Name** | **Markets****Model****Change****(A)** | **Simulation****available****crop****(B)** | **Iteration 1****(Maize)****available****area****remaining****(crop area****still****needed)** | **Iteration 2****Soybean-****available****area****allocation** | **Iteration 3****Hay-****available****area****allocation** | **Final****simulated****change****(C)** |
|  |
| 1 | Grain Maize | +2.6275 | 0.8268 |  |  |  |  | +2.6275 |
| 2 | Soybean | +2.3537 | 2.288 |  |  |  |  | +2.3537 |
| 3 | Grain Sorghum | 0 | 0 |  |  |  |  | 0 |
| 4 | Cotton | 0 | 0 |  |  |  |  | 0 |
| 5 | Winter Wheat | -0.8746 | 6.747 | 0 | (1.7529) |  |  | -0.8746 |
| 6 | Spring Wheat | - | - | - |  |  |  | - |
| 7 | Hay - grass | +0.2259 | 3.721 |  |  |  |  | +0.2259 |
| 8 | Hay - alfalfa | - | - | - |  | - | - | - |
| 9 | Peanuts | 0 | 0 |  |  |  |  | 0 |
| 10 | Oats | -0.2399 | 0.252 | 0 | (1.513) |  |  | -0.2399 |
| 11 | Barley | -0.2026 | 1.122 | 0 (1.3104) |  |  | -0.2026 |
|  |
| 12 | Other Crop –sunflower | -0.0035 | 9.230 | 0 | (1.3069) |  |  | -0.1038 |
|  |  |
| 13 | Rice | 0 | 0 | 0 |  |  |  | 0 |
| 14 | Other Crop-canola | -0.1003 | - | 0 (1.2066) |  |  | - |
|  |  |  |  |  |
| 15 | Other Grass(CRP) | -0.7475 | 0.1301 | 0 | (1.0765) |  |  | -0.1301 |
|  |  |  |  |  |  |  |
| 16 | Re-allocate hayand alfalfa |  |  |  |  |  |  | 0 |
|  |  |  |  |  |  |
|  |  |  |  |  |
| 17 | NLCDGrassland |  | 13.297 | -1.0765 | -2.3537 | -0.2259 | -3.656 |
|  |  |  |

**Table SI II.4:** State-level Crop area allocation procedure for North Dakota (million acres). Column B is the 2002 estimated BELD cropland and column C is the simulated 2022CROP area.

**II.B.3. Downscaling state crop area re-allocation to grid cell**

1. Calculate state-level reduction R,

 | 2 , |

Where: Ax2y= Crop x area available for re-allocation to crop y (Column A, Table S4) in State

s. AX, S= Total area of crop x in state s

Using Table S3 as an example, assume crop x is rainfed soybean, crop y is rainfed grain maize and s is Illinois. The numerator is Column A(2.0495 mill ac) and the denominator is 9.9609 mill ac (not shown). R then evaluates to .2058

2. Calculate the rainfed or irrigated area of crop x in= grid × i to be re-allocated to increasing crop y.

Where: Ax,s,i = Total area of crop x in state s and grid cell i

If we assume there are 1000 ha of rainfed soybean cropland in Illinois grid cell i, then 205.8 ha of rainfed soybean area would be re-allocated to grid cell i rainfed grain maize.

Note that the EPIC model is defined such that the character of the land being re-allocated represents the dominate soil type associated with crop x as defined by the Natural Resources Inventory (NRI) for the HUC-8 in which the grid cell resides.

East of 100o Latitude, both rain fed and irrigated cropland reallocation occurs. West of 100⁰ Longitude, all re-allocation is assumed to be irrigated. That is, if a farmer is going to invest in a land reallocation, it is only economically viable to do so for irrigated crops. If there is insufficient irrigated cropland available, then it is assumed that rain fed cropland will be converted to irrigate cropland, *i.e.*, irrigation expansion.

Crop classes that contain multiple crops, e.g., hay (grass and alfalfa) and wheat (spring wheat and winter wheat) are tracked as a single entity at the state level, but grid-cell level re-allocation is handled a little differently. When wheat or hay cropland is available for re-allocation, e.g., the area demanded is split equally between the two crops. When area is to be added, it is added proportionally to each crop following their 2002 areas. Note that this can result in changes in crop area relationships in 2022CROP.

**Part III: EPIC Model Description and General Simulation Design.**

The EPIC model maintains coupled soil ammonium, nitrate, phosphorus and carbon budgets. A crop species-specific potential growth is simulated for each day. This potential is then reduced in response to nutrient, water, temperature, aeration, and aluminum stresses. When nutrient stress is indicated, EPIC is directed to make a fertilizer application. Applications are made at planting, approximately 30 days after planting, and subsequently as needed (minimum 7-day separation) until plants reach 50% of maturity. Planting dates are dynamically determined on the basis of crop species, soil temperature, and local weather conditions.

The 2002 and 2022BASE scenarios are generated using the FEST-C1\_2 interface. The FEST-C implementation of EPIC performs simulations on a 12km rectangular grid cell basis. The user provides the domain extent, projection and grid cell resolution. The interface than automatically creates all the input files necessary to perform an EPIC simulation. When instructed to “run”, the interface creates a series of scripts that execute the simulation. For this application, we perform simulations for 137241 12km x 12km rectangular grid cells for up to 22 rainfed and 22 irrigated crop species. A high-resolution land use database, the Biogenic Emissions Land use Database (BELD, available at <http://www.cmascenter.org>) defines the crops and crop areas modeled for each grid cell. The National Resource Inventory (NRI) is used to associate one “typical” soil and crop within each simulation grid cell. A 25-year spin up simulation is performed for each grid cell soil/crop combination to stabilize soil biogeochemical pools reflecting defined management and local climate conditions. Soil erosion is turned off during spinup, but CO2 and Markets model yield trends are included. Soil status at the end of the spin up period is used as initial conditions for the scenario simulations and all erosion processes are active.

Scenario 2022CROP requires additional simulation steps. When a crop is reallocated, an additional EPIC simulation must be defined in which the original crop soil is combined with the “receiving’ crop variety. For instance, if soybean cropland is shifted to grain maize, then simulations for grain maize grown on original (*i.e.*, 2022BASE) grain maize soil as well as grain maize grown on previous soybean soil must be performed. This biogeochemical “memory” is particularly useful in diagnosing agricultural N and P system responses on aggregate scales.

EPIC requires knowledge regarding changes to existing biomass/biogeochemical relationships responsible for biomass (yield) change. The Markets model provides no such information other than the projected trend which includes responses to endogenous and exogenous factors, and so assumptions regarding the exact source of these changes must be made. For this application, we modify the relationship between the partitioning of total biomass to harvested biomass, *i.e.*, grain yield. This can be done through the Harvest Index (HI) parameter. HI is the fraction of above ground biomass that is the grain yield. An increase in HI says that a larger fraction of total plant biomass is removed as grain at harvest. This could mean, for example, that there are more grain heads on each plant, or that there are more grains per head. This is roughly equivalent to hypothesizing that there is a higher protein content in the grain. Multiple stressors (water, temperature, oxygen and nitrogen) condition the potential HI-driven yield change, so there may be considerable spatial heterogeneity in the final simulated yield change. It is important to note that modification of different process relationship(s) e.g., increased tolerance for high planting density would produce a different biogeochemical system outcome. Increased nitrogen use efficiency, *i.e.*, resource input efficiency is not considered in this application because the EPIC simulation already includes N-demand based applications, *i.e.*, right time, right place, and right amount. Grain yield (HI) and biomass (CO2) trends are included in both future scenarios because they are independent of any specific energy future.