04 | Fossil Energy Consumption and Greenhouse Gas Emissions, Including Soil Carbon Effects, of Producing Agriculture and Forestry Feedstocks

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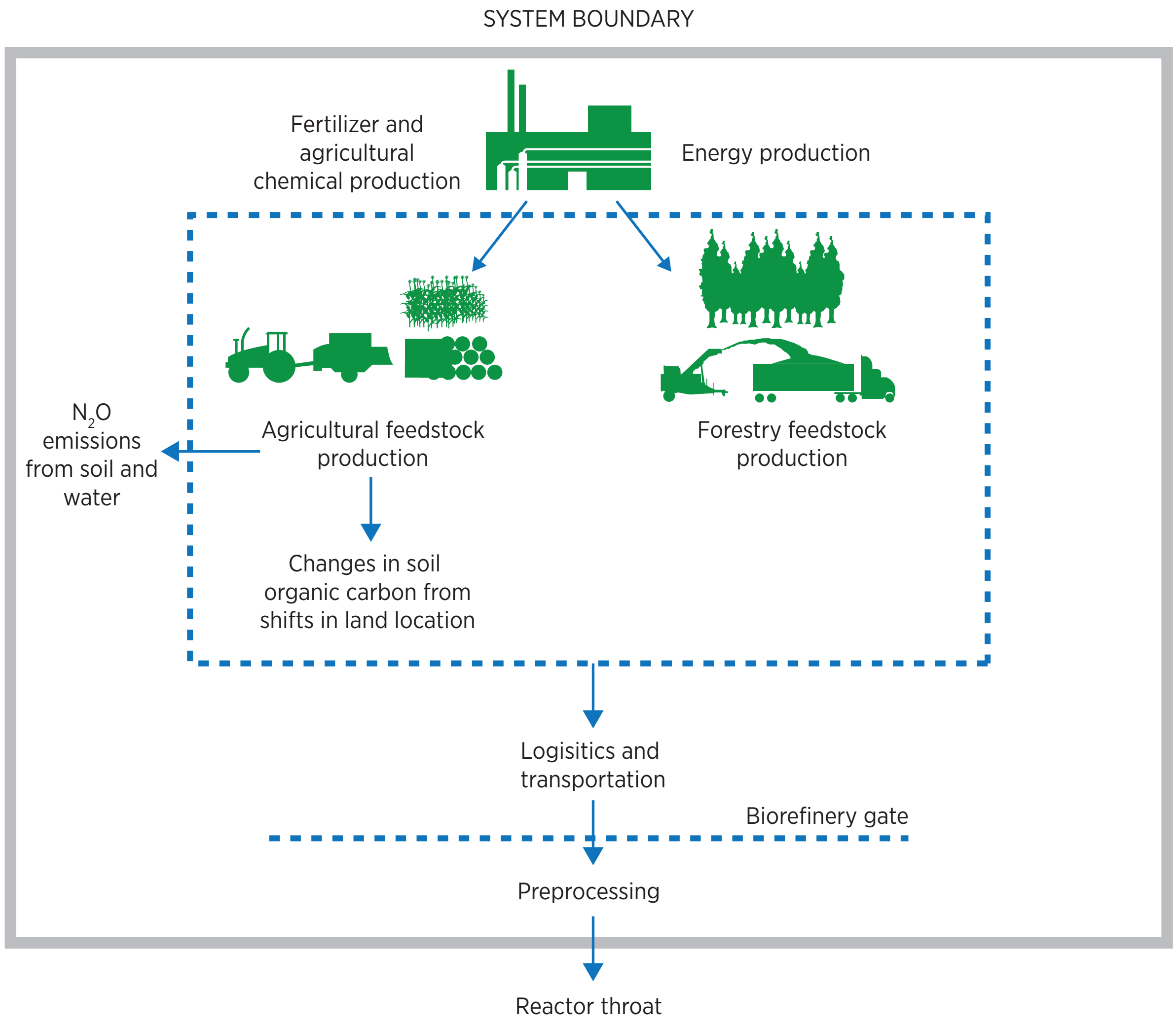
4.1 Introduction

One key measure of the environmental effects of producing biomass is the associated greenhouse gas (GHG) emissions. In this chapter, GHG emissions refers to the carbon dioxide equivalent (CO_2e) of CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions combined with their 100-year global-warming potentials in the Intergovernmental Panel on Climate Change's *Fifth Assessment Report* (IPCC 2013). Furthermore, an objective of expanding the domestic biomass supply is to reduce fossil energy and petroleum consumption through application of biomass toward different processes and products that currently use fossil energy sources as feedstocks. In this chapter of the *2016 Billion-Ton Report (BT16)* volume 2, fossil energy consumption and GHG emissions associated with producing biomass—including the upstream energy consumed and emissions released from fertilizer production, agricultural chemicals, and fuel used in farming—are estimated. In addition, we consider the contribution of changes in soil carbon to net GHG emissions as a result of producing feedstock on land that was previously in other land covers or under different management practices prior to production of biomass estimated to be grown under *BT16* volume 1 scenarios. This analysis was carried out with the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model as released by Argonne National Laboratory (ANL) in 2015.

The results presented in this chapter include the GHG emissions and fossil energy consumption associated with select scenarios defined in the first volume of *BT16*. These scenarios are the base case for 2017 (agricultural base case and forestry baseline combined; BC1&ML 2017)[1] and base and high-yielding 2040 cases (BC1&ML 2040, HH3&HH 2040). *BT16* volume 1 analyses did not include a business as usual case for forestry and agriculture and analysis of associated GHG emissions does not either. Results are presented at the county level and include calculated GHG emissions and energy consumption per dry ton of feedstock for each feedstock type. The results reflect the GHG and energy intensity of producing only agricultural and forest-derived biomass in each *BT16* scenario, not the emissions and energy associated with the entire agricultural and forestry sectors. National-level results for GHG emissions and fossil energy consumption are also presented. The system boundary for the analysis of agricultural and forestry feedstocks is shown in figure 4.1. The system boundary for both types of feedstocks is similar and includes direct energy use during feedstock production, transportation, and preprocessing; energy required for fertilizer and chemical production; and N_2O emissions from fertilizer application and biomass decomposition. However, changes in soil organic carbon (SOC) are only evaluated for agricultural feedstocks. Furthermore, because forested area was held constant (agricultural land did not expand into forested land), and therefore forested areas were not cleared in Volume 1 scenarios, changes in above-ground carbon were not considered. Please see Chapter 3 for a discussion of land use change in *BT16* scenarios and section 4.2.3 for additional discussion of above ground carbon. Materials and energy consumed in the manufacture of farming/forestry equipment and trucks used for biomass transportation are excluded from this analysis. Indirect GHG emissions from growing biomass—for example, from indirect land-use change brought about by market factors—are outside of the system boundary.

Furthermore, we incorporate cases from Rogers et al. (2016) in which the biomass produced per *Volume 1* is converted to biofuel, bioproducts, and biopower that can then displace petroleum-derived fuels, products, and power. This exercise permits an estimation of GHG emissions and fossil energy consumption reductions as compared to business as usual (BAU) scenarios and expands the system boundary beyond that of the *BT16* analysis (fig. 4.1). However, the expansion of boundaries to include reduction of emissions from fossil energy consumption does not account for changes in costs in fossil fuel-based and bio-derived fuels and products over time.

Figure 4.1 | System boundary of this chapter's analysis. All steps within the gray box are included.



4.2 Methods

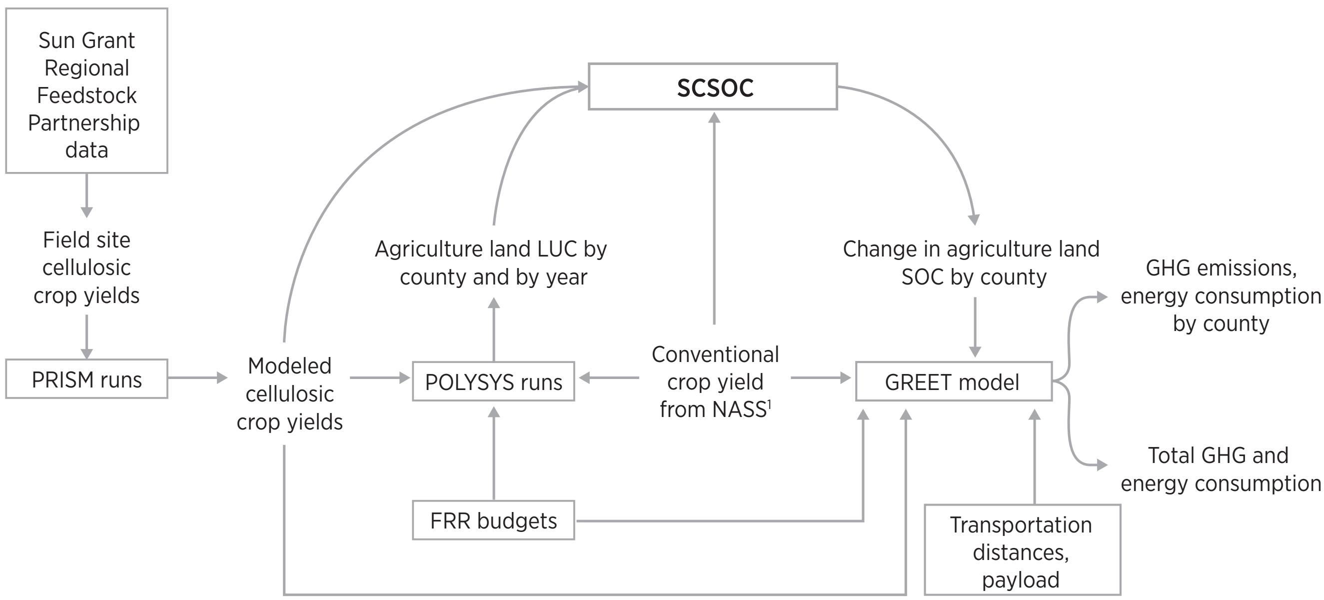
This section provides an overview of the methodology for estimating fossil energy consumption and GHG emissions in *BT16* for base-case (BC1 2017 and BC1 2040) and high-yield (HH3 2040) scenarios for agriculture, and moderate growth in housing/low growth in wood energy (ML 2017 and ML 2040) and high growth in housing/high growth in wood energy (HH 2040) scenarios for forestry (see chapter 2 for details regarding each scenario). Figures 4.2 and 4.3 present the data and calculation flow used to estimate GHG emissions associated with biomass production in the agricultural and forestry sectors. The following subsections describe each step of this methodology including data sources and assumptions.

4.2.1 Material and Energy Consumption during Feedstock Production

To estimate fossil energy consumption and GHG emissions associated with the production of biomass, the first phase shown within the system boundary (fig 4.1), energy, fertilizer, and chemicals consumption

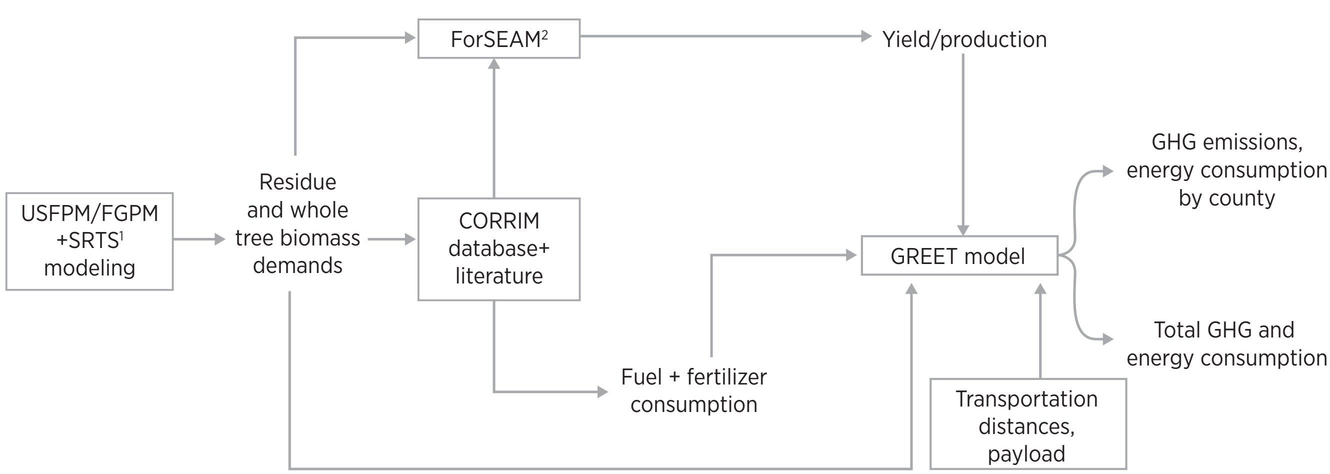
[1] This chapter uses combinations of agricultural and forestry scenarios to provide a projection of possible environmental effects from both types of biomass. Therefore, the convention of the "&" sign is used to represent a combination of two scenarios.

Figure 4.2 | Schematic of methodology applied to estimate GHG emissions associated with producing agricultural biomass. The fossil energy consumption estimation methodology is analogous but does not incorporate input from SCSOC (Surrogate CENTURY Soil Organic Carbon model, based on CENTURY, which is available from Colorado State University).[1] NASS: represents the National Agricultural Statistics Service from the U.S. Department of Agriculture (USDA). FRR Budgets: Farm Resource Regions as defined by the USDA are depicted in figure 4.10. For each FRR, there is one budget containing fuel, fertilizer, and agricultural chemical consumption per feedstock. Transportation distances, payload, and pre-processing fuel consumption are based on results in chapter 6 of *BT16* volume 1.



[1.] NASS: represents the National Agricultural Statistics Service from the U.S. Department of Agriculture

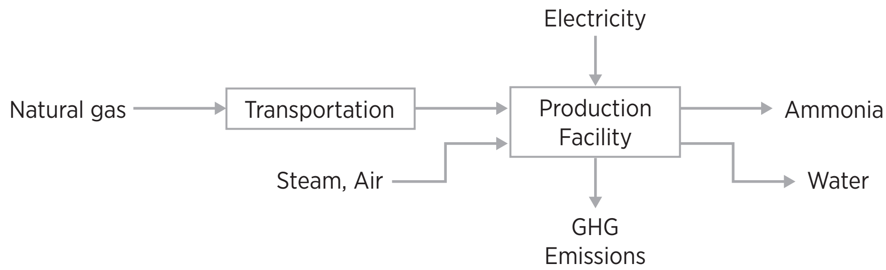
Figure 4.3 | Schematic of methodology applied to forestry-derived feedstocks to estimate GHG emissions from biomass production. Fossil energy consumption estimation methodology is analogous. Transportation distances, payload, and pre-processing fuel consumption are based on BT16 volume 1, chapter 6 results. (CORRIM – Consortium for Research on Renewable Industrial Materials)



1. U.S. Forest Products Module/Global Forest Products Model (USFPM/GFPM) with the Subregional Timber Supply (SRTS) to determine wood energy demands

2. ForSEAM is a version of POLYSYS developed for forestry

Figure 4.4 | Process to produce ammonia fertilizer, the emissions from which are included in the total emissions associated with biomass produced with ammonia as a fertilizer. (Upstream burdens to produce and deliver natural gas and electricity to the fertilizer plant, not shown in the figure, are also included.)



per unit area of land for each crop and the yield of each crop are required. For analyses of the agricultural sector, Farm Resource Region (FRR) budgets are the source of fuel, fertilizer, and chemical consumption. In the case of forest-derived feedstocks, fertilizer application and energy consumed in harvesting and site prep derives from the literature and from a Consortium for Research on Renewable Industrial Materials (CORRIM) database. On-site fuel, fertilizer, and chemical consumption could be called "purchased energy" or "on-site materials consumption." GREET estimates the upstream burdens (i.e., consumption of materials, energy, and emissions) associated with producing these fuels, fertilizers, and chemicals to yield a "full fuel-cycle" result for material and energy inputs to farms at the county level. Figure 4.4 provides an example of how full life-cycle GHG emissions associated with ammonia production are calculated in GREET (Johnson, Palou-Rivera, and Frank 2013). The calculation accounts for natural gas and electricity production to the point of use at the ammonia facility. At the facility, methane reforming, a water-gas shift reaction, and methanation occur. Carbon dioxide is produced by the water-gas shift reaction and is emitted to the atmosphere, which is accounted for in GREET. Additionally, emissions from transporting ammonia-plant inputs to the production facility and produced ammonia to farms are included. The total of these upstream emissions from ammonia production is assigned to biomass produced with ammonia as a fertilizer. Similarly, upstream emissions associated with all inputs to the production of agriculture and forestry biomass are included in this analysis. We note that feedstock production emissions for any given crop reflect those incurred in the year the feedstock is harvested. A full description of the calculation of energy and GHG intensity of agricultural and forest-derived biomass is contained in appendix 4-A.

4.2.2 Estimation of SOC Changes

An in-depth analysis of SOC changes upon bioenergy-crop-relevant land transitions using the surrogate CENTURY soil organic carbon (SCSOC) model at both state (Kwon et al. 2013) and county levels (Qin et al. 2016a) was conducted in previous work. SCSOC uses calculations and parameters from CENTURY, but it has been modified to permit simulation of bioenergy crop production (Qin et al. 2016a). Important inputs to this model include crop yield, the root-to-shoot ratio, soil type, and weather data (Kwon et al. 2013; Qin et al. 2016a). SCSOC-estimated changes in SOC are treated as emission factors (EFs) in units of carbon dioxide mass per area per year. These EFs can be combined with estimates of changes in land allocation (e.g., a change in the crop planted on a land parcel or a change in land cover from pasture to cropland) from an economic model like POLYSYS (the agricultural economic model used to generate biomass supply estimates for in *BT16* volume 1) for different biomass-production scenarios to yield the GHG implications of large-scale feedstock-production increases.

Figure 4.2 and figure 4.5 illustrate how we have adopted this approach to estimate SOC EFs for application in *BT16* for agricultural crops. In particular, the SOC EFs (denoting SOC changes) can be estimated for each specific land-allocation change determined by POLYSYS (fig 4.5). These EFs were then combined with actual land-area change associated with each land-allocation change to calculate total SOC change for a specific scenario of land that transitioned from one type to another (fig 4.5). SOC changes associated with forestry systems are not quantified in this analysis. These species-dependent changes are influenced by many silvicultural management factors such as nutrient management and harvest method (Lal 2005). Moreover, the extent and composition of litter influence these changes. At present, there are not sufficient data and modeling capability to address SOC changes of forestry systems in the *BT16* although some considerations for the evaluation of soil organic carbon changes in forestry systems are provided in appendix 4-B. In future analyses, SOC changes in forestry systems for biomass production may be examined. In the following subsections, we first explain how we conducted SOC modeling with SCSOC. The next subsection describes how the SOC EFs are paired with output from POLYSYS that describes how land moved into and out of production of crops in the *BT16* scenarios.

4.2.1.1 Application of Soil Carbon Modeling to BT16 Agricultural Scenarios

Important inputs to the SCSOC model include bioenergy and other crop yields at the county level. Yield is a major factor determining above- and belowground biomass production which influence soil organic matter inputs. These inputs contribute to the accumulation of SOC. In SCSOC, historical conventional crop yields (e.g., corn, wheat, and soybean) are based on USDA-NASS statistical data (USDA 2015). The reference yields in the start year (2015) of the POLYSYS-modeled production period for energy crops such as switchgrass, miscanthus, poplar, and willow are based on the Climate Group's Parameter-elevation Relationships on Independent Slopes Model (PRISM). SOC and POLYSYS economic modeling to estimate land-allocation changes consistently use these yield inputs—this is important because yields drive results of both models, which are being used together. For the land-use change (LUC) period (2015–2040), biomass yield is determined by scenarios, with a 1% annual yield increase rate in BC1 and 3% in HH3, which are consistent with POLYSYS yield assumptions. In SOC modeling for the GHG emissions analysis, all conventional crops were grown with conventional tillage while most energy crops are modeled as being produced with no tillage. (*BT16* volume 1 modeling did include different tillage scenarios, and future work may refine treatment of tillage in SOC modeling.) SOC simulations also consider the potential impacts of erosion by applying the erosion rates for croplands and pasture, hay, and grasslands obtained from National Resources Inventory erosion estimates (Natural Resources Conservation Service), which are based on the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation (WEQ) (Dunn et al. 2014). Climate-related inputs to SCSOC are based on county-level monthly temperature and precipitation data from weather stations between 1960 and 2010. Soil texture classes (e.g., sand, clay, and loam) within each county are determined from the Harmonized World Soil Database (Qin et al. 2016a).

Figure 4.5 | Schematic of data sources and estimations of SOC changes for agricultural feedstocks. POLYSYS estimates both land area change and allocation changes for each allocation change. (CCLUB – Carbon Calculator for Land Use Change from Biofuels Production)

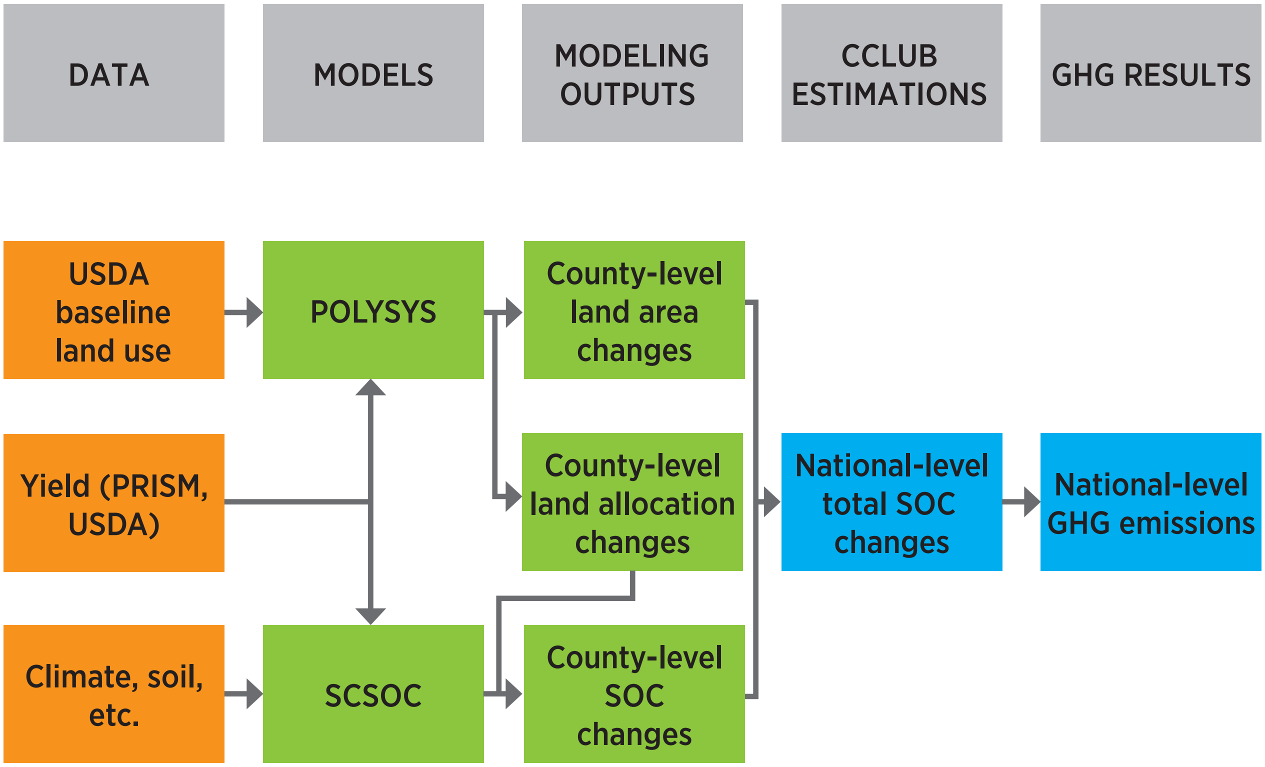


Table 4.1 lists the crops simulated in POLYSYS and how SOC changes associated with them are modeled with SCSOC. Crops that fall into the same crop cohort (e.g., barley, oats, or wheat) are simulated with comparable SOC-modeling settings with specific parameters describing biomass production and return (e.g., harvest index or residue return rate). Rice, eucalyptus, pine, and energy cane are not specifically modeled for SOC change since these crops are associated with less than 1% of the land area that underwent a land-management or land-cover change per POLYSYS outputs in both BC1 and HH3 scenarios.

The SOC model was run at a county level prior to 1881 until 2040 for each potential land transition from one use or land cover to another (e.g., pasture to miscanthus) to calculate the SOC change over the biomass feedstock production period (25 years).

The SOC change rate (SOCr) (Mg C ha^{-1} yr^{-1}), also referred to as SOC *EF*, indicates the average annual SOC change over time *(T)* (fig 4.6). A positive *SOCr* indicates a SOC loss while a negative value indicates a SOC gain.

For county *i* undergoing a given land transition (e.g., pasture to miscanthus) *j* over a number of years T (starting from time *0* to *T*):

Equation 4.1:

$$SOCr_{ij} = \frac{SOC_{0,ij} - SOC_{T,ij}}{T}$$

These county-level EFs were matched with associated amounts and types of changes in land allocation from POLYSYS. For example, the emission factor for a pasture-to-miscanthus production in Lyon County, Kansas, was applied to the 39,000 hectares that

Table 4.1 | Simulation of Crops in SOC Modeling

POLYSYS crops*	SOC modeling approach	Notes
Land use history (prior to 2015)		
- Barley, corn, cotton, oats, rice, sorghum, soybeans, and wheat	Cropland†	Cropland and pasture are assumed to represent historical land patterns according to the 2015 crop types in POLYSYS
- Hay, pasture	Pasture‡	
Land allocation (2015–2040)		
- Corn, soybeans, and wheat	Corn, soybeans, wheat †	Used existing SCSOC parameters
- Switchgrass and miscanthus	Switchgrass and miscanthus‡	Used existing SCSOC parameters
- Willow and poplar	Willow and poplar‡	Used existing SCSOC parameters
- Barley, cotton, oats, sorghum, and biomass sorghum	Barley (wheat), cotton (grass), oats (wheat), sorghum (corn), and biomass sorghum(corn) †	Crops are simulated under similar crop cohorts (in parentheses) with specific parameters (e.g., harvest index or residue return rate)
- Rice, eucalyptus, pine, and energy cane	N/A	Crops existed in POLYSYS but are not included in SOC modeling because of their insignificant contribution to overall shifts in land allocation
- Idle land	N/A	Land moving into and out of the POLYSYS idle land category was assumed to experience no SOC change because the idle land category has no specified characteristics or classification regarding vegetation growth or residue management

* Included only crops associated with land use change. NA, not applicable. †Crops under conventional tillage and ‡no tillage as assumed for analysis for this chapter only.

experienced this transition between 2015 and 2040. Application of POLYSYS output for this purpose is described further in the next section. The total SOC change (Mg C) in county i associated with biomass production until t_x (which is 2040) is calculated as equation 4.2.

Equation 4.2:

$$\Delta SOC_{Total,i} = \sum_{j=1} SOCr_{i,j} \cdot A_{i,j} \cdot P_{i,j} \cdot (t_x - 2015)$$

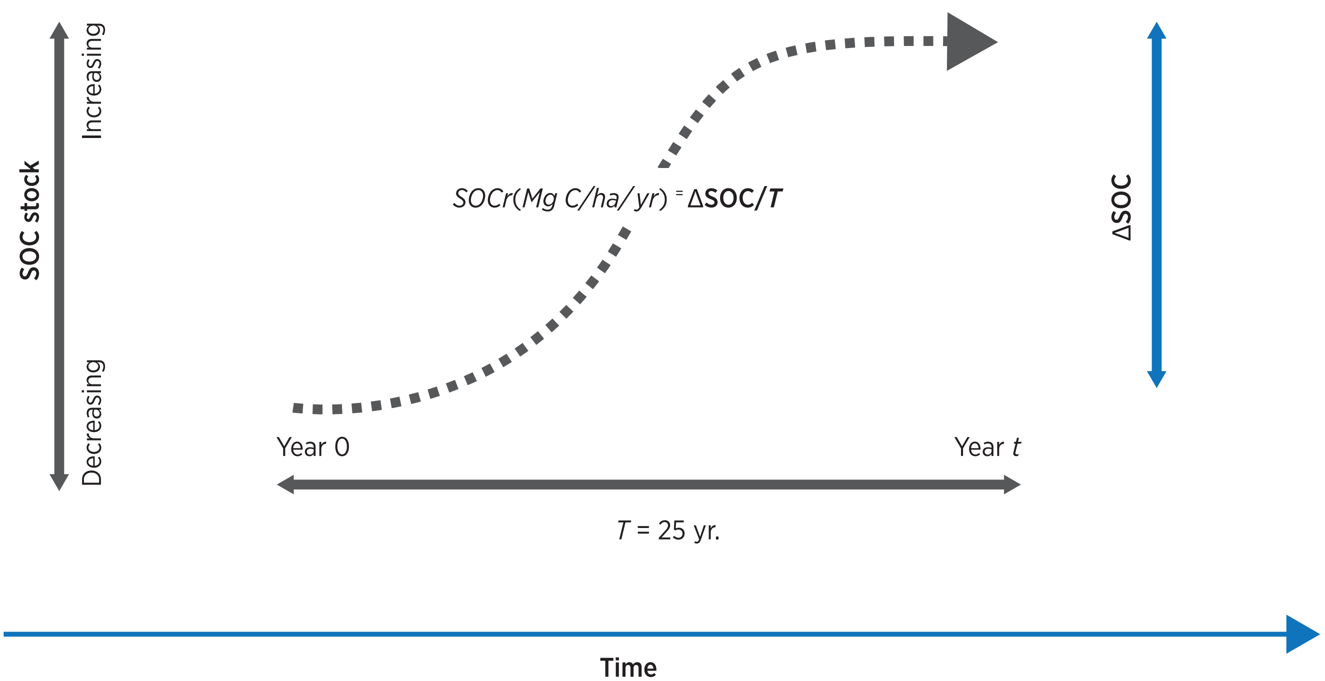
In this equation, A is the land area, P is the probability of a certain land transition (e.g., pasture to miscanthus) (ΣP_i=1, see next section) and t_x is the target biomass production year (here 2040). This calculation produces the total SOC change over the 25-year production period, which is divided by total agricultural biomass production in the county over the same period. All biomass produced in a given county then, regardless of type, is assigned the same SOC change intensity (SOC per unit biomass basis). A positive SOC change value indicates net carbon loss, and a negative value indicates net carbon gain. The SOC change, in terms of carbon, is converted to GHG emissions by a factor of carbon content in carbon dioxide (44/12). For detailed SOC model descriptions, please refer to our earlier publications (Kwon et al. 2013; Dunn et al. 2014; Qin et al. 2016a).

4.2.1.2 Applying POLYSYS Outputs to Estimating County-Level SOC Changes in BT16 Scenarios

There are two key challenges in using land allocation outputs from POLYSYS to model SOC changes relevant to *BT16* scenarios. These challenges and the techniques devised to overcome them are conceptualized in figure 4.7. The first challenge is that the SCSOC model relies on information about land-use history going back more than 100 years (fig. 4.7*A*). POLYSYS does not consider land-use history, but only begins tracking areas of land in a given county planted with certain crops at the start of the simulation (i.e., 2015). The second challenge is that POLYSYS does not keep track of the changes in the land allocation or cover of any given parcel of land at a sub-county level over time after 2015 (fig. 4.7*B*). Rather, the model output contains the area of land in one county planted in any given crop each year. If land area planted with corn decreases, that decrease may represent land newly planted with soy or with switchgrass, for example. This feature of POLYSYS output presents a challenge for SOC modeling that relies on information about the change in land use for a single parcel of land over time.

Regarding the first challenge pertaining to land-use history, SCSOC needs to adopt a historical land-use pattern without complete information from POLYSYS. In previous analyses (e.g., Qin 2016a), the land-use history, which strongly influences results, was originally constructed for simulating historical SOC dynamics by dividing the entire simulation of the land's history prior to the year the land undergoes a change in allocation into three periods: pristine prior

Figure 4.6 | SOC stock change and change rate



to 1881, 1881-1950, and 1951 to present (e.g., 2010) (fig. 4.7). Pristine land use is either grassland for native grassland and permanent pasture or forest for all forest cover. These land-history patterns are designed to represent major land uses over time as well as to capture SOC changes over a relatively long time period—SOC pools are not stable under short, frequent changes in land use. In the BT16 analysis, to overcome the first challenge, two major land-use types are assumed to represent historical patterns according to the land allocation in 2015 (fig. 4.7C). Based on earlier simulations of land-use history (Kwon et al. 2013; Qin et al. 2016a), the first, historical cropland includes all conventional crops in POLYSYS (e.g., corn, soybeans, wheat, and oats) and the second, pasture, is used for pasture and hay. Sensitivity of results to land-use history can be explored in future work.

Regarding the second challenge, POLYSYS outputs are used to generate probability matrices for feedstock production between 2015 (the year in which POLYSYS simulations begin) and 2040. The probability describes the distribution of designated

Figure 4.7 | Conceptualization of land-use/land-allocation change in simulations in different modeling systems A) LUC modeling framework in previous studies with land use history included (Kwon et al. 2013; Qin et al. 2016a); B) POLYSYS output in the form of annual county-level land-use matrices; and C) the land patterns used in this analysis to capture both land-use history and longer-term (25-year) land-use matrices from POLYSYS. Each row represents one unit of land experiencing changes of land use through time. The pixel color indicates a specific land use during different time periods.

Table 4.2 | Land-Area and Land-Use Allocation Pattern Outputs in POLYSYS

County	Land area	Initial (2015) allocation	Final allocation	Probability
1	A1	Corn	Switchgrass	P_1
1	A1	Corn	Miscanthus	P_2
1	A2	Soybeans	Switchgrass	P_3
-	-	-	-	-

land allocations (e.g., agricultural land planted with switchgrass or willow) originating from each of the 2015 land allocations at the county level (Table 4.2). This approach does not take into account the many potential changes in land allocation in a county over the 25-year time horizon of this analysis, but allows SOC to approach a relatively stable state so that a reasonable emission factor can be modeled for lands that changed initially from cropland or pastureland. While this analysis adopts a 25-year time horizon given the parameters of the *BT16* study, in previous analyses (e.g., Qin et al. 2016a), researchers chose a 30-year time horizon for biofuel feedstock production to match the time horizon that the U.S. Environmental Protection Agency (EPA) uses in its modeling for the Renewable Fuel Standard analysis (EPA 2010). A 30-year time horizon was also chosen because SOC typically returns to equilibrium within 30 years following a land transition (Qin et al. 2016b). An exception is if forested land is cleared and planted in corn; in that case, SOC can take many decades to stabilize. Forest land, however, is restricted from transition to agricultural land in *BT16* as described in volume 1.

Readers should keep in mind these two key limitations involved in estimating SOC changes associated with *BT16* scenarios. The SOC changes reported here should be viewed as estimates that indicate the directionality and estimated magnitude of SOC changes associated with the specific *BT16* scenarios rather than as a prediction of SOC that would exactly occur at the county level or would occur as compared to a business as usual scenario. Future work may investigate sensitivity of results to the key assumptions including land history prior to allocation change and tillage practice. Alternative techniques in using POLYSYS output to generate estimates of SOC changes may also be examined.

4.2.3 Changes in Aboveground Carbon

Potential aboveground carbon changes of the select scenarios are not considered in this chapter. Of all potential land transitions, clearing forested land to grow crops incurs the most significant amount of aboveground carbon change. The carbon stock in the trees is lost, and then every year, some amount of carbon that would have been sequestered and added to the existing carbon stock is not sequestered (Dunn et al. 2013). This latter missed opportunity to capture atmospheric carbon is called foregone sequestration. However, this type of land-allocation change would not occur under the *BT16* scenarios because of modeling constraints placed upon POLYSYS and ForSEAM as described in volume 1 that preclude the exchange of land between forestry and agriculture.

The types of land allocation changes that are simulated in the *BT16* scenarios – land use shifts within the agricultural sector - are not likely to cause significant changes in aboveground carbon. The primary land cover types in the POLYSYS 2015 start year prior to transition are cropland and pastureland. In the case of agricultural land, crops are harvested annually, and there is not a significant carbon stock on the land to be lost. Similarly, pastureland undergoes an annual cycle in the amount of biomass because significant portions of aboveground biomass are lost due to grazing, fire, and natural death. There is no foregone sequestration in either case because there is little stable, existing carbon stock on the land to continue to build as is the case in forests. Therefore, the only significant change in aboveground carbon stock is the loss of any initial carbon stock, which could be amortized over the period of study, which in this case is 25 years. One interesting case is the conversion of pastureland or cropland to the production of short-rotation woody crops. In this situation, the aboveground carbon stock is likely built over time as the woody crop sequesters carbon, but this sequestration is much shorter-lived than it would be for tree species with longer rotation lengths.

It is important to note that the two challenges that impact the estimation of SOC changes would affect the estimation of aboveground carbon changes if it were undertaken in this analysis. The first challenge of not knowing the land-use history prior to 2015 precludes knowledge of the aboveground carbon stock at the time of the change in land allocation. Furthermore, the absence of dynamic POLYSYS output regarding the progression of what is planted on any given sub-county parcel of land over time translates into a lack of information regarding how carbon stocks change on that parcel of land.

4.2.4 Representative Bioeconomy Cases

The analysis presented in this chapter is limited to the system boundary in figure 4.1, which ends after feedstock logistics and transportation. This system boundary does not enable analysis of the extent to which using biomass feedstocks for fuel, power, and chemicals offers a potential GHG benefit on a life-cycle basis relative to using fossil-derived feedstocks. Investigating this question requires evaluation of cases that specify the end uses of the biomass produced. To address this question, this chapter references an analysis undertaken by Rogers et al. (2016) to assess the size and benefits of a Billion-Ton Bioeconomy (BTB). The intent of assessing the GHG and energy impacts of the BTB cases is to provide the full life-cycle GHG and energy impacts of using the amount of biomass produced in the *BT16* scenarios.

For the purposes of the BTB analysis, the "bioeconomy" describes the integral role of abundant, sustainable, and domestically produced biomass (agriculture and forestry-derived) in producing biofuels, generating bioheat and power, and producing renewable chemicals and other bio-based compounds to grow the U.S. economy. It is important to note that although Rogers et al. (2016) considered several cases for biomass end uses including a base case, and cases in which ethanol, jet fuel, biopower, and bioproducts were prioritized for biomass use, the biomass produced could be used for any number of purposes. Furthermore, the analysis did not consider indirect effects or overall demand associated with price changes of biomass and fossil based feedstocks. The BTB analysis adopted two levels of biomass availability in the year 2030 based on the low- and high-yield *BT16* scenarios for that year.

To estimate GHG emissions and energy benefits associated with the BTB cases, a tool called Bioeconomy Air and Greenhouse Gas Emissions (AGE) was developed to estimate the energy, air quality, and GHG impacts of the bioeconomy cases as compared to an "all fossil" baseline case (Rogers et al. 2016). AGE includes *BT16* and BAU parameters for biofuels, conventional fuels, biopower, and biochemicals. The AGE tool allocates biomass by feedstock type to production of different types of biofuels, bioproducts, biopower, and steam. The AGE tool estimates the production amounts of biofuels, bioproducts, biopower, and steam using conversion factors or yield assumptions from specific biomass feedstock types to end products and calculates the amounts of conventional fuels, products, power, and steam that are displaced. AGE calculates the total energy consumption, GHG emissions, and air pollutant emissions in each scenario and its respective "all fossil" scenario on the basis of life-cycle GHG emissions and energy consumption for conventional fuels, biofuels, biopower, conventional power, biochemicals, and conventional chemicals generated by GREET. Using GREET as an AGE parameter source ensures a consistent basis for analysis of biofuels, conventional fuels, and other end products with the rest of the *BT16* GHG analysis. In this application of Bioeconomy AGE to the *BT16* analysis, the feedstock GHG emissions as presented in the above section are used to override GREET default values in Bioeconomy AGE to estimate the life-cycle GHG emissions of biofuels, bioproducts, biopower, and steam derived from various feedstocks in *BT16*. The total biomass tonnage by biomass type used for these scenarios is only the biomass delivered to the reactor throat at less than $100 per dry ton. However, the GHG emissions for the production of all biomass available from *BT16* volume 1 is used, even if their logistics is too cost prohibitive for delivery to the reactor throat.

4.3 Results

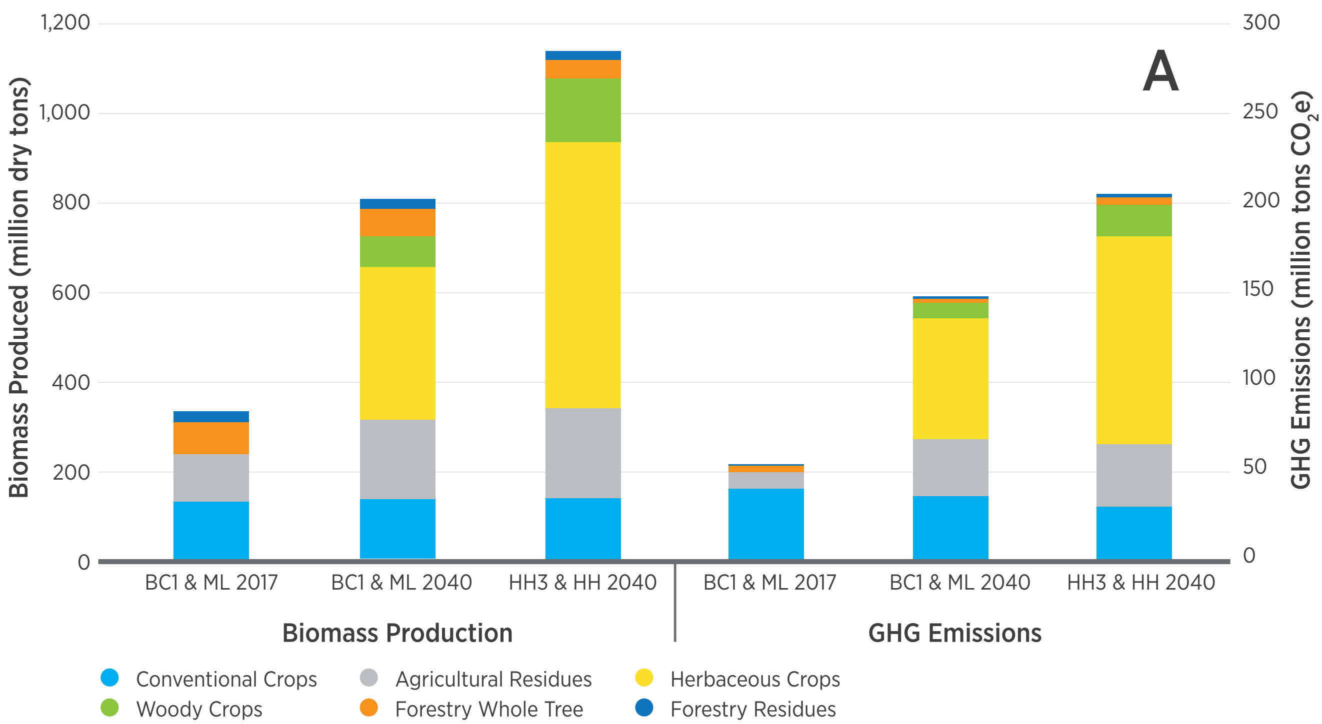
Results are presented in three sections. First, energy consumption and GHG emissions associated with forestry and agricultural operations are described. Next, section 4.3.2 describes SOC changes at a county level associated with changes in land allocation in the agricultural sector based on the POLYSYS modeling in volume 1. Finally, section 4.3.3 combines operational and SOC change-related GHG emissions to describe at a county level the net GHG emissions associated with the 2040 base-case and high-yield scenarios developed in volume 1.

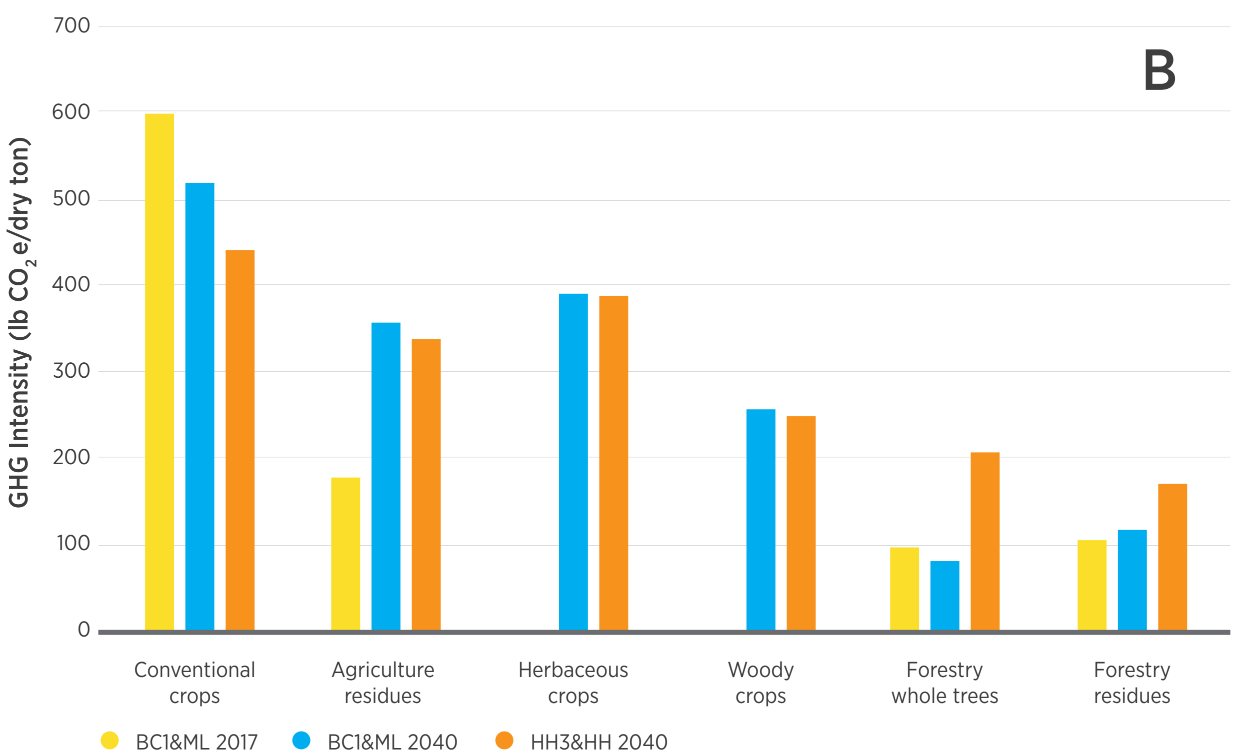
4.3.1 Energy Consumption and GHG Emissions Associated with Forestry and Agricultural Operations and Logistics

Figure 4.8A displays the breakdown of biomass produced nationwide and associated GHG emissions under the BC1&ML 2017, BC1&ML 2040, and HH3&HH 2040 scenarios. On the national scale, the GHG intensity (GHG emissions divided by the total produced biomass) is 331, 364, and 359 lb CO_2e per dry ton of total biomass, for the BC1&ML 2017, BC1&ML 2040, and HH3&HH 2040 scenarios, respectively. The GHG intensity is lower under the high-yield scenario in 2040 compared to the base-case scenario in 2040 because feedstock yields in the HH3&HH 2040 scenario are higher while some of the agricultural inputs per acre stay constant (e.g., fertilizer application rate or diesel consumption in harvesting).

Figure 4.8*B* provides the GHG intensity for producing each feedstock type for all three scenarios. Conventional crops have a higher GHG emissions intensity than all other feedstocks, which decreases between the 2017 and 2040 scenarios because yields increase. The herbaceous crops' GHG emissions intensities only slightly decrease between the base-case and high-yield 2040 scenarios, (392 compared with 390 lb CO_2e per dry ton) because most of the inputs for these feedstocks are applied on a per dry ton of biomass harvested and are not affected by higher yields in the HH3 2040 scenario. Woody crops see the same trend, with intensities of 258 lb and 250 lb CO_2e per dry ton for the base-case and high-yield 2040 scenarios, respectively. The contribution of agricultural residues to potential biomass produced in 2017 is higher than the contribution of this feedstock type to GHG emissions (fig 4.8A). In the 2040 scenarios, however, shares of total biomass tonnage and GHG emissions contributed by agricultural residues are roughly equal. This increased intensity is caused by a shift from conventional logistics in 2017 to advanced logistics in 2040. Advanced logistics, used to pelletize biomass at a regional depot, consume more energy than conventional logistics per ton of biomass. See *BT16* volume 1, chapter 6, for a full discussion of logistics operations in 2017 as compared to 2040. A summary of logistics modeling assumptions is provided in chapter 2 of this volume.

Figure 4.8 | Potential biomass production and GHG emissions (all production emissions and only feasible logistics emissions) (A) and GHG intensity (B) by crop type. Conventional crops (e.g., corn and soybeans), agricultural residues (e.g., corn stover, wheat straw, oat straw, sorghum stubble, and barley straw), herbaceous crops (e.g., switchgrass, miscanthus, energy cane, and biomass sorghum), woody crops (e.g., poplar, willow, loblolly pine, and eucalyptus), and forest biomass (e.g., hardwoods, softwoods, mixed woods) are included.





Forestry whole tree biomass has a lower share of GHG emissions than does agricultural biomass. The GHG intensities for the production of forestry biomass are lower than other crops because not all forestry plots are subject to site preparation, which consumes diesel fuel, and because fertilizers are either not used or are used more sparingly than they are for agricultural crops. On a per-dry-ton basis, logistics operations and corresponding emissions are roughly equivalent between whole-tree feedstocks and non-crop agricultural feedstocks and are not a reason for differing GHG intensities of forest-derived and agricultural feedstocks. One difference regarding forestry whole-tree biomass is that the GHG-emission intensity is lower for the BC1&ML 2040 scenario compared to the BC1&ML 2017 scenario, which is due to the logistics stipulation leaving any biomass with a delivered cost of more than $100 per dry ton on the field. There are more instances of biomass left on the field for the 2040 base-case scenario compared with the 2017, and as a result, the energy-intensive GHG emissions of advanced logistics are not included for this biomass. Overall, this analysis finds that forest residues are a minor contributor both to biomass tonnage and GHG emissions.

Figure 4.9 displays the breakdown of total potential biomass production and GHG emissions from producing the biomass associated with *BT16* scenarios BC1&ML 2017 by FRR (regions depicted in fig 4.10) in the BC1&ML 2017 scenario. In nearly every FRR, GHG emissions are dominated by conventional crops. FRR 7, the heart of corn and soy production in the United States, could potentially have the highest level of GHG emissions GHGs compared to other FRRs. The FRR that exhibits the second-highest modeled GHG emissions is in the North Central United States (FRR 9). FRRs 4 and 10–13, which have whole trees as the dominant feedstock type, would not be significant contributors to national GHG emissions from biomass production. In 2017 scenarios, herbaceous crops and forestry crops do not contribute to GHG emissions in any FRR, as they are not yet produced.

In the BC1&ML 2040 scenario (fig 4.11), the contribution of herbaceous crops and residues rise, compared to the 2017 scenario, especially in the Central Plains, including a large part of Texas (FRRs 7 and 8). FRR 5—which includes Tennessee, Kentucky, and West Virginia—also exhibits notable GHG emissions from herbaceous crop production. On the other hand, the western United States sees little biomass production and, correspondingly, low GHG emissions associated with biomass production in the BC1&ML 2040 scenario.

In the HH3&HH 2040 scenario (fig 4.12), the main FRRs contributing to GHG emissions do not change, but emissions associated with producing herbaceous crops and agricultural residues experience the most significant increases in FRRs 7 and 8. It is increased production of these energy grasses that, in fact, drive increased emissions between BC1&ML and HH3&HH scenarios for 2040.

The estimated GHG intensity of producing each feedstock for all three scenarios (not including transportation emissions) is presented in figure 4.13. Annual crops, corn and especially soybeans, would have much higher GHG emissions per dry ton than the crop residues regardless of yield scenarios. This is mainly a result of agriculture diesel and fertilizer consumption. For conventional crops, diesel and fertilizers are needed for soil preparation, planting, and harvesting, while using agriculture residues as biomass results in limited fuel consumption for residue collection and fertilizer consumption only to replace the nutrients lost due to residue removal.

For herbaceous and woody crops, estimated GHG intensities fall mostly below 200,000 g-CO_2e per dry ton, although willow and poplar in the BC1 2040 scenario (fig 4.13B) have larger variations in GHG intensity than other biomass types. For these two feedstocks, the fertilizer and diesel inputs are based

Figure 4.9 | Estimated total GHG emissions (A) and biomass production (B) in each FRR by crop type for BC1&ML 2017. Conventional crops (e.g., corn and soybeans), agricultural residues (e.g., corn stover, wheat straw, oat straw, sorghum stubble, and barley straw), herbaceous crops (e.g., switchgrass, miscanthus, energy cane, and biomass sorghum), woody crops (e.g., poplar, willow, loblolly pine, and eucalyptus), and forest biomass (e.g., hardwoods, softwoods, mixed woods) are included.

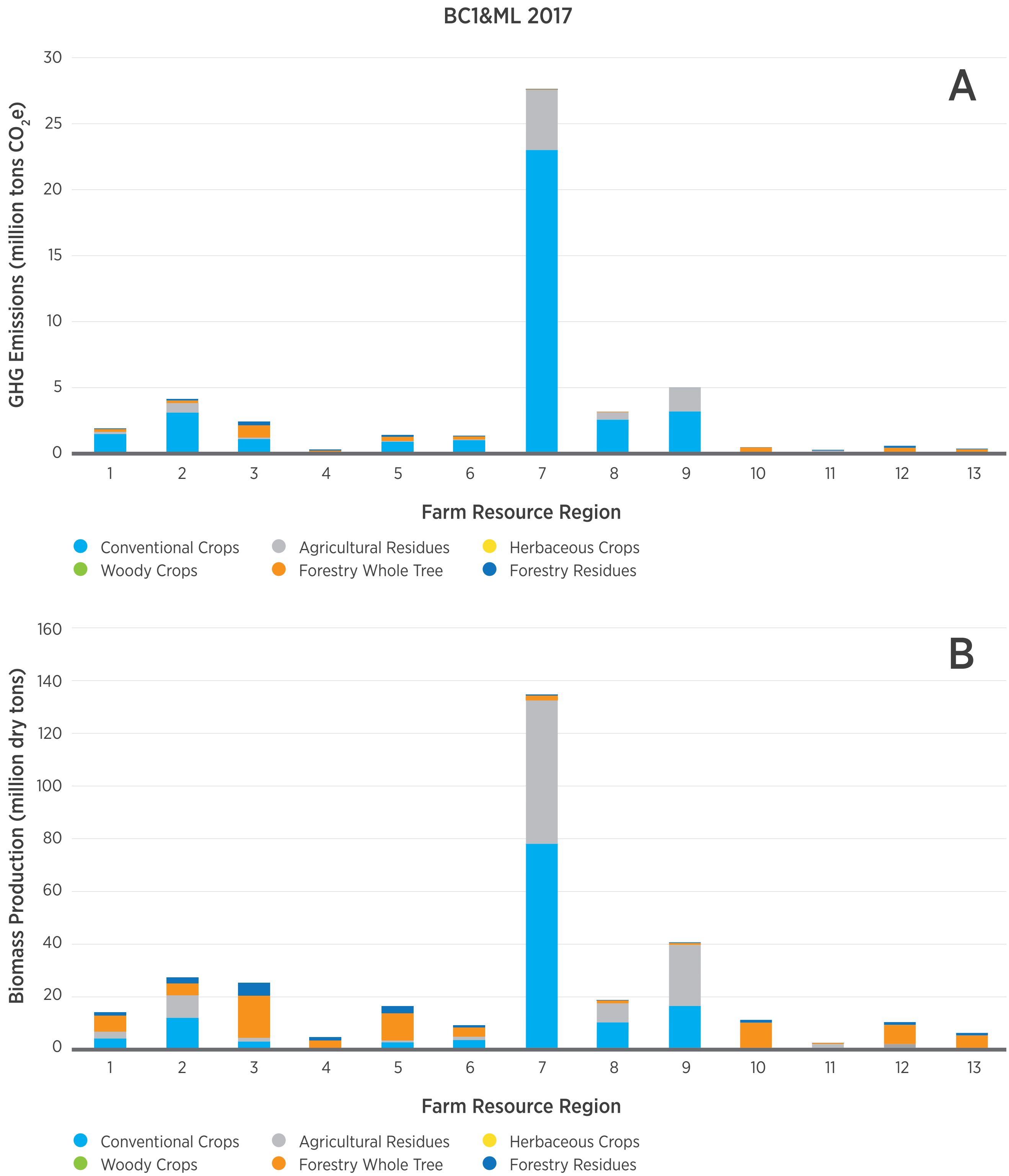
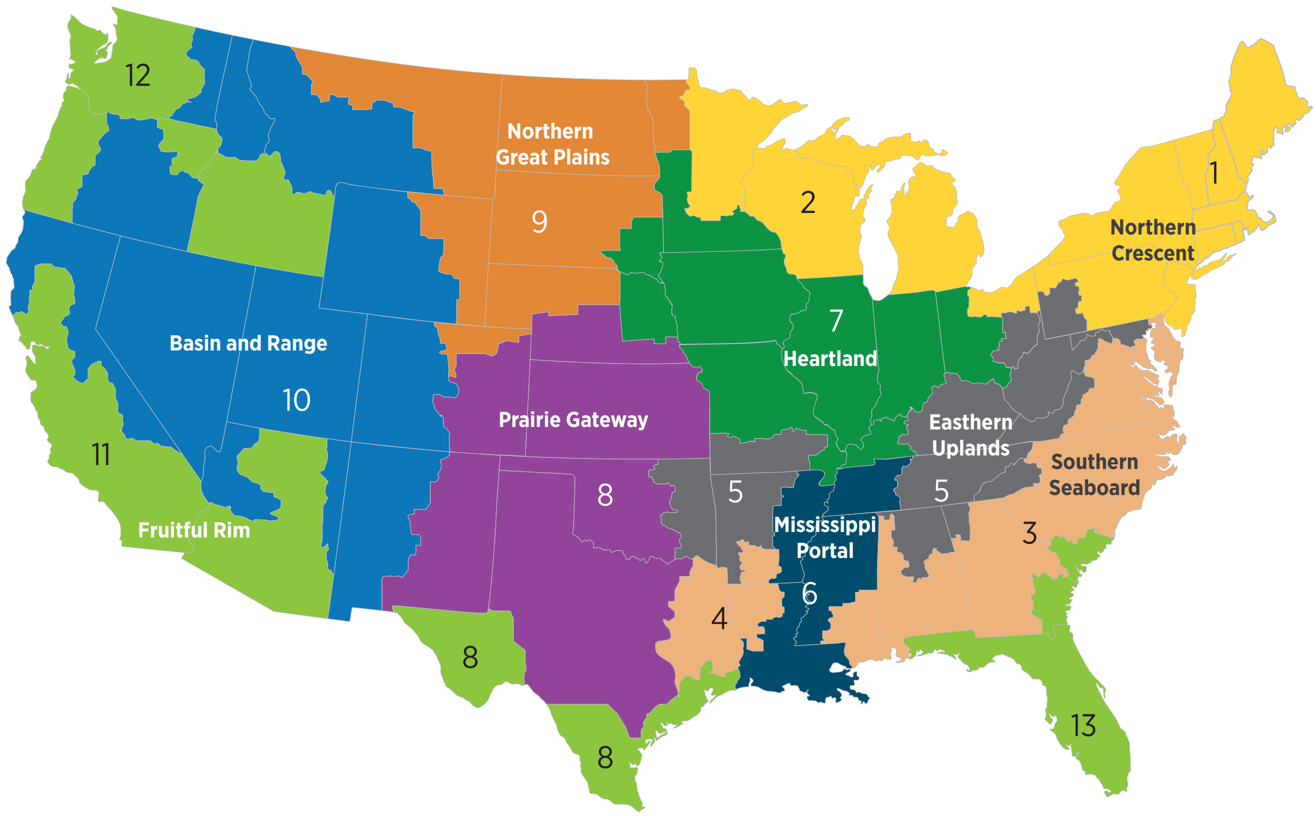


Figure 4.10 | USDA Farm Resource Regions



on planted acres which, in some instances, greatly exceed the harvested acres. For example, in Lincoln County, Colorado, more than 23,000 acres would be planted in poplar, but only 2,300 of those acres are harvested because not all acres had reached the end of the rotation. GHG emissions reported herein include diesel and fertilizer consumption for planted acres. In counties such as Lincoln County, Colorado, with a low harvested-to-planted acres ratio, GHG intensity would therefore be high. Another factor influencing GHG intensity is biomass yield, in large part because, as described, some FRR budgets report fertilizer and fuel inputs on a per-acre basis. When yields are high, GHG intensities are lower compared to counties with lower yields. For poplar in the BC1 2040 scenario (fig 4.13*B*), the county-level harvested yields range from 17–67 dry tons per acre in that year, while in the HH3 2040 scenario (fig 4.13*C*) the harvested yields range from 19–89 dry tons per acre. The states with the highest harvested poplar yields include Georgia, Indiana, and Kentucky. In both the BC1 and HH3 2040 scenarios, Harlan County, Kentucky, has the highest harvested poplar yield at 67 and 89 dry tons per acre, respectively. However, in the BC1 2040 and HH3 2040 scenarios, respectively, Harlan County, Kentucky, contributes only 390 and 510 dry tons of poplar biomass. As a result, the relatively low GHG intensity of potentially producing poplar in these counties is not a major driver of GHG results. In fact, the bulk of poplar production in the 2040 scenarios comes from counties with GHG intensities for poplar production that fall toward median GHG intensities for producing this type of biomass.

Figure 4.11 | Estimated total GHG emissions (A) and biomass production (B) in each FRR by crop type for the BC1&ML 2040 scenario. Conventional crops (e.g., corn and soybeans), agricultural residues (e.g., corn stover, wheat straw, oat straw, sorghum stubble, and barley straw), herbaceous crops (e.g., switchgrass, miscanthus, energy cane, biomass sorghum), woody crops (e.g., poplar, willow, loblolly pine, and eucalyptus), and forest biomass (e.g., hardwoods, softwoods, and mixed woods) are included.

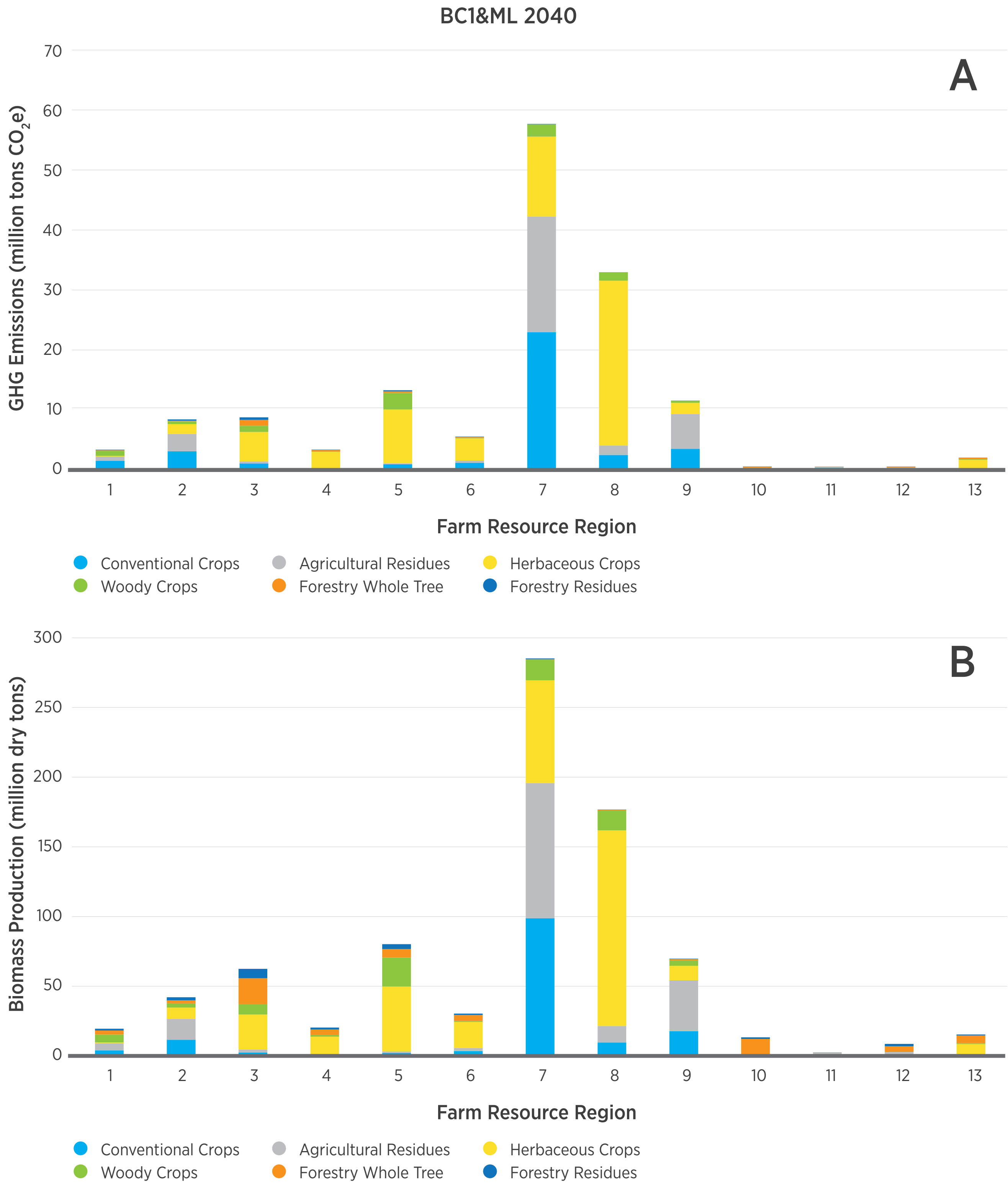


Figure 4.12 | Estimated total GHG emissions (A) and biomass production (B) in each FRR by crop type for the HH3&HH 2040 scenario. Conventional crops (e.g., corn and soybeans), agricultural residues (e.g., corn stover, wheat straw, oat straw, sorghum stubble, and barley straw), herbaceous crops (e.g., switchgrass, miscanthus, energy cane, and biomass sorghum), woody crops (e.g., poplar, willow, loblolly pine, and eucalyptus), and forest biomass (e.g., hardwoods, softwoods, and mixed woods) are included.

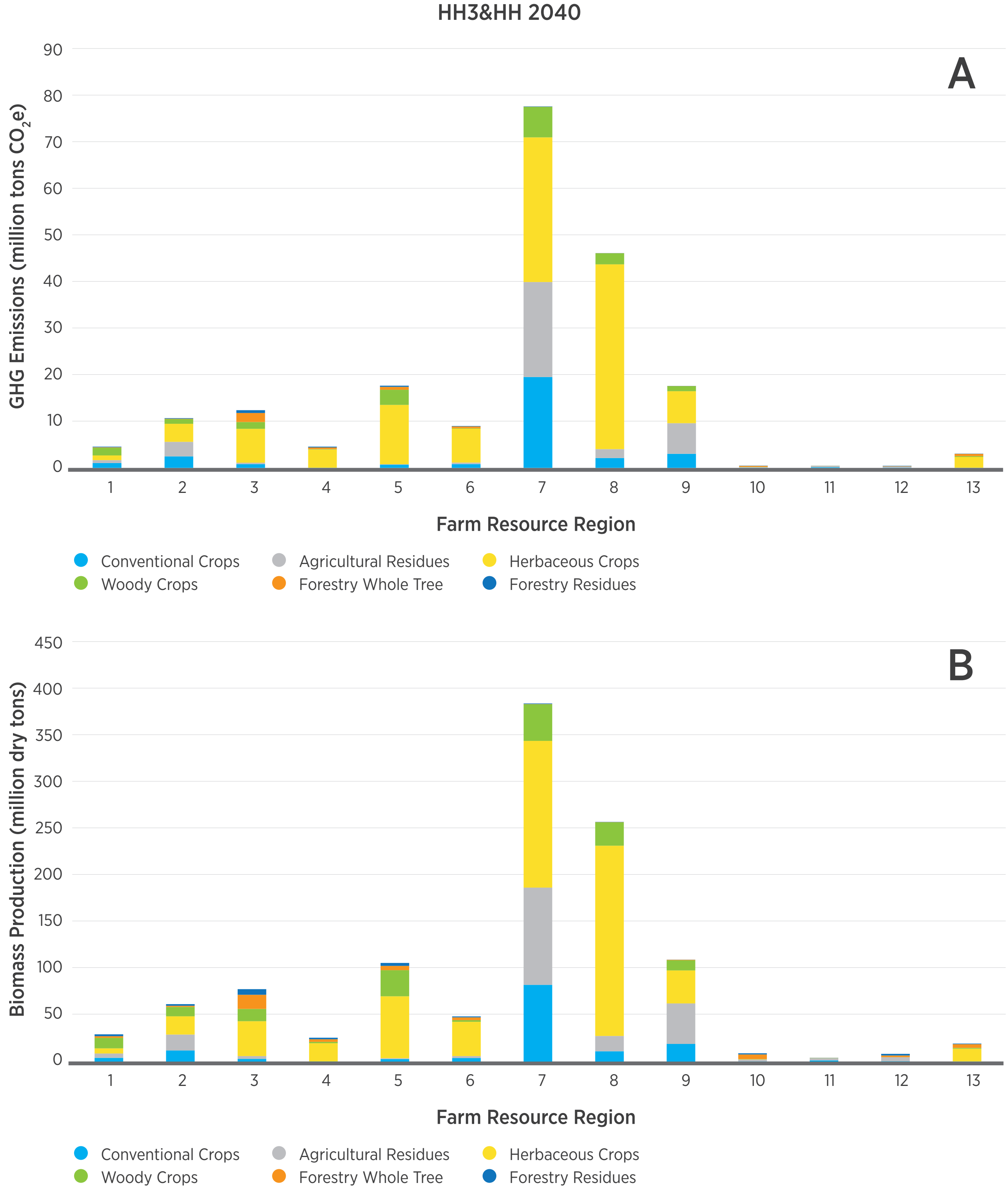


Figure 4.13 | Estimated intensity of GHG emissions-associated agricultural activities, including operations and logistics, under three scenarios. (A) BC1 2017, (B) BC1 2040, and (C) HH3 2040. Herbaceous and woody energy crops are not available in 2017 (a). In the boxplot: the box limits indicate the 25th and 75th percentiles, center line shows the median, whiskers are 1.5 times the interquartile range, and the box width is proportional to square-root of the number of observations. The number "1" denotes crop grain (for annual crops) or tree (for wood), and "2" denotes crop or tree residues.

Acronyms: COR – corn; SOY – soybeans; BAR – barley; OAT – oat; SOR – sorghum; WHE – wheat; BIO – biomass sorghum; ENE – energy cane; MIS – miscanthus; SWI – switchgrass; EUC – eucalyptus; PIN – pine; POP – poplar; WIL – willow; HLO – hardwood lowland; HUP – hardwood upland; MIX – mixed wood; SNA – softwood natural; and SPL – softwood planted.

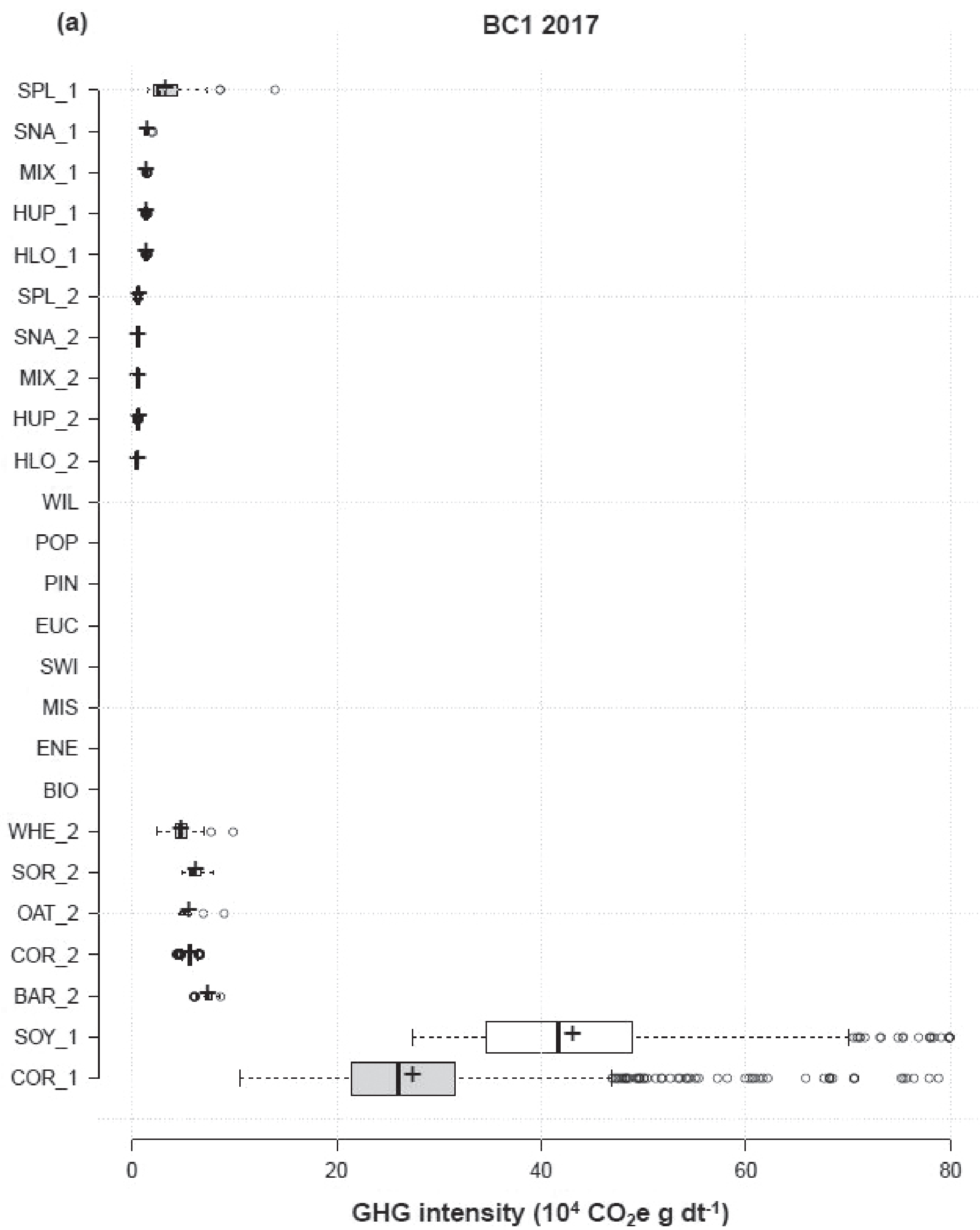


Figure 4.13 | *continued*

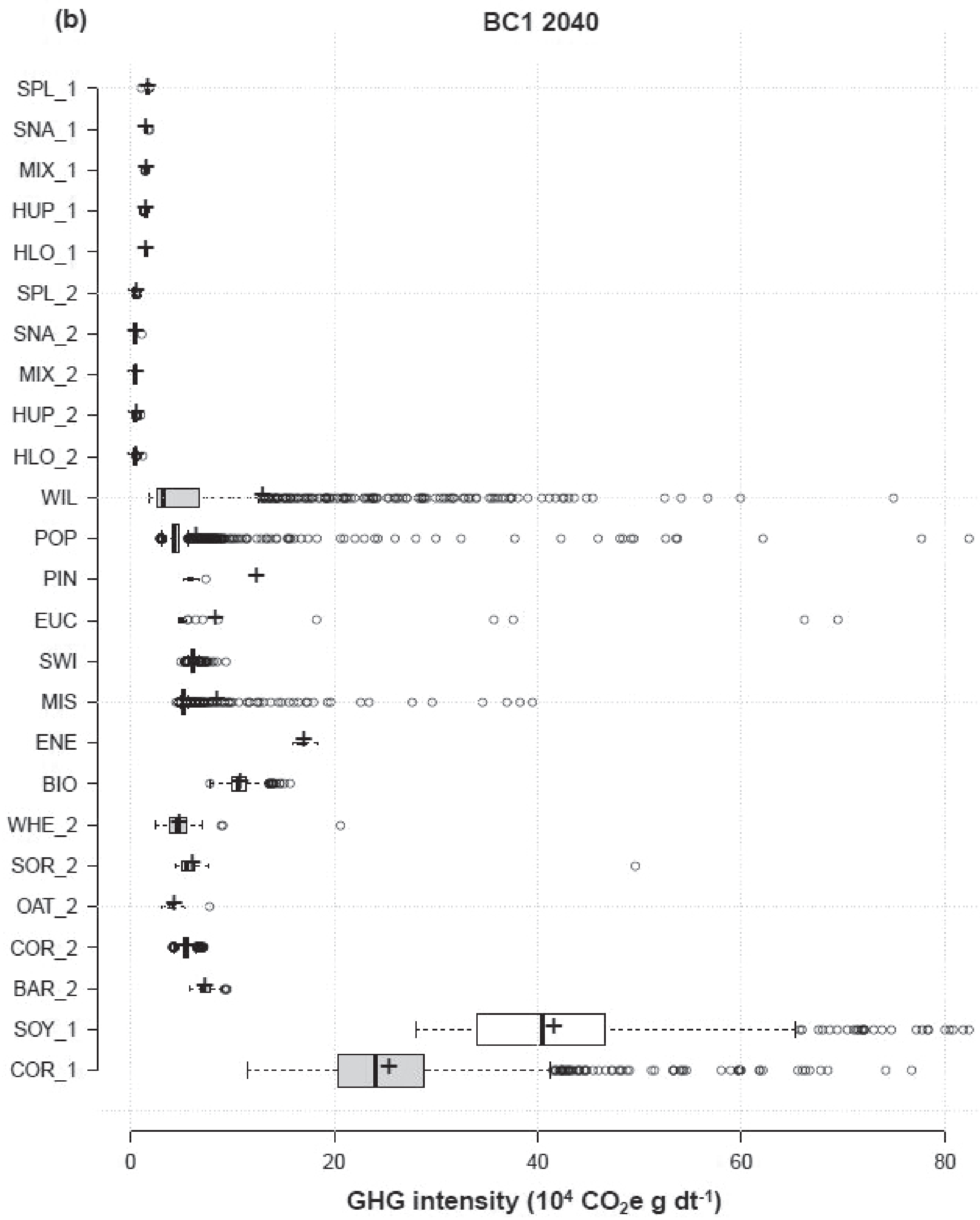
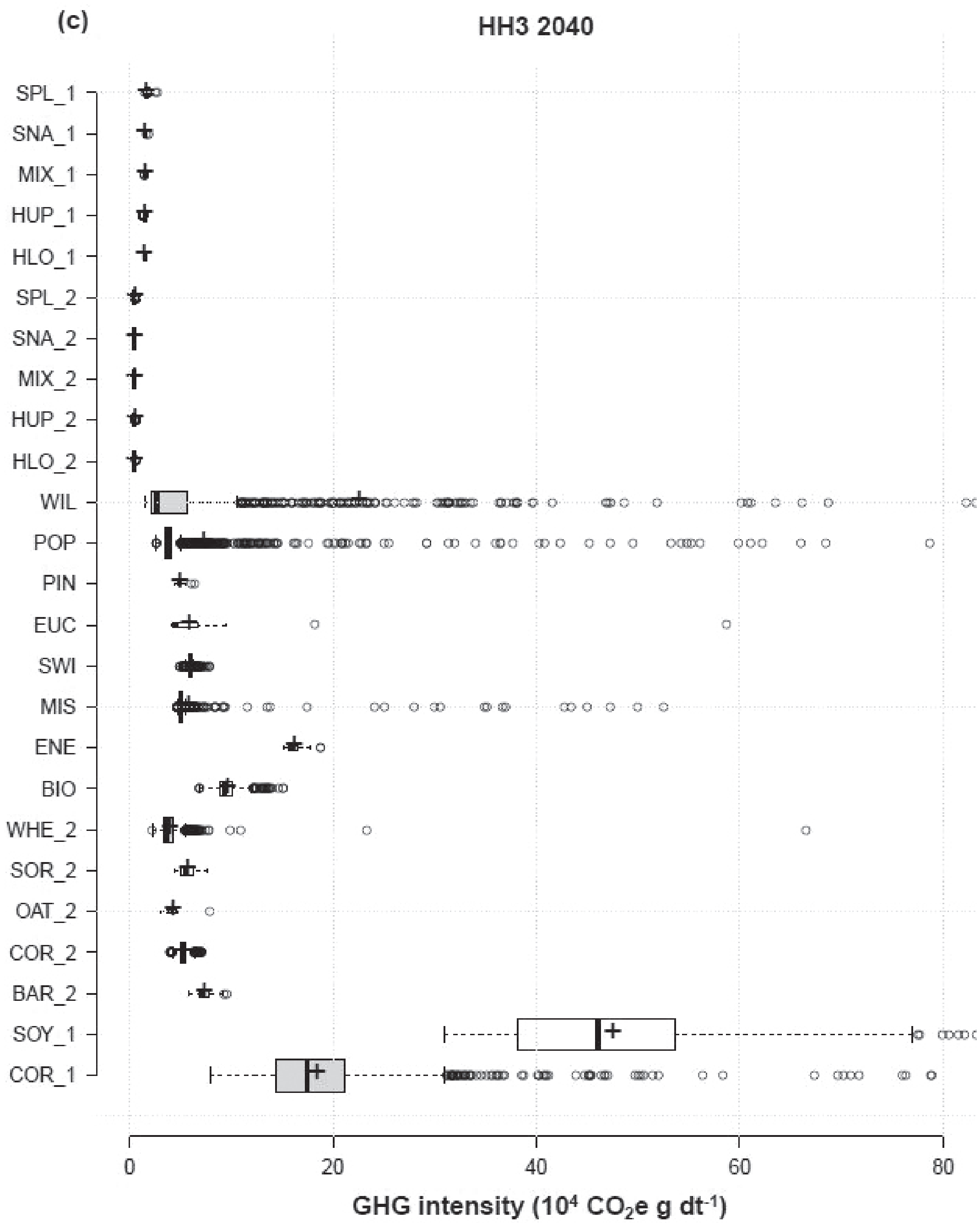


Figure 4.13 | *continued*



In the BC1 2040 scenario (fig 4.13*B*), the harvested yields for willow are slightly less variable than for poplar, ranging between 10–36 dry tons per acre. Potential willow yields also exhibit less variation than poplar yields (10–45 dry tons per acre) in the HH3 2040 scenario (fig 4.13*C*). Switchgrass harvested yields range from 1.1–9.8 dry tons per acre in the BC1 2040 scenario and from 1.2–14.1 dry tons per acre in the HH3 2040 scenario. It should be noted that these harvested yields are lower than those for poplar and willow because switchgrass is harvested every year while poplar and willow are harvested every 4 and 8 years, respectively. The GHG-intensity range for switchgrass (fig 4.13 *B* and *C*) is smaller than the range for the short-rotation woody crops (SRWCs) both because of this narrower yield range and because a good portion of fertilizer consumption for willow is independent of yield (applied on a per-dry-ton basis). In short, when agricultural inputs are yield-dependent, the variation in potential biomass yield seen in different counties across the United States has a significant influence on the range of GHG intensities for any one type of biomass.

For forestry-derived biomass, the diesel that would be consumed during harvesting and collection is the main contributor to GHG emissions. The GHG intensity for forestry residues ranges between 5,200 and 6,400 g-CO_2e per dry ton for all three scenarios (fig 4.13 *A*, *B*, and *C*). The only input for residues is fuel, which is used on a per-dry-ton basis. Some variation by location is based on the type of equipment used (medium versus large chipper, and small versus medium loader). For whole-tree harvesting, the simulated GHG intensity ranges from 14,000–15,000 g-CO_2e per dry ton. However, for the softwood planted whole trees, additional fuel would be consumed, and fertilizer is applied during site preparation, which could result in GHG intensities as high as 415,000 g-CO_2e per dry ton. For the softwood-planted biomass types, especially under the ML 2017 scenario (fig. 4.13A), there is a much larger variation in the GHG emissions per-dry-ton values because of significant variation in the quantity of biomass harvested per acre. Again, the same amount of fertilizer and chemicals are consumed per acre regardless of yield in each county, so counties with high harvested biomass per acre see less-GHG-intensive softwood biomass. If production per acre is low, GHG intensities run higher. Both the ML and HH 2040 scenarios have some counties with small amounts of biomass harvested per acre, but not to the same degree as ML 2017. Again, changes in aboveground biomass for forestry-derived feedstocks were not considered because the amount of forested land did not change, given restrictions placed on transitions between agricultural and forested lands in volume 1. If the amount of forested land did change or significant changes in forest management practices occur, this would result in changes in above ground carbon, and additional considerations inherent to temporal forest carbon analyses would need to be adopted into the analysis. These considerations, which include the spatial scale and the timing of emissions pulses, are described in detail in Lamers (2013), EPA (2014), and Daystar (2016) among other references.

4.3.2 GHG Emissions from SOC Changes on Agricultural Lands

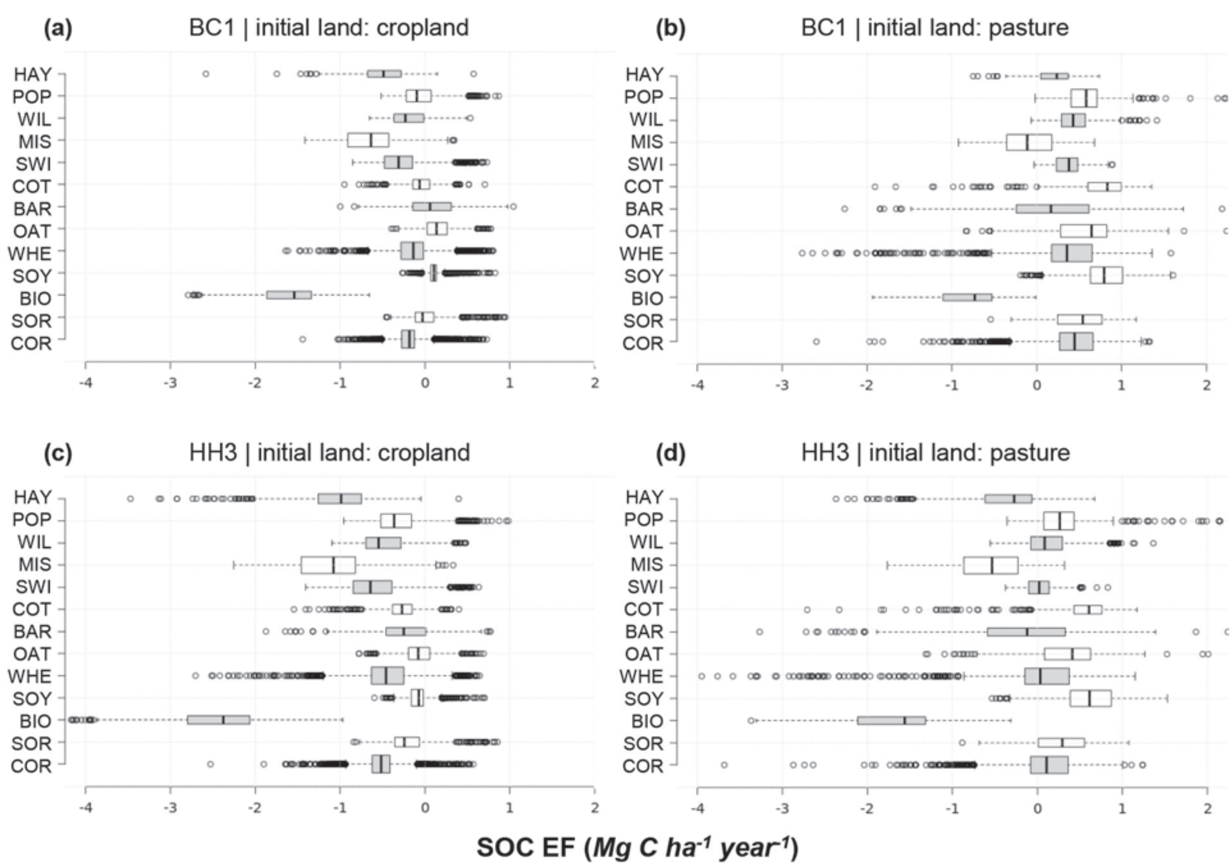
According to POLYSYS simulations, the area of land that would be allocated to different uses in 2040 as compared to 2015 totals about 41 and 50 Million hectares (Mha) under BC1 and HH3 scenarios, respectively. Overall, cropland and pasture areas would decline, while areas planted in major energy crops would expand on net (chapter 3). Most of the land producing major energy crops in 2040 scenarios is either pasture or one of the three major cropland types of corn, soybeans, or wheat. Under the 2040 BC1 scenario, these land types are mainly allocated to switchgrass (27%) and miscanthus (20%); corn and poplar each share about 9% of the total amount of transitioned land. However, under the HH3 scenario, crop management on half of these lands would be altered to grow miscanthus (30%) and switchgrass

(19%), and another 19% to poplar (10%) and willow (9%). Regardless of the scenarios, only a very small amount (less than 0.2% each) of the lands would be planted in eucalyptus, pine, or energy cane. Barley, oats, rice, and hay each share less than 1% of the total land converted. Note again that POLYSYS contains a land category termed "idle" that is used as a pool to balance total land-use transitions. This analysis assumes land transitioning into and out of this category—a sizeable quantity—does not experience SOC change because it is not a land category in practice, and therefore, it is very difficult to establish a reasonable land-use history to inform SOC modeling.

The estimated SOC change varies spatially and among different land transitions. In general, when cropland represents the initial 2015 land allocation, SOC EFs are lower than when pasture represents the initial land allocation (fig 4.14). On average, growing energy crops on historical cropland typically leads to soil carbon gains (fig 4.14*A* and *C*). When pasture is used to produce biomass, however, only a few energy crops such as miscanthus and biomass sorghum, which both have high biomass yields, are estimated to sequester carbon in soil (fig 4.14*B* and *D*). Biomass yield is a key factor in determining the SOC balance. Often, high yield means more biomass can

Figure 4.14 | Soil organic carbon EFs for lands transitioned from initial 2015 cropland or pastureland to land with different crop types under BC1 and HH3 2040 scenarios. In the box plot, the box limits indicate the 25th and 75th percentiles, the center line shows the median, the whiskers are 1.5 times the interquartile range, and the box width is proportional to the square root of the number of observations. A positive value indicates SOC loss while a negative value indicates SOC gain.

Acronyms: COR – corn; SOR – sorghum; BIO – biomass sorghum; SOY – soybeans; WHE – wheat; OAT – oats; BAR – barley; COT – cotton; SWI – switchgrass; MIS – miscanthus; WIL – willow; POP – poplar; and HAY– hay.



be returned to the soil, which adds soil organic matter. Yield is also one of the most important determinants affecting the differences between emissions in BC1 and HH3 scenarios (fig. 4.14*A* compared to fig. 4.14*C* and fig. 4.14*B* compared to fig. 4.14*D*). However, it should be noted that, besides land-transition types and yield, many factors contribute to SOC dynamics, including spatially specific climate and soil conditions, and agricultural management practices. This is partly the reason why the SOC EFs vary spatially even under the same land-transition type. For instance, residue return is a common practice in the United States; however, the estimated return rate, the proportion of biomass residue that is returned to soil, differs from county to county, depending on modeling constraints applied in POLYSYS to limit soil erosion and maintain soil quality in general (chapter 4 in *BT16* volume 1). Therefore, in some cases, especially for land that is allocated to conventional crop production, EFs can vary significantly because residue return amounts vary even though the crop yield is relatively stable across the nation (fig. 4.14). For example, the estimated return rate varies from 10%–100% for barley straw and 20%–100% for corn stover and wheat straw (100% means full return). Return rates in the *BT16* analysis are determined through specific POLYSYS modeling for *BT16* scenarios as described in volume 1. Additionally, for crops that are not widely grown for biomass (e.g., biomass sorghum or barley) or are not significantly affected by land transitions (e.g., hay), based on POLYSYS output, we estimated SOC EFs for only a limited number of counties. EFs for these crops could therefore exhibit a wider range than others (fig. 4.14).

With POLYSYS-estimated land transitions and model-derived estimates of SOC changes in the scenarios, GHG emissions stemming from SOC changes at the county level are calculated on both a per-dry-ton feedstock basis (fig 4.15*A*–*C*) and in total for each county (fig. 4.15*D*–*F*). The results indicate that for the BC1 scenario (fig. 4.15*A* and 4.15*B*), the Midwest and the southeastern coast have significant potential for SOC gains and, correspondingly negative GHG emissions per mass of dry ton feedstock. The highest GHG emissions sink for BC1, occur in the Midwest for 2017 (fig. 4.15*D*) and eastern Kansas, northern Missouri, and southern Illinois for 2040 (fig 4.15*E*). Significant SOC losses that translate into high GHG emissions are more dominant in the BC1 scenario with its lower yields and occur mostly in the South. Notable hotspots that could experience significant SOC losses from feedstock production are several counties in North Dakota, Montana, and Colorado for the BC1 2017 scenario; these hotspots are focused in Oklahoma, eastern Texas, and western Arkansas for the BC1 2040 scenario (fig. 4.15*C*). As biomass yields are highest in the 2040 HH3 scenario, SOC losses are less severe and SOC gains are more significant in this scenario than in the BC1 2040 scenario. Texas, the Midwest, and the East Coast have the highest potential to act as GHG sinks on a per-dry-ton feedstock basis. Counties with the greatest SOC gains overall, and therefore the highest negative GHG emissions, are in the Midwest and South, most notably in central Texas. (fig. 4.15*F*).

The SOC-related GHG emissions are directly driven by the area of land in a county that changes in allocation from one use to another (based on POLYSYS output) and the corresponding SOC change for that allocation shift (derived from SCSOC). This analysis suggests that the areas with the greatest potential for SOC gains in 2040 are significant miscanthus producers, including counties in Illinois, Indiana, Iowa, Kansas, and Missouri (fig. 4.15*E* and 4.15*F*). Biomass sorghum has great SOC-sequestration potential, but its planting area is limited, and its contribution to SOC increases in the national landscape as conceived in this study is not significant compared with miscanthus (fig. 4.14).

A primary reason for SOC-related GHG-emission hotspots in the scenarios is the transition of pastures to crops that deplete soil carbon. Under BC1 scenarios, the use of permanent pasture to produce energy crops, especially switchgrass and poplar, caused significant SOC-related GHG emissions in counties in Texas and Oklahoma (fig. 4.15*D* and 4.15*E*). Results for California, in particular, illustrated that several counties could exhibit high GHG intensities under this scenario (fig. 4.15*A–C*). In addition to transitions from pasture to poplar that cause SOC loss, crop-residue removal (e.g., corn stover or barley straw) contributed significantly to GHG emissions. For locations that do not grow dedicated energy crops, residue removal could be one of the biggest factors contributing to overall GHG emissions. For instance, removing straws of wheat, oat, and barley, which reduces SOC, is one of the reasons why many Montana counties show GHG emissions as a result of soil carbon changes in scenarios (fig. 4.15). These results suggest the importance of further developing strategies that can mitigate GHG emissions from declining soil carbon levels including manure application and cover crop adoption (Qin et al. 2015).

At the national level, the total SOC-related GHG emissions are negative for all three scenarios (BC1 2017, BC1 2040, and HH3 2040) (fig. 4.15*D–F*), which suggests that land shifts overall result in a net SOC sink. For BC1 2017 and BC1 2040, the size of the sink is 3.0×10^{12} g CO_2e and 3.9×10^{12} g CO_2e, respectively. HH3 2040, however, has a much larger sink with 89.8×10^{12} g CO_2e.

4.3.3 Spatial GHG Emissions Including Agricultural and Forestry Operations, Logistics and Preprocessing, and SOC Changes

Figure 4.16 and Figure 4.17 present the spatially explicit GHG intensities and total GHG emissions, respectively, associated with potential agricultural and forestry biomass production from the scenarios. Agricultural GHG emissions include estimates

Figure 4.15 | County-level SOC change-induced GHG intensity and total GHG emissions associated with potential biomass production from the agriculture sector under 2017 and 2040 BC1, and 2040 HH3 scenarios, compared to a 2015 reference.

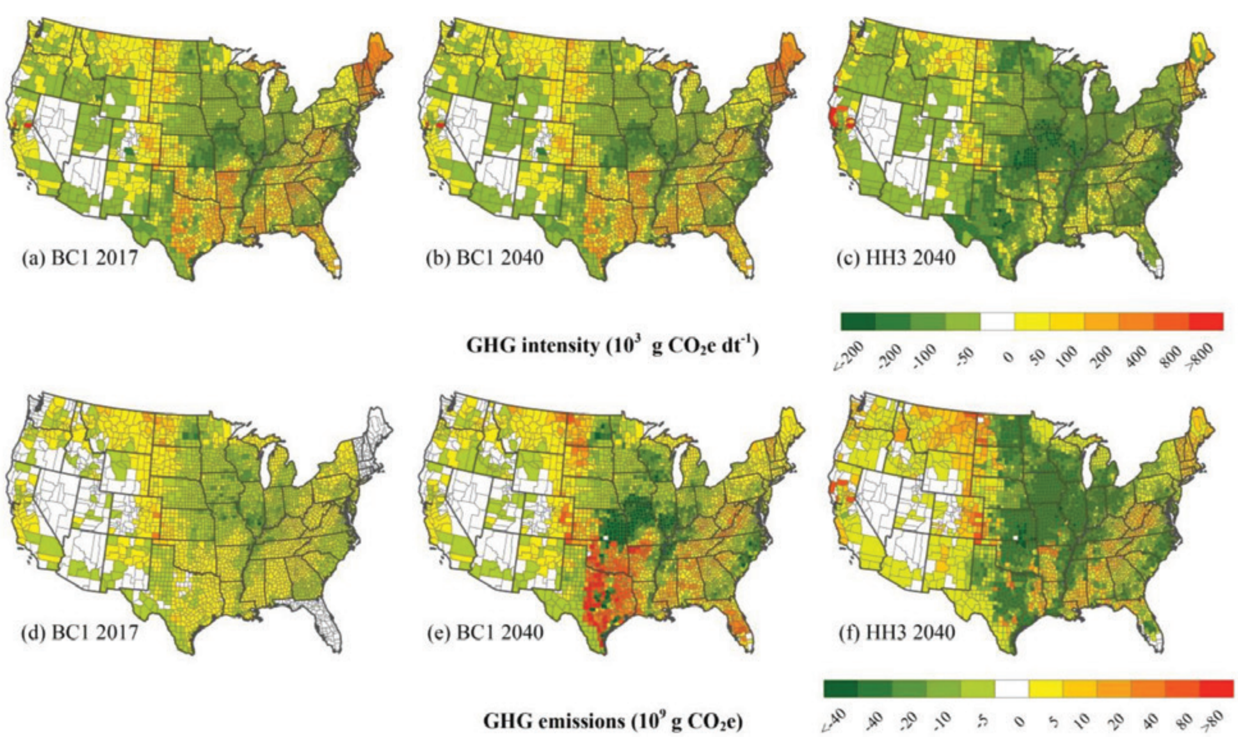
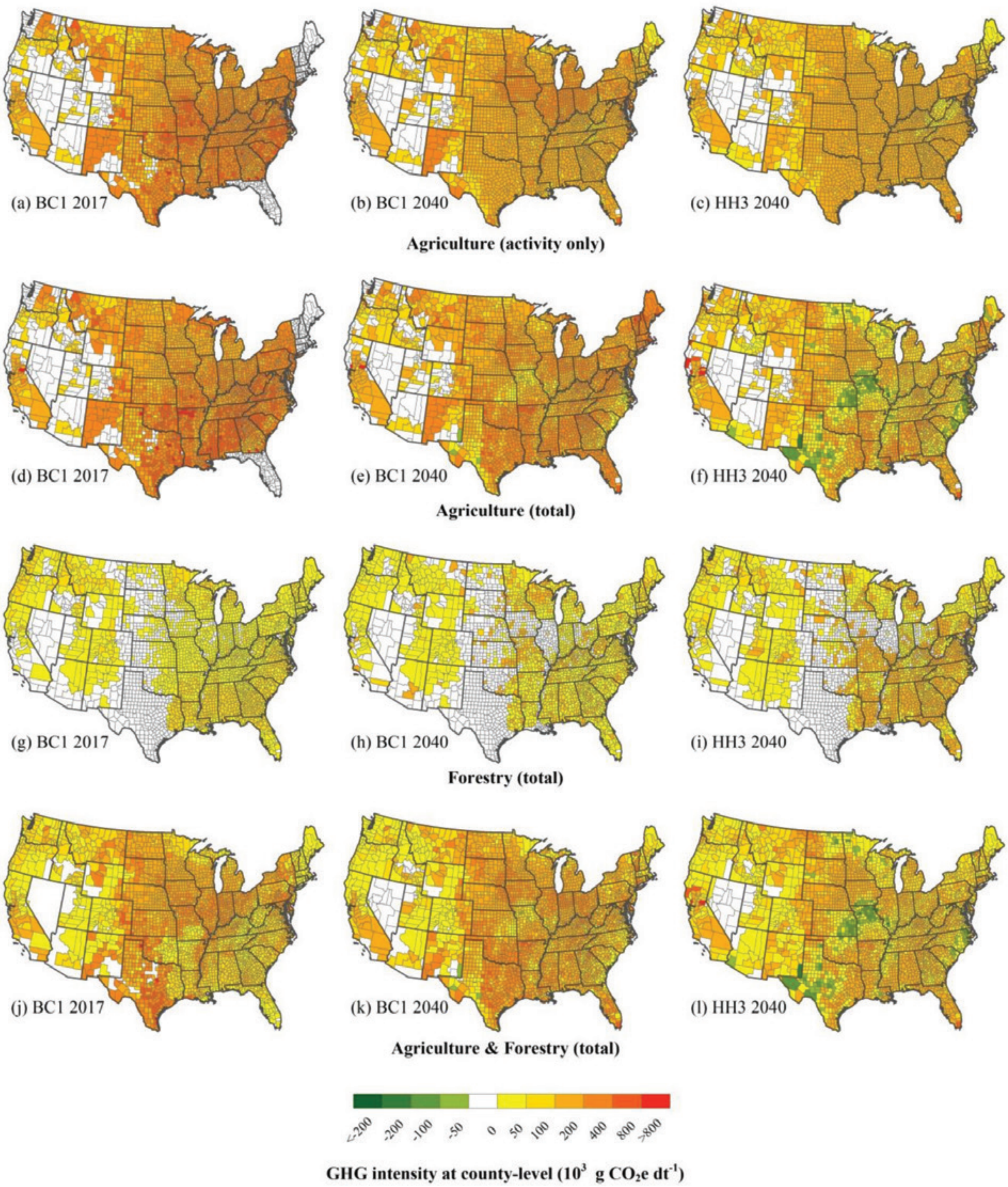


Figure 4.16 | Estimated county-level GHG intensity associated with biomass-feedstock production from agriculture and forestry sectors under 2017 and 2040 BC1, and 2040 HH3 scenarios. From top to bottom: agricultural activities without considering SOC change, agricultural biomass total GHG emissions with SOC change, forestry operations total (which does not consider SOC changes), and total emissions associated with producing all biomass, agricultural and forest-derived.



for farming operations, SOC changes, and logistics where biomass would be delivered to the biorefinery. Forestry GHG emissions, however, do not include SOC changes. Prohibition of land area changes between forestry and agriculture sectors in *BT16* scenarios translated into zero change in above ground carbon for forests that produce feedstocks. For GHG intensity in terms of a GHG-emissions-per-mass basis, agricultural feedstocks in the scenarios generally have relatively higher intensities than forestry-derived feedstocks when SOC changes are not considered (fig .4.16, first row compared to the third row). With SOC gains included for agricultural biomass, however, the GHG intensity in many counties could even be negative, which suggests net GHG sinks in these areas. For example, with agricultural activities and SOC changes considered under the HH3 2040 scenario, the modeled GHG intensity is well below zero, reaching to more than 100 kg CO_2e net GHG sink per dry ton biomass production in western Texas, eastern Kansas, and northern Missouri (fig. 4.16*F*). Even with additional GHG emissions from forestry-derived feedstocks, these areas could still result in a considerable GHG sink (fig. 4.16*L*). The reasons for potential SOC sequestration are explained in Section 4.3.2. Among three scenarios for agricultural feedstocks (fig. 4.16*A–F*), the HH3 2040 scenario has the lowest overall GHG intensity while BC1 2017 has the highest (fig. 4.16). This is mainly attributed to feedstock type and yield difference. Compared with BC1 2017, BC1 2040 assumes newly grown energy crops, which generally have lower GHG intensities than corn and soybeans—the crops predominantly used in BC1 2017. The HH3 2040 scenario, alternatively, has energy crops and highest crop yields (for both conventional and energy crops), resulting in lower GHG intensity.

To show total GHG emissions from biomass production under each yield scenario, fig. 4.17 combines analysis for GHG intensity and specific biomass production in each county. Without SOC changes included, the GHG emissions are primarily dominated by total biomass production in the county. For example, total GHG emissions are highest in the Midwest for agricultural feedstocks (fig. 4.17*A–C*), and in the Northwest and Northeast for forestry-derived feedstocks (fig. 4.17 *G–I*). When SOC changes are considered, noticeable changes are apparent in the western Texas, eastern Kansas, and northern Missouri areas of the HH3 2040 scenario where total GHG emissions are negative, suggesting that these areas could still act as GHG sinks after accounting for all GHG emissions from feedstock-production activities and logistics (fig 4.17*F*). Of course, there are other, less-noticeable changes, including decreased GHG emissions in some areas (e.g., Missouri in BC1 2040, fig. 4.17*E* compared to fig. 4.17*B*), or slightly increased GHG emissions in other areas or scenarios (e.g., eastern Texas, fig. 3.17*E* compared to fig. 4.17*B*). These changes are in line with the distribution of SOC changes (fig. 4.14). As feedstock production increases, either because of newly grown energy crops (i.e., BC1 2040 or HH3 2040) or higher yields (i.e., HH3 2040), the total GHG emissions tend to increase from BC1 2017 to BC1 2040 and then HH3 2040 (fig. 4.17*A–C*), except where SOC sequestration plays a significant role (e.g., fig 4.17*F*). For forestry-derived biomass, the GHG emissions trend is not as clear as for agricultural feedstocks because of the relatively smaller production of forest-derived biomass (fig. 4.17*G–I*).

To gain a sense of GHG-emissions drivers and spatial variations, contributors to total GHG emissions in the HH3&HH 2040 scenario are displayed for two counties, Vernon County, Missouri, and Gonzales County, Texas. The biomass produced in each county and corresponding GHG emissions are depicted in figures 4.18 and 4.19, respectively.

Figure 4.17 | Estimated county-level total GHG emissions associated with biomass production from the agriculture and forestry sectors under 2017 and 2040 BC1&ML, and 2040 HH3&HH scenarios. From top to bottom: agricultural activities (including transportation and logistics) without considering SOC change, agricultural total with SOC change, forestry total (which does not consider SOC changes), and total of both agriculture and forestry.

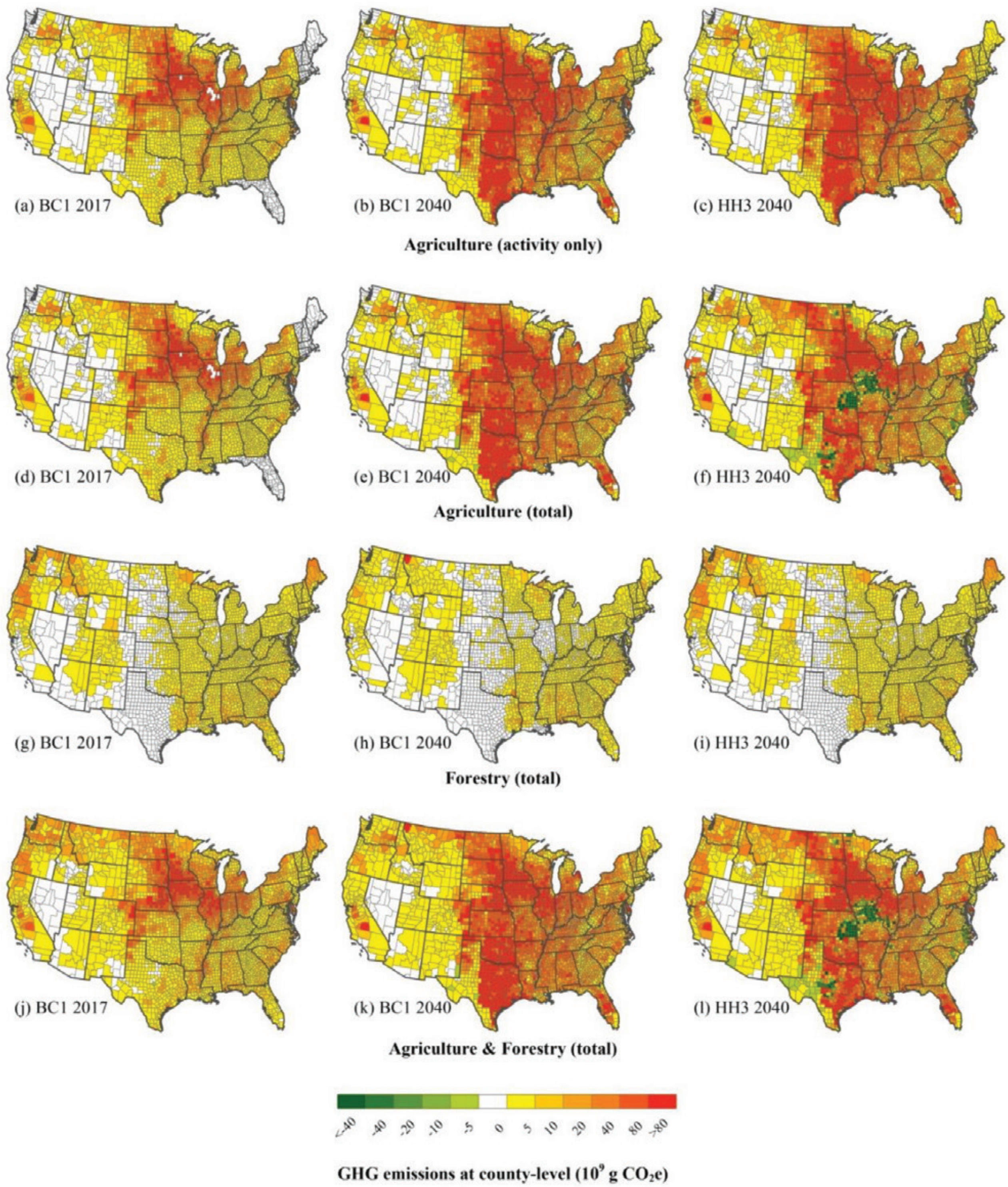


Figure 4.18 | Total potential biomass production by crop type in Vernon County, Missouri, and Gonzales County, Texas, in the HH3&HH 2040 scenario.

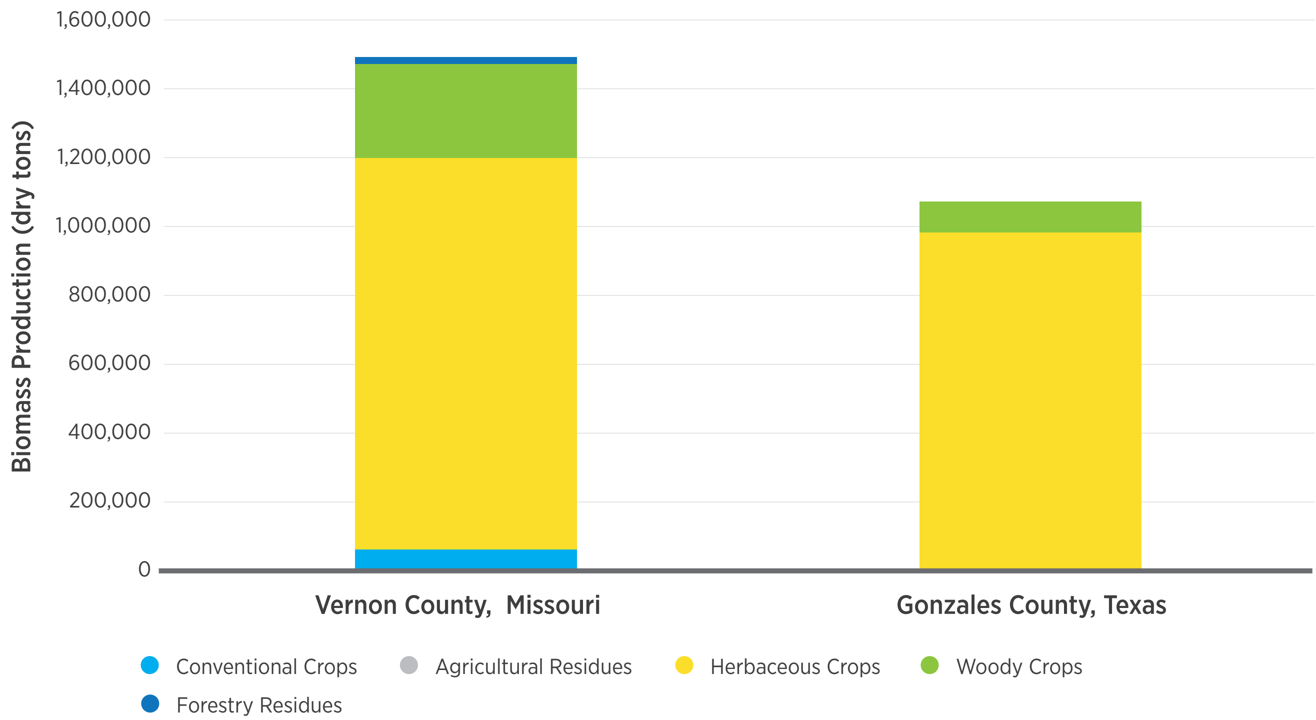
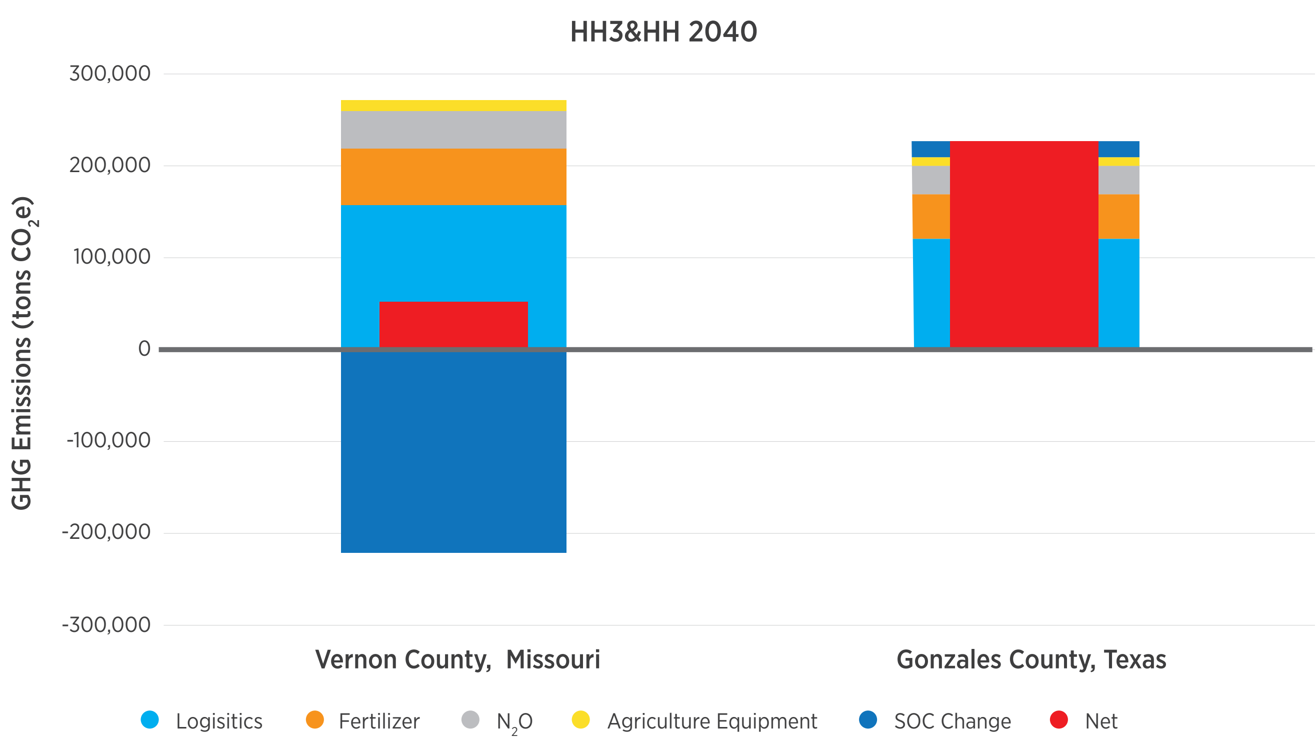


Figure 4.19 | Breakdown of estimated GHG emissions in Vernon County, Missouri, and Gonzales County, Texas. Each category represents the sum of the emissions of all of the feedstocks produced in the county in the HH3&HH 2040 scenario.



Both counties produce mostly herbaceous and woody crops in the 2040 scenarios. Vernon County would also produce conventional crops, as well as more biomass overall. In both counties, logistics contribute more than 50% to GHG emissions (excluding soil-carbon change-related emissions). The advanced logistics operations employed in the 2040 scenarios are energy-intensive. The second-largest contributor to modeled GHG emissions, aside from soil carbon-related emissions, is consumption of fertilizer and agricultural chemicals followed by nitrous oxide emissions stemming from fertilizer use. The operation of agricultural equipment is a minimal contributor to GHG emissions in these counties. Setting aside soil carbon changes, to reduce GHG emissions associated with biomass production, the energy efficiency of logistics operations and fertilizer efficiency should be improved.

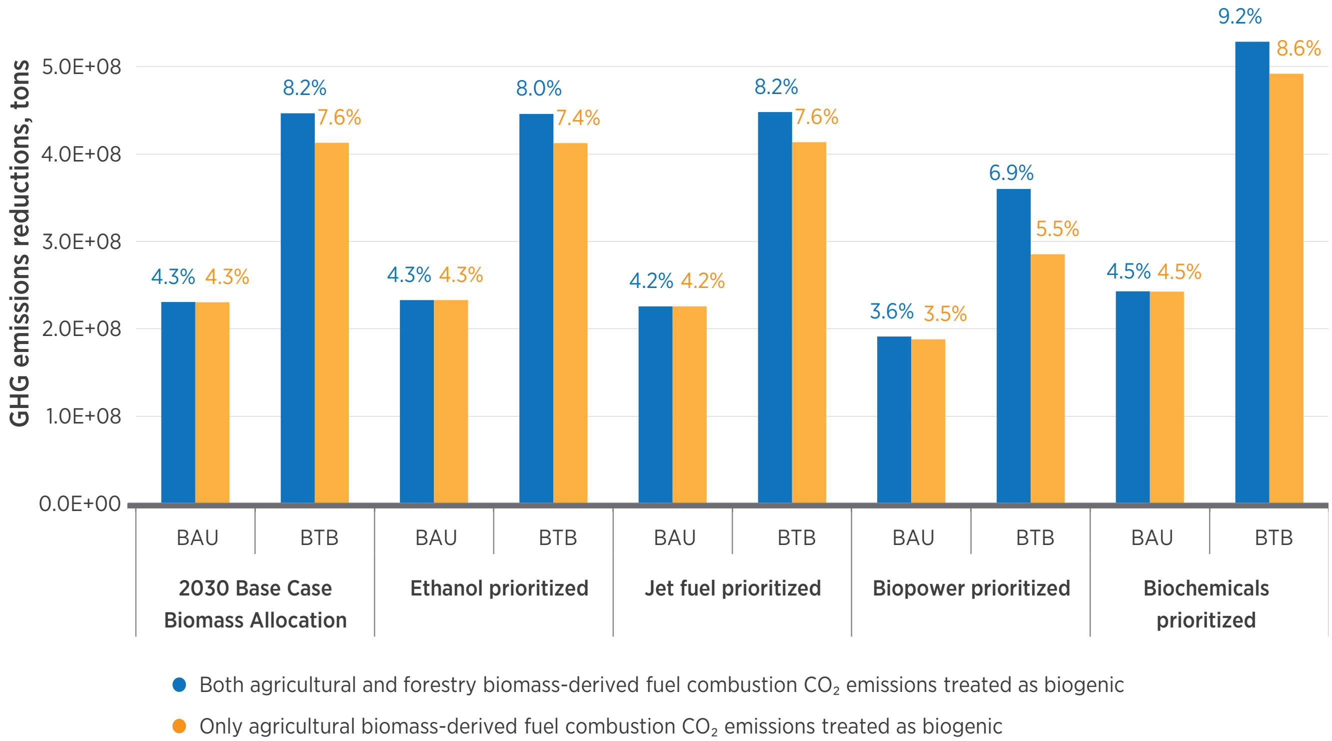
County-level SOC changes reported in this chapter are subject to the limitations described earlier. Nonetheless, figure 4.19 shows that potential production of over 1 million tons of herbaceous crops in Vernon County, 90% of which is miscanthus, significantly contributes to SOC gains in that location. In Gonzales County, SOC would decline despite significant production of herbaceous crops, 99% of which is switchgrass, which has lower yield than miscanthus and is less of a contributor to soil carbon sequestration. Miscanthus yield in Vernon County is 15.3 dry ton per acre whereas switchgrass yield in Gonzales County is 6.8 dry ton per acre. Growing high-yielding crops as energy crops can drive down GHG emissions associated with producing biomass.

4.3.4 Reduction in GHG Emissions for Representative Bioeconomy Cases

Examining GHG emissions associated with potential biomass that is produced and delivered to the reactor throat does not address the systems-level question of whether using bio-derived rather than conventional fossil feedstocks for fuel, power, and chemicals offers a GHG benefit on a life-cycle basis. There are many potential end uses for biomass—this chapter adopts end-use cases developed by a team of researchers as part of a BTB analysis to examine potential economy-wide GHG reductions from increased use of biomass, either at BAU biomass availability or at biomass availability levels as estimated in *BT16* (HH3 2040 scenario). Cases include a base case as well as cases that emphasize the production of ethanol, power, jet fuel, and bioproducts. These cases were developed with input from the U.S. Department of Energy, USDA, and other bioeconomy stakeholders and are documented in a journal article (Rogers et al. 2016). The methodology for this analysis is described in section 4.2.4.

Figure 4.20 summarizes the estimated GHG-emission reductions in various bioeconomy cases in 2030 as defined in Rogers et al. (2016), with the biomass availability in a BAU case and in the *BTB* case, in comparison to the estimated GHG emissions in the respective “all fossil” scenarios. The “all fossil” cases derive all fuel, power, and chemicals from fossil sources. The figure contains five cases that reflect different prioritizations of biomass use. In the 2030 base case, no one particular application of biomass is prioritized, but the remaining cases prioritize biomass use for ethanol, jet fuel, biopower, and biochemicals. In this analysis, two treatments of fuels produced from forest-derived biomass are considered. In the first, combustion CO_2 emissions of energy products produced from these feedstocks are treated as offset by biogenic carbon in the fuel. This is a conventional treatment for combustion emissions from annual and perennial feedstock-derived energy products, but it is under examination for fuels produced from forest-derived biomass (Daystar et al. 2016). In the second treatment, emissions from forestry biomass-derived fuels are treated as fossil carbon emissions that are not offset by biogenic carbon in the fuel. This result is a bookend case. When biogenic carbon dioxide emissions from forest-derived bioenergy are assumed

Figure 4.20 | Future potential (2030) avoided annual GHG emissions in various bioeconomy cases developed in Rogers et al. (2016).



to be carbon neutral, the GHG-emission reductions in the BTB cases can range from 6.9% in the heat and power end-use case to 9.2% in the bioproduct end-use case. When these emissions are not treated as carbon neutral, the GHG-emission reductions are lower and range from 5.5% in the heat and power end-use case to 8.6% in the bioproduct end-use case.

4.4 Discussion

It is important to note that the results reported in this chapter are a function of the *BT16* framework established in volume 1 (DOE 2016). Key parameters established in that volume influencing these results include crop residue-removal rates, land-allocation changes, limitations on land conversion that hold forested area constant, budgets for fertilizer, and agricultural- and forestry-equipment use. The magnitude of influence of each of these parameters on the results is dependent on the feedstock.

4.4.1 Implications of Results

In this chapter, GHG emissions and fossil energy-consumption estimates associated with scenarios BC1&ML 2017, BC1&ML 2040, and HH3&HH 2040 are as reported in Table 4.3.

Drivers of the national-level estimated GHG emissions vary by county. One common driver is logistics operations, especially under the long-term advanced logistics scenario. Efforts to improve the energy efficiency of logistics would improve GHG and energy impacts of biomass. Another driver of estimated GHG emissions is the yield for each feedstock. In general, counties with higher yields experience lower GHG emissions intensities, especially those where most or all of the agricultural inputs (energy and fertilizer) are applied on a per-acre basis regardless of yield (e.g., corn, soybeans). For example, conventional tilled corn produced in the BC1 2040 scenario has yields ranging from 334 bushel per acre down

Table 4.3 | Estimates of total biomass produced, GHG emissions, and fossil energy consumption for evaluated scenarios

Scenario	Total biomass produced (million dry tons per year)*	GHG emission (million tons CO_2e per year)	Fossil energy consumption (million Btu)
BC1&ML 2017	330	54	4.0×10^8
BC1&ML 2040	810	150	1.3×10^9
HH3&HH 2040	1,100	200	2.3×10^9

* Total includes biomass that would have total delivered costs exceeding $100/dry ton

to 38 bushel per acre. The GHG emissions for these scenarios to the farmgate (excluding transportation and preprocessing emissions) are 1,023,000 and 94,000 g-CO_2e per dry ton of biomass produced for the lowest and highest yields, respectively. On the other hand, the fertilizer, chemical, and diesel inputs of some other feedstocks (e.g., perennial crops) have less of an overall influence on results. For miscanthus, the highest and lowest yields for the BC1 2040 scenario were 12.2 and 1.9 dry tons per acre, respectively. This corresponded to GHG emissions to the farmgate of 50,900 and 77,900 g-CO_2e per dry ton of biomass for the highest and lowest yields, respectively. GHG emissions are also dependent on the FRR in which a county is located. Budgets that dictate energy and fertilizer inputs vary by FRR, but not greatly. For corn, fertilizer amounts are different in each FRR, as well as the amount of herbicides and insecticides applied. On the other hand, the FRR budgets for miscanthus vary only in the amount of potassium and lime applied per acre. Other fertilizer and chemical application rates on a per-dry-ton basis are the same in all counties for miscanthus.

An additional GHG emissions driver is soil carbon changes. In general, planting of deep-rooted species like miscanthus and biomass sorghum could contribute to soil carbon storage. The SOC implications of other energy crops like switchgrass and SRWCs vary depending on local factors like yield, soil type, and weather. Soil carbon change estimation in this analysis faced several limitations as discussed in section 4.2.2.2.

Even though biomass production results in GHG emissions, life-cycle analyses illustrate that net GHG reductions are possible when biomass feedstocks are used instead of fossil feedstocks to produce fuel, power, and chemicals. The examples considered in section 4.3.4 illustrate that for the portfolio of end uses considered in various 2030 cases , GHG-emissions reductions (between 4%–9%) and fossil energy reductions could be expected from broader use of biomass-derived energy and products that displace conventional energy and products produced from fossil fuels.

One important point regarding the results in this chapter is that they are estimates and aim to indicate potential GHG-emissions hotspots from producing biomass and to illuminate GHG drivers so that efforts can be made to mitigate them.

4.4.2 Uncertainties and Limitations

In addition to the limitations in SOC modeling discussed earlier in this chapter, some limitations of this study include not considering temporal aspects associated with forestry-derived feedstocks or soil-carbon changes associated with producing this biomass. Additionally, the development of estimates of SOC changes was limited by the absence of land-use history prior to land-conversion information from POLYSYS. It was also limited by a lack of information regarding which land types were used directly for crop production, necessitating the development of the land-use matrices described earlier. Additional limitations include assuming conventional tillage for conventional crops and accounting only for corn-corn rotations. Finally, increased validation of SOC modeling results for energy crops, for which few data are available, will help improve estimates of SOC changes in future analyses.

4.5 Summary and Future Research

In this analysis, we estimated the GHG emissions and fossil energy consumption that would be associated with scenarios BC1&ML 2017, BC1&ML 2040, and HH3&HH 2040 at the county level. The scenarios were selected to examine potential effects of national biomass expansion and yield changes on GHG emissions. For agricultural feedstocks, we incorporated SOC changes in the analysis. Furthermore, we considered illustrative scenarios in which the biomass resource estimated in 2040 was put toward a number of end uses and compared modeled GHG emissions and fossil energy consumption in the bioeconomy cases to a BAU scenario. We also considered and discussed carbon accounting considerations related to aboveground biomass and forest-derived feedstocks.

Overall, GHG emissions associated with the BC1 & ML 2017, BC1 & ML 2040, and HH3 and HH 2040 scenarios were 54, 150, and 200 million tons CO_2e, respectively. Key drivers of results were preprocessing in advanced logistics operations in place in 2040, which consumes a good deal of energy, and SOC changes, especially where deep-rooted feedstocks are estimated to grow.

Several aspects of future research are envisioned to build upon this analysis. One of these is to explore sensitivity of SOC changes to assumptions, including the treatment of tillage (the current analysis assumes all corn is produced with conventional till) and the effects of rotation. All corn is assumed to be in a corn-corn rotation—the influence of adopting corn-soy rotations and other rotations as informed by USDA data can be investigated in the future. Moreover, the influence of assumptions regarding crop yield, land-use history, and land-transition matrices on results can also be investigated. SOC-change hotspots and techniques to mitigate factors that cause them will also be a focus of this additional work, as will quantifying aboveground carbon changes to compute these and assess their relative contribution. A second aspect of future research is to introduce temporal-emissions accounting to our treatment of forest-derived feedstocks. Another area to explore in the context of emissions is advanced logistics, as they can be GHG-intensive. Ways to improve efficiency for biomass preprocessing can also be evaluated. The investigators in this and other chapters have noticed some modeling differences among chapters. For instance, evapotranspiration was estimated using the Blaney-Criddle method in SOC modeling (Kwon et al. 2013), while Penman-Monteith's approach was used in the water analysis (chapter 5). Even though both modeling approaches have been independently validated, it would be valuable to harmonize the methodology among analyses for different environmental indicators in future work. Finally, with all environmental effects (e.g., SOC, GHG emissions, water quality, water quantity, air quality, and biodiversity) of biomass production quantified spatially, it is necessary and feasible to identify hotspots considering these effects jointly and to provide information on potential preventive measures that can protect vulnerable regions.

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Appendix to Chapter 4 – Fossil Energy Consumption and Greenhouse Gas Emissions of Producing Agriculture and Forestry Feedstocks

Appendix 4-A: Detailed Methodology

In this appendix, we provide a detailed account of how Farm Resource Region (FRR) budgets, POLYSYS model outputs, and forest-biomass related data were used to generate the results in this chapter.

Calculating County-Level Greenhouse Gas Emissions and Fossil Energy Consumption

Potential greenhouse (gas) GHG emissions and fossil energy consumption for annual feedstocks, perennial crops, short rotation woody crops, and forest biomass, as described in the following subsections, are calculated based on the agricultural and forestry budgets that provide material and energy intensity of feedstock production.

Rather than use county-level POLYSYS outputs of fuel, fertilizer, and chemical consumptions, which stem from interpolation of raw crop budget data at the FRR level down to the Agricultural Statistical District (ASD) level (309 in the United States) and again down to the county level (3,000 in the United States), we used the FRR-level crop budgets themselves. In the current analysis, all assumed fertilizer, herbicide, and energy consumption amounts are taken from the FRR-level budgets. The amounts of energy, fertilizer, and chemicals to produce a given biomass type are the same for each county in one FRR. Intensities (e.g., the amount of energy consumed per dry ton of biomass) vary based on county-specific yield.

Fertilizer consumption in FRR budgets is reported as the amount of active ingredient (i.e., nitrogen, phosphorus, potassium, and lime). GREET contains emission factors for all of these active fertilizer ingredients. Emission factors for potassium and lime fertilizers were calculated directly, and those for nitrogen and phosphorus fertilizers were calculated by weighting the total fertilizer use by different fertilizer types in the United States and using their corresponding emission factors (Johnson et al. 2013). POLYSYS contains seven herbicides that are used for the cellulosic feedstocks including quinclorac; atrazine; 2,4-D amine; glyphosate; metolachlor; pendimethalin; and metribuzin. Of those herbicides, GREET only contains parameters for atrazine and metolachlor, in addition to two other herbicides, acetochlor and cyanazine. For this analysis, it is assumed that the other five herbicides have energy and GHG intensities that have the same average as that for the existing herbicides in GREET. Based on information in the crop budgets, herbicides account for a small percentage of the total mass of fertilizers and herbicides consumed in production of each feedstock (approximately 2%). For this reason, and based on previous analyses that showed a minimal contribution to biofuel life-cycle GHG emissions from insecticides and herbicides (Wang et al. 2012), it is expected that the contribution of these chemicals to biomass-production GHG emissions would be small. Therefore, we do not expect that using an average herbicide value from GREET (average of all four available in GREET) would significantly affect the energy and GHG estimates presented in this chapter.

Energy, including fuels and electricity, is directly consumed in farming equipment during feedstock production and harvesting, as well as in trucks during feedstock transportation. Diesel is the primary fuel type consumed. In adapting the FRR budgets for use in GREET, off-road diesel is assigned to be the fuel used in farming equipment such as tractors, while fuel consumed in on-road trucks that transport biomass is assumed to be on-road diesel. One key difference between off-road and on-road diesel is sulfur content, with on-road diesel containing 15 parts per million (ppm) sulfur, and off-road diesel containing 163 ppm sulfur. Electricity, natural gas, or propane may also be consumed during agricultural operations. GREET contains upstream production data for all of the energy types consumed in feedstock production. The development of these data are documented in several sources (Burnham et al. 2012; Cai et al. 2012, 2013; Elgowainy et al. 2014). One key note about electricity is that the grid composition varies by region. This analysis assigns a spatially explicit electricity grid based on the county where feedstock production is occurring. Each county was assigned a grid mix based on the North American Electric Reliability Corporation (NERC) region mixes (EIA 2015). Counties that are located in multiple regions are assigned the region in which most of the county's area lies.

Per–land-area consumption of energy, fertilizers, and chemicals is divided by yield per land area for the different crops at the county level to generate estimates of the material and energy intensity of producing each of the feedstock types. County-level yields that are used for this purpose are generated in two different ways (fig. 4.2). For conventional crops (e.g., corn or soybeans), yield data come directly from the U.S. Department of Agriculture's (USDA's) National Agricultural Statistics Service (NASS) (2015). Cellulosic crop yields (e.g., miscanthus or switchgrass) are estimated with PRISM. PRISM has been calibrated with yields from the Sun Grant Regional Partnership field trials. The model estimates yields for each cellulosic feedstock from climate and soil data. As a result, yields are spatially explicit at the county level. Dividing FRR-level material and energy data per area of land by county-level yield data produces per-feedstock mass intensity values that are also at the county level and are used as GREET inputs (e.g., grams of nitrogen/dry ton feedstock).

This analysis explores whether production of seeds and rhizomes should be included in the system boundary. POLYSYS output includes the cost of seeds and rhizomes but does not estimate the materials and energy consumed for their production. GREET default material and energy intensity data for feedstock production do not include the seed or rhizome production stage. It is expected that the energy and material intensity of seed production can be neglected in the *BT16* volume 2 analysis because previous analyses have shown that seed production contributes little to life-cycle GHG emissions of first-generation biofuel crops (e.g., corn and soy) (Shapouri et al. 2010; USDA 2013). For example, Landis, Miller, and Theis (2007) estimate that seed production contributes less than 0.002% to the energy for corn farming and transportation to the refinery. Planting stock production for willow is also a small contribution to the life-cycle GHG emissions of producing and transporting willow chips to a biorefinery (Caputo et al. 2014). Production data for other cellulosic crops are scarce, but it is assumed that seed production is also a minor contributor to life-cycle GHG emissions for cellulosic crop production. Currently, rhizome production for miscanthus is excluded from energy and GHG-intensity calculations. The contribution from these rhizomes may be small because they may have similar energy intensities as the planting stock for willow. However, they may be included in future analyses.

Annual Feedstocks (Corn and Soybeans)

Fuel, fertilizer, and agricultural chemical inputs for each feedstock produced in each county are multiplied by their respective, GREET-derived GHG emission factors and fossil energy consumption factors (table 4A.1). The GHG emission calculations also include the carbon dioxide emissions from lime (calcium carbonate) application. This value is estimated by multiplying the lime application rate by a 49.2% loss rate and converting subsequent carbon loss to carbon dioxide loss. Nitrous oxide emissions from nitrogen fertilizer nitrification-denitrification and biomass decomposition are included as well. For all feedstocks in BT16, it is assumed that 1.525 % of the nitrogen, on a kg-N basis, in applied fertilizer is emitted as nitrous oxide (Wang et al. 2012). For all feedstocks, it is assumed that 1.225% of the nitrogen in the biomass remaining on the field (assumed to be 10% by weight of the feedstock) is emitted as nitrous oxide during decomposition (ANL 2015). This percentage is multiplied by the nitrogen content of the relevant feedstock (table 4A.2). The nitrogen contents taken from the Bioenergy Feedstock Library (INL 2016) are for the type of feedstock that would be used in a final application (e.g., stem wood, not leaves, for willow). To convert GHG emissions per acre and per mass of feedstock produced, we used the amount of feedstock produced per planted acre because fertilizer, tilling, and other management practices would be carried out for all planted acres, not solely harvested acres. It is important to note that in calculating per-dry-ton GHG and energy intensity estimates, this analysis takes into account that some of the corn and soybeans in each county would be used for other industries (e.g., animal feed). The results are based on the portion of these feedstocks that are used as a bioenergy or bioproduct feedstock as determined by POLYSYS.

Table 4A.1 | Emission Factors Used to Calculate GHG Emissions (ANL 2015)

		GHG emissions (g-CO_2e/gal or lb)	Fossil energy consumption (Btu/gal or lb)
Fuel and Fertilizer	Off-road diesel	10,080	155,477
	On-road diesel	12,355	154,230
	Nitrogen	1,768	26,526
	P_2O_5	678	9,146
	K_2O	293	3,557
	$CaCO_3$	6.1	76.5
Herbicides	*Corn*	9,182	112,997
	Willow, poplar, eucalyptus, switchgrass, miscanthus	9,162	112,742
	Soybeans	9,487	116,746
Insecticides	*Corn, poplar, soybeans*	10,604	133,159

Table 4A.2 | Nitrogen Content of Annual, Perennial, and Wood Feedstocks

Feedstock	Nitrogen content of above- and below-ground biomass	Unit	Source
Biomass sorghum	9,343	g-N/dry ton	(INL 2016)
Corn	5,900	g-N/dry ton	(ANL 2015)
Energy cane	3,900	g-N/dry ton	(ANL 2015)
Eucalyptus	1,996	g-N/dry ton	(INL 2016)
Loblolly pine	3,991	g-N/dry ton	(INL 2016)
Miscanthus	3,175	g-N/dry ton	(INL 2016)
Poplar	3,629	g-N/dry ton	(INL 2016)
Soybeans	15,782	g-N/dry ton	(ANL 2015)
Switchgrass	5,715	g-N/dry ton	(INL 2016)
Willow	2,449	g-N/dry ton	(INL 2016)

Agricultural Residues (Corn Stover, Barley Straw, Sorghum Stubble, Wheat Straw, and Oat Straw)

Budget information for residues includes the energy used for residue collection and the amount of supplemental fertilizers applied as a result of residue collection to maintain soil nutrient levels. (GHG emissions associated with fertilizer applied to the crops themselves are not credited to the residue.) As with the annual crops, the fuel and fertilizer consumption were multiplied by their GHG emission factors from table 4A.1. The GHG-emission calculations also include nitrous oxide emissions from supplemental nitrogen fertilizer nitrification-denitrification and avoided nitrous oxide emissions from biomass that was removed from the field. (If this biomass had remained on the field, it would have emitted nitrous oxide as it decomposed.) The avoided nitrous oxide emissions are calculated using the aboveground nitrogen content of the biomass (table 4A.3).

Table 4A.3 | Aboveground Nitrogen Content of Harvest Residues

Feedstock	Nitrogen content of aboveground biomass (g-N/dry ton)	
Barley straw	6,350	(de Klein et al. 2006)
Corn stover	7,000	(ANL 2015)
Sorghum stubble	7,000	(de Klein et al. 2006)
Oat straw	6,350	(de Klein et al. 2006)
Wheat straw	7,000	(de Klein et al. 2006)

Perennial Feedstocks (Switchgrass, Miscanthus, and Energy Cane)

The emission calculations for the perennial feedstocks differ from those undertaken for the annual crops and residues because perennials undergo a multiple-year, multiple-harvest rotation. Each year in the rotation differs in terms of energy expended, fertilizers applied, and biomass yielded. Although POLYSYS output relates how much perennial crop is harvested from each county in each year, the output does not convey at what point in the rotation the perennial crop is harvested in a specific farm or plot. Fertilizer application for perennials tends to be concentrated in the initial rotation years, but feedstock harvested in later years has still benefitted from this fertilizer application. To spread the burden of fertilizer application and energy consumption across biomass produced over the entire rotation, these burdens are amortized over the rotation length at the county level (table 4A.4).

Table 4A.4 | Rotation Length and Yearly Maximum Yield Percentage

Feedstock	Rotation length (years)	Percentage of maximum yield by year
Switchgrass	10	Year 1: 50%; Year 2: 75%; Years 3–10: 100%
Miscanthus	15	Year 1: 0%; Year 2: 50%; Years 3–15: 100%
Energy cane	7	Year 1: 75%; Years 2–7: 100%

Equation 4A.1 relates the technique used to calculate an annual average fuel consumption and nutrient use when these values come from POLYSYS on a per acre basis.

Equation 4A.1:

$$\text{Fuel or Nutrient Use}\left(\frac{\text{gal or lb}}{\text{ac}}\right) = \frac{\sum_{1}^{10}\text{Yearly use of all operations}}{\text{Rotation Length}}$$

On the other hand, some fertilizer application rates after the establishment year are reported on a per-dry-ton basis because this rate is dependent on the amount of biomass removed from the field. In this case, a rotational average fertilizer consumption is developed because the amount of biomass produced varies by year. The application rate and the maximum yield (maximum output values based on the PRISM runs for each location, see section 4.2.4 of volume 1), summarized in equation 4A.2 are used for this calculation. This equation sums the product of the nutrient application for each year and the amount of biomass produced. This value is divided by the total biomass produced.

Equation 4A.2:

$$\text{Rotational Average Nutrient Use}\left(\frac{\text{lb}}{\text{dt}}\right) = \frac{\sum_{i=1}^{10}(\text{Nutrient Application})_i * (\text{Percent of Max Yield})_i * (\text{Max Yield})_i}{\sum_{i=1}^{10}(\text{Percent of Max Yield})_i * (\text{Max Yield})_i}$$

The final rotational average nutrient use is determined in Equation 4A.3.

Equation 4A.3:

$$\text{Rotational Nutrient Use}\left(\frac{\text{lb}}{\text{dt}}\right) = \frac{\sum_{i=1}^{10}(\text{Nutrient Application})_i * (\text{Percent of Max Yield})_i}{\sum_{i=1}^{10}(\text{Percent of Max Yield})_i}$$

The emissions due to nitrous oxide loss from fertilizer and biomass decomposition along with carbon dioxide emissions from applied lime are also considered for perennials as with the other agricultural crop types. The chemical- and fuel-use values are multiplied by their respective emission factors (table 4A.1) to arrive at county-level GHG emissions on a per-acre and per-dry-ton basis. These values are multiplied by the planted acres and total dry tons produced to arrive at the total GHG emissions.

Woody Feedstocks (Willow, Eucalyptus, Poplar, and Loblolly Pine)

The analysis for woody feedstocks is similar to that for perennials, but biomass is not harvested every year. The emissions are calculated in a similar way by using equations A4.2 and 4A.3 and considering nitrous oxide emissions from decomposing biomass and fertilizer undergoing nitrification-denitrification. However, compared to perennial scenarios, some of the fuel used for harvesting is reported on a per-dry-ton basis. As a result, the per-acre values are amortized over the rotation of the woody biomass. The per-dry-ton fuel consumption is calculated with equation 4A.3, with the percentage of maximum yield replaced by the percentage of biomass harvested. Loblolly pine and poplar are harvested only once, but eucalyptus and willow rotations undergo multiple harvests. For this analysis, it is assumed that 100% of the biomass for these feedstocks is removed during each harvest. GHG emissions of nitrous oxide emissions from fertilizer nitrification-denitrification and carbon dioxide emissions from lime decomposition were included. The GHG emissions were multiplied by the planted acres and dry tons produced to arrive at the total GHG emissions in each county.

Forestry-Derived Feedstocks

Forestry budgets derived from the CORRIM database and literature (see chapter 3 of volume 1) were used to generate the fossil energy and GHG intensity of forest-derived biomass including lowland and upland hardwoods, mixed woods, and natural and planted softwoods, in addition to their residues. The calculations for the forestry sector are similar to those for the agricultural sector. One important consideration is the technique used to assign burdens to residues—the forestry analysis approach (chapter 3 of volume 1) assigns 10% of energy and fertilizer resources to residues as opposed to the rest of the harvested trees. For consistency, this chapter uses the same level of fuel and nutrient intensity for the estimation of fossil energy consumption and GHG emissions associated with forest residues as chapter 3 of volume 1. In the future, other methods of allocation may be explored, including mass allocation.

Feedstock Logistics

Potential logistics scenarios to deliver biomass to biorefineries were developed in the *BT16* volume 1 analysis and are presented in chapter 6 of that volume, for a selected group of feedstocks. The analysis estimates the transportation distances required for each type of biomass produced in each county for both a near-term scenario using conventional logistics systems to deliver bales or wood chips to the biorefinery and in 2040 using advanced logistics (pelletization at regional depots). For conventional logistics, the biomass is transported to the biorefinery as is, while in advanced logistics the biomass is first taken to a depot, processed into blended feedstock pellets, and then transported to the biorefinery. The feedstocks that are considered in the logistics analysis of *BT16* volume 1 include corn stover; miscanthus; switchgrass; biomass sorghum; woody feedstocks including eucalyptus, pine, willow, and poplar; and forestry-derived whole trees and residues. Transportation parameters (e.g., payload, fuel economy with payload, and fuel economy without payload [for backhaul trips]) for these feedstocks are provided in table 4A.5. Transportation and logistics inputs for other biomass types not analyzed in *BT16* volume 1, including corn, soybeans, energy cane, and other non-corn stover agricultural residues, were estimated separately. For example, transportation fuel consumption for corn and soybeans is taken from GREET, which uses trucks. The transportation distances for both of these feedstocks in GREET is 10 miles one-way to the collection stack and 40 miles one-way to the biorefinery. The GHG emissions for transporting both of these feedstocks is 18,000 g-CO_2e/dry ton. The analogous transportation information was not available in GREET® for agricultural residues and energy cane. Therefore, we assumed all crop residues not subject to logistics analysis in volume 1 have the same transportation-related energy intensity as does corn stover in GREET. The related parameters include a transportation distance of 53 miles, a fuel economy of 5.7 miles/gallon, and a load capacity of 17 dry tons/load. For these residues, the resolution of logistics energy use and GHG emissions is available at a national level, rather than at the county level. An important assumption for this portion of the analysis is that we assigned all burdens to the county of feedstock origin rather the county where the biorefinery may reside or any intervening county.

Table 4A.5 | Logistics Information for Transportation of Feedstocks (taken from BT16, volume 1, chapter 6)

	Payload (dry ton/ load)	Fuel economy with load (miles/ gal-diesel)	Fuel economy without load (miles/gal-diesel)	Data source
Corn stover	17	5.6	7.7	(Webb, Sokhansanj, and Turhollow 2013a)
Switchgrass/ miscanthus	17	5.6	7.7	(Webb, Sokhansanj, and Turhollow 2013b)
Sorghum cane	21	5.5	7.7	(An and Searcy 2012)
All woody feedstocks	17	4.8	7.7	(INL 2014)
Pellets	21	5.5	7.7	(Webb, Sokhansanj, and Turhollow 2013b)

At the biorefinery itself, the feedstock undergoes some basic processing steps for delivery to the reactor throat. The Idaho National Laboratory Design Case (INL 2013) provided an estimate of this energy intensity, which is primarily due to consumption of electricity on a per dry ton feedstock basis for the same feedstocks considered in *BT16* volume 1 (chapter 6 in that volume). The diesel consumption and preprocessing electricity for these feedstocks are summarized in table 4A.6. Electricity values are similar for all conventional feedstocks and all advanced feedstocks. However, the diesel consumption for corn stover is lower than forestry feedstocks because preprocessing of stover only consumes diesel for vehicle loading, while preprocessing of forestry feedstocks consumes diesel for chipping, which is a more energy-intensive process than vehicle loading. For corn, the preprocessing information is used for a corn dry-grind biorefinery at 8 kilowatt-hours per dry ton of corn (Kwiatkowski et al. 2006). The same type of information was not found for soybeans, but given that they are also ground before the reactor throat, the same electricity consumption on a per-ton-biomass basis is used. *BT16* volume 1 analyses did not assess preprocessing energy consumption for agricultural residues described earlier as also lacking transportation and logistics analysis in volume 1. To estimate preprocessing energy consumption for these residues, we assumed that it is as energy-intensive to preprocess them as it is corn stover (table 4A.6). *BT16* volume 1 (chapter 6) assumes that any biomass with a delivered cost greater than $100/dry ton is not considered feasible and would in essence be left on the field. Therefore, we do not consider GHG and energy consumption emissions associated with transportation and preprocessing of this biomass, but do account for the GHG emissions associated with its production (e.g., fuel, fertilizer, chemical consumption on the farm).

Table 4A.6 | Preprocessing Energy Consumption for Feedstocks (taken from *BT16*, volume 1, chapter 6)

	Diesel (Btu/dry ton)	Source (Btu/dry ton)
Conventional logistics		
- Corn stover	26,300	123,000
- Forest whole tree and residues	154,000	136,000
Advanced logistics		
- Corn stover		655,000
- Biomass sorghum		592,000
- Miscanthus		643,000
- Switchgrass		643,000
- Forest whole tree and residues		653,000

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Appendix 4-B: Sustainability of Extracting Primary Forest Residue Biomass

4B.1 Introduction

Harvesting timber from forests creates ecological disturbances that affect myriad properties and processes. These disturbances have been studied for decades. The disturbance type and severity, coupled with the ecosystem properties, determine whether the ecosystem can be resistant (i.e., little change is evident in the ecosystem), resilient (i.e., initial change is followed by recovery to similar conditions), or irreversibly altered. While specific, long-term responses of all processes are not yet known, the effects of harvesting timber on a site's productivity are well understood. The harvesting of other materials in addition to those traditionally removed for wood products (e.g., smaller-diameter trees, branches, or leaves) as well as potentially higher trafficking, can increase the severity of the ecological disturbance; this increase in severity raises additional questions regarding ecosystem responses and the sustainability of site productivity (Janowiak and Webster 2010). Research on these impacts began in the 1970s and has increased recently due to a rise in general interest in woody biomass for energy.

4B.2 Research on Site Productivity Following Biomass Harvests

Harvesting biomass for energy from forests occurs in a wide variety of management types from short-rotation, purpose-grown woody crop systems to intensively managed plantations, to extensively managed forests and woodlands (Stone 1975). Within the most intensive woody-biomass feedstock systems, maintaining site productivity is imperative to efficient management. Nutrient deficiencies that may be present are mitigated as a matter of course through fertilization. The management of these systems in terms of technological inputs to manage water, nutrients, and non-crop vegetation is more intensive than traditional forestry, but usually less intensive than typical agricultural systems. Similarly, the ecological sustainabiilty of these systems must be considered relative to previous land use (Blanco-Canqui 2010; Holland et al. 2015). In comparison to annual systems, short-rotation woody crops offer several environmental advantages. For example, when sited on marginal agricultural land, these systems improve soil productivity and offer additional environmental benefits such as improved water quality and wildlife habitat.

Within conventionally managed forest ecosystems, there are concerns over biomass harvesting, thinning operations, and ecological impacts from the removal of additional wood following conventional stem-only harvests (Page-Dumroese, Jurgensen, and Terry 2010). Some dead woody biomass is left on-site as it serves several important ecological functions in forest ecosystems that are affected by harvesting (Harmon et al. 1986). This dead woody material serves as a habitat for a variety of organisms, including fungi, mosses, liverworts, insects, amphibians, reptiles, small mammals, birds, and regenerating plants. In cool climates, downed logs act as nurse logs for seed germination and stand establishment. Birds forage, nest, and hunt in and on dead wood. Dead woody material affects ponding, sediment trapping, and aeration in streams; it also impacts site productivity through several mechanisms.

This dead biomass alters a site's water balance and quality by storing and releasing water and by reducing runoff and erosion. Dead woody material supports biological nitrogen fixation, thereby increasing on-site levels of nitrogen, and it contains nutrients that are cycled back into the soil. It is also commonly used during harvest operations to protect wet soil areas from compaction and rutting and is used post-harvest to help limit runoff and erosion from skid trails and forest roads.

4B.3 Compaction

Biomass harvesting operations cause ground disturbance and some result in increased trafficking compared to traditional harvesting. These disturbances result in physical changes such as compaction, soil mixing, and altered surface hydrology; however, the extent, duration, degree, and distribution of the impacts are site-, soil-, and harvest method-specific (Cambi et al. 2015). In addition, woody debris is sometimes used to protect soils from disturbance or from erosion, and biomass harvesting could reduce this resource.

Under the Long-Term Soil Productivity experiment (LTSP) in North America, compaction has had mixed effects on tree growth over a period of 10–15 years. In most cases, compaction has had little to no significant impact on early survival or productivity (Ponder Jr. et al. 2012). Sites with clayey soil textures have reported declines in young tree growth due to compaction (Gomez et al. 2002), while productivity increased on loamy and coarse-textured soils after compaction due to improvements in water-holding capacity or other physical attributes. Compaction effects occurring across a range of textures in southern pine sites resulted in increased tree productivity due to a reduction in competing vegetation (Scott et al. 2014).

The loss of nutrient capital and organic matter due to biomass harvesting is of particular concern for sustaining site productivity and carbon sequestration potential. While biomass harvesting includes more sources than just residue from conventional harvest systems, the majority of research in the United States on nutrient removals from biomass harvesting focuses on the impact of whole-tree harvesting relative to conventional harvesting and the removal of small-diameter trees for silvicultural and fire-protection purposes. Whole-tree harvest is usually defined as all woody biomass contained in standing trees aboveground, where complete-tree harvest removes the stump and large root biomass, as well. More-intensive biomass harvesting removes existing dead wood from the site. Logging residues, or the remainder of the standing tree after the conventionally merchantable bole is removed, contain a disproportionately high nutrient content relative to the bole. For example, whole-tree harvesting removed 47% more biomass (165 Mg ha^{-1} versus 112 Mg ha^{-1}) on average than stem-only harvesting from 6 hardwood and 5 conifer stands, but 86% more nitrogen (321 versus 172 kg ha^{-1}), 105% more phosphorus (37 versus 18 kg ha^{-1}), and 112% more calcium (216 to 459 kg ha^{-1}), respectively (Mann et al. 1988). Small-diameter trees removed in thinning operations or in dedicated short-rotation woody crop systems also have a comparatively high nutrient capital due to a larger proportion of high nutrient-concentration biomass (e.g., leaves, needles, branches, or bark). Thus, the nutrient removal is much greater in biomass-harvesting systems than in conventional harvesting systems relative to the actual amount of biomass harvested. Therefore, it is important to manage the retention of portions of the biomass to ensure long-term productivity by leaving residues or by time of harvest.

Two recent reviews (Thiffault et al. 2011; Achat et al. 2015) analyzed existing studies regarding the soil and tree growth impacts of whole-tree harvesting compared to stem-only harvesting. Based on these empirical data sets, it is clear that removing the more nutrient-rich materials (e.g., branches or foliage) can cause reductions in soil fertility and affect tree growth by altering microclimate, fertility, and other vegetation; however, these impacts are minor and inconsistent. For example, a global meta-analysis (Achat et al. 2015) found that subsequent tree growth (e.g., volume, basal area, or biomass) was reduced by a median 3.1% (-15.1% in Quartile 1 to 2.8 % in Quartile 3) across 48 studies when branches and foliage were harvested in addition to boles. Experimental treatments often have a greater impact on tree growth by affecting competing vegetation (Thiffault et al. 2011), which is not an indicator of long-term site productivity (Burger 1994).

Within the United States, the LTSP experiment was initiated specifically to answer questions about the impact of varying degrees of organic-matter removal on soil and site productivity. The most recent network-wide review of the first 10 years following treatment found no consistent impact of intensive organic-matter removal on tree growth (Ponder Jr. et al. 2012). By age 15—the time when nutrient deficiencies tend to be most prevalent—most of the U.S. sites in the LTSP study had reached canopy closure. Recent regional and individual site reports concluded that the most intensive treatment, which removed all organic material including the forest floor (which was not intended to be an operational treatment), resulted in minor reductions in growth on some sites, but that whole-tree harvesting vary rarely reduced tree growth (Holub et al. 2013; Scott et al. 2014; Curzon et al. 2014). One exception of this occurred on sites inherently deficient in phosphorus in Louisiana, Mississippi, and Texas (Scott and Dean 2006; Scott 2016). Other trials in the United States have similarly shown little, if any, response in changes to a site's productivity or to most mineral soil properties (Johnson et al. 2002; Roxby and Howard 2013; Jang et al. 2015); when responses do occur they are highly site specific.

While empirical evidence indicates that biomass harvesting in the United States will not cause widespread or severe reductions in productivity due to decreases in fertility or soil porosity, few studies have examined long-term (rotation-age or longer) results or results from repeated biomass harvests. Thus, a cautionary approach has been suggested by most reviews (Janowiak and Webster 2010). In addition, there are some regional-, soil-, and forest-specific concerns. For example, some forests in the eastern United States are at a relatively high risk of calcium loss from harvest (Adams et al. 2000; Huntington 2000). The loss is due to low-calcium geologic parent materials, decades of acid precipitation that have leached much of the natural calcium capital from the soil, and, in the southeastern United States, the high degree of weathering. In southeastern pine forests, certain geologies are markedly low in phosphorus and routinely fertilized to overcome their natural deficiency and to avoid induced deficiency by harvest removals. Nitrogen is a limiting factor throughout the United States, with the exception of the Northeast. However, in dry or cold forests where nitrogen cycling is retarded due to climate, nitrogen losses in harvested materials may substantially reduce productivity by lowering decomposition and nitrogen-mineralization rates. Continued research is needed to identify specific forest and soil types where nutrient removals may exacerbate potential deficiencies or where soil disturbance from biomass harvesting will not be sustainable (Vance et al. 2014; Vadeboncoeur et al. 2014).

Based on the ecological and productivity-related roles of dead woody debris and the fact that some timberland owners may not want or be able to fertilize, in order to mitigate potential productivity loss from increased nutrient removals, some level of organic matter should be retained to protect these functions. Some of the material may be present in a stand prior to harvest, while some is created as logging residue or by density-induced natural mortality.

Because dead wood is important in many complex functions, and the amount needed to perform these functions varies widely across climatic, geologic, edaphic, and vegetation gradients, a single retention percentage should not be used as an actual guideline. Rather, retention guidelines should be developed at state-to-local geographic scales, by forest type, and by harvesting intensity. Several states and the two largest certification programs in the United States (Sustainable Forestry Initiative® and Forest Stewardship Council) have released guidelines that address the productivity and ecological functions of dead wood (Evans et al. 2013). Most of the guidelines are for general timberland conditions, with some additional restrictions for special areas, such as critical plant or animal habitat, shallow soils, or steep slopes.

For example, Maine requires all coarse woody material that exists prior to harvest to be retained after harvest and at least 20% of the logging residues with less than 3-inch diameters should be retained. Minnesota recommends that 20% of the logging residues be retained and scattered throughout the harvest tract. Wisconsin's guidelines require 5 tons per acre of woody material to be retained, but the material can be derived from either logging slash or woody material present prior to harvest. Pennsylvania's guidelines call for 15%–30% of the harvestable biomass to be retained, while Missouri requires 33% retention. Sensitive sites and soils are also protected. Minnesota suggests avoiding biomass harvesting in areas with threatened, endangered, or otherwise sensitive plant or animal habitats formed within riparian management zones, on certain organic soils, and on shallow soils with aspen or hardwood cover types. In general, the literature and harvest guidelines indicate that a 30% retention rate of logging residues on slopes less than a 30% grade and a 50% retention rate on steeper slopes are reasonable and conservative estimates of the amount of material needed to maintain productivity, biodiversity, and carbon sequestration and to prevent erosion and compaction.

For the United States, Janowiak and Webster (2010) offer a set of guiding principles for ensuring the sustainability of harvesting biomass for energy application. Others (Vance et al. 2014; Gollany et al. 2015) offer strategies for continued research. These principles include:

- Increasing the extent of forest cover, including the afforestation of agricultural, abandoned, and degraded lands, as well as the establishment of plantations and short-rotation woody crops
- Adapting forest management to site conditions by balancing the benefits of biomass collection against ecological services provided (e.g., old-growth forests provide ecological services and habitat benefits that greatly exceed bioenergy benefits); using best management practices
- Retaining a portion of organic matter for soil productivity and deadwood for biodiversity; considering forest fertilization and wood-ash recycling
- Using biomass collection as a tool for ecosystem restoration where appropriate.

When these principles are applied through state-based best management practices or biomass-harvesting guidelines or certification, biomass harvesting can be sustainably practiced with reduced negative impacts on the environment, and harvesting can be a much-needed tool for achieving forest health-restoration objectives.

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