Analysis of Lifecycle Water Requirements of Transportation Fuels: Corn-based Ethanol - Model Description

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Abstract

This document describes the methodology and data sources for the "Analysis of lifecycle water requirements of transportation fuel: corn based ethanol – model version 2.0". The model estimates blue water (surface and ground), and green water (precipitation) requirements for ethanol from corn grain and corn cob (crop residue) based on default or user inputs of crop evapotranspiration, pre-irrigation water requirements for salt leaching and crop establishment, irrigation methods and the efficiencies of conversion technologies, and projected crop yields. Water requirements also depend upon procedures adopted for calculating co-product credits at various stages of the lifecycle. The model characterizes water requirements in terms of withdrawal and consumption; and source – ground water, surface water, precipitation, and soil moisture.

The spreadsheet based model is available at http://www.its.ucdavis.edu/download/UCD-ITS-RR-10-11.xls

The model is part of a series exploring water footprint of future transportation fuels including biofuels and electricity. Other models currently under development examine the lifecycle water requirements of electricity from geothermal resources and concentrated solar power, and biodiesel from soybeans.

Acknowledgement

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Notations

AE	Application efficiency of irrigation system
AWR	Applied water requirement
BR	Bio-refinery water requirements
CWR	Crop water requirements
CIMIS	California Irrigation Management Information System
CUP	Consumptive Use Program
ET	Evapotranspiration (inches)
ET_o	Reference evapotranspiration (inches)
ET_c	Crop specific evapotranspiration (inches)
ET_a	Applied or irrigation water portion of crop specific evapotranspiration (inches)
E_e	Embodied water of energy inputs
EtOH	Ethanol
IWR	Irrigation water requirements
K_c	Crop coefficient
P_s	Portion of crop specific evapotranspiration met by precipitation during crop growing season
P_{os}	Portion of crop specific evapotranspiration met by soil moisture (which is related to precipitation during off season)
SL	Pre-irrigation water required for salt leaching
SBM	Soybean meal
SBH	Soybean hull
SO	Soybean oil
L_a	Irrigation application losses
L_c	Conveyance losses
USDA	US Department of Agriculture
USGS	US Department of Geological Survey
VMT	Vehicle miles traveled

1 Model objectives

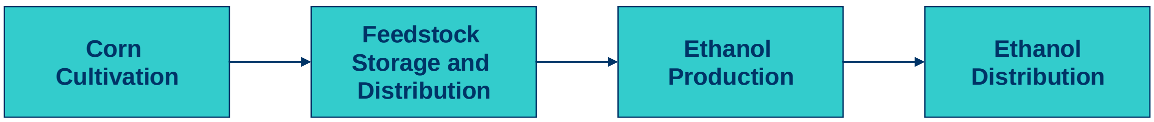
The "Model for lifecycle water analysis of corn-based ethanol" (model) estimates blue (surface/ground) and green (precipitation and soil moisture) water requirements to produce ethanol from:

- corn grain
- crop residue (corn cob)

2 System boundary

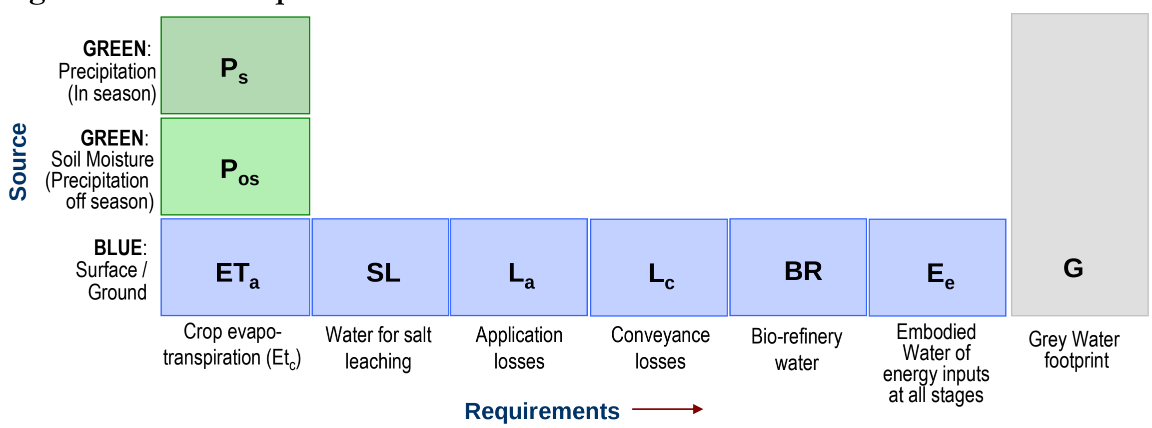
The model adopts a lifecycle perspective and considers water requirements from corn cultivation, feedstock storage and transport, ethanol production at the bio-refinery, to ethanol distribution. The following figure summarizes water requirements included in this study:

Figure 2.1: Lifecycle perspective for ethanol from corn



2.1 Water requirements considered

Figure 2.2: Water requirements of ethanol from corn



The above figure summarizes the sources of water along the vertical axis and requirements for water considered in our study along the horizontal axis. Grey water demand is not included in our analysis.

2.1.1 Sources of water

The focus of this study is freshwater use – water with low concentrations of dissolved solids[1]. Freshwater is further classified as blue and green water, where blue water represents surface and ground water and green water represents precipitation and soil moisture (Gerbens-Leenes, Hoekstra et al. 2009). We do not consider grey water use which is a measure of pollution and is measured by the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards.

[1] Per US Geological Survey (USGS 2010), freshwater has concentration of total dissolved solids (TDS) of less than 1,000 mg/L. Water with increasing levels of dissolved solids are classified as lightly saline (1,000 - 2,000 mg/L), medium saline (3,000 - 10,000 mg/L), and highly saline (10,000 – 35,000 mg/L).

- **Green water**

Green water usage represents the consumptive use of precipitation (Gerbens-Leenes, Hoekstra et al. 2009). We also include the depletion of soil moisture in our definition of green water usage. The net change in soil moisture content during a crop season represents use of off-season precipitation, and hence is included under green water.

As summarized in Figure 2.2, we consider green water use only with respect to evapotranspiration requirements of crops.

- **Blue water**

We adopt the following two indicators of blue water usage – withdrawal and consumptive use ((Owens 2001; Bayart, Bulle et al. 2010). *Water withdrawal* is the removal from a natural surface water body or groundwater aquifer for industrial, agricultural or domestic usage. C*onsumptive use* denotes the use of freshwater when it is not released into the same watershed because of evaporation, product incorporation, or evapotranspiration by crops. Discharge into different watersheds or the sea, and sinking to a deep salt sink is also counted under consumptive use. The difference between withdrawal and consumption represents *non-consumptive use* of water and is referred to as *water released*.

Table 2.1: Consumptive & non-consumptive water requirements of ethanol

Water requirement	Consumptive use or loss	Non-consumptive use or loss
Cultivation Stage		
Crop evapotranspiration (ET_c)	ET of applied water	
	Effective precipitation (P_s) and soil moisture depletion (P_{os})	
Salt leaching (SL)		Deep percolation below the root zone
Application losses (L_a)	Evaporation from soil surface, open ditches and crop canopy	Run-off and seepage losses
	Drift losses (sprinkler system)	
Conveyance losses (L_c)	Evaporation from open canals	Seepage losses
	ET by vegetation in and around canals	
Ethanol production stage		
Bio-refinery (BR)	Process water	
	Cooling tower evaporation	Cooling tower blowdown
All stages		
Embodied water of energy inputs (E_e)	Water consumption during production of fuels – diesel, electricity, etc – used across the lifecycle	Not considered

The water requirements considered in Figure 1 are described below.

- Crop evapotranspiration (ET_c)

ET_c constitutes the greatest proportion of water requirements for bio-ethanol production. ET_c is computed in a two steps. First, reference evapotranspiration (ET_o) is computed using the daily Penman-Monteith equation. ET_o measures the evaporative demand of the atmosphere and is independent of crop type and crop development. It depends upon four climatic parameters: solar radiation, ambient temperature, dew point temperature or relative humidity, and wind speed. Crop specific evapotranspiration (ET_c) accounts for differences in leaf anatomy, stomatal characteristics, aerodynamic properties and albedo, all of which cause the crop evapotranspiration to differ from the reference crop evapotranspiration under the same climatic conditions. Further, due to variations in the crop characteristics throughout its growing season, ET_c changes from sowing till harvest. The model uses a crop coefficient (K_c) to calculate ET_c using the following relationship:

$$ET_c = K_c \times ET_o \qquad \text{(Equation 2.1)}$$

where,

ET_c is crop specific evapotranspiration
K_c is crop specific coefficient
ET_o is reference evapotranspiration

Demand for crop evapotranspiration is met through three sources:

$$ET_c = P_s + P_{os} + ET_a \qquad \text{(Equation 2.2)}$$

where,

P_s is precipitation during the crop growing season (green water)
P_{os} is the water available from soil profile (green water)
ET_a is irrigation water applied (blue water)

The extent of evapotranspiration requirements met through soil moisture content (P_{os}) depends upon (i) the moisture holding capacity of the soil. For example, silt loams and silty clay loams can hold around 2 inches of water per foot of depth while sandy soils can hold less than 1 inch per foot of depth; and (ii) the root depth of the crop concerned[2].

P_s captures "effective" precipitation which is equal to total precipitation during the season minus any losses due to runoff or deep percolation.

- Water required for salt leaching (SL)

Prior to spring planting of corn, pre-irrigation water is often applied to flush excess salts through the soil ((Wichelns, Horner et al. 1987; Wichelns, Houston et al. 1996), and to avoid crop stress during growing season. The amount of water required for salt leaching depends

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2 A detailed description of water from soil profile is available at Broner, I. (2005). Irrigation scheduling: the water balance approach. Crop Series, Colorado State University..

upon precipitation, the irrigation technology and corresponding distribution uniformity, and soil profile. Precipitation during and after the crop season, and excess irrigation water applied in response to irrigation system efficiencies leach salts from the crop's root zone. Here SL refers to net additional irrigation water requirements.

Crop, Application and Irrigation water requirements (CWR, AWR and IWR)

Crop water requirement is the sum of crop evapotranspiration and pre-irrigation water for salt leaching and crop establishment

$$CWR = ET_c + SL \quad \text{(Equation 2.3)}$$
$$= ET_a + P_s + P_{os} + SL$$

AWR is the applied water requirement and is the total water that needs to be delivered to the field or farm

$$AWR = ET_a + SL + L_a \quad \text{(Equation 2.4)}$$

Irrigation water requirement is the total water that needs to be conveyed from the source given the crop evapotranspiration requirement not met by precipitation or soil moisture (ET_a), application inefficiencies (L_a) and conveyance losses (L_c)

$$IWR = AWR + L_c \quad \text{(Equation 2.5)}$$
$$= ET_a + SL + L_a + L_c$$

We assume water withdrawal for salt leaching will be returned back to the source therefore water consumption of SL = 0.

- Irrigation application losses (L_a)

This accounts for inefficiencies in the irrigation system installed to meet the ET_a portion of the crop evapotranspiration.

$$L_a = ET_a \times (1\text{-}AE) \quad \text{(Equation 2.6)}$$

where,

L_a is excess water that needs to be applied over and above ET_a

AE is the application efficiency and lies between 0% and 100%.

There are a number of performance measures (Burt, Clemmens et al. 1997) and these measures are defined differently in the literature. The application efficiency (AE) measure adopted by us is based on Howell (2003) and is defined as the fraction of irrigation required by the crop to the water delivered to the field or farm. Solomon (1988) has identified various sources of water losses as enunciated below. Over-watering is the most significant cause of water loss in any irrigation system. The major losses associated with surface irrigation systems are direct evaporation from the wet soil surface, runoff losses, and seepage losses from water distribution ditches. The losses associated with sprinkler irrigation (other than those due to over-watering) are direct evaporation from wet soil surfaces and crop canopy, wind drift and evaporation losses from the spray, system drainage and leaks. Leaks are also responsible for losses from drip irrigation. Evaporation from soil surface, open ditches and crop canopy accounts for the consumptive portion of L_a. On the other hand, runoff and seepage losses are non-consumptive losses.

As a result of non-consumptive losses associated with irrigation systems, measurement of application efficiencies depend upon the spatial boundary selected for analysis. Efficiency measurements increase as we move from field and farm to a water district or water basin. The difference arises due to two reasons. First, excess water runoff from a farm can be beneficially used in a downstream farm. Second, water released from a farm through runoff or deep percolation might have environmental benefits and hence cannot be considered a loss. As a result, Jensen (2007) questions the use of the term "efficiency" and proposes use of alternative terms like "coefficient" or "fraction."

In this model, application efficiency is considered at a field/farm level.

- Conveyance losses (L_c)

L_c accounts for losses from water supply conveyance systems. As in case of L_a, L_c includes both consumptive and non-consumptive losses. Consumptive losses are primarily due to evaporation and evapotranspiration by vegetation in and near canals; and due to deep percolation to salt sink during conveyance. Non-consumptive losses include water that seep through channels and return as surface flow or recharge groundwater aquifers. This water is not consumed and available for alternative uses including agricultural use.

- Bio-refinery water (BR)

Process and cooling water is required during conversion of feedstock to ethanol. BR_{gr} and BR_{cb} represent bio-refinery water for conversion to ethanol of corn grain and corn cob respectively.

- Embodied water of energy inputs at all stages (E_e)

While the focus of our LCA model is onsite "first-level" water requirements, i.e. direct water inputs during corn cultivation and ethanol production; we also consider "second-level" water requirements as a result of onsite energy inputs. For example, we account for diesel used for corn harvesting and biomass transportation, and electricity and natural gas consumed at the bio-refinery. The corresponding water requirements of these fuels are included to calculate total requirements. We do not, however, consider water requirements for production of materials and equipments, such as fertilizers, pesticides, manufacturing of farm equipment, acids and enzymes for ethanol conversion; nor do we consider the corresponding water requirements for the embodied energy for their production.

For simplicity, we only account for water consumption intensity of energy inputs (water consumed per unit energy input required) and ignore water withdrawal intensity (water withdrawn per unit energy input required). This simplification does not affect the results in a significant way because of two reasons. First, such "second level" water requirements constitute less than 1% of total water requirements because of relatively lower water intensity of conventional fuels. Second, the only energy input with a large difference between water withdrawal and consumption intensity is electricity - 16 gallons/kWh of withdrawal versus 0.5 gallons/kWh for consumption (USGS 1998; USGS 2009). However, electricity consumption is only around 9% of total lifecycle energy consumption for ethanol from dry mill plants; and around 2% for ethanol from wet mill plants (ANL 2010).

- Grey water footprint

Grey water is an indicator of the degree of freshwater pollution that occurs during the entire lifecycle. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards (Gerbens-Leenes, Hoekstra et al. 2009). We do not consider grey water footprint in the current version of the model.

2.2 Feedstocks considered

In addition to ethanol from corn grain, we also analyze water intensity of ethanol from corn stover. A review of recent literature highlighted a number of shortcomings in using the entire corn stover to produce ethanol. These are in the areas of (i) soil protection (Wilhelm, Johnson et al. 2004; Wilhelm, Johnson et al. 2007), (ii) transportation and logistics of feedstock (Atchison and Hettenhaus 2003), (iii) harvesting of feedstock (Atchison and Hettenhaus 2003). Harvesting only the cob portion of stover and excluding the stalk and leaves avoids the above mentioned shortcomings.

2.3 Geographical regions considered

The model may be used for corn production anywhere in the country, and may be used at the level of county, agricultural district or state depending upon availability of data.

In the appendix, we have suggested values for various location specific variables for California (CA), and the following states in the US Corn Belt –Illinois (IL), Indiana (IN), Iowa (IA), Kansas (KS), and Nebraska (NE).

2.4 Functional units

Estimates of water requirements may be expressed as either "intensity" or "productivity" indicators. "Intensity" oriented units have the volume of water in the numerator. The denominator could be (i) volume of the biofuels (Mubako and Lant 2008; Chiu, Walseth et al. 2009; Wu, Mintz et al. 2009), (ii) energy of the biofuel output which in turn could be either the higher heating value or HHV (Gerbens-Leenes, Hoekstra et al. 2009) or LHV, (iii) vehicle distance travelled (King and Webber 2008).

"Productivity" oriented units have the volume of water in the denominator while the energy output in the numerator.

This difference between intensity- and productivity-oriented units to represent water requirements of biofuels is analogous to the two units to represent fuel economy of a vehicle – i.e. miles per gallon and gallons per mile.

In our model, estimates of water requirements are presented in two forms: (i) gallons of water (withdrawn or consumed) per gallon of **un-denatured** ethanol produced, and (ii) gallons of water (withdrawn or consumed) per vehicle mile traveled (VMT). For the later, we assumed vehicle energy efficiency estimate of 5,914.75 BTU per VMT based on VMT weighted average energy intensities of passenger cars and light trucks (Davis, Diegel et al. 2010)[3].

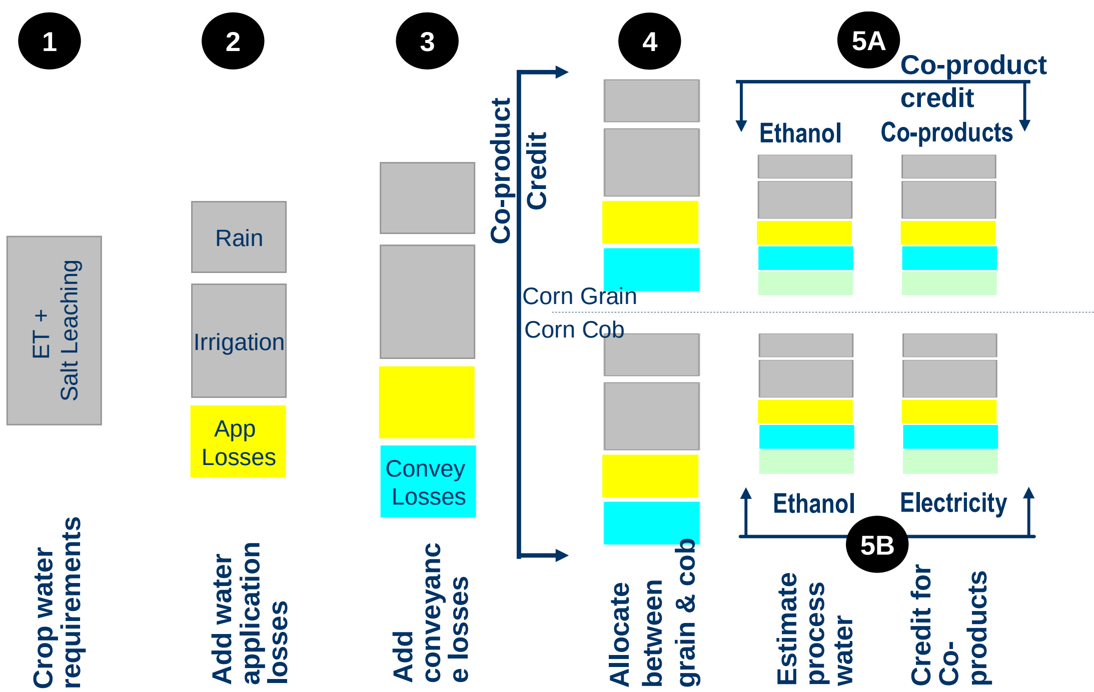
[3] The total VMT and energy intensity for passenger cars in 2008 were 1,615 billion vehicle-miles and 5,465 BTU per vehicle-mile respectively. The equivalent figures for light trucks were 927 billion vehicle-miles and 6,699 BTU per vehicle-mile respectively. The above figures are based on the 29th edition of Transportation Energy Data Book by Oak Ridge National Laboratory Davis, S. C., S. Diegel, et al. (2010). Transportation energy data book - Edition 29. Oak Ridge, TN, Oak Ridge National Laboratory.

In contrast, King and Webber (2008) assumed a vehicle efficiency of 5,663 BTU/VMT. The difference was primarily because the weights were based on fleet strength of cars and light trucks and not actual VMT.

3 Methodology

In this section we discuss our five step process to assess the water intensity of ethanol from corn grain and corn cob.

Figure 3.1: Framework for estimation of water requirements of ethanol from corn and crop residue (corn cob)



3.1 STEP 1: Estimate crop water requirement

3.1.1 Crop evapotranspiration

Crop evapotranspiration, and its components P_s, P_{os}, and ET_a, is an input to our model. These may be estimated using a number of models like the (i) CROPWAT model developed by United Nation's Food and Agricultural Organization (FAO 1998; FAO 2010), (ii) Consumptive Use Program (CUP) developed by California Department of Water Resources and the University of California, Davis to determine ET_c (Orang, Snyder et al. 2005; CA DWR 2010); (iii) CROPSIM model developed by University of Nebraska at Lincoln and Nebraska Department of Natural Resources (Martin 2009)[4]. Description of these models and analysis of their differences is outside the scope of this document. Some of the differences could be significant, for example the CROPWAT and CUP models use different values for crop coefficient K_c for corn - for example the growing season K_c is 1.05 for the CUP and 1.20 for the CROPWAT model.

[4] We have not used the CROPSIM model. Information on CROPSIM is based on Martin (2009)

The crop seasons – planting and harvesting dates – may be taken from USDA (1997).

In addition to ET_c, the above mentioned models give the amount of crop evapotranspiration met through in-season precipitation (P_s), through soil moisture depletion (P_{os}) based on selected soil type, and finally the requirement for irrigated water (ET_a).

The ET_c estimated by these models assumes standard conditions i.e. disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions (FAO 1998). In actual practice, presence of pests and diseases, soil salinity, low soil fertility, and water shortage or water-logging (a situation associated with excessive irrigation on poorly drained soils) may reduce crop yields and the evapotranspiration rate below ET_c. Similarly, while models may predict the necessity for irrigation, crops may be rain-fed or non-irrigated in actual practice. This may lead to not only lower water consumption but also lower yields. For example, average state-wide yields of irrigated and non-irrigated corn in Nebraska are 187 and 123 bushels/acre respectively (USDA 2010).

To address the above discrepancy, ET_a values may be based on prevalent practice instead of being theoretically estimated assuming ideal conditions. The above mentioned models may be used to calculate effective precipitation (P_s) and soil moisture depleted (P_{os}); while ET_a estimates may be taken from USDA's Farm and Irrigation Survey (FRIS)[5]. Analysis may be undertaken separately for irrigated and non-irrigated corn.

In Appendix A2, we have summarized the results of CROPWAT model for 16 meteorological stations in the states of IL, IN, IA, KS and NE. Together, these states accounted for nearly 60% of total US corn production in 2009. The agricultural districts in which these stations are located represent 30-65% of the corresponding state's corn production in 2009 (USDA 2010). We have also included CROPWAT results for one meteorological station in California; the corresponding agricultural district produced 70% of California's corn in 2009 (USDA 2010). The choice of the meteorological stations was driven by availability of data in the CLIMWAT database where monthly climate data averaged over at least 15 years can be easily exported for use by the CROPWAT model.

We have also summarized the state-wide average values of applied water intensity based on 2008 FRIS (USDA 2010). The applied water intensity estimated by FRIS is the sum of ET_a and L_a. In other words, FRIS gives estimates of total irrigation applied per acre in a given state, and the applied water meets applied evapotranspiration requirements as well as accounts for the application inefficiencies.

ET_a values are likely to differ between regions within a state. For example, western Nebraska has significantly lower precipitation than eastern Nebraska; but calculated crop ET requirements are only marginally higher (Martin 2009). However, ET_a values averaged at the level of an agricultural district or county are not available.

[5] FRIS gives estimates of total irrigation applied per acre in a given state. The applied water meets the applied evapotranspiration and salt leaching requirements, as well as accounts for the application inefficiencies. In other word, the FRIS estimates of applied water is the sum of ET_a and L_a.

3.1.2 Pre-irrigation water for salt leaching

We calculated the SL requirements based on "Rhoades" equation as enunciated in FAO Irrigation and Drainage Paper -23 (Ayers and Westcot 1994) and summarized in Appendix A3. Since irrigation water is the primary source of salts (Hoffman 2010), it may be assumed that water is not required for salt leaching in regions where agriculture is almost completely rainfed like Iowa, Indiana, and Illinois (USDA 2010).

For Nebraska, the requirements range from 2 to 5% of ET_c. Based on assumed ET_c, the leaching requirements may also be expressed as 0.55 and 1.4 inches for eastern and western NE respectively. These levels of salt leaching requirements would be met entirely through application of excess irrigation water (due to irrigation system inefficiencies) and precipitation after crop season. This is confirmed by the 2008 FRIS (USDA 2010) which found negligible amount of water-use in NE to leach salts. As a result, we assume SL=0 for Nebraska.

For California, Hanson (1993) calculated the leaching requirements for corn grown in SJ valley to be 5% of crop evapotranspiration. As in case of NE, we assume that application inefficiencies (higher in CA than NE because of dominance of surface/furrow irrigation) preclude the need for additional water for salt leaching.

We did not calculate theoretical salt leaching requirements for Kansas. Per 2008 FRIS (USDA 2010) estimates, water was applied for salt leaching in less than 0.1% of irrigated acreage in the state. Based on FRIS estimates and also the results of our calculations for theoretical SL requirements in the states Nebraska and California, we assume SL=0 for Kansas.

3.2 STEP 2: Estimate application losses

Volume of AWR (applied water requirements) depends upon the application efficiency (AE) of the irrigation system adopted. Central pivot and linear move sprinkler system is the predominant sprinkler system used for corn grain irrigation, while furrow irrigation is the predominant surface irrigation system (Orang, Snyder et al. 2005; USDA 2010). Based on Salas et al. (2006) and Howell (2003), we assumed irrigation efficiencies of 85% and 75% for sprinkler systems and furrow irrigation respectively. Further, we assume that 10 percentage points of the above inefficiencies are consumptive losses, while are remaining are non-consumptive.

Appendix A4 details out the share of various irrigation systems for corn irrigation in NE and CA; and the basis for above assumption regarding relative shares of consumptive and non-consumptive losses.

3.3 STEP 3: Account for conveyance losses

In this step we account for losses from water supply conveyance systems. As mentioned before, consumptive losses include evaporation and evapotranspiration by vegetation in and near canals; and deep percolation to salt sink during conveyance. These losses are treated as withdrawn and consumed. Non-consumptive losses primarily includes include seepage. These losses are treated as withdrawn but released.

Conveyance losses are zero for IL, IN and IA. For NE, conveyances losses are 12% of total irrigation water withdrawn, with consumptive portion of the losses accounting for by 1 percent point. Unlined canals in Nebraska account for such high conveyances losses in NE. For CA, the corresponding figures are 3.23% and 2.36%. For KS, the corresponding figures are 4.23% and 1%. We have detailed out the assumptions and data sources in Appendix A5.

3.4 STEP 4: Partition estimated water between corn grain and cob

Total water estimated at end of step 3 (viz. $ET_c + SL + L_a + L_c$) is partitioned between grain and cob: Embodied water of energy used in agriculture is also partitioned between corn and grain

Water allocated to grain $= ET_c^{gr} + SL^{gr} + L_a^{gr} + L_c^{gr} + E_e^{gr}$ (Equation 3.1)
Water allocated to cob $= ET_c^{cb} + SL^{cb} + L_a^{cb} + L_c^{cb} + E_e^{cb}$ (Equation 3.2)

The partitioning is based on the following sub-steps: (i) estimation of dry tons of corn grain and cob harvested based on corn yields and corn-cob yield ratio, (ii) account for losses in dry matter as a result of storage, (iii) allocate water based on alternative allocation procedures

3.4.1 Estimate grain and cob yields

The model allows users to enter corn grain yield. Average crop yields were taken from USDA (USDA 2010). Corn grain yields, averaged over a 5-year period between 2005 and 2009, are given in Appendix A6. For Nebraska and Kansas, with nearly equal shares of rain-fed and irrigated corn production, data on yields are available for both rain-fed and irrigated corn. On the other hand, yields of irrigated corn for IL, IN and IA are available only for 2007 in the 2007 Census of Agriculture (USDA 2009). Irrigated corn constitutes between 1-4% of total production in these states. We ignore irrigated corn and water requirements of ethanol from irrigate corn from these regions, although share of irrigated corn may rise in future in response to higher corn prices. In California, the entire corn is irrigated.

To analyze cob yields, we reviewed the literature for corn-cob yield ratios. Based on field studies in Colorado and Texas, Halvorson and Johnson (2009) reported a cob-grain mass ratio of 0.14 where the grain was considered at 15.5% moisture content and cob was oven dried. This corresponds to a ratio of 0.17 when both are oven dried. The field studies were conducted with multiple N fertilizer treatments, varying tillage systems, and different growing seasons. Based on field studies in Tennessee, Pordesimo, Hames et al. (2005) found a corn-grain mass ratio of 0.18 where both grain and cob were oven dried; and measurements were undertaken at the time of grain physiological maturity, which occurred at 118 days after planting. The mass ratios before and after were different, albeit in a small way. Schwietzke et al (2009) reported similar cob-grain yield ratio. This model assumes a default value of 0.18 for the cob-grain yield ratio.

Appendix A6 gives the average cob yields for the selected regions in the US.

3.4.2 Account for biomass storage losses

Grain and cob are cultivated and harvested seasonally, but have to support year round ethanol production. This necessitates storage of feedstock which is subject to dry matter losses largely due to microbial activity. Losses are largely dependent upon storage conditions - outdoor versus indoor storage, type of ventilation system, and use of fungicides and insecticides. While storage losses for corn cobs are not available, a number of studies have reported storage loss rates for corn stover. Based on field tests at Wisconsin, Shinners, Binversie et al. (2007) found that after eight months, dry matter losses were 3.3% for dry stover bales stored indoors and 18.1% for those stored outdoors. Zych (2008) found similar dry matter losses for cobs stored outside from winter to summer. However, cobs in the interior of the piles which were well ventilated had lower losses. Perlack and Turhollow (2002) assumed a 10% loss in stover dry matter due to storage and handling for their calculation of logistics costs of corn stover.

USDA'a Integrated Farm System Model (IFSM) assumes a 1% DM loss of corn during storage (Rotz, Corson et al. 2009). Our model also defaults to 1% as the storage loss for both corn grain and cob. It is likely that most of dry matter losses due to microbial activity is in the sugars rather than other biomass components like ash and lignin. This implies a more than 1% reduction in ethanol yield. In the version of our model, we have not accounted for such differences.

3.4.3 Procedures to calculate co-product credit and partition water between grain and cob

The model allows partitioning of water requirements during the cultivation stage on the basis of two separate allocation procedures – mass and energy content, and system expansion or displacement method.

- Mass and energy basis

Under the mass basis for allocation, water may be allocated proportional to the relative mass of corn and cob. The relative masses of corn and cob were discussed earlier. Similarly, energy basis of allocation will allocate water based on relative energy content (BTU / lb) of corn grain and cob. Based on Pordesimo, Hames et al.(2005), we assume that the energy content of grain and cob are equal. Hence, the two allocation methods will yield the same result.

- Commercial value basis

Allocation based on market value has not been considered in this version of the model due to non-availability of price of corn cob. Further, today cob has limited market value because cellulosic ethanol production process has not yet been commercialized.

- System expansion or Displacement method

System expansion method is recommended by Kim, Dale et al. (2009) and Wu, Wang et al. (2006) to examine environmental burdens of ethanol from stover. In this method of calculating co-product credits, only the incremental environmental burden resulting from harvesting of cob (stover) will be allocated to cob (stover). In our context, this includes increased soil water evaporation due to removal of biomass, increase in fuel consumption and corresponding increase in second-level offsite water consumption, and finally additional nutrient requirements and hence incremental water for salt leaching. Wu, Wang et al. (2006) suggest that baseline environmental burdens may be allocated to ethanol from crop residue after it is established on a commercial scale.

The approach to calculate and assign incremental environmental burdens to cob is equivalent to a displacement method where (i) the cob is treated as the main product in the current system with corn grain harvested for ethanol is a co-product, (ii) the corn grain displaces corn grain from another system where cob is not harvested but is incorporated back to the soil (based on personal communications with S Kim September 2010).

Kim, Dale et al. (2009) estimate incremental fossil energy requirements due to cob harvesting in six different locations in the US Corn Belt. Additional energy is required for harvesting of stover, additional nutrients (agrochemicals) in the subsequent growing season, and drying of cob. Corn cob is assumed to enter the combine, and harvested simulta,ously with grain using an additional wagon. The study reports an average incremental fossil energy input of 400 BTU/ dry lb (0.93 MJ/kg) of cob. Kim, Dale et al. (2009) assumed cob-grain yield ratio of 0.17; implying energy allocation to corresponding grain is 5320 BTU/ dry lb (12.35 MJ/kg).

We do not have information on moisture loss and need for incremental nutrients due to cob harvesting; however we expect them to be negligible given that cob constitutes less than 20% of the residue biomass. Further, there are limited nutrients in cob, and hence harvesting of cob will not necessitate additional fertilizer application. Our system expansion model considers only the embodied water of the incremental fossil energy expended.

3.5 STEP 5: Bio-refinery water requirements and co-product crediting

In this step, we first estimate water required for conversion to ethanol of corn grain and corn cob in a bio-refinery represented by BR^{gr} and BR^{cb}. This gives the total water required for both the corn and cob pathways. Further, the E_e^{gr} (E_e^{cb}) is expanded to include energy used in corn grain (cob) storage and transportation; and subsequent conversion of the grain (cob) to ethanol.

$$TWR^{gr} = ET_c^{gr} + SL^{gr} + L_a^{gr} + L_c^{gr} + BR^{gr} + E_e^{gr} \quad \text{(Equation 3.3)}$$
$$TWR^{cb} = ET_c^{cb} + SL^{cb} + L_a^{cb} + L_c^{cb} + BR^{cb} + E_e^{cb} \quad \text{(Equation 3.4)}$$

where,

TWR^{gr} is the total water required in the corn grain pathway
TWR^{cb} is the total water required in the cob pathway

TWR for each of the pathways is subsequently partitioned between ethanol and co-products.

$$TWR^{gr\text{-}EtOH} = TWR^{gr} - TWR^{gr\text{-}cp} \quad \text{(Equation 3.5)}$$
$$TWR^{cb\text{-}EtOH} = TWR^{cb} - TWR^{cb\text{-}cp} \quad \text{(Equation 3.6)}$$

where,

$TWR^{gr\text{-}EtOH}$ represents the portion of TWR^{gr} that is partitioned to ethanol from corn grain

$TWR^{gr\text{-}cp}$ represents the portion of TWR^{gr} that is partitioned to co-products produced during conversion of corn grain to ethanol

$TWR^{cb\text{-}EtOH}$ represents the portion of TWR^{cb} that is partitioned to ethanol from corn cob

$TWR^{cb\text{-}cp}$ represents the portion of TWR^{cb} that is partitioned to co-products produced during conversion of corn cob to ethanol

3.5.1 STEP 5A: Ethanol from corn grain (Grain pathway)

The following table gives the ethanol yields and water requirements for dry mill and wet mill bio-chemical conversion plants. The default values assumed by the model are also indicated. Yields and water use reported by Mueller (2010) are based on a survey administered by University of Illinois at Urbana-Champaign in 2008. The survey covered plants representing 66% of installed dry mill ethanol capacity during the year 2008. Estimates by Perrin, Fretes et al. (2009) are based on a survey of seven dry mill plants in north central Midwest states. The plants were built or modernized after mid-2005 with a minimum annual capacity of 50,000 million gallons. Estimates by Wu (2008) are based on a 2007-survey administered by Renewable Fuels Association (RFA) and covered 22 facilities representing 36% of ethanol production in 2006.

Table 3.1: Yield of ethanol (anhydrous and un-denatured) and process & cooling water requirements – corn grain pathway

	Ethanol yield (gal/ bu grain)		**Water requirement** (gal/gal EtOH)	
	Dry mill	Wet mill	Dry mill	Wet mill
Current / near term technology				
GREET 1.8d (ANL 2010)	2.80	2.61		
Mueller (2010)(1)	2.78		2.72	
Perrin et al (2009) (2)	2.79			
Wu (2008)(3)	2.68	2.61	3.16	4.11
This model's default assumptions	**2.79**	**2.61**	**2.72**	**4.11**

Notes: (1) Yields and water requirements adjusted for denaturant, the volume of which averaged 2.5% of denatured ethanol by volume.
(2) Perrin et al (2010) indicate that volume of denaturant (usually gasoline) could range from 1.96% and 4.76%, but did not collected the exact volume from surveyed firms. Yield reported by Perrin et al (2010) have been adjusted by volume of denaturant reported by Mueller et al (2010)
(3) Adjusted based on volume of denaturant reported by another report by Argonne National Laboratory (Arora et al 2008) and equal to 4.7% by volume of denatured ethanol

Our model can credit ethanol for various co-products based on three different approaches: energy allocation method, market value allocation method, and displacement method.

The displacement method follows a four-step process (General Motors 2001). First, the amount of co-products produced in an ethanol plant is estimated. Second, the products to be displaced by these co-products in marketplace are identified. Third, the displacement ratios between co-products and the displaced products are determined. Finally, environmental burdens in terms of water withdrawal and consumption of producing the amount of displaced products are estimated. The estimated amounts of environmental burdens are subtracted from total environmental burdens of ethanol pathway.

For the first three steps, we take values from available literature. Subsequently, we estimate the water use of identified products being displaced by co-products of corn grain ethanol.

- **Co-products produced**

The co-products of dry and wet mill ethanol plants are given in the following table. The co-product yields are expressed without taking their moisture content into consideration. We have adopted the values from GREET 1.8d (ANL 2010).

Table 3.2: Corn grain ethanol production - co-product yields (dry lb / gal un-denatured EtOH)

	GREET 1.8d (ANL 2010)	Perrin, Fretes et al. (2009)(1)	Mueller (2010)(2)
Dry Mill			
Distiller's grain solubles (DGS)	5.63	5.34	5.79
Corn oil			0.006
Wet Mill			
Corn gluten meal or CGM	1.22		
Corn gluten feed or CGF	5.28		
Corn oil	0.98		

Notes:
(1) Adjusted for presence of denaturant equal to 2.5% of the volume of denatured ethanol (Mueller 2010)
(2) Mueller (2010) reported a weighted average yield of 5.30 lbs / gallon of denatured ethanol of dry DGS, and 2.15 lbs / gallon of denatured ethanol of Wet DGS. The average moisture content of DDGS and WDGS estimated by Mueller (2010) are 10.8% and 57.2% respectively[6]. We adjusted for the moisture content as well as presence of denaturant.

- **Displaced products and displacement ratios**

The following table identifies displaced products and displacement ratios adopted by GREET version 1.8d (ANL 2010).

Table 3.3: Displacement ratios assumed by various studies / models (1)

	GREET 1.8d (ANL 2010)	Notes:
Dry Mill		
DGS	Displaces 0.781 lbs of corn, 0.307 lbs of SBM and 0.023 lbs of N2 in Urea	In GREET 1.8d, 1 lbs of SBM displaces 1.2 lbs of raw soybean (RSB). Therefore, 1 lbs of oven-dried DGS displaces 0.368 of RSB in addition to corn and urea.

[6] The average moisture content assumed by GREET 1.8d (ANL 2010) are 12% and 60% for DDGS and WDGS respectively.

Wet Mill		
CGM	Displaces 1.529 lbs of corn and 0.023 lbs of N2 in Urea	
CGF	Displaces 1 lbs of corn and 0.015 lbs of N2 in Urea	
Corn oil	Equal mass of soybean oil	

(1) The displacement ratios are expressed in terms of mass of displaced products (as-is moisture content) per unit oven-dried mass of co-product from the ethanol pathway.

The model defaults to displacement ratios used in GREET 1.8d. The following two figures summarize the yields of ethanol and co-products from the **dry mill** conversion process, displacement ratios, and masses of products displaced per bushel of corn grain.

Figure 3.2: Yield of ethanol and co-products from dry mill and masses of displaced products (per bushel of corn grain input)

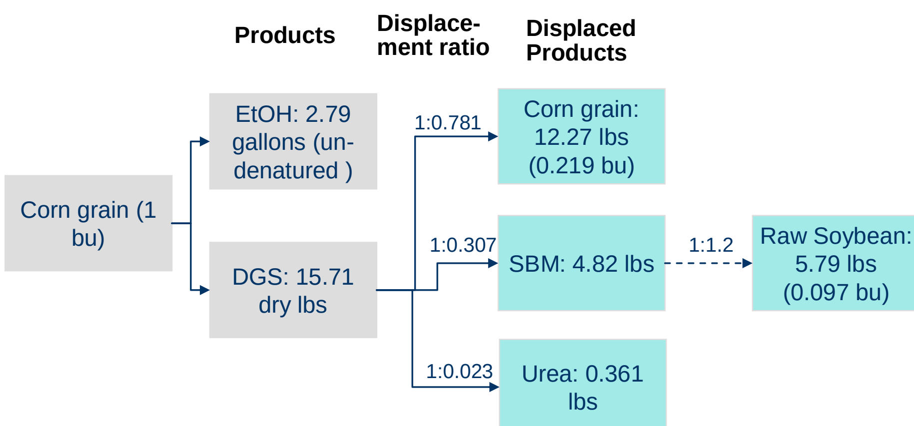
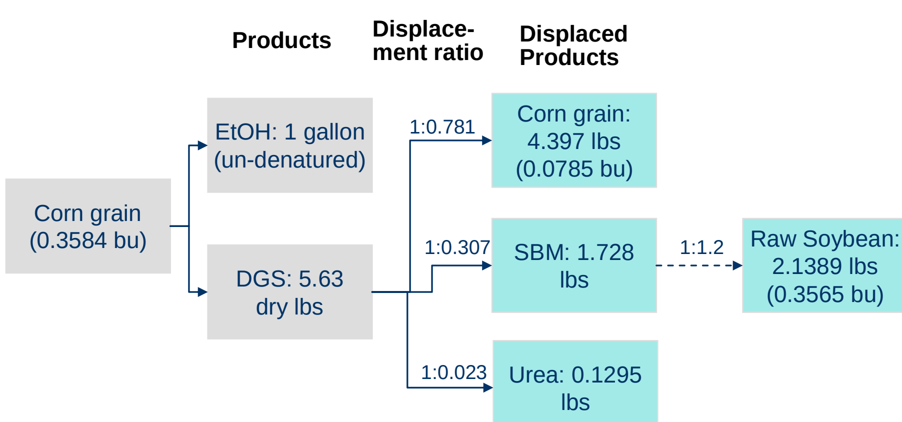


Figure 3.3: Yield of co-products from dry mill and masses of displaced products (per gallon of undenatured ethanol produced)



SBM production process also produces co-products like soybean oil (SO) and soybean hull (SBH). This necessitates identification of a product displaced by SBM which does not have co-products so that water requirements can be estimated without need for partitioning. Per GREET 1.8d, SBM displaces raw soybean at a ratio of 1:1.2.

The following two figures summarize the yields of ethanol and co-products from the **wet mill** conversion process, displacement ratios, and masses of products displaced per bushel of corn grain.

Figure 3.4: Yield of ethanol and co-products from wet mill and masses of displaced products (per bushel of corn grain input)

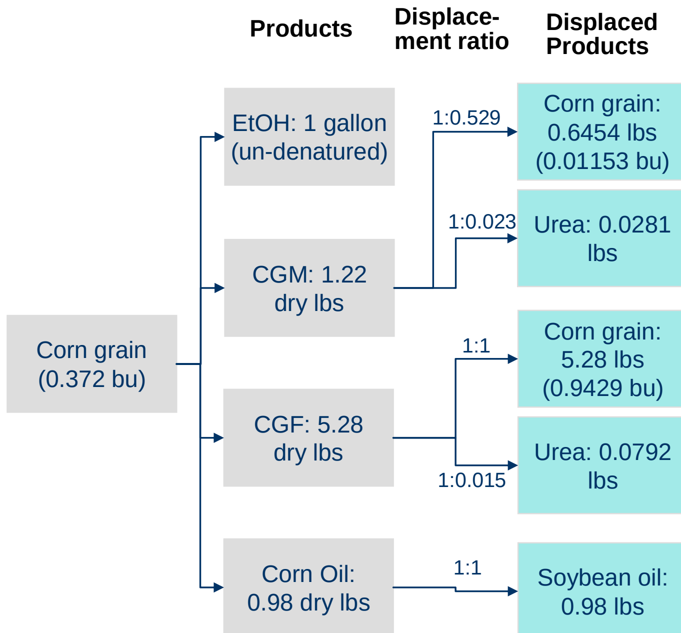
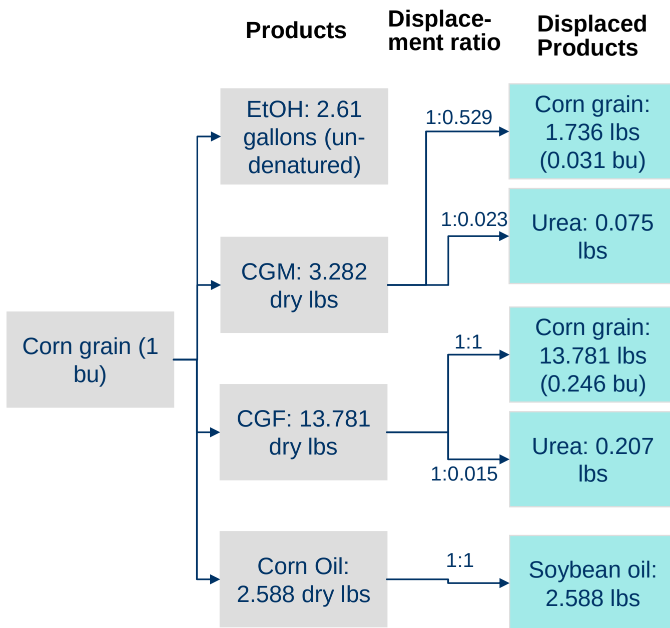


Figure 3.5: Yield of co-products from wet mill and masses of displaced products (per gallon of un-denatured ethanol produced)



- **Water consumption of displaced products**

The model assumes that **corn** displaced by the various co-products for animal feed is grown in the same region as the corn used for ethanol production. Further, co-products from rain-fed (irrigated) corn grain are displaced by rain-fed (irrigated) corn. Water withdrawal and consumption figures estimated in Steps 1 through 4 are used to calculate the water intensity of displaced feed corn.

Similarly for **soybean**, we estimate water requirements from Steps 1 to 4 based on user inputs of evapotranspiration requirements met through precipitation during crop season, soil moisture depletion and finally applied water.

Total water required by raw soybean (RSB)

$$TWR^{RSB} = ET_a^{soy} + P_s^{soy} + P_{os}^{soy} + SL^{soy} + L_a^{soy} + L_c^{soy}$$
$$= ET_c^{soy} + SL^{soy} + L_a^{soy} + L_c^{soy} \qquad \text{(Equation 3.7)}$$

The model defaults to the application efficiency assumed for corn grown as ethanol feedstock – since soybean is rotated with corn it will depend upon the same irrigation system as corn. The same justification also applies behind assumption of conveyance losses. For places like California, where soybean is not grown, the user may use water requirement values applicable for a different state. In Appendix A2, we have summarized the CROPWAT estimates of P_s, P_{os}, and ET_a, for various meteorological stations in IL, IN, IA, KS and NE; and also actual applied water intensity based on 2008 FRIS (USDA 2010). In Appendix A6, we have summarized average soybean yields from 2005 to 2009. For NE and KS, averaged irrigated and non-irrigated yields are also presented.

We had to adopt a different approach to estimate water requirements of **soybean oil (SO)**. As in case of SBM, SO has other co-products (SBM and SBH), necessitating us to identify a product displaced by SO which does not have co-products so that water requirements can be estimated without need for partitioning. However, all products displaced by SO – canola oil, sunflower oil, etc. have other co-products during their production process. To overcome this problem, we partition water requirements between SO and its co-products on a market value basis[7]. This approach is recommended when displacement basis is not feasible (Wang, Huo et al.).

The following table summarizes some of the key assumptions pertaining to crushing of soybean to produce soybean oil and other products:

Table 3.4: Soybean crushing - assumptions

	Assumption	Source
Yields (lbs per bushel of soybean)	SO: 11.45 SBM: 44.00 SBH: 3.45 (1)	5 year average from USDA's Oil crop yearbook (USDA 2010)
Market Prices (cents per lbs of product	SO: 32.24 SBM: 0.1213 SBH: 0.0463 (2)	As above
Water Requirements (gallons / bushel of RSB crushed)	Withdraw: 3.5 Consumed: 1.6	Omni Tech (2010) which is based on survey of 15 soybean oil processors.

(1) GREET 1.8d (ANL 2010) assumes 11.11 lbs of SO and 49.78 lbs of lower grade SBM (44% protein content).
(2) GREET 1.8d (ANL 2010) assumes prices of 38.4 and 0.118 cents/lbs of SO and lower grade SBM respectively

Based on the above information, 40.2% of water requirements are allocated to SO (42.1% in case of GREET 1.8d. Mass basis of allocation, as was undertaken by a number of studies on lifecycle analysis of soybean based biodiesel (Sheehan, Camobreco et al. 1998; Pradhan, Shrestha et al. 2009; Omni Tech 2010), would have allocated around 20% of the water requirements to SO.

The water requirement of **Urea** is ignored in this analysis because of lack of information. Further, we do not include the embodied water of on-site energy inputs during soybean crushing in our estimate of TWR^{soy}. Both the above values are likely to be small.

- **Summary of co-product credits and partitioning ratios**

The following table summarizes the effect of the method adopted for crediting ethanol for various co-products:

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[7] In GREET 1.8d, SBH is not one of the products of crushing operations. The SBH is blended to SBM to produce an SBM with average protein content of 44% (measured with moisture content). When SBH is not blended, the SBM is of a higher grade with an average protein content of 48%. For 2009, it is estimated that 92% of the SBM sold in the US were of the higher protein grade; up from 50% in the early 1980s (based on personal communication with Mark Ash, USDA, July 2010).

Table 3.5: Net water partitioned to corn grain ethanol after adjusting for credit for co-products

Method	Dry milling plant	Wet milling plant
Energy content based (1)	61% of TWR^{gr}	69% of TWR^{gr}
Market value based (1)	76% of TWR^{gr}	70% of TWR^{gr}
Displacement method (2)		
- Green water partition (3)(4)	45-55% of TWR^{gr}	40-50% of TWR^{gr}
- Blue water partition (irrigated corn)	~55% of TWR^{gr}	~50% of TWR^{gr}
- Blue water partition (rainfed corn)	100% of TWR^{gr}	95-98% of TWR^{gr}

Notes: (1) Percentagae partitioned to ethanol is constant across geographical regions and is true for both green and blue water. (2) Percentage partitioned to ethanaol varies spatially. (3) Results are for both irrigated and rain-fed crops. (4) For CA, the value is -15% because we assume thata co-products are displaced by soybean from US Corn Belt which have a much larger green water component.

3.5.2 STEP 5B: Ethanol from Corn Cob

Before, we consider the ethanol yield and process & cooling water requirements for specific conversion technology pathways, we look at the maximum potential ethanol yield from cob. . This takes the reported values of dry matter weight fraction of polymeric sugars in corn cob and uses US Energy Efficiency and Renewable Energy's (EERE) Theoretical Ethanol Yield Calculator (EERE 2010) to calculate the maximum possible ethanol yield assuming 100% efficiency in the conversion process. The tool uses the following factors to calculate yield: 1.11 pounds of C6 sugar per pound of C6 polymeric sugar (glucan, galactan and mannan); and 1.136 pounds of C5 sugar per pound of C5 polymeric sugar (xylan and arabinan). Each pound of sugar yields a maximum of 0.51 pounds of ethanol, and there are 6.55 pounds of ethanol per gallon.

It is thus independent of state of conversion technology.

Table 3.6: Maximum potential ethanol yield from grain and cob

	Estimated best case ethanol yield (gal/dry ton)		
	Corn grain	**Cob**	**Stover**
Schwietzke, Kim et al. (2009)	135	128	108
EERE (2010)	124		113
Aden et al. (2002)			113
Sheehan et al (2003)			113
Values assumed in this model	130	128	112

Wu, Mintz et al.(2009) and Wu, Mintz et al. (2009) report multiple conversion technologies using either biochemical conversion (BC) or thermo-chemical conversion (TC). However, none of them are in commercial operation and data about ethanol yield and water consumption are likely to be uncertain. We have modeled BC technology which consists of the following four steps: (i) pretreatment including physical sizing and prehydrolysis of the lignocellulosic biomass using dilute aid; (ii) cellulose hydrolysis via enzymatic hydrolysis; (iii) fermentation; (iv) purification/distillation of ethanol. Water is required both as process water and cooling water in all the four steps. The only co-product of the BC process is electricity through the combustion of lignin residue. Electricity demands of the bio-refinery process are met internally and the surplus is exported to the grid.

Table 3.7: Ethanol yields and process & cooling water requirements for the cob portion

	Ethanol yield (gallons/ dry ton)		Water required	Electricity produced
	Stover	Calculated cob yield (1)	(gal/gal EtOH)	(kWh/dry ton)(5)
Current / near term technology				
Wu, Mintz et al. (2009) (2)			5.9 - 9.8	
Sheehan et al (2003) (3)	61.8 - 82.4	70.7 – 94.2		169.5
Wu, Wang et al. (2006)	90.0	103.13		215.5
Wooley, Ruth et al. (1999) (4)	68.0 – 94.0	77.7 – 113.0	4.6 - 6.7	114.6 – 226.8
GREET 1.8d (ANL 2010)	90.0	102.0		205.2
This study's assumptions		**100.0**	**6.0**	**205.0**

Notes:

(1) Estimated based on same level of conversion efficiency and maximum theoretical ethanol yield calculated in Table 3.6
(2) The water requirements are for ethanol from switchgrass. The higher range is based on current technology, while the lower range is based on expected improvements in near term.
(3) The lower yield is based on current technology demonstrated at a pilot scale with zero conversion to ethanol of the three sugars galactan, mannan and arabinan.
(4) The lower ethanol yield is based on prevailing technology, while the higher yield was projected for year 2020. Future conversion efficiencies were assumed at a much higher level (around 95%) than Sheehan et al (2003) (85-90%). Electricity production is initially going to rise from 114 to 228 kWh/dry ton with corresponding rise in ethanol conversion efficiency (stover feedstock) of 68 to 81 gallons / dry ton. Subsequently, it will fall to 118 kWh / dry ton with increase in ethanol conversion efficiency to 94 gallons / dry ton.
(5) Electricity produced is based on stover feedstock. We do not expect this value to change for cob because of similar fraction of mass constituted by lignin

Since electricity is the only co-product, the model allows users to choose energy based allocation. However, this method allocates water volumes to electricity on a gallon per kWh basis is absurdly higher than electricity generated from conventional feedstocks. The model uses system displacement method as the default option whereby credit available to cob ethanol is based on the state's average water footprint of thermoelectric electricity (USGS 1998).

3.6 Onsite energy consumption

Energy is required at various stages of ethanol production. Diesel is required for farm equipment operation, transportation of feedstock to bio-refineries, and distribution of ethanol; electricity, coal and natural gas are used for bio-refinery operations. Because cellulosic ethanol production is a net electricity generator, no energy inputs need to be considered in the bio-refinery stage of the ethanol from cob pathway.

Table 3.8: Energy requirements for ethanol production

Fuel		Farming	Ethanol from grain			Ethanol from cob(++)
			Transp.	**Wet mill**	**Dry mill**	**Transp.**
	Units	*Per Bushel*	*Per Bushel*	*Per Gallon*	*Per Gallon*	*Per Dry Ton*
Diesel/Gasoline	*Gallons*	0.06	0.04			1.83
Natural Gas	*ft3*	1.96		29.48	27.62	
Coal	*tons*			0.00	0.00	
Electricity	*kWh*	0.20			1.09	

Notes:

- Source: Energy requirements are based on GREET 1.8c (ANL 2010). Energy requirements are in terms of units defined in second column of this table. Thus diesel/gasoline consumption during farming is 0.06 gallons per bushel of grain.

++ Values for corn stover

For simplicity, we consider only the water consumption of various fuels. The default water consumption values for various fuels assumed by the model are given below:

Table 3.9: Embodied water of various fuels

	Water Consumption	**Sources**	**Notes**
Diesel / Gasoline	5 gal / gal gasoline	Wu et al (2009), Gleick (1994)	Includes extraction and refining of crude oil.
Natural Gas	5 gal / thousand cubic feet of NG	Gleick (1994)	Includes extraction, processing and pipeline operations
Coal	50 gallons / ton of coal	Gleick (1994), Lovelace (2005)	Includes mining (average of surface and underground), refinement and transportation
Electricity	0.67 gallons / kWh of power generated	USGS (1998) King & Webber (2008)	Includes average power plant cooling requirements of 0.47 gal/kWh and other lifecycle stage requirements of 0.18. The latter includes coal mining & beneficiation (0.03), uranium mining & enrichment (0.80) and natural gas extraction (0.08). State averages (for thermoelectricity production only) may be used for regional analysis.

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5 Appendix A1: Spatial resolution and temporal of key input parameters

Table: A1.1: Spatial resolution and temporal coverage of key input parameters

	Source	Spatial resolution	Temporal Coverage
Crop ET			
Meteorological data	CLIMWAT (for CROPWAT); CUP has weather data for stations in CA. Manual input possible	Meteorological data pertains to a specific **station** which may be representative for a county or agricultural district. CLIMWAT database has weather information for 2-3 stations per state in the US	CLIMWAT provides monthly weather data averaged over at least 15 years
P_s & P_{os}	CROPWAT; CUP for CA	Ps & Pos calculated for specific **meteorological stations**. Data for multiple stations may be averaged to represent a state	Depends upon the underlying meteorological data.
ET_a (calculated, ideal conditions)	CROPWAT; CUP for CA	As above	As above
ET_a (actual)	USDA's Farm and Ranch Irrigation Survey	**State average** for a specific crop. Data also available for a specific irrigation system - sprinkler and surface irrigation	FRIS surveys conducted once every five years, the latest one being 2008. Data represents practice adopted in a particular year and not an average over several years
Other water requirements			
Salt Leaching (SL)	USDA's Farm and Ranch Irrigation Survey	Data on total acreage in a state where applied water was used for salt leaching. Specific amounts of water used not available	As above
Application Losses (L_a)	Model defaults to averages based on Salas (2003) and Howell 2006	Field/Farm level efficiency.	
Conveyance losses (L_c)	USGS (1998) and CA DWR (2005)	State average	USGS data available for 1995.CA DWR (2005) for 2001
Biorefinery water use (BR)	Based on Mueller (2010) and Wu et al (2008)	National average	
Other parameter values			
Ethanol yields	Based on Mueller (2010) and GREET 1.8d (ANL 2010)	National average	

Crop yields	USDA	Average at state, agricultural district and county level	Annual data available. For irrigated corn and soybean yields in IL, IA and IN data available only for Census years (2007 latest)

6 Appendix A2: Meteorological stations for CROPWAT analysis

In this section, detailed information about the following 16 meteorological stations in the states of California (CA), Illinois (IL), Indiana (IN), Iowa (IA), Kansas (KS) and Nebraska (NE) are given. CLIMWAT provides monthly climate data averaged over at least 15 years for the 12 stations.

Table: A2.1: Meteorological stations analyzed in out study

Station	Agricultural District (AD)	Corn production (2009) AD's share of total state production	Corn production (2009) Share of irrigated corn	SB production (2009) AD's share of total state production	SB production (2009) Share of irrigated SB
California					
- Fresno	San Joaquin Valley	69%	100%	--	--
Illinois					
- Peoria	Central	16%		13%	
- Moline	North West	17%		8%	
- Chicago	North East	9%		10%	
- Springfield	West Southwest	15%		13%	
Indiana					
- Evansville	Southwest	12%		23%	
- Indianapolis	Central	22%		13%	
Iowa					
- Des Moines	Central	15%		15%	
- Sioux City	West Central	16%		16%	
Nebraska					
- Lincoln	East	25%	60%	31%	46%
- Valentine	North	4%	91%	3%	85%
- North Platte	Southwest	10%	79%	3%	93%
Kansas					
- Concordia Blosser	North Central	7%	38%	16%	14%
- Dodge City	Southwest	25%	96%	3%	~100%
- Kansas City	Northeast	16%	4%	21%	~0%
- Topeka	East Central	7%	10%	17%	4%
- Wichita	South Central	12%	82%	13%	51%

Source: USDA (2010)

The agricultural districts in which the stations are located account for between 30-65% and 30-50% of the corresponding state's corn and soybean production respectively. We do not consider ethanol from rainfed corn grown in the Southwest agricultural district of Kansas because of negligible shares of both corn and soybean that are rainfed. Similarly, we do not consider ethanol from irrigated corn in Northeast agricultural district of Kansas because of limited irrigation in that region.

6.1 Evapotranspiration estimates for corn

In the following table, we give the various components of crop evapotranspiration for corn cultivation estimated by CROPWAT. We also give the state-wide average ETa estimated in the 2008 FRIS (USDA 2010).

Table A2.2: Crop evapotranspiration estimates for corn grown in various regions

	CROPWAT results (1)					State-wide average applied water estimates from 2008 FRIS (USDA 2010)(3)		
	Planting Date (2)	P_s	Rain loss	P_{os}	Calculated ET_a	Average	Sprinkler irrigation	Surface irrigation
California	15-Apr					24.0	21.6	25.2
Fresno		0.77	0.04	4.01	32.31			
Illinois	5-May					6.0	6	6
Peoria		12.70	2.92	1.88	8.27			
Moline		15.36	3.08	3.31	4.08			
Chicago		12.65	3.00	2.81	8.12			
Springfield		11.87	2.55	3.85	8.18			
Indiana	5-May					7.2	7.2	0
Evansville		12.06	3.04	3.10	7.89			
Indianapolis		12.54	2.91	0.96	8.30			
Iowa						6.0	6	13.2
Des Moines	5-May	14.33	2.40	1.31	8.08			
Sioux City		11.50	2.62	0.22	13.07			
Nebraska	10-May					9.6	9.6	10.8
Lincoln		11.65	2.46	2.28	12.02			
North Platte		10.12	1.44	0.22	17.93			
Valentine		9.20	0.89	2.57	16.37			
Kansas	10-May					15.6	16.8	14.4
Concordia Blosser		12.50	3.36	1.92				
Dodge City		9.95	2.04	1.26				
Kansas City		14.74	3.44	2.48				
Topeka		13.56	3.88	2.57				

(1) For CROPWAT model, we assumed loamy soil and rooting depth of 67 inches for corn.
(2) Planting dates are based on USDA (1997)
(3) Applied water estimates are equal to the sum of applied water evapotranspiration (ET_a) and application losses (L_a).

6.2 Evapotranspiration estimates for soybean

Table A2.3: Crop evapotranspiration estimates for soybean grown in various regions

	CROPWAT results (1)					State-wide average applied water estimates from 2008 FRIS (USDA 2010)(3)		
	Planting Date (2)	P_s	Rain loss	P_{os}	Calculated ET_a	Average	Sprinkler irrigation	Surface irrigation
Illinois	15-May					0.5	0.5	1.1
Peoria		9.43	1.71	3.44	4.39			
Moline		11.20	1.67	1.73	4.28			
Chicago		9.08	1.40	4.24	4.41			
Springfield		8.96	0.90	4.73	4.39			
Indiana	20-May					0.5	0.5	--
Evansville		8.43	1.72	4.64	4.41			
Indianapolis		9.19	1.37	2.86	4.49			
Iowa	20-May					0.4	0.4	--
Des Moines		9.50	1.42	3.98	4.32			
Sioux City		8.27	1.00	1.50	8.85			
Nebraska	25-May					0.6	0.6	0.6
Lincoln		8.11	1.91	3.67	8.72			
North Platte		7.11	1.11	4.41	8.72			
Valentine		7.21	0.88	5.49	8.87			
Kansas	20-May					12.0	12.0	9.6
Concordia Blosser		9.78	1.82	4.05				
Dodge City		7.88	1.00	5.48				
Kansas City		11.27	1.77	3.06				
Topeka		10.44	2.32	3.16				

Notes:

(1) For CROPWAT model, we assumed loamy soil and rooting depth of 50 inches for corn.
(2) Planting dates are based on USDA (1997)
(3) Applied water estimates are equal to the sum of applied water evapotranspiration (ET_a) and application losses(L_a).

The following table gives state-wide average applied water estimates made for the years 2008, 2003 and 1997 in the respective FRIS surveys. Lower precipitation in Nebraska in 2003 led to higher applied water (ET_a) in Nebraska.

Table A2.4: Applied water estimates for 2008, 2003 and 1997

	Corn			Soybean		
	2008 FRIS	**2003 FRIS**	**1997 FRIS**	**2008 FRIS**	**2003 FRIS**	**1997 FRIS**
California	24.0	28.8	39.6			
Illinois	6.0	7.2	7.2	6.0	7.2	7.2
Indiana	7.2	6.0	6.0	6.0	4.8	4.8
Iowa	6.0	6.0	6.0	4.8	4.8	4.8
Kansas	15.60	16.8	18.0	12.0	13.2	13.2
Nebraska	9.6	14.4	10.8	7.2	12.0	7.2

7 Appendix A3: Water required for salt leaching

Pre-irrigation water required for salt leaching for a particular crop may be calculated using the following "Rhoades" equation from Ayers & Westcot (1994):

$$LR = \frac{EC_w}{5(EC_e) - EC_w}$$

where,

LR: Leaching requirements needed to control salts within the tolerance (EC_e) of the crop expressed a fraction or percentage of total crop evapotranspiration (ET_c).

EC_w: Average salinity of the water. It is expressed in terms of electrical conductivity and has the units deciSiemens per meter (dS/m)

EC_e: Average soil salinity (electrical conductivity) tolerated by the crop (corn).

Relationship between TDS (Total dissolved solids) and Electrical conductivity (EC)

A mathematical relationship between TDS (expressed in terms of parts per million or equivalently mg/L) and EC (expressed in terms of dS/m) is given by (Hoffman 2010):

TDS (mg/L) = EC_w (dS/m)* 640

Thus a TDS of 1,000 mg/L corresponds to an EC of approximately 1.6dS/m.

LR above represents a fraction or percentage of total crop evapotranspiration (ET_c). This differs from SL in our report which is expressed in inches. The average salinity for water supplied for evapotranspiration may be given as:

$$EC_w = \frac{EC_p * (P_s + P_{os}) + EC_a * ET_a}{(P_s + P_{os} + ET_a)}$$

where,

EC_p is the average salinity of precipitation and assumed to be 0 dS/m

EC_a is the average salinity of irrigation water applied. This in turn may be the weighted average of ground and surface water.

P_s, P_{os}, and ET_a as defined before represent effective precipitation, soil moisture depleted and ET of applied water respectively.

The above equation indicates that the average salinity of water varies between regions and is dependent upon the relative shares of precipitation and applied water, and salinity of ground and surface water supplied for irrigation.

EC_e value is usually chosen so as to result in at least a 90% or greater yield. The following table gives EC_e values for corn and other crops (Ayers and Westcot 1994). The table shows that corn is quite sensitive to salt levels.

Table A3.1: Impact of soil salinity (dS/m) on yield potential of corn and other crops

	Percentage of yield potential		
	100%	**90%**	**75%**
Corn	1.7	2.5	3.8
Corn Silage	1.8	3.2	5.2
Soybean	5.0	5.5	6.3

In this section, we calculate the theoretical amount of water required for salt leaching. Since irrigation water is the primary source of salts (Hoffman 2010), we need not calculate salt leaching requirements for regions where agriculture is almost completely rainfed like Iowa, Indiana, and Illinois (USDA 2010; USDA 2010). Salt accumulation is a likely problem in Nebraska and California where irrigation is predominant or significant.

7.1 Nebraska

Hoffman (2010) reports that groundwater, which accounts of 85% of irrigation water in NE, has electricity conductivity below 1.5 dS/m except for relatively small regions along the Platte River and some aquifers in northwest and eastern NE. Many of the wells listed by Hoffman (2010) have an EC of 0.8 or less. Similarly, surface water which accounts for the remaining 15% of irrigation water, have electrical conductivity of below 1 dS/m.

Assuming 1.5 dS/m for groundwater and 1 dS/m for surface water, the average salinity of irrigation water is around 1.4 dS/m. Based on Martin (2009), we assume a ET_c and ET_a of 28.5 and 5 inches for eastern NE, and 29 and 12 inches for western NE. Based on these assumptions, the average salinity of evapotranspired water is 0.24 dS/m for eastern NE and 0.58 dS/m for western NE.

Note: For Eastern NE: $\left[EC_w = (0 + 1.4 * 5) / 28.5 \right]$

For Western NE: $\left[EC_w = (0 + 1.4 * 12) / 29 \right]$

The leaching requirements are then:

LR (eastern NE) = $0.24 / (5 * 2.5 - 0.24)$ = 0.019 or 1.9% of ET_c.

LR (western NE) = $0.58 / (5 * 2.5 - 0.58)$ = 0.049 or 4.9% of ET_c.

Based on assumed ET_c, the leaching requirements may also be expressed as 0.55 and 1.4 inches for eastern and western NE respectively. These levels of salt leaching requirements would be met entirely through application of excess irrigation water (due to irrigation system inefficiencies) and precipitation after crop season. This is confirmed by the 2008 FRIS which found negligible amount of water-use in NE to leach salts. As a result, we assume SL=0 for Nebraska.

7.2 California

Per USDA, water is used for salt leaching in around 5% of total harvested acreage (2007 Census of Agriculture and 2008 FRIS). However, no information is available about the amount of water applied and salt leaching requirement for acreage used for corn cultivation.

Hanson (1993) calculated the LR requirements for corn grown in SJ valley to be 5% of crop evapotranspiration (Hanson (1993) assumed an average electrical conductivity of 0.5 dS/m for irrigation water in SJ valley). On the other hand, Cost and Return studies conducted by the University of California Cooperative Extension for corn grown in the southern San Joaquin Valley indicates that pre-irrigation water requirements are nearly 20% of crop water requirements (UCCE 2008). Pre-irrigation water is applied not only for salt leaching but also for crop establishment.

In absence of further information, we assume SL equal to zero for California.

8 Appendix A4: Irrigation application losses

8.1 Irrigation system efficiencies

Our irrigation efficiencies are based on Salas, Green et al. (2006) and Howell (2003). The efficiencies reported by the two studies are summarized below:

Table: A4.1: Application efficiency of irrigation systems

Type of Irrigation System	Salas et al. (2006)	Howell (2003)(1)
Surface irrigation		
- Basin	85%	85%
- Border	78%	65%
- Furrow (2)	68%	65-80%
- Wild flooding	60%	
Sprinkler		
- Hand move or portable	70%	
- Center Pivot and Linear Move	83%	80-90%
- Solid Set or Permanent	75%	
- Side roll sprinkler	70%	75%
- LEPA (low energy precision application)	90%	95%
Drip / micro irrigation		
- Surface drip	88%	85%
- Buried drip	90%	90%
- Sub-irrigation	90%	
Sub-surface Drain Lines		75%

Notes: (1) Average field level efficiencies; (2) Per Howell (2003), graded furrow have an average efficiency of 65% while level furrows have higher efficiencies of 80%.

USDA's 2008 FRIS gives the state-wide average share of sprinkler (pressure) systems and gravity (surface) irrigation systems. 2008 FRIS also gives the nation-wide share of various types of surface and sprinkler systems to irrigate corn grain, however a state-wide detailed breakup is not available.

Table A4.2: Share of sprinkler systems in corn grain irrigation in 2008

	CA	IL	IN	IA	NE	KS	US (2008)	US (2003)
Sprinkler Systems	21%	100%	100%	99%	85%	95%	83%	78%
Gravity (Surface) irrigation	79%				15%	5%	17%	22%

Notes: (a) The shares are calculated by dividing corn produced using sprinkler irrigation by total irrigated corn produced in 2008 (b) Based on 2008 FRIS (Table 28).

Central pivot and linear move sprinkler system is the predominant sprinkler system used for corn grain irrigation, while furrow irrigation is the predominant surface irrigation system (Orang, Snyder et al. 2005; USDA 2010). Given the above, we assume an irrigation efficiency of 85% for sprinkler systems and 75% for furrow irrigation.

8.2 Consumptive versus non-consumptive losses

In this section, we divide the excess irrigation applied into consumptive losses – evaporative losses; and non-consumptive losses – ground run-off and deep percolation / seepage.

8.2.1 Sprinkler systems

Consumptive losses for sprinkler irrigation have been well documented. Such losses happen in three areas. Water may be lost through evaporation and wind drift as it travels from the sprinkler nozzle to the crop canopy. Once on the canopy, water may be lost through evaporation from the leaves. Finally, some of the water that reaches the soil surface may be lost due to soil evaporation. The first two losses are sometimes referred to as spray losses and constitute most of the consumptive losses from these systems.

Mclean, Ranjan et al. (2000) have cited a number of studies which report evaporative spray losses from 15% to 50%. (Lamm, Howell et al. (2006) report that total consumptive losses from above canopy sprinkler systems, like the Center Pivot System, can be between 8-15%; while below canopy systems like LESA (low elevation spray application) have around 2% losses due to soil evaporation. Evaporative losses depend primarily upon weather conditions - wind speed, vapor pressure deficit, air temperature, and solar radiation; and equipment type and condition. Evaporative losses can be reduced by irrigating when climatic demand is lowest – nighttime or early morning; or by using smaller nozzle diameters.

Well maintained sprinkler systems should have leak and drainage losses below 1%, but poorly managed systems have shown losses of near 10% (Solomon 1988)

As mentioned before, we have assumed a application efficiency of 85% for center pivot sprinkler systems. Of the losses, 10 percent points are assumed to be consumptive, while the remaining 5 percent points are non-consumptive.

8.2.2 Surface irrigation systems

We did not find the relative share of consumptive and non-consumptive losses for surface irrigation. Cech(2009) indicates that furrow irrigation systems have low evaporative losses and high percolation rates, but has not quantified these losses. In absence of any further information, we have assumed that 10 percent points of the losses associated with furrow irrigation are consumptive and remaining non-consumptive.

8.3 Variability in application efficiency

Observed efficiencies (AE) of any irrigation system may differ widely from the maximum potential AE. System design and implementation, and management determine real world efficiencies. Thus installing a drip system does not always result in higher irrigation efficiencies. As reported by Jensen (2007), unless a drip system is properly maintained and operated, the irrigation efficiency achieved may be no better than that achieved with a traditional surface system. Similarly, Lewis, McGourty et al. (2008) found that vineyards using drip irrigation systems varied widely in the amount of water applied per acre (from 0.2 acre-feet to 1.3 acre-feet) suggesting that management practices are an important determinant of applied water. Edkins (2006) reports wide variability in observed application efficiencies in a study of irrigation system performance in New Zealand.

Table A4.3: Variability of water application efficiencies in a New Zealand survey

Type of sprinkler system	Number of measurements	Avg. application efficiency (%)	Observed efficiency range
- Hand move or Portable	2	89%	88%-91%
- Linear move	13	89%	80%-93%
- Center pivot	7	88%	85%-94%
- Side roll sprinkler	8	90%	86%-92%

Notes: Based on . Edkins (2006)

9 Appendix A5: Conveyance Losses

For conveyance losses in Nebraska, IL, IN and IW, we take statewide estimates from USGS (1998) which has estimated such losses for the year 1995. Subsequent nationwide water use estimates by USGS for 2000 and 2005 do not include conveyance losses. As noted before, we are not considering irrigated corn in the states of IL, IN and IA; hence conveyance losses for these states are not important.

USGS's estimates do not indicate the proportion of loss that are consumptive – surface evaporation and evapotranspiration by vegetation in and near canals; or non-consumptive like run-off and deep water percolation. The extent of losses as well as the relative shares of consumptive and non-consumptive losses depend upon a number of factors like whether the canals are lined or not (unlined canals will lead to higher seepage losses), maintenance of canals, average length of conveyance, and weather conditions.

For Nebraska, the high water losses result from unlined canals (based on personal communication with Doug Hallum, Integrated Water Management Coordinator, Department of Natural Resources, State of Nebraska; October 2010). Unlined canals and consequent seepage of water have led to rise in groundwater levels close to canals by 50 feet and growth of half a mile of vegetation around Platte Rive where previously none (Hotchkiss 1991). Consumptive losses in NE are assumed to be 1% (personal communication with Doug Hallum; October 2010).

For California, detailed water portfolio information is available for the year 2001 (CA DWR 2005). Total conveyance losses in California expressed as a percentage of water withdrawn for irrigation was 3.23% in 2001 (CA DWR 2005) and reduced from 5.78% in 1995 (USGS 1998). Further, of the total conveyance losses, around 73% was consumptive (CA DWR 2005). The recent lining of the All American Canal should lead to lowering of total conveyance losses and increase in relative share of consumptive losses.

For Kansas, the total conveyance losses are 4.23% based on USGS (1998). We did not get references about the consumptive portion of these losses and assumed it to be 1% of total water withdrawn.

Table A5.1: Irrigation water conveyance losses

	Total losses as percent of irrigation water withdrawn		Consumptive losses
	USGS (1998) estimates	CA DWR (2005) estimates for CA	Percent of irrigation water withdrawn
California	5.78%	3.23%	2.36%
Indiana	0%		
Illinois	0%		
Iowa	0%		
Kansas	4.23%		1%
Nebraska	12%		1%

10 Appendix A6: Crop yields

In this section, we summarize data about yields of corn grain and soybean for the various agricultural districts listed in Appendix A2.

Since the meteorological data is averaged over a number of years, we present here the yield averaged over 5 years between 2005 and 2009.

10.1 Corn grain

As the following table shows, corn cultivation is predominantly rain-fed in the states of Illinois, Iowa and Indiana. In California, the corn cultivation depends completed on applied irrigation water, while in case of Nebraska irrigated corn constitutes almost half of total corn produced.

Table A6.1: Average state yields of corn grain in 2007

	Percent acreage irrigated	Entire crop irrigated		None of the crop irrigated		Part of crop irrigated	
		Yield (bu/acre)	Production share	Yield (bu/acre)	Production share	Yield (bu/acre)	Production share
California	100%	182.2	100.0%				
Illinois	2%	172.9	0.2%	171.8	93.1%	170.9	6.7%
Indiana	4%	146.0	0.3%	150.1	86.0%	156.0	13.7%
Iowa	1%	114.0	0.1%	166.0	97.7%	152.8	2.2%
Kansas	42%	192.0	30.4%	103.1	32.4%	141.8	37.2%
Nebraska	44%	174.1	30.0%	119.3	50.0%	158.3	20.0%

Source: 2007 Census of Agriculture (USDA 2009)

For NE, yields of irrigated corn are significantly higher than rain-fed corn. The equal shares of irrigated corn and rain-fed corn may warrant separate and independent analysis of water intensity of ethanol from both types of corn.

Table A6.2: Average yield (bu/acre) of irrigated and non-irrigated corn in Nebraska between 2005 and 2009

Agricultural District	Combined yield	Yield of irrigated corn	Yield of non-irrigated corn	Share of irrigated corn produced in that region (2005-2009)
Entire NE	161.4	186.5	122.7	63.3%
East	163.2	186.9	134.9	62.9%
North	168.4	181.4	78.8	94.2%
Southwest	151.8	184.3	76.4	84.4%
Entire KS	135.4	188.6	96.6	48.3%
North Central	126.6	178.4	101.2	45.5%

Southwest	182.4	196.4	48.4	~98%
Northeast	134.0	175.0	130.3	3.8%
East Central	111.2	169.0	103.5	11.7%
South Central	150.6	180.2	78.8	84.4%

As mentioned before, we assumed a cob-grain yield ratio of 0.18 when both are oven-dried. The corresponding corn cob yields expressed in dry ton / acre in Nebraska is given below

Table A6.3: Average corn cob yield (dry ton/acre) from irrigated and non-irrigated corn in Nebraska and Kansas between 2005 and 2009

	Combined yield	Yield from irrigated corn	Yield from non-irrigated corn
Entire NE	0.69	0.79	0.52
East	0.69	0.80	0.57
North	0.72	0.77	0.34
Southwest	0.65	0.78	0.33
Entire KS	0.58	0.80	0.41
North Central	0.54	0.76	0.43
Southwest	0.78	0.84	0.21
Northeast	0.57	0.75	0.55
East Central	0.47	0.72	0.44
South Central	0.64	0.77	0.34

Source: Our calculations

For IN and IA, irrigated corn yields are lower than rain-fed. This may be because of irrigated lands are less fertile croplands brought into production to take advantage of higher corn prices in recent years (Fargione and Plevin 2010). The low shares of irrigated corn, limited information explaining lower yields of irrigated corn, and non-availability of USDA data on irrigated corn volumes and yields for all years, precludes analysis of water intensity of ethanol from irrigated corn cultivated in the states of IN, IA and IL.

Table A6.4: Average yield of corn grain & cob, and production shares in CA, IL, IN & IA between 2005 and 2009

	Agricultural district	Corn grain yield (bu/acre)	Corn cob yield (dry ton / acre)	Share of total US corn production (2009)
California	Entire state	178.8	0.76	0.2%
	- San Joaquin Valley	178.5	0.76	
Illinois	Entire state	166.8	0.71	15.7%
	- Central	178.0	0.76	
	- Northeast	167.8	0.71	
	- Northwest	172.2	0.73	
	- West Southwest	164.8	0.70	
Indiana	Entire state	159.2	0.68	7.1%

	- Central	162.5	0.69	
	- Southwest	158.7	0.68	
Iowa	Entire state	172.6	0.74	18.6%
	- Central	178.5	0.76	
	- West Central	171.5	0.73	

Source: National Agricultural Statistics Service (USDA 2010)

10.2 Soybean

Table A6.5: Average yield (bu /acre) of irrigated and non-irrigated soybean (SB) in Nebraska and Kansas between 2005 and 2009

Agricultural District	Combined yield	Yield of irrigated SB	Yield of non-irrigated SB	Share of irrigated SB produced in that region (2005-2009)
Entire NE	50.5	57.7	44.1	48%
East	51.1	58.8	46.0	46%
North	49.7	53.0	32.1	89%
Southwest	54.7	57.3	27.4	95%
Entire KS	35.4	53.6	34.0	~20%
North Central	41.3	55.6	38.8	17.1%
Southwest	52.6	54.3	18.0	99.3%
Northeast	43.8	55.3	43.0	1.5%
East Central	31.8	50.0	31.3	2.7%
South Central	39.2	53.1	27.4	60.0%

Source: National Agricultural Statistics Service (USDA 2010)

Table A6.6: Average yield of soybean and production shares in IL, IN & IA between 2005 and 2009

	Agricultural district	Average SB yield (bu/acre)	Share of total US SB production (2009)
Illinois	Entire state	46.2	12.8%
	- Central	51.4	
	- Northeast	46.8	
	- Northwest	49.0	
	- West Southwest	45.6	
Indiana	Entire state	47.8	7.9%
	- Central	50.9	
	- Southwest	45.3	
Iowa	Entire state	50.5	14.5%
	- Central	52.8	
	- West Central	49.9	

Source: National Agricultural Statistics Service (USDA 2010)

11 Appendix A7: Embodied water of energy consumed

Average freshwater intensity of thermoelectricity is given in the following table:

Table A7.1: Fresh water consumption and withdrawal

Gallons / kWh

	Consumption (1)	**Withdrawal (2)**		**Consumption (1)**	**Withdrawal (2)**
Alabama	0.14	26.46	Montana	0.92	1.79
Arizona	0.30	0.40	Nebraska	0.18	42.65
Arkansas	0.27	17.64	Nevada	0.54	0.60
California	0.05	2.24	New Hampshire	0.11	6.22
Colorado	0.49	1.18	New Jersey	0.07	7.65
Connecticut	0.08	2.45	New Mexico	0.60	0.61
Delaware	0.01	15.64	New York	0.82	20.94
D .C	1.54	21.32	North Carolina	0.22	26.02
Florida	0.14	1.24	North Dakota	0.35	12.88
Georgia	0.57	8.02	Ohio	0.91	22.21
Hawaii	0.04	0.00	Oklahoma	0.49	1.23
Idaho		0.87	Oregon	0.79	0.37
Illinois	1.01	24.01	Pennsylvania	0.52	11.63
Indiana	0.40	18.32	Rhode Island	0.00	0.01
Iowa	0.11	24.02	South Carolina	0.25	26.38
Kansas	0.56	3.71	South Dakota	0.01	0.68
Kentucky	1.05	13.51	Tennessee	0.00	40.59
Louisiana	1.50	37.01	Texas	0.42	14.02
Maine	0.28	3.51	Utah	0.54	0.59
Maryland	0.03	3.92	Vermont	0.33	32.69
Massachusetts	0.00	1.09	Virginia	0.06	20.30
Michigan	0.48	28.61	Washington	0.27	8.38
Minnesota	0.42	19.62	West Virginia	0.56	14.93
Mississippi	0.38	3.46	Wisconsin	0.47	44.51
Missouri	0.29	25.18	Wyoming	0.47	1.75
US Average	**0.45**	**16.05**			

Notes (1) Source USGS (1998). Data for 1995
(2) Source USGS (2009). Data for 2005