Technical Assumptions

The technical section offers detailed information about the derivation of the input values given in the student manual. There is no direct need for the instructor to be familiar with these derivations, but they are provided so that there is some understanding of the uncertainty of the values and so that an instructor may read directly from the technical literature, if desired, to learn more about the source of these numbers. Sensitivity analysis, changing a particular parameter and observing the effect on the overall results, is a key part of this type of modeling, and instructors are strongly encouraged to help students make changes to the base model and examine the impact. However, note that in many cases some values are linked together in subtle ways. For example, assuming a higher than normal yield for a given year would increase the yield in the spreadsheet but would then also increase the greenhouse gas emissions and energy needed for transporting the crop from field to processing plant. Open discussion with students about these points and what modifications are needed is encouraged.

The following sections describe the derivation of crop yields, energy content, and energy inputs for the production of cellulosic biomass. Values are reported for three crops, *diverse prairie grasses* (DP), *switchgrass* (SG), and *corn stover* (CS). Note corn stover results are for corn stover alone. Calculations for corn grain ethanol are included in the *results summary*, as well as the *model answer key excel file* and comparison guide. These numbers should technically be combined with corn stover results as most fields would be used for both purposes. Corn grain is used for a variety of purposes other than ethanol, however, and the overall corn LCA will vary based on grain use.

Assumptions for Energy Model

Crop Yields

The table in step three of the student manual lists yield per hectare for the three energy crops. [DP] The value for diverse prairie (3860 kg/ha) is the depleted soil value from Tilman, et al [1]. This value is from the "Net Energy Balance of Prairie Biomass" section and is based on work done at the Cedar Creek study area in Minnesota. Tilman, et al [1], also report yields for fertile prairie as much higher, 6000 kg/ha. In this case, the energy inputs for crop production increase by about 16 %. As a possible variation after base case modeling is complete, this higher yield can be used, with each input value in stage one multiplied by a factor of 1.16.

[SG] The value for switchgrass (11,200 kg/ha) is the average US yield reported by Sokhansanj, et al [2], in the "Introduction and Objectives" page. Note that the baseline yield for various regions of the country are given in Table 1, and that the range is given in the text as 4500 kg/ha in the Northern Plains to 23,000 kg/ha in Alabama, indicating considerable variability depending on region. ** As a very rough estimate for local variation, any yield in this range could be used. "Chemical application" and fertilizer" inputs in the following sections could be scaled in linear fashion (though they are not likely to be truly linear) by dividing the desired yield by 11,200 kg/ha and then multiplying the inputs in those sections by the resulting ratio.

[CS] The corn stover value is based on an aggressive removal rate of 70% of stover, which Sheehan, et al [3], indicate is possible for no-till cultivation. The value in the table is derived by taking values from the last paragraph of the "Constraining Residue Removal Based on Soil Erosion" section of the Sheehan [3] paper. Specifically, 40,000,000 metric tons of residue available on 4.8 million hectares indicates 8.33 metric tons of residue per hectare. Removing seventy percent allows for collection of 5830 kg/ha. Under more significant restrictions for conventional till, only forty percent of stover could be removed, so the yield per hectare could drop as low as 3,330 kg/ha. Lower stover removal would require less energy for fertilizer replacement and transportation to a processing plant. Roughly estimating these effects are linear suggests that the "chemical application" and "transportation" inputs for corn stover production could be multiplied by 0.57 for the lower yield of 3,330 kg/ha.

**Note that changing the crop yield will have impacts in fertilizer requirements since the amount of fertilizer is in part based on the amount of nutrient removal with the energy crop. A significant energy impact is also seen where a larger yield per hectare requires more fuel per hectare to transport the crop to the processing plant.

Energy Inputs

Energy inputs are divided into two stages, crop production and transportation (stage 1) and crop processing (stage 2). Stage one values are reported in MJ/ha and stage 2 values are reported in MJ/kg of feedstock.

Stage 1—Crop production and transportation

Planting:

[DP] Diverse prairie seed for degraded prairie is listed as 134 MJ/ha annually by Tilman, et al

[1] (table S2 of supporting online material). Adding energy for initial planting and dividing this across an expected thirty-year lifetime brings the total to 171 MJ/ha.
[SG] Sokhansonj et al [2] give the annual energy production input for switchgrass seed to be 20 MJ/ha (this seems small compared to the prairie seed; see note in paper just before table 4). Adding energy for operating equipment for planting brings this total to 138 MJ/ha.

[CS] Since corn stover is a residue left over from grain corn, no additional energy input is allocated for seed as no additional planting is needed to produce this crop.

Chemical Application:

[DP] Tilman, et al [1], give "pesticide and fertilizer production and distribution" as 103 MJ/ha for diverse prairie (table S2). It seems from the note below the table that this is for production and delivery of fertilizer and pesticide to the field, excluding application.

[SG] In table 4, Sokhansonj, et al [2], give separate figures for fertilizer (5007 MJ/ha) and a composite pesticide and herbicide category (1998 MJ/ha). Summing these figures allows for a total agricultural chemical input of 7005 MJ/ha. It seems that application may be included in this figure.

[CS] Corn stover is assumed to have additional chemical costs since removing the stover also removes nutrients. Sheehan, et al [3], report the nitrogen, phosphorus, and potassium content of corn stover. For purposes of preventing soil erosion, Sheehan, et al [3] report that, even if all crop management was converted to no-till planting, 30 % of corn residue must remain in the field for erosion prevention. The same study reports 40 million metric tons of stover produced on 4.8 million hectares of land in Iowa, resulting in a yield of 8.33 metric tons per hectare, of which 5.83 metric tons can then be harvested. In the same study, Sheehan, et al, give weight percent of nitrogen (0.45%), phosphorus (0.08%), and potassium (0.76%) in corn stover (table 3). Multiplying these percentages by stover removal of 5.83 metric tons per hectare gives estimates of the amount of fertilizer needed to replace nutrients because of stover collection. In this case, this results in a need for 26.2 kg nitrogen fertilizer, 4.66 kg phosphorus fertilizer and 44.3 kg potassium fertilizer. Using energy requirements for fertilizer production and distribution from Hill, et al [6] (supporting information table 1), it is possible to calculate a total energy cost for fertilizer necessary to replace nutrients lost with the stover. Final calculations are summarized in table 1 below. The overall energy cost for fertilizers needed to produce the collected corn stover then totals to approximately 1660 MJ/ha.

Table 1. Energy requirement for corn stover replacement fertilizer.

Nutrient	Wt percent in stover (%)	Removal with stover (5830 kg/ha * wt percent) (kg)	Energy for fertilizer production and distribution (MJ/kg)	Nutrient replacement energy (MJ/ha)
nitrogen	0.45	26.2	51.47	1350
phosphorus	0.08	4.66	9.17	42.7
potassium	0.76	44.3	5.96	264

Harvesting

[DP] Tilman, et al [1], list the energy cost of planting and harvesting diverse prairie to be 543 MJ/ha. This cost is comprised of an energy input to establish the prairie and annual fuel needs for mowing, baling, and fertilizing. Most of this energy (505 MJ/ha) is used to harvest the biomass while the remainder (37.2 MJ/ha) is the energy cost to prepare the land and plant the prairie in the first year, distributed evenly over an assumed 30 year lifespan. These costs are for reported yields of 3.862 Mg/ha for degraded prairie. There is additional energy needed to move bales on and off of the tractor trailers used to haul them to the processing plant. At 24 L/ha of diesel (note to table S2) with diesel counted as 36.6 MJ/L, this adds an additional 878 MJ/ha. Assuming most of this value is included in bringing bales from the field to the edge of the field and loading them onto tractor trailers, this will be included in the harvesting inputs and not transportation inputs; it is assumed that this is more consistent with the methods of Sokhansonj, et al [2]. This gives a total harvesting energy cost of 1383 MJ/ha.

[SG] Sokhansonj, et al [2], give much higher energy inputs for harvest. At yields of roughly three times the diverse prairie yields stated in Tilman, et al [1], the harvest energy requirements are given as roughly 290 MJ/Mg which indicates a harvest energy use of 2,900 MJ/ha for yields reported at 10 Mg/ha (figure 7); this correlates to 3,250 MJ/ha for a yield of 11.2 Mg/ha if scaling is linear.

[CS] Sheehan, et al [3] list fuel use for collecting each metric ton of corn stover as a function of the stover yield in figure 7 (p. 129). At a yield of 5.83 t/ha the fuel use is listed as roughly 8.0 L/t. Multiplying the yield per hectare by the fuel volume per ton and the energy content per liter of diesel (from Tilman, et al [3]: 36.6 MJ/L) provides an energy for stover collection of 1700 MJ/ha. Per a note on page 128, this includes the energy necessary to collect large round bales (544 kg each) and stack them at the edge of the field.

Farm Equipment:

[DP] Tilman, et al [1], give embodied energy for farm equipment, allocated over a 30 yr life span for a 240 ha farm, to be 188 MJ/ha annually (table S2).

[SG] Sokhansonj, et al [2] give a similar figure for machinery (table 4) or 182 MJ/ha.

[CS] Corn stover is accounted as 30% of the average of the above values since there is no new equipment needed to plant or cultivate corn land and some equipment (e.g. tractors) will have dual use. Nonetheless, some contribution is required as specialized equipment will be needed for stover collection. The indicated fraction of the average of the above values is 56 MJ/ha.

Transportation:

[DP] Tilman, et al [1], give fossil fuel use for biomass transport as 1,174 MJ/ha, including the staging and loading inputs described above. Removing those inputs, then, gives the transportation energy needs as 293 MJ/ha for diverse prairie.

[SG] Sokhansanj, et al [2] give energy needs for transporting switchgrass from farm to refinery in table 7. At a yield of 10 t/ha transportation energy input is reported as 516 MJ/t for a plant that has more similar (43 km maximum) collection radius to the corn stover and prairie grass plants assumed in this section. Note, though, that the 43 km maximum distance is still significantly less than the 40 km average distance assumed for the other two calculation in this section. These assumptions give a final energy requirement of 5,160 MJ/ha for transportation. This seems unusually high given the scale of transportation energy calculated for the other two biomass sources being considered. Scaling from the value given for corn stover but adjusting for the larger mass of the switchgrass yield provides an estimated transportation energy input of 850 MJ/ha.

[CS] Sheehan, et al [3] do not report fuel costs for transportation of corn stover from field edge to processing facility. Assuming the same distance traveled as the diverse prairie but more mass results in a somewhat larger transportation energy requirement. Tilman, et al [1], indicate loads of 27 bales, each 680 kg, transported 40 km to final destination at a vehicle fuel efficiency of 2.2 km/L. Since Sheehan assumes 580 kg bales the load capacity is scaled here to 33 bales. Stover collection of 5,830 kg/ha dictates roughly 11 bales/ha, so the stover from 3.0 acres can be loaded on one truck. Allocating accordingly, the fuel energy requirement is 444 MJ/ha for transport from field edge to processing plant. This will vary significantly if the average trip distance or vehicle efficiency is different than what was assumed here.

Stage 2- crop processing

The next sections describe the chemical and biological processing needed to produce ethanol and co-products from the feedstocks considered above. Energy inputs are expressed in units of MJ/kg of feedstock, where the mass of feedstock is intended to by on a dry basis.

Conversion Rate

[DP, CS] Conversion rates (liters EtOH per kg dry biomass) vary for different studies and different feedstocks. The table in the student manual gives values that are related to each other in the sense that Tilman, et al [1], assume for diverse prairie the value used by Sheehan, et al [3], for corn stover (0.255 liters/kg); this appears in the Tilman paper [1] in the second paragraph of the "Biomass Conversion to Usable Energy" section.

[SG] The value for switchgrass (0.250 liters/kg) depends on several values. Laser, et al [5], in the "Mass and energy balances results summary" report ethanol yield of 318 liters per dry Mg (0.318 liters/kg) of feedstock, and a total LHV efficiency of 43.3 % (40.4 % EtOH, 2.9 % electricity). Hamelinck, et al [6], indicate a total efficiency (ethanol plus electricity) of thirty-eight percent (HHV) for their base case scenario using hybrid poplar (page 405) and comment that efficiency for switchgrass will be lower due to losses in acid pretreatment particular to the composition of switchgrass. Tilman, et al [1], refer to Hamelinck, et al [8], suggesting switchgrass conversion efficiency (electricity plus ethanol) will be 34 % ("Biomass conversion to Usable Energy" notes). Using this last figure as a conservative estimate of the total (ethanol plus electricity) efficiency and the proportions of ethanol and electricity from the Laser study suggests the following calculation, which adjusts the values from the Laser study for a lower efficiency that is consistent with the source of the conversions rates for the other feedstocks:

(34 % / 43.3 %)*(0.318 liters/kg) = 0.250 liters/kg, very similar to that reported for corn stover and diverse prairie. This calculation ignores small differences for HHV and LHV efficiencies, as the efficiency is a comparison of both the heating value of the starting material and product, both on the same basis. This difference is more significant if an absolute amount of energy is reported.

Note: Projections for mature cellulosic conversion technology [5] suggest that conversion rates of 0.428 L/kg are achievable. Given the chemical similarities of diverse prairie grasses, switchgrass, and corn stover it is unlikely that the conversion rate for any of these feedstocks would be significantly different than the others, though there are some indications that switchgrass might be slightly more difficult to process than some other feedstcks. As a variation, conversion rates for all three feedstocks could be increased to 0.428 L/kg for [DP] and [CS] with [SG] set to perhaps 0.408 L/kg to investigate the sensitivity of the comparison between fuels to conversion rate. An alternative scenario (though impossible due to internal energy needed for conversion) scenario to explore would be increasing conversion rate to 100 % of feedstock energy. Due to differing feedstock energy contents (see "Energy Content of Energy Crops" section at the end of stage 2 inputs) this will result in different conversion rates for different crops: [DP] 0.877 L/kg, [SG] 0.791 L/kg, [CS] 0.853 L/kg.

Pretreatment

[DP] Detailed energy accounting is not available in the literature for diverse prairie biomass processing, with most estimates assuming it to be similar to switchgrass. In Tilman, et al [1], two studies are references for cellulosic biomass conversion, Sheehan's [3] study of corn stover and Hamelinck's study of hyrbrid poplar [8]. Assuming the diverse prairie to be converted in the same general facility type as switchgrass, energy inputs for switchgrass processing will be used as estimates for diverse prairie processing. In this case, energy input for producing chemicals for pretreatment of feedstock is 1.13 % of fuel LHV, equal to 0.189 MJ/kg for biomass valued at 16.7 MJ/kg.

[SG] 0.189 MJ/kg; see comments immediately above for [DP].

[CS] Corn stover similarly is modeled in a facility that uses biomass to generate electricity and heat to avoid external inputs to biomass processing. Sulfuric acid is needed for pretreatment, and the energy is listed as less than one percent of the energy of the feedstock. Sheehan, et al [3] report 2000 dry metric tons feedstock per day and an energy input of 358 Mkcal/hr. This converts to about 1.5 million MJ per hour which, divided by the hourly mass flow rate (2,000,000 kg/24hr) yields an energy content of 18.0 MJ/kg. Therefore, the unit mass input for pretreatment chemicals becomes 0.1 MJ/kg.

Hydrolysis and Fermentation

[DP] Similar to pretreatment, the external energy input required for hydrolysis and fermentation is small since heat and electric power are produced using waste material from the hydrolysis and fermentation. Enzymes as external input appear to be 2.18 % of the LHV of the biomass feedstock for the switchgrass, so that value (16.7 MJ/kg * 0.0218) will be used for both diverse prairie and switchgrass: 0.364 MJ/kg.

[SG] 0.364 MJ/kg; see comments immediately above for [DP].

[CS] Sheehan, et al [3] describe a facility through which input corn stover is used to produce enzymes to make cellulase for hydrolysis. Since heat, power, and raw materials are thus derived from corn stover, the external energy input is zero for this stage. However, this difference from processing for the other feedstocks results only from the specific system design for Sheehan's study, and not necessarily from inherent differences in the processing needed for the feedstock. Assuming that the enzymes needed are different in each case, the energy required to produce them could still be similar. Additionally, if the corn stover processing plant were to not make enzymes on site, it would require an external input at this stage but might have a higher co-product production if resources were not diverted to enzyme production. As a result, the same value will be used at this stage for energy input, and, as an approximation, the same amount will be added to what Sheehan reports for co-product energy in a later stage: 0.364 MJ/kg.

Ethanol Separation

[DP] As is seen above for processing plants of this kind, heat and power are derived internally from biomass residue left after hydrolysis and fermentation, so even though considerable heat and power are used to separate the ethanol from the fermentation mixture, the inputs are all internal: 0 MJ/kg.

[SG] 0 MJ/kg; see immediately above for [DP].

[CS] 0 MJ/kg; see first entry in this section for [DP].

Co-Products

[DP] Hill, et al [1], report electricity as a co-product in an amount equivalent to 9.0% of the energy content of ethanol product. With ethanol at 21.1 MJ/L and a yield of 0.255 liters of ethanol per kg of feedstock, this indicates electricity production equivalent to 0.484 MJ/kg relative to the amount of feedstock.

[SG] Laser, et al [5] report net electricity production as 2.96 % of switchgrass energy content, resulting in 0.494 MJ/kg electricity co-production for a switchgrass energy content of 16.7 MJ/kg (see next section). Alternatively, Laser, et al [9] separately report a different feedstock processing pathway which would produce electricity and a protein animal feed that also can be assigned an energy value. These values are 0.346 MJ/kg electricity and 1.38 MJ/kg protein animal feed, for a total co-product of 1.73 MJ/kg.

[CS] Sheehan [3] reports byproduct electricity equal to 4.5 % of the total feedstock energy input. For a corn stover energy content of 18.0 MJ/kg (see next section) this dictates electricity export at a rate of 0.81 MJ/kg. Adding to this 0.364 MJ/kg that in the current model is not diverted for enzyme production (see hydrolysis and fermentation above) yields a total co-product of 1.17 MJ/kg.

Energy Content of Energy Crops

The fuel energy in the ethanol produced can be compared to the total energy in the feedstock using the average energy content of the different feedstocks, given below.

[DP] Tilman, et al [1] assume an energy content of 18.5 MJ/kg in dry diverse prairie grasses.

[SG] Laser, et al [5] report the energy content of switchgrass as 16.7 MJ/kg.

[CS] Using values from Sheehan's daily rate of corn stover input (2000 Mt/day) and hourly energy input (358 Mkcal/hr) it is possible to derive an energy content for corn stover: 18.0 MJ/kg.

Alternate Energy Scenarios

Significant improvement and understanding of how this life cycle model works can be made when assumptions used in the base case are changed. Assumptions could be certainly changed at the discretion, intuition, and further research of the teacher. The comparisons appear in a separate document, but the assumptions used to develop them is summarized here.

Information gathered from various researchers at GLBRC was used to derive several scenarios for comparison with the base case data outlined above. Summary notes that informed those scenarios follows:

It seems difficult to estimate variation in crop yield based on amount of precipitation. Yield is a complex combination of climate, soil, aspect, history, and time. It is possible to estimate reduction in corn stover based on reported reduction in corn grain for dry years, but only to a very limited extent. A counter-example was given indicating that early dry conditions could lead to small amounts of stover but high amounts of grain if adequate rain falls later in the growing season. Adequate rain early could lead to tall plants producing large amounts of stover but little corn grain if conditions later are dry.

Timing of rainfall for growth of switchgrass is very important, rather than the actual amount of rainfall; early season rains are critical. Variation is expected with biomass yields--swings up or down 50 to 100 percent is not abnormal from year to year. Nitrogen availability can be limiting, as well.

Variation in diverse prairie would likely closely match that of switchgrass in dry conditions. Even though diverse prairie, as a mixture of species is considered by some people to be more drought resistant than a switchgrass monoculture, in actuality most of the biomass productivity results from only a few species that are similar to switchgrass.

Two studies that examine yield variation, could be reviewed for more information: Schmer, et al, PNAS 2008; Adler, et al, Agronomy Journal 98:1518–1525 2006.

Works Cited:

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7. Laser, M, Jin, H, Jayawardhana, K, Dale, B, and Lynd, L. 2009. “Projected mature technology scenarios for conversion of cellulosic biomass to ethanol with co-production thermochemical fuels, power, and/or animal feed protein”. Biofuels, Bioproucts & Biorefining 3:231 - 246.

Assumptions for Greenhouse Gas Emission Model

(Numbers correspond to the *system boundary diagram* on page 19.)

1- Seed:

[CS]- The GHGs associated with the production of seed have been allocated to the corn grain. If the need for the corn grain did not exist, then the corn would not have been planted. Moreover, no additional planting steps are required for the corn stover.

[SG]- Monti et. al. [1] suggests that 8 kg of SG seed is required per ha. When Monti et al. conducted their study, they assumed the production cost of producing SG would be similar to the production of rye grass. I used GHG emission factors given by the GaBi software for the production of rye grass to get an estimation of the GHG emissions emitted by producing and distributing SG seed. The GHG emissions associated with 1 kg of SG are 9.82 X 10-4 kg CO_2eq. However, if we assume that a SG plot takes 2 years to establish and is harvested for 10 years, then the cost of the GHG emissions must be spread out over twelve years.

[DP]- Tilman et. al. [2] report an energy value for the production and distribution of diverse prairie seed to be 134 MJ/ha. I assume that the prairie seed must be collected by hand and that cars must be driven to existing prairies in order for the collection to occur. I then used the GHG emissions associated with the production, distribution, and combustion of gasoline. When combusted, 1 kg of gasoline produces 44.1 MJ. According to the BESS [3] model the 1MJ from the combustion of gasoline produces 69 gCO_2eq. If we add this value to the GHGs emitted from producing and distributing gasoline (1 kg gasoline = 0.755 kgCO_2eq) [4] and then divide the total by 30 (the assumption being that the prairie will last for 30 years), we get the GHG value for prairie seed production.

2- Planting:

[CS]- Again, I have allocated all GHGs associated with the planting of corn to the corn grain.

[SG]- According to Sokhansanj et. al. [5], 0.182 GJ per 1000 kg dry SG are needed for planting SG. This energy results from the combustion of diesel fuel. The combustion of 1 GJ of diesel produces 74.01 kgCO_2eq [3]. Also, the production of diesel must be taken into account. There are 43.1 MJ/kg diesel, and 1 kg of diesel production and distribution produces 0.517 kgCO_2eq [4]. Since SG takes two full years to establish and and is productive for 10 years, we need to divide the planting value by 12 to account for one planting every 12 years.

[DP]- According to Tilman et. al. [2], planting a diverse prairie requires 30.5 L of diesel fuel. The energy density of 1 L of diesel is 36.6 MJ. The production assumptions for diesel include: 43.1 MJ/kg diesel, and 1 kg of diesel production and distribution emits 0.517 kgCO_2eq [4]. The combustion of 1 GJ of diesel produces 74.01 kgCO_2eq [3]. The diverse prairie will exist for 30 years so each of these values were divided by 30.

3- Nitrogen Fertilizer:

[CS]- If CS is removed from the field, more nitrogen (N) must be applied in subsequent years to replace the N in the CS that was removed. In order to determine how much of the GHG emissions should be attributed to the production of CS, I have allocated based on the percent of N in the dry CS removed from the field. For example, if 1000 kg CS are removed from the field and 0.45% of CS is N by mass, then 4.5 kg of N were removed from the field. Therefore, the GHG emissions associated with the production of 4.5 kg of N would be allocated to CS production. The production of one kg of general N fertilizer emits 1.96 kg kgCO_2eq [4].

[SG]- Spatari et al. [6], assumes that 0.0117 kg of N fertilizer will be applied for each dry kg of SG harvested. One kg of general N fertilizer produces 1.96 kg kgCO_2eq [4].

[DP]- No nitrogen fertilizer would be applied to a diverse prairie. Establishing a diverse prairie is difficult due to opportunistic weed species that thrive in high N soils. As a result, an annual crop such as Round-up ready corn would be grown the year before establishment in order to eliminate weed species growth and to reduce N in the soil. Once established, prairie species would receive N through natural means, such as via leguminous forbs that fix nitrogen from the atmosphere.

4- Phosphorus Fertilizer (DAP = diammonium phosphate):

[CS]- The same allocation technique used for N fertilizer was applied to P fertilizer. According to Sheehan et. al. [7], P represents 0.08% of the mass of CS. The production of one kg of DAP emits 1.61 kgCO_2eq [4].

[SG]- Spatari suggests that 0.00016 kg of P fertilizer is applied for each kg of dry SG harvested.

[DP]- Tilman suggest that 0.0002 kg of P fertilizer is applied for each kg of dry DP harvested.

5- Potassium Fertilizer:

[CS]- The same allocation technique used for N fertilizer was applied to K fertilizer. According to Sheehan et. al. [7], K represents 0.76% of the mass of CS. The production of one kg of K fertilizer emits 0.531 kgCO_2eq [4].

[SG]- Spatari assumes that 0.00025 kg of K fertilizer is applied to the field for each kg of dry SG harvested.

[DP]- No mention of K fertilizer was made for DP by Tilman. Therefore, I have assumed K application to be zero.

6- Pesticide (general):

[CS]- Spatari [9] does not account for pesticide use in her LCA for CS. I am assuming that they may be assuming Bt- corn which naturally produces anti-pest compounds. Therefore, I assume no pesticides are applied to corn fields. Furthermore, if pesticides were applied, they would be allocated completely to the corn grain.

[SG]- Spatari [9] assumes that 0.000031 kg of atrazine is applied per kg of SG harvested. Atrazine has been banned in parts of Wisconsin, therefore, I have taken a GHG emission value from GaBi for a general pesticide instead of atrazine. The production and distribution of 1 kg of general pesticide emits 7.72 kgCO_2eq.

[DP]- No pesticide application would occur in a diverse prairie. It is thought that the annual mowing of the prairie might simulate the disturbance of fire, thus keeping most unwanted species out of the prairie.

7- Net Primary Productivity:

Net primary productivity is equal to the difference between the rate at which plants in an ecosystem produce useful chemical energy (Gross primary productivity) and the rate at which they use some of that energy during respiration. In this model, we are most interested in the mass of dry feedstock harvested from the field. Perennial plants, such as SG and DP plants, sequester significant amounts of carbon in their roots but, there is great debate in the LCA community about the biosequestration of carbon and how to do the accounting for the CO_2 [8]. The debate centers around one question: How long does the carbon need to be sequestered in order for it to be counted as sequestered? Roots of living plants grow, die and decompose thoughout the plant's lifetime. Sinistore notes that many LCAs do not account for carbon sequestration in plant root biomass due to lack of available and generalizable data. Research does exist on the rate of carbon sequestration in soils by perennial plants such as SG and DP plants. However, the predictability and the reliability of these data types would introduce too much variability into the overall analysis and capturing that variability is outside of the scope of this LCA.

8- Harvesting:

[CS]- Currently, harvesting CS requires a two-pass system, even though there are combines that have been invented to collect CS and corn grain simultaneously. According to Sheehan, 0.293 GJ of diesel are required for harvesting CS per 1000 kg dry CS. Diesel production assumptions include an energy density of 43.1 MJ/kg diesel, and 1 kg of diesel production and distribution emits 0.517 kgCO_2eq [4]. The combustion of 1 GJ of diesel produces 74.01 kgCO_2eq [3].

[SG]- According to Sokhansanj, 0.290 GJ of diesel are required for harvesting SG per 1000 kg dry SG.

[DP]- I have made the assumption that, since the method for harvesting DP is virtually the same as havesting SG, 0.290 GJ of diesel are required for harvesting DP per 1000 kg dry DP.

9- Transportation to the Ethanol Plant:

[CS]- To stay consistent with the energy portion of the model, the average round trip for the transporation of CS is 80km. The efficiency of a Class 8b heavy-duty truck is 2.1 L of diesel per km. According to Sheehan, 1 bail of CS has a mass of 580 kg and 17 bails can be transported per trip. The density of diesel is 0.832 kg/L, and 1 kg diesel contains 43.1 MJ. Each GJ of diesel released from combustion gives off 74.01 kgCO_2eq. For each kg of diesel produced and distributed, 0.517 kgCO_2eq are produced.

[SG]- According to Sokhansanj et. al. [5], the average round trip for the transporation of SG is 80km. I make the same assumptions for SG as I did for CS.

[DP]- According to Tilman et al [2], 1 bail of DP has a mass of 680kg and they also report that each trip can hold 27 bails. I then used the same assumptions from above about vehicle efficiency, density of diesel, diesel energy costs, and GHGeq.

10- Pretreatment and Hydrolysis:

Methodology followed: NREL-SSCF

NREL = National Renewable Energy Lab

SSCF = Simultaneous Saccharification and Co-fermentation—where enzymatic hydrolysis and fermentation happen in the same tank (instead of 2 separate tanks)

Heat to dry the feedstock comes from LPG (liquified petroleum gas). Spatari assumes 0.2 kg of LPG is consumed per 1 kg of feedstock. The production and distribution of 1 m3 of LPG emits 283 kgCO_2eq. The density of LPG is 2.155 kg/m3. The combustion of LPG emits 63.1 kgCO_2eq per 1 GJ. One kg of LPG contains 46.1 MJ.

MacLean and Spatari [9] assume the use of near-term NREL-SSCF technology, which requires dilute sulfuric acid for pretreatment of the feedstock and enzymes for enzymatic hydrolysis. They assume that 0.026 kg of sulfuric acid is required to treat 1 kg of feedstock. The production and distribution of 1 kg of sulfuric acid emits 0.279 kgCO_2eq.

According to MacLean and Spatari [9], the production of cellulase is not easily understood due to proprietary issues surrounding their production and various different methods for producing the different cellulases. However, the authors suggest that the production and distribution of 1 kg of cellulase emits 2.264 kgCO_2eq.

11- Neutralization:

The acidic solution produced after pretreatment requires neutralization before the enzymes can be introduced to hydrolyze the cellulose and yeast can be introduced to ferment the resulting sugars.To do this, NREL-SSCF uses a lime solution. Spatari [9] assumes 0.029 kg of lime is required for each kg of feedstock. The production and distribution of 1 kg of lime emits 0.928 kgCO_2eq.

12- Fermentation:

In the fermentation process, yeast ferment the sugars released during hydrolysis, and generate ethanol and carbon dioxide as waste products. DAP can be used both as a buffer for neutralization and as a nutrient for the yeast. 1 kg of DAP emits 1.61 kgCO_2eq [4].

13- Separation:

We assume, as Spatari [6] does, that the heat created from the combustion of the residual, unfermented biomass (such as lignin and other sugars) will be used for distillation and no fossil fuel energy sources will be needed for separation. Many of my mentors highly doubt that there would be no additional fossil energy burned for separation. However, since multiple published papers make this claim, I have also used this assumption.

14- Energy Co-Production:

One of the most controvertial assumptions I dealt with conducting this LCA centered on the electricity co-product. Since lignin is not digested during the NREL-SSCF near-term process and because some sugars such as arabinose, mannose, and galactose remain in the mixture after distillation, this resulting syrpy solution can be burned in a Rankine electricity generation cycle. The heat generated from the combustion of the slurry heats water which forms steam which is then passed through a turbogenerator to produce electricity. According to a set of complex equations derived by Spatari [6], some of the electricity is used for all of the workings of the ethanol plant, an excess of electricity is also generated. The excess electricity, reported to be 2.5 kWh/L EtOH, can then be sold back to the grid. The electricity sold back to the grid displaces electricity that otherwise would have been produced by a mixture of fossil fuels, nuclear, hydro, wind and other power sources. As assumed by Spatari, I used the US national electricity grid mix to determine the amount of CO_2eq displaced by the burning of residual biomass from cellulosic ethanol production. The electricity from burning the biomass displaces fossil CO_2eq and results in a credit, or negative number in the model. One kWh is equal to 3.6 MJ and 1 MJ of electricity from the US national electricity grid mix emits 0.749 kgCO_2eq.

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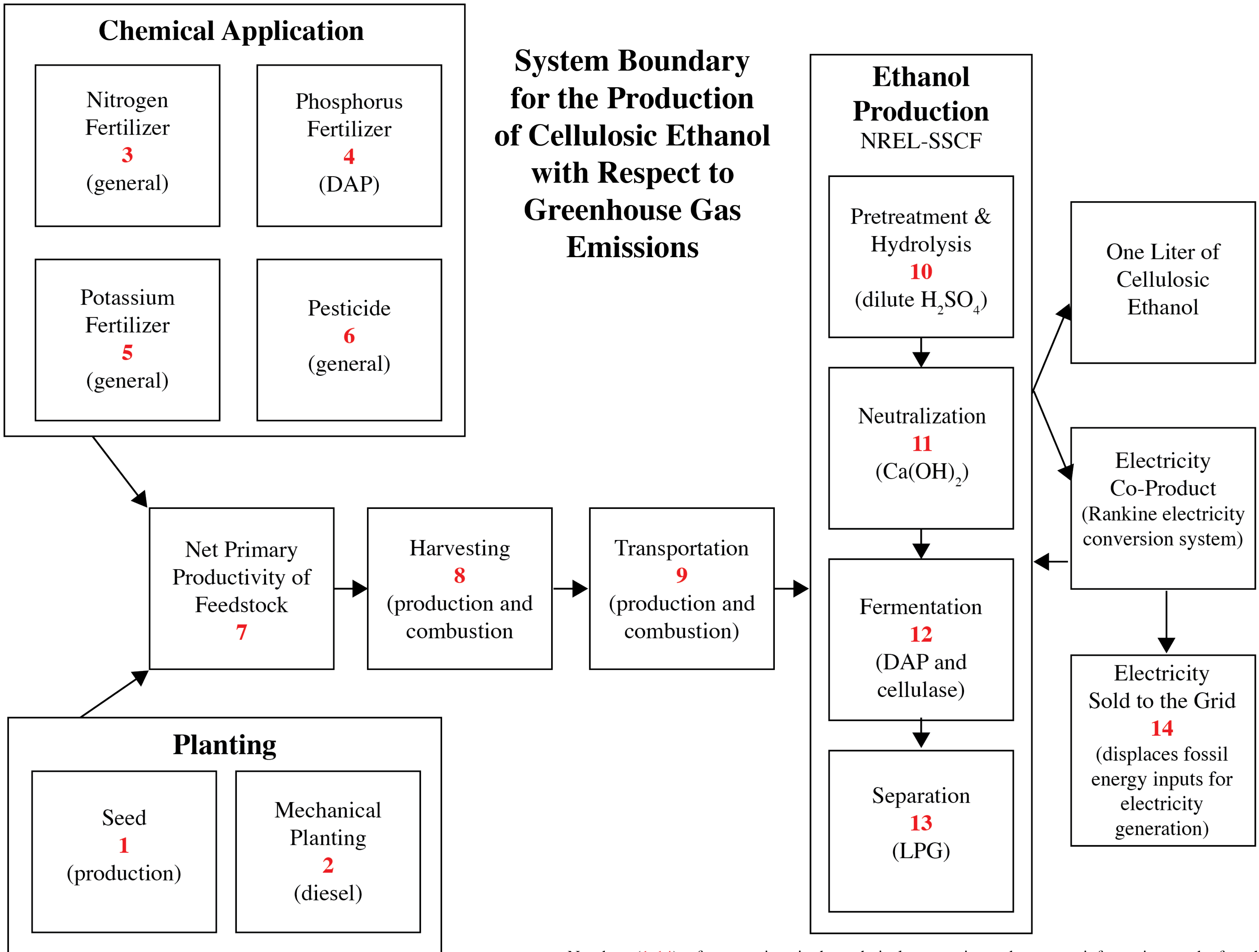

Numbers (1-14) refer to sections in the technical assumptions where more information can be found.