08

Water Consumption Footprint of Producing Agriculture and Forestry Feedstocks

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8.1 Introduction

The management of our nation's water resources faces increasingly pressing challenges that are exacerbated by an expanding population, growing energy demands, and a changing climate. To build a sustainable water future, crosscutting, innovative strategies are needed (White House 2016). A recent SECURE Water Act Section 9503(c) report identifies warmer temperatures, changes in precipitation, decreasing snowpack, and the timing and quality of streamflow runoff across major river basins as threats to water availability (DOI 2016). The U.S. Department of Energy (DOE) identified water use and water resources as critical components of environmental sustainability to be addressed in bioenergy development (DOE 2016a).

As with any biological system, the production of bioenergy feedstocks relies on water, as well as soil, climate, and other environmental variables. Water use in bioenergy production varies extensively by feedstock and region (Phong, Kumar, and Drewery 2011; Georgescu, Lobell, and Field 2011; Wu et al. 2009; Evans and Cohen 2009). Industrial development, however, can significantly affect the availability of water resources (Schuol et al. 2008; Faramarzi et al. 2009; Glavan, Pintar, and Volk 2012). From an economic perspective, the value of water varies from one location to another, depending on the richness of water resources in that vicinity (Frederick, Vanden-Berg, and Hanson 1995). Hoekstra and Hung (2005) analyzed water intensity across the supply chain and from production system to use communities. In addition, the different priorities for water use, both regionally and across time, result in economic and environmental trade-offs that must be identified and addressed (Williams and Al-Hmoud 2015). Variations in stressors (e.g., drought, competing water use) associated with water supply and consumption among regions could result in substantial impacts on energy production, and the ripple effect of these stressors can be felt across regions in multiple sectors (Fulton and Cooley 2015; Heberger and Donnelly 2015; Scown, Horvath, and McKone 2011). Historically, irrigation has been a major factor in the water footprint of conventional bioenergy and agricultural products because of the demand from annual crops in certain regions (White and Yen 2015; Chiu and Wu 2012; Scanlon et al. 2012; Gerbens-Leenes, Hoekstra, and van der Meer 2009).

Irrigation accounts for about 80% of water demand globally; if it is not appropriately managed, irrigation could have significant effects on the global water system (Rost et al. 2008). A recent report showed that the rate of groundwater depletion has increased markedly since about 1950, with maximum rates of depletion occurring during the most recent period (2000–2008) (Konikow 2013). Improvements in technology and irrigation practices can impact water use substantially (Levidow et al. 2014; Cooley, Gleick, and Christian-Smith 2009).

Evapotranspiration is the sum of evaporation from the land and water surface and plant transpiration to the atmosphere. Research indicates transpiration is the larger component of evapotranspiration (ET) (Jasechko et al. 2013). Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. Evapotranspiration is an important part of the water cycle.

Despite the facts that all biomass requires water and that the water demand is to be met by either rainfall or irrigation, some biomass, such as perennial grasses, can grow without irrigation or with significantly less irrigation than other crops in some regions. The long root system of perennial grasses is able to retrieve moisture from deep soil, which can also benefit water quality (chapter 4). However, biomass feedstock yields depend heavily on regional soil and climate conditions, so no single type of crop is an appropriate feedstock for the entire United States. A regional feedstock portfolio that provides high yield while demanding less irrigation would be ideal.

The *2016 Billion-Ton Report* (*BT16*) presents scenarios of a gradual transition from the current biomass feedstock-production system to a future feedstock mix. It focuses on the production of non-food, high-yield cellulosic energy crops (DOE 2016b). The current U.S. energy portfolio could be further diversified by increasing the share of bioenergy; this would improve energy security as mandated by Congress in the Energy Policy Act of 2005, which was expanded under the Energy Independence and Security Act of 2007 (Pub. L. 110-140 2007).

The objectives of this chapter are (1) to develop an estimate of water consumption for major potential *BT16* production scenarios and (2) to conduct geospatial analysis to examine the interplay between feedstock mix and water consumption, as well as geospatial patterns of water consumption footprints for different feedstock mixes. A further aim is to support planning for future regional water resources at federal and local levels. Water footprint analysis considers consumptive water use for biomass production, representing water resource demand and geospatial trends for future scenarios. Water footprint analysis highlights the impact a future scenario would have on water demand at the national scale and, in this case, provides county-level details—a key issue in natural resource availability. Water consumption is particularly relevant when analyzing regional water scarcity and the impact of human activities on water availability.

This assessment focuses on the water consumption aspect of water use. Whereas the term "water use" sometimes refers to water withdrawal, here we designate water use to refer to water consumption. Thus, the terms "water use," "consumptive water use," and "plant water requirement" that appear in this chapter all refer to water consumption by feedstocks in their growing stage. In addition, this study calculates the rainwater demand of all feedstocks and irrigation water demand of conventional crops, not the actual irrigation water volume withdrawn. By definition, water

consumption in feedstock production represents the quantity of water that is (1) removed from a defined system via ET and (2) not immediately returned to the original water source.

This work builds upon previous studies (Wu, Zhang, and Chiu 2014; Chiu and Wu 2012, 2013; Wu and Chiu 2014) on the geospatially explicit water footprint of bioenergy feedstock production in the United States, as well as related model development (Wu et al. 2015; ANL 2013). The chapter examines the water resource requirements of select *BT16* scenarios by conducting a geospatial analysis and estimating the water consumption footprint at three scales: county, state, and national (at a regional resolution). Changes and the distribution of water consumption are analyzed. These results can improve our understanding of the implications that transitioning to cellulosic biomass production would have on regional water use and highlight regional characteristics under the scenarios, thereby aiding the planning and development of new bioenergy and other biomass projects.
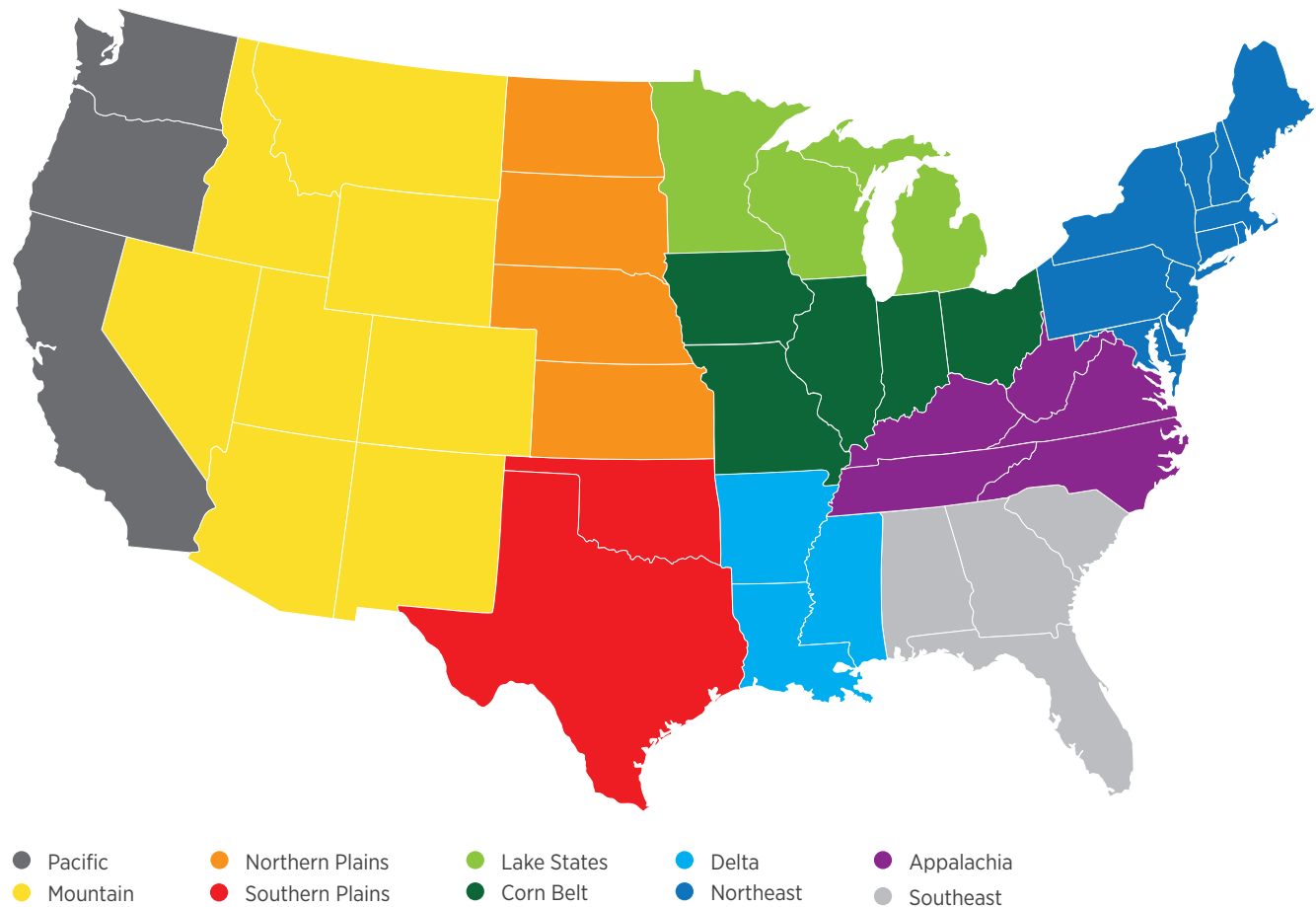
8.2 Methods

8.2.1 Scope of Assessment

A water footprint is developed for the selected *BT16* feedstock production scenarios at county-level resolution for the conterminous United States. The study analyzes select biomass feedstocks, including the following: corn grain (the portion used for ethanol), corn stover, soybean (the portion used for biodiesel), wheat straw, switchgrass, *Miscanthus × giganteus*, short-rotation woody crop (SRWCs) (willow, hybrid-poplar, and southern pine), and resources from softwood and hardwood forest stands. Other energy crops and municipal solid waste (MSW) are not included, either because they are in the early stages of development or because complete county-level data are lacking. (A qualitative analysis of water consumption in *BT16* microalgae scenarios is included in chapter 12.) The analysis does not include food crops

or plants that serve non-bioenergy purposes. The term "biomass" designates feedstock produced for bioenergy or other purposes, which is all of the feedstock analyzed in this chapter.

Crops receive water from either precipitation or irrigation. In this study, irrigation of conventional crops (e.g., corn and soybeans) is attributed to corn grain and soybeans. Energy crops (e.g., perennial grasses, SRWCs) are assumed to be rain-fed. Water withdrawn and applied for irrigation can be used by crops, contributes to runoff to streams, or percolates into the soil. The water footprint analysis accounts for consumptive water use by crops. In this chapter, we define rainwater stored in the soil or intercepted by the plant and subsequently used in plant growth as "rainfall" and consumptive irrigation water requirements as "irrigation." This analysis does not account for irrigation efficiency due to irrigation technology differences or biorefinery water use. The water footprint analysis is conducted at the county, state, and regional levels. Figure 8.1 depicts the agriculture resource regions for the United States analyzed in this chapter. This chapter differs from chapter 7 in that this chapter addresses the water footprint in producing feedstock from annual crops, perennial grasses and SRWCs, and residues and whole trees from forests, whereas chapter 7 examines the impacts that removing feedstocks from the forest would have on water yield in the forestland. Water quality is described in chapters 5 and 6 of this report.

Figure 8.1 | Biomass feedstock production regions for this analysis

Legend				
Pacific	Northern Plains	Lake States	Delta	Appalachia
Mountain	Southern Plains	Corn Belt	Northeast	Southeast

8.2.2 Scenarios

This chapter analyzes the water consumption that may be associated with realizing the potential biomass availability scenarios from *BT16* volume 1, all assuming a roadside price of up to $60 per dry ton (see executive summary, fig ES.1). Six agricultural and forest scenarios were selected for this study: BC1 2017, ML 2017, BC1 2040, ML 2040, HH 2040, and HH3 2040 (see chapter 2). Each scenario covers a different feedstock mix and production year at the feedstock price of $60 per dry short ton,[1] representing current and future biomass potential. Scenario BC1 2017 represents feedstock harvested from current annual crops for which the yield increases at an annual rate of 1%; scenario ML 2017 represents feedstocks collected from forest stands in the form of residues and whole-tree biomass in 2017; scenario BC1 2040 illustrates crop-yield increases at the same rate as that of scenario BC1 2017 with the addition of energy crops (perennial grasses and SRWCs); scenario ML2040 represents a scenario where a slightly decreased quantity of forest resources is available as feedstock; scenario HH2040 is a future scenario where feedstock potentially available from forest resources is further decreased; and scenario HH3 2040 illustrates a simulation in which the agriculture crop yield increases at a 3% annual rate by 2040 (see *BT16* volume 1). Feedstocks included in each scenario are presented in table 8.1, which shows the pairs of agricultural and forestry scenarios in a particular year that were evaluated together for water consumption. Forestry feedstock production under scenarios ML 2017, ML 2040, and HH 2040 are estimated separately from agriculture scenarios (BC1 2017, BC1 2040, and HH3 2040). In the *BT16* volume 1 scenarios, perennial crops (switchgrass, miscanthus, and SRWCs) are not available in 2017; they are available in 2040. The estimated water footprint for the feedstock production scenarios in this chapter reflects that model assumption. Descriptions of the forestry scenarios can be found in chapter 2, 6, and 7 and in more detail in *BT16* volume 1.

Table 8.1 | *BT16* Feedstock Scenarios

Scenario	Feedstock Types				
BC1&ML 2017	Corn stover, wheat straw	Corn grain, soybean			Forest residues and whole-tree biomass (hardwood, softwood)
BC1&ML 2040	Corn stover, wheat straw	Corn grain, soybean	Switchgrass, *Miscanthus × giganteus*	SRWC: willow, hybrid poplar, pine	Forest residues and whole-tree biomass (hardwood, softwood)
HH3&HH 2040	Corn stover, wheat straw	Corn grain, soybean	Switchgrass, *Miscanthus × giganteus*	SRWC: willow, hybrid poplar, pine	Forest residues and whole-tree biomass (hardwood, softwood)

[1] Tons are reported as dry short tons throughout this report, unless specified otherwise.

The forest resource is broken down into residue, saw log, pulp, and whole-tree biomass through clearcut and thinning operations (table 8.2). Only residue and whole-tree biomass are used as feedstock in the *BT16* assessment. The distribution of each feedstock type and harvested feedstock volume is described in *BT16* volume 1.

8.2.3 Description of Water Footprint Accounting for Crops, Grasses, and Forest Resources

Water-footprint accounting has been recognized as a useful method for assessing regional water-resource availability and use for water governance, policy analysis, and planning (White and Yen 2015; Ringersma, Satjes, and Dent 2003; Falkenmark and Rockstrom 2004 and 2006), and it was incorporated into the International Organization for Standardization's (ISO's) standard 14046 for the water footprint (ISO 2014). The concept of water footprint accounting was first introduced by Chapagain and Hoekstra (2004)

and Hoekstra and Hung (2005) under the United Nations' Food and Agriculture program. The application of the water footprint in various regions and countries was well documented in peer-reviewed literature (Ayres 2014; Mekonnen and Hoekstra 2011; Liu, Zehnder, and Yang 2009; Staples et al. 2013; Wu, Chiu, and Demissie 2012; Hoekstra et al. 2011; Siebert and Döll 2010; Hoekstra and Chapagain 2007). The central part of the water footprint for bioenergy is feedstock water use. Mekonnen and Hoekstra (2011) used the CROPWAT model (FAO 2013) to simulate consumptive water use for 126 crops based on the Penman-Monteith method. Crop water use was estimated at 0.5° grid scale globally by using the G-Epic model (Liu et al. 2007). Similar approaches were adopted in the Soil and Water Assessment Tool (SWAT)[2] (Williams 1990) and the CENTURY model for plant-soil nutrient cycling.[3]

Various researchers (Gerbens-Leenes, Hoekstra, and van der Meer 2009; Scown, Horvath, and McKone 2011; Chiu and Wu 2012, 2013; Staples et al. 2013) analyzed water footprints for different types

Table 8.2 | Forest Resources Feedstock Categories in Scenarios ML 2017, ML 2040, and HH 2040

Forest Type	Stand Category	Operation	Feedstock Type	
Hardwood	Lowland	Clearcut	Whole tree	Residue
		Thinning	Whole tree	Residue
	Upland	Clearcut	Whole tree	Residue
		Thinning	Whole tree	Residue
Softwood	Natural	Clearcut	Whole tree	Residue
		Thinning	Whole tree	Residue
	Planted	Clearcut	Whole tree	Residue
		Thinning	Whole tree	Residue
Mixedwood		Clearcut	Whole tree	Residue
		Thinning	Whole tree	Residue

[2] See http://swat.tamu.edu.

[3] See http://www.cgd.ucar.edu/vemap/abstracts/CENTURY.html.

of biomass feedstocks (e.g., corn, sugarcane, soybean, wheat, perennial grasses, SRWCs, and forest resources) in the United States. The calculated crop water-use values were verified with measurements gathered by field instrumentation and remote sensing, as well as on the basis of values derived from satellite imagery data (Wu, Chiu, and Demissie 2012). Results indicate that the water footprint methodology closely resembles peak monthly water use by corn in the crop-growing season. A county-level water footprint resource, called the Water Analysis Tool for Energy Resources (WATER) (http://water.es.anl.gov), was recently developed to assess water sustainability of fuels in the United States (Wu et al. 2015).

In this study, we adopt a water footprint approach to assess consumptive water use for various feedstock production scenarios from agriculture and forestry by using the WATER model. The methodologies employed in this chapter are consistent with methods used in the Water Supply Stress Index Model (WaSSI) (chapter 7), SWAT (chapter 5), and CENTURY (chapter 4). Descriptions of water consumption in the growth stage of crops, perennial grasses, and forest resources are presented in appendix 8-A. Consumptive water use is quantified for the production of feedstocks (corn and soybeans, grasses, SRWCs, and forest resources) by estimating ET. Methods for estimating ET that were used in this analysis are described in appendix 8-A. Water footprint is presented as water intensity, which is annual volume of water consumption per volume of feedstock produced (in dry short tons), or total annual volume of water consumption.

8.2.4 Data Sources

The water footprint is estimated by using historical climate data, including temperature, precipitation, solar radiation, and wind speed, which are available as national average values between 1970 and 2000 from the National Oceanic and Atmospheric Ad-

ministration (NOAA). These data points, collected from more than 3,000 weather stations throughout the United States, were screened for data quality and geographic coverage and processed to generate a historical climate norm (Chiu and Wu 2012; Wu, Chiu, and Demissie 2012). That data set was used for this study. *BT16* scenario land management and feedstock production data are generated by the POLYSYS model (*BT16* volume 1). Acreages of each feedstock type and production yield, as well as county-level biomass feedstock mix for each agriculture scenario, were provided by POLYSYS. Types of feedstock, harvest operation, total production, and acreages of forest residues and whole-tree biomass growing the feedstock were provided by the ForSEAM model (see *BT16* volume 1).

Water footprint modeling parameters are adopted from the WATER model and literature. WATER provides monthly crop water use parameter K_c, accounting for the entire growing season, for each crop. The leaf area index (LAI) of different types of forest stands is collected from McCarthy et al. (2007); Oishi, Oren, and Stoy (2010); Albaugh et al. (1998); Antonarakis et al. (2010); and Sampson et al. (2003). The LAI of perennial grass is from the SWAT model. The proportion of hardwood and softwood in mixed stands is based on historical data from the USDA Forest Inventory and Analysis (FIA) Program (see http://www.fia.fs.fed.us). Additional climate and geography data were collected as needed from NOAA, USDA, and U.S. Geological Survey (USGS) databases.

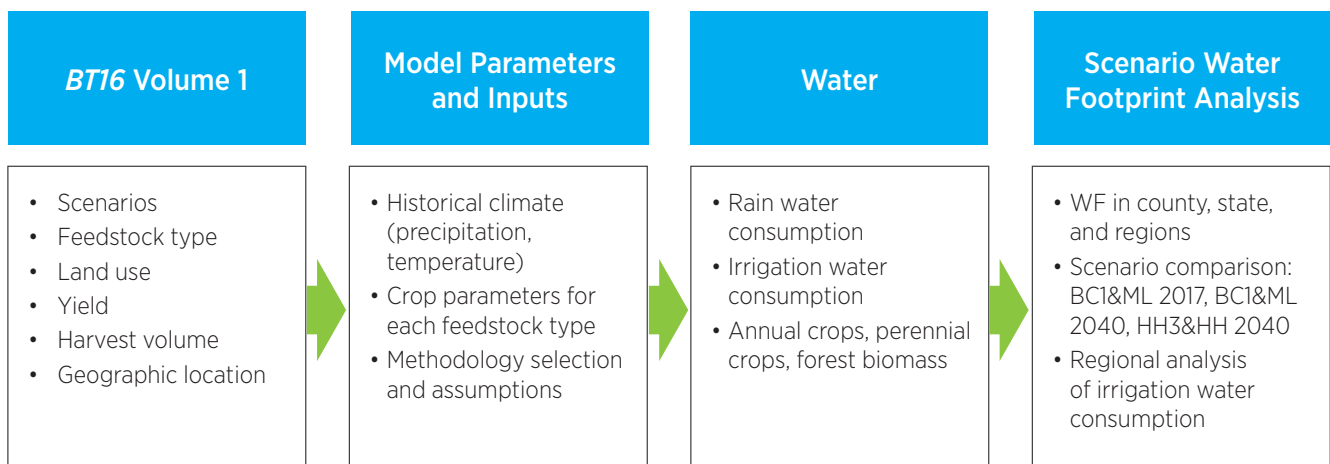## 8.2.5 Description of Water Footprint Implementation

This study models water footprint for feedstock production scenarios by using eight steps, as illustrated in figure 8.2:

1. County-level feedstock production and harvest volume, acreage, and fertilizer management options are assembled into a water footprint database for each scenario, feedstock, and product class.

2. The *BT16* raw data for each scenario are sorted by feedstock component and processed into the input format.

3. Climate parameters supporting reference and feedstock ET calculations in various regions are determined; crop growth parameters and modeling methods for each feedstock type (annual crops, grasses, trees) are selected.

4. Using monthly time steps for each feedstock, growing-season plant water demand is computed according to equations 8.1–8.19 (see appendix 8-A) by using WATER.

5. County-level consumptive water use is estimated based on input feedstock data for each feedstock for each scenario.

6. Weighted average water footprint at the county level is obtained by aggregating results for individual feedstocks to determine the county-level water footprint of the feedstock-mix.

7. The state and regional water footprints for each scenario are processed from the county-level values.

8. The data are examined and regional analysis is applied to dissect the interplay between production yield, feedstock type, and water footprint in different regions. Results are presented on annual basis.

Consumptive water use by biomass is allocated on the basis of the fractions of the crop that are harvested for potential biomass production. Table 8.3 shows the fraction of corn grain for bioenergy production at the national level, ranging from 36.2% (scenario BC1 2017) to 28.4% (scenario HH3 2040), as estimated in *BT16* volume 1. The fraction of wheat straw that was collected for feedstock is negligible at the national level (*BT16* volume 1). The consumptive water use estimate is based on harvest acreage. Agriculture residues (corn stover and wheat straw) are harvested at different rates from county to county in *BT16* scenarios (see volume 1).

Figure 8.2 | Water footprint modeling for biomass production scenarios

BT16 Volume 1	Model Parameters and Inputs	Water	Scenario Water Footprint Analysis
• Scenarios • Feedstock type • Land use • Yield • Harvest volume • Geographic location	• Historical climate (precipitation, temperature) • Crop parameters for each feedstock type • Methodology selection and assumptions	• Rain water consumption • Irrigation water consumption • Annual crops, perennial crops, forest biomass	• WF in county, state, and regions • Scenario comparison: BC1&ML 2017, BC1&ML 2040, HH3&HH 2040 • Regional analysis of irrigation water consumption

The attribution method is an important determinant of water consumption. Irrigation water consumption for conventional crops could be attributed to grain or grain and residue, depending on allocation methods. With the purpose-based method, the irrigation water consumption during the crop growing season is allocated to grain. In the mass-based method, the irrigation water is allocated between grain and residue. Both methods are available in WATER. To be consistent with carbon and GHG accounting in Chapter 4, in which fuel and chemical inputs and resultant emissions during the crop growing season are attributed to grain (additional chemical inputs after harvest attributed to residue), the purpose-based attribution method was elected.

BT16 volume 1 estimated land areas and production volume for the forest feedstocks. Forest resources include several feedstock types that are harvested from the same piece of land. For example, saw log, residue, and pulp are different components of the whole tree. The feedstock types also differ depending on the forest operations, either clearcutting or thinning (see chapter 7 for details). Clear-cutting operations generate residue, saw log, and pulp, while thinning operations generate residue and whole tree. Therefore, the model allocates land area to each feedstock (residue and whole-tree) based on weight proportion of biomass harvested for bioenergy and operations and historical residue yield derived from forest inventory analysis (FIA) database (http://www.fia.fs.fed.us/). The feedstock allocation scheme applies to all three types of forest—softwood, hardwood, and mixedwood—to generate a county-level land allocation map for each forestry scenario.

Mixed stands are composed of softwood and hardwood trees. The water footprint of mixed stand types is calculated based on the proportion of hardwood and softwood in the total feedstock. *BT16* volume 1 provides county-level ratios of softwood to hardwood for the mixedwood harvest, which are calculated from the historical forestry dataset in FIA. This dataset is used to derive water footprints for mixedwood in all scenarios. The consumptive water use for forest resources is established by totaling the water footprints of mixedwood, softwood, and hardwood.

Irrigation water is not applied to forest resources and SRWC feedstocks because they are assumed to receive their required water from rainfall. Similar assumptions are applied to perennial grass feedstocks. See chapter 2 for a discussion of the irrigation assumptions embedded in the biomass yields in *BT16* volume 1.

8.3 Results and Discussion

8.3.1 Water Footprint of the Biomass Production Scenarios

8.3.1.1 BC1&ML 2017 Scenario

The BC1&ML 2017 scenario combines estimates of potential feedstock production from both annual conventional agriculture crops (scenario BC1 2017) and forest residues and whole-tree biomass (scenario ML 2017). In calculating potential forest residues and whole-tree biomass feedstock volumes, scenario ML

Table 8.3 | Corn Grain Harvest Scheme for Future Scenarios

Scenario[4]			
Parameter	BC1 2017	BC1 2040	HH3 2040
Average fraction of corn harvest for use in bioenergy production	36.2%	32.16%	28.4%

[4] The forestry scenarios are not included here because they have no corn grain.

2017 assumes existing forest land acreage. Figure 8.3 presents rainfall consumption by forest feedstock for scenario ML2017. The water footprint in scenario ML 2017 includes estimates for hardwood, softwood, and mixed stands under different harvest operations. Chapter 2 describes in detail the different types of forest harvesting operations indicated here, such as clearcut and thinning. A total of 88 million tons of biomass is harvested from forestlands in ML 2017 (*BT16* volume 1).

Scenario BC1 2017 represents current modeled biomass feedstock production from annual agriculture crops and residues. A total of 235 million tons of corn grain, soybean, corn stover, and wheat straw could be harvested nationally. For the areas that grow agriculture feedstock for biomass, production varies significantly, from 2 tons to 1.8 million tons for each county. The majority of the production is generated in the upper Midwest region of the country. (See figure 8.1 for a map of regions.) When agriculture crops

and forest biomass are combined, the BC1&ML 2017 scenario shows four major production regions: agriculture feedstock–dominant in the Midwest, and forest biomass feedstock–dominant in the Southeast, Pacific, and Northeast (figure 8.4). Together, these regions could generate a total of 323 million tons of feedstocks from annual crops and forest biomass.

Rain water consumption for biomass production is spatially heterogeneous (figure 8.5) as a result of the aggregated distribution of regional feedstock types under BC1&ML 2017. Of the rain water used for biomass production in the scenario, a majority contributed to forest biomass in the Southeast (90%) and Delta (67%) regions. In the Corn Belt and Northern Plains, 80% of the rainwater consumed by biomass would be used to grow annual crop-based feedstock. As illustrated in figure 8.5, total rainwater use in each state depends on the acreages used for biomass production. In the BC1&ML 2017 scenario, states in Southern Plains, Delta, Southeast and Appalachia regions

Figure 8.3 | Rainwater requirements under scenario ML 2017
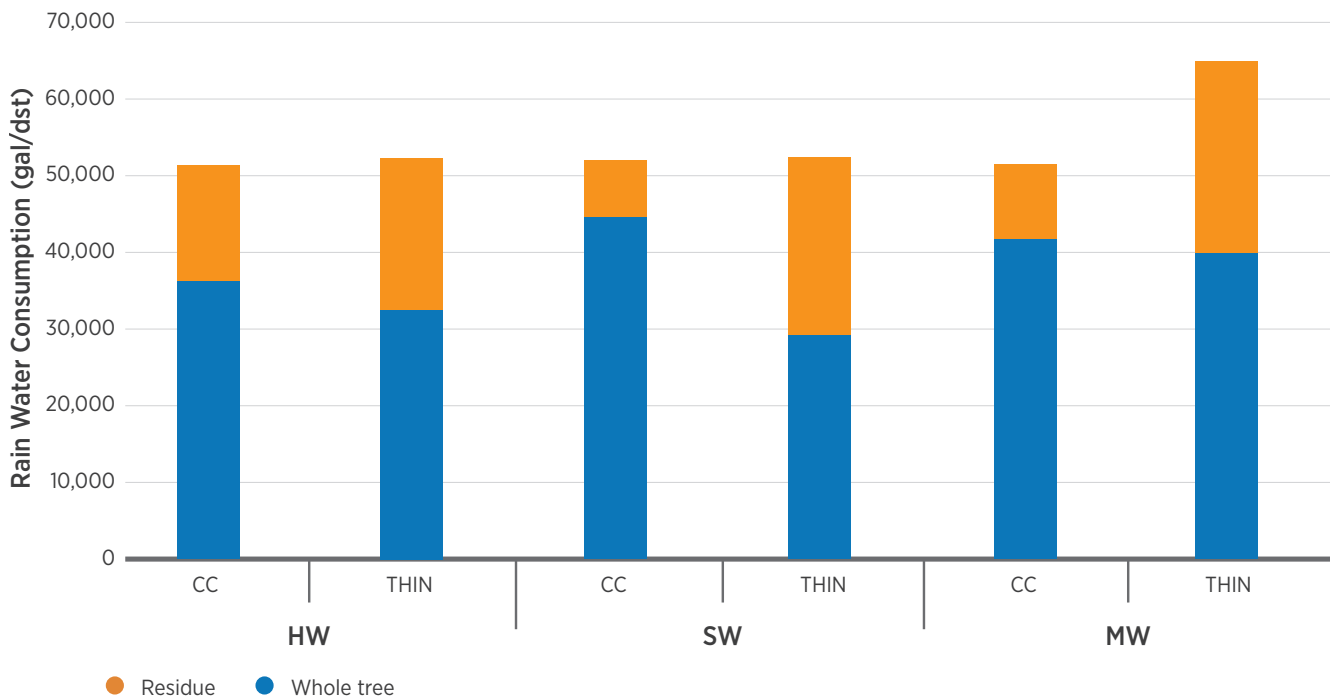
Abbreviations: CC = clearcut; THIN = thinning; HW = hardwood; SW = softwood; MW = mixedwood.

Figure 8.4 | Biomass feedstock production under scenario BC1&ML 2017

Legend:
- Annual Crops
- Perennial Crops
- Forest wood

Feedstock (10³ dst)
- < 178
- 178 – 416
- 416 – 685
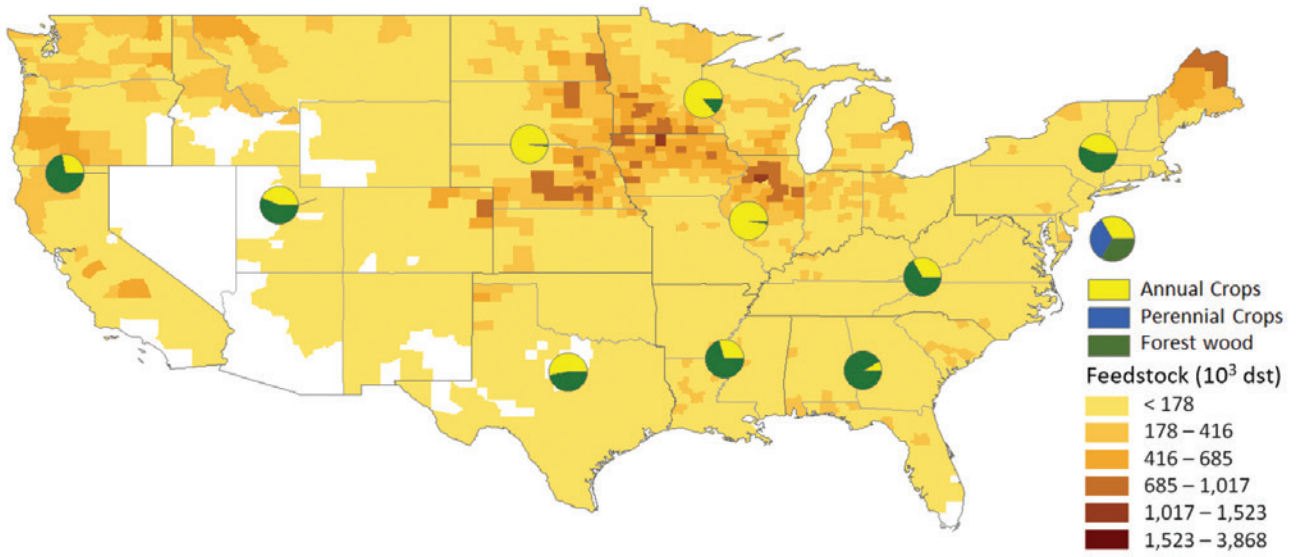- 685 – 1,017
- 1,017 – 1,523
- 1,523 – 3,868

Figure 8.5 | Biomass feedstock production rainwater requirements under scenario BC1&ML 2017. Gal/ac is gallon per acre of biomass. Bgal is billions of gallons.
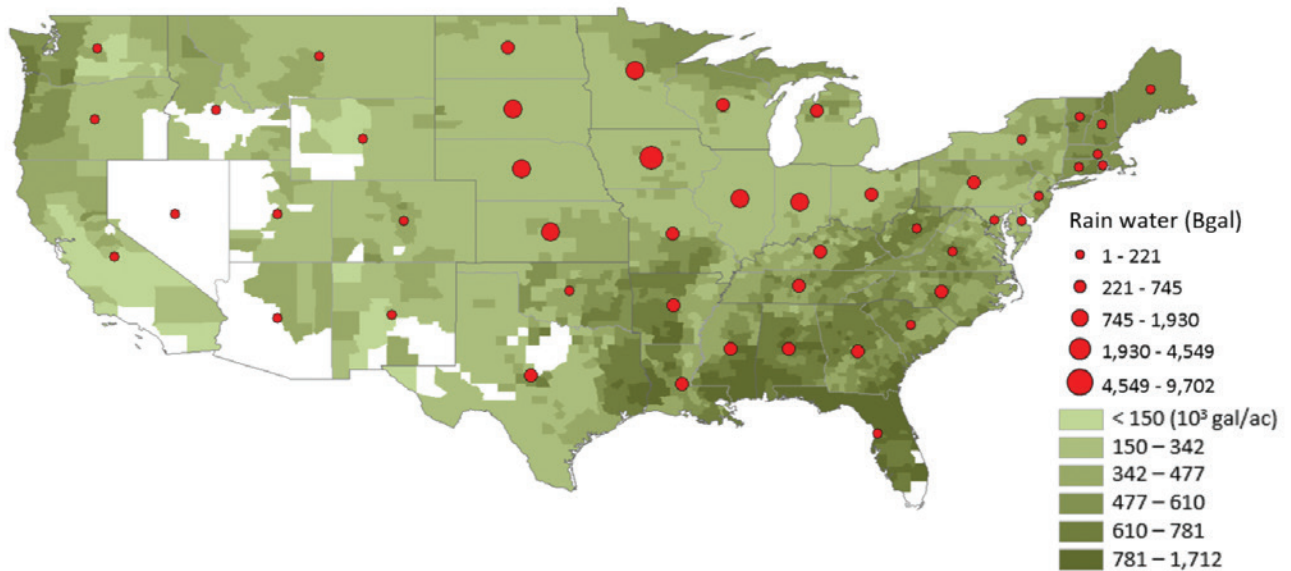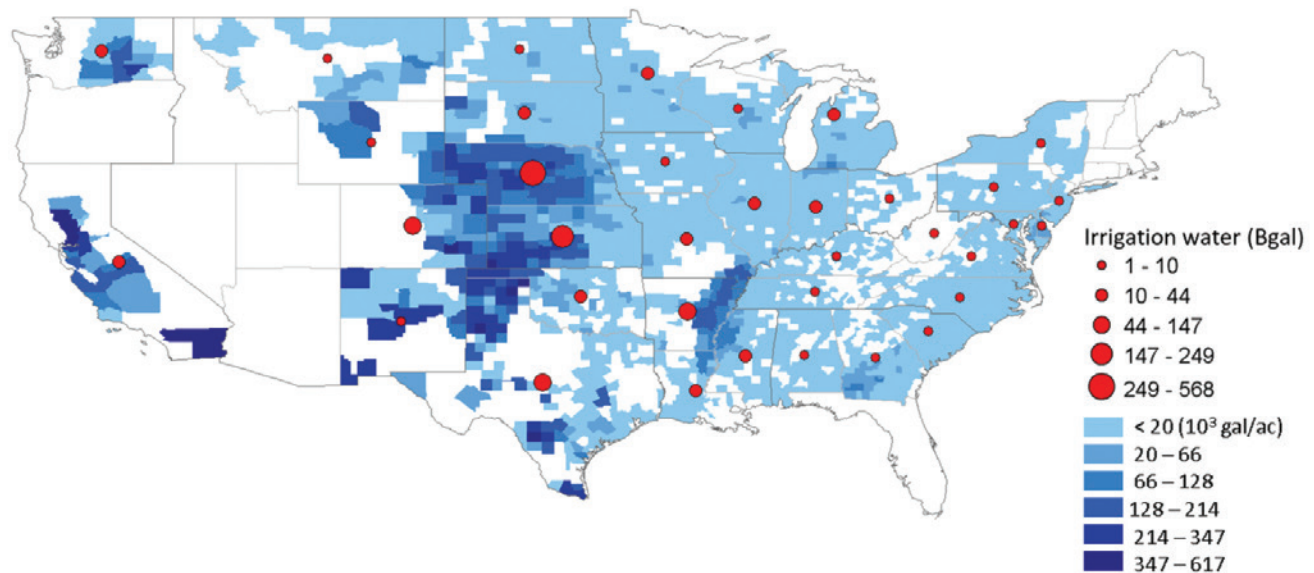

Rain water (Bgal)
- 1 - 221
- 221 - 745
- 745 - 1,930
- 1,930 - 4,549
- 4,549 - 9,702

- < 150 (10³ gal/ac)
- 150 – 342
- 342 – 477
- 477 – 610
- 610 – 781
- 781 – 1,712

Figure 8.6 | Biomass feedstock production irrigation requirements under scenario BC1&ML 2017. Irrigated biomass consists entirely of corn grain and soybean. Gal/ac is gallon per acre of biomass. Bgal is billions of gallons.

would require low to modest total rainwater because land area for biomass feedstock is relatively small. In the Corn Belt, a total of 6 trillion gallons of rainwater could be consumed per year by biomass production from agricultural and forest resources. The Northern Plains could consume 3.6 trillion gallons. Biomass production in the BC1&ML 2017 scenario would consume 17 trillion gallons of water from rainfall. In both figures 8.5 and 8.6, the shaded areas represent county-level rainwater use per acre of biomass (gal/acre), and circles represent state total volume (billion gallons).
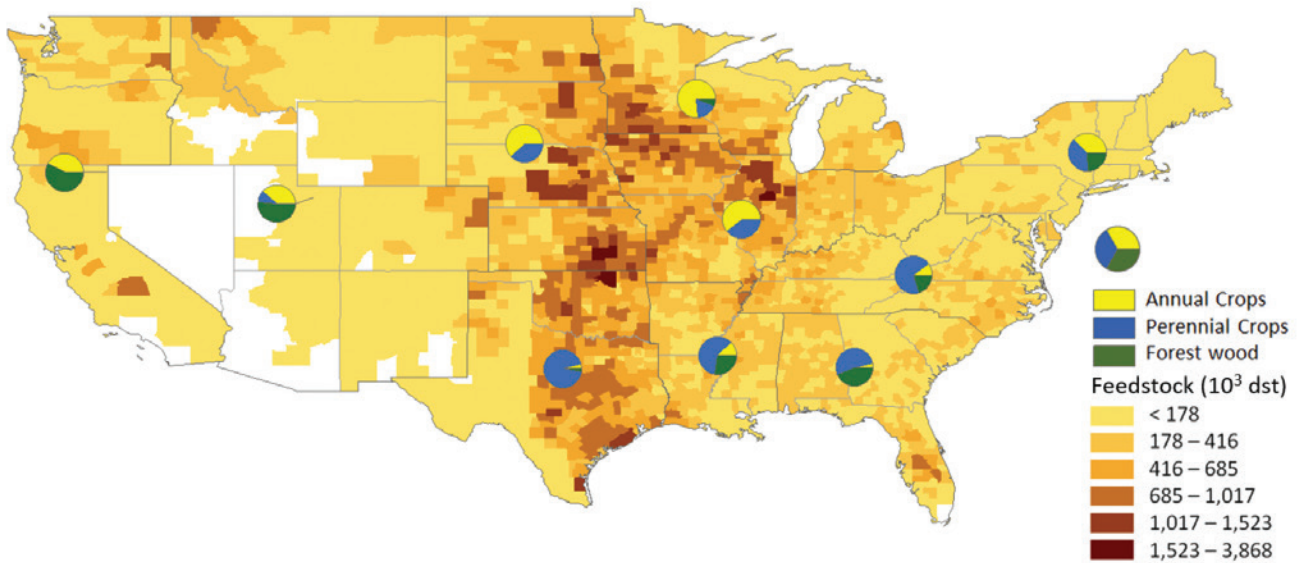
Similarly, state total irrigation water consumption varies depending on feedstock type and acreage. For the regions that require irrigation to grow the feedstock (i.e., corn grain and soybean), approximately 1.4 trillion gallons of water would be consumed in this production scenario. Quantities varying from 20,000 gallons to 617,000 gallons of irrigation water would be required to grow an acre of annual crop feedstock in each county across the United States (figure 8.6). A significant portion of this water would be concentrated in the High Plains. Several other states—for example, New Mexico, California, and Washington—have similar irrigation demand per

acre. Because of relatively small acreages attributed to feedstock production, the total volume of irrigation water in these states is low. Irrigation consumption in the states of the Corn Belt, where the bulk of current annual feedstock is produced from much larger land areas, is also low as a result of minimal irrigation requirements to grow each acre of crops (figure 8.6) in the region.

8.3.1.2 BC1&ML 2040

The BC1&ML 2040 scenario estimates a larger increase in potential feedstock production due to the growth of perennial grasses (switchgrass, miscanthus) and SRWC (willow, hybrid poplar, southern pine), in addition to annual agricultural crop feedstock (crop residue) and a slight decrease in the mass of forest residues and whole-tree biomass feedstocks. Scenario BC1&ML 2040 estimates a potential production of about 800 million tons of biomass per year, nationally (See chapter 1). This total is approximately 40% more than the estimated biomass production volume under the BC1 2017 scenario. The production area increased in the Southern Plains, Northern Plains, and Midwest regions compared to BC1 2017.

Figure 8.7 | Biomass feedstock production under scenario BC1&ML 2040

Legend:
- Annual Crops
- Perennial Crops
- Forest wood

Feedstock (10^3 dst)
- < 178
- 178 – 416
- 416 – 685
- 685 – 1,017
- 1,017 – 1,523
- 1,523 – 3,868

In BC1 2040 other locations began to produce perennial feedstock, such as switchgrass and miscanthus, as well. Perennial grasses and SRWCs can retrieve rainwater percolated in deep soil through their long root systems. As a result, they consume primarily rainwater. In land that was previously idle or used to grow annual crops, introducing a perennial cropping system translates to increased rain water consumption (figure 8.8). Total rainwater used for production of potential biomass under BC1&ML 2040 would be 43 trillion gallons in the United States. Of the quantity of rainwater consumed for feedstock, 31% would be used by annual crops, 67% by perennial crops, and 3% for forest biomass. Regional distribution of the rainwater consumption in BC1&ML 2040 is similar to that in BC1&ML 2017. Although both rainwater

Figure 8.8 | Biomass feedstock production based on rainwater under scenario BC1&ML 2040. Gal/ac is gallon per acre of biomass. Bgal is billions of gallons.

Rain water (Bgal)
- 1 - 221
- 221 - 745
- 745 - 1,930
- 1,930 - 4,549
- 4,549 - 9,702
- < 150 (10^3 gal/ac)
- 150 – 342
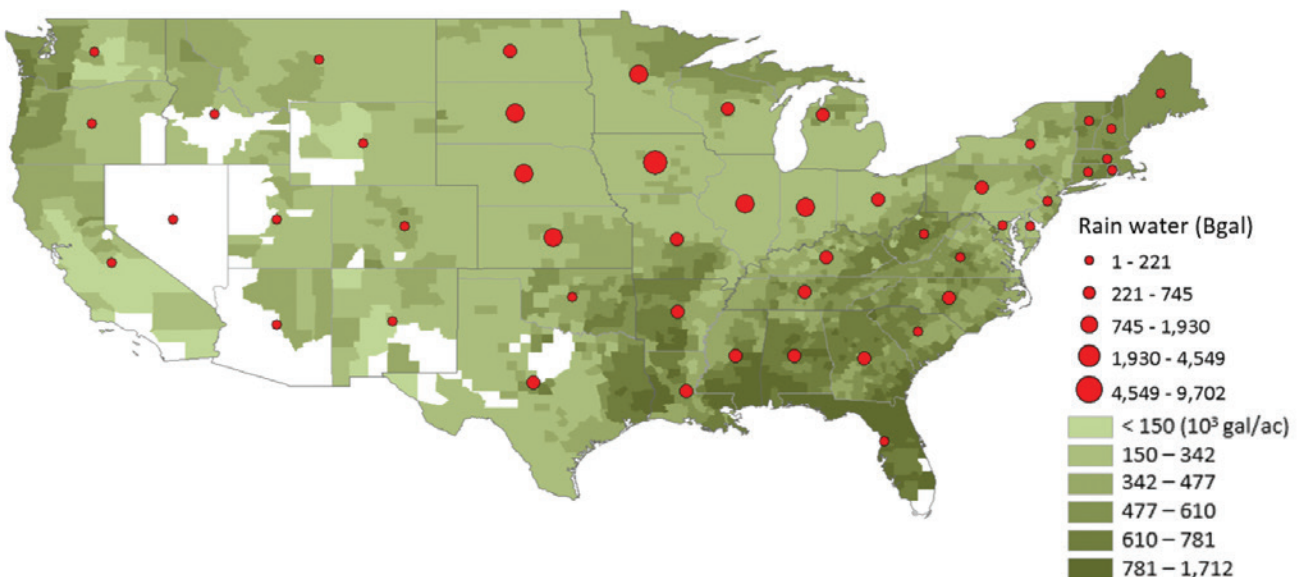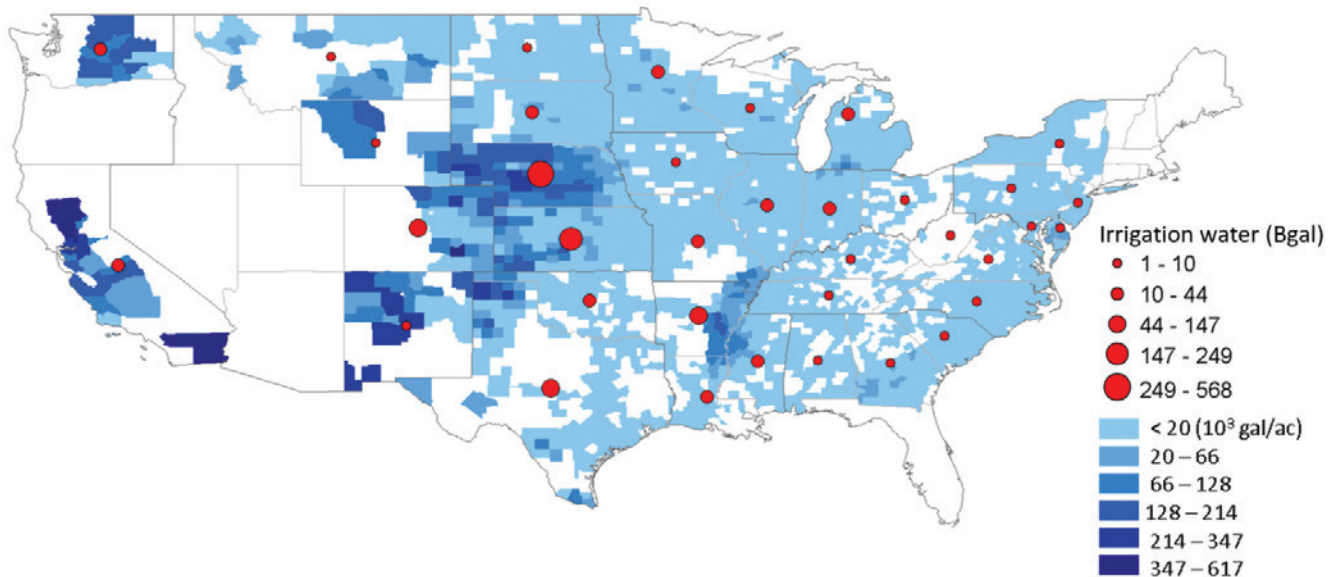- 342 – 477
- 477 – 610
- 610 – 781
- 781 – 1,712

Figure 8.9 | Irrigation requirements for biomass feedstock production under scenario BC1&ML 2040. Gal/ac is gallon per acre of biomass. Bgal is billions of gallons.

and irrigation water are consumed in the production of biomass, rainwater is generally preferred because of its low cost, both economic and environmental, especially in water-rich regions.

Under scenario BC1&ML 2040, irrigation intensity (gal/acre) for biomass production either remained at the same level or decreased, compared to scenario BC1&ML 2017, especially in a few states in the High Plains region (figure 8.9). This decrease results from a reduction of annual crop acreages and an increase of perennial energy crops. For example, corn and soybean acreages were reduced by 75,000 acres in Nebraska and Kansas compared to BC1&ML 2017. In the same period the energy crop acreage increased by 6.3 million acres. The energy crops are not irrigated; therefore, irrigation water consumption decreased while feedstock production increased between the two scenario periods. Nationally, the scenario would consume 1,186 billion gallons of irrigation water, which is a 14% reduction from consumption in the BC1&ML 2017 scenario.

8.3.1.3 Scenario HH3&HH 2040

Under the high-yield scenario, HH3&HH 2040, which combines the high-yield feedstock production scenario from agriculture (scenario HH3 2040) and the high housing-high wood energy scenario from forestry (scenario HH 2040), estimates of perennial feedstock production could increase significantly and become dominant in the 1.3-billion-ton total-feed-stock availability (see *BT16* volume 1). The majority of the potential perennial feedstock is produced in the Midwest and Southern regions (figure 8.10). Also under the scenario, more land that historically grows highly irrigated crops would move to the production of less- or non-irrigated perennial energy crops.

For the same reason as indicated in the discussion of the BC1&ML 2040 scenario, slightly more rain-water would be consumed by feedstock growth (figure 8.11), whereas irrigation demands would further decrease, compared to BC1&ML 2017 (figure 8.12). It is estimated that under the scenario, 48 trillion gallons of rainwater would be consumed for feedstock production. Figure 8.11 shows increased rainwater-use intensity in the Northern Plains, South-

Figure 8.10 | Biomass feedstock production under scenario HH3&HH 2040

Annual Crops
Perennial Crops
Forest wood

Feedstock (10^3 dst)
- < 178
- 178 – 416
- 416 – 685
- 685 – 1,017
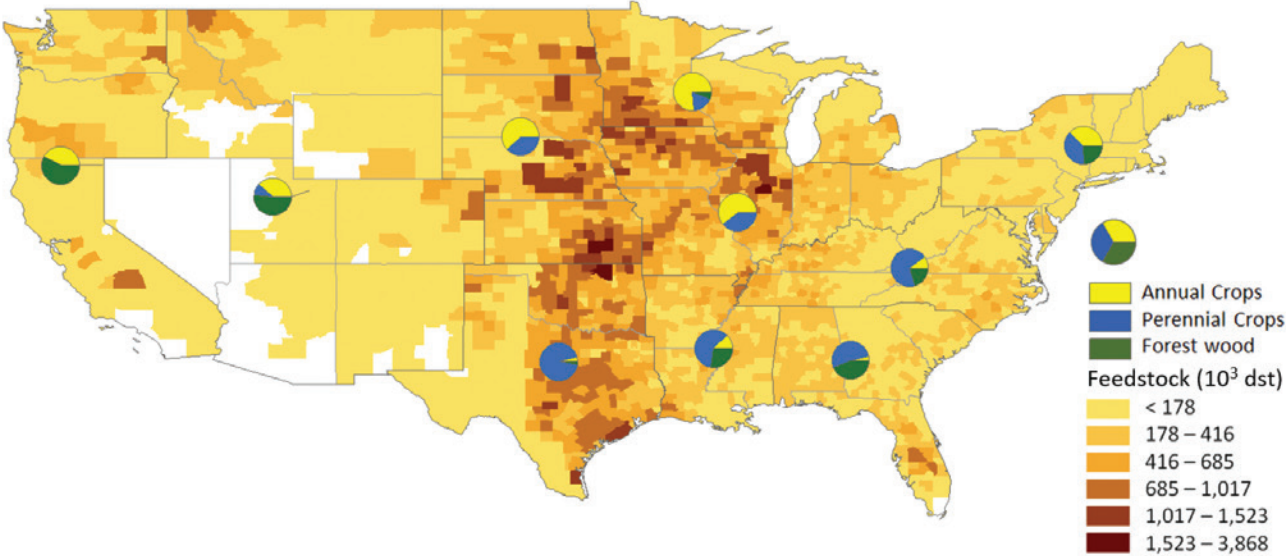- 1,017 – 1,523
- 1,523 – 3,868

Figure 8.11 | Rainwater requirements for biomass feedstock production under scenario HH3&HH 2040. Gal/ac is gallon per acre of biomass. Bgal is billions of gallons.
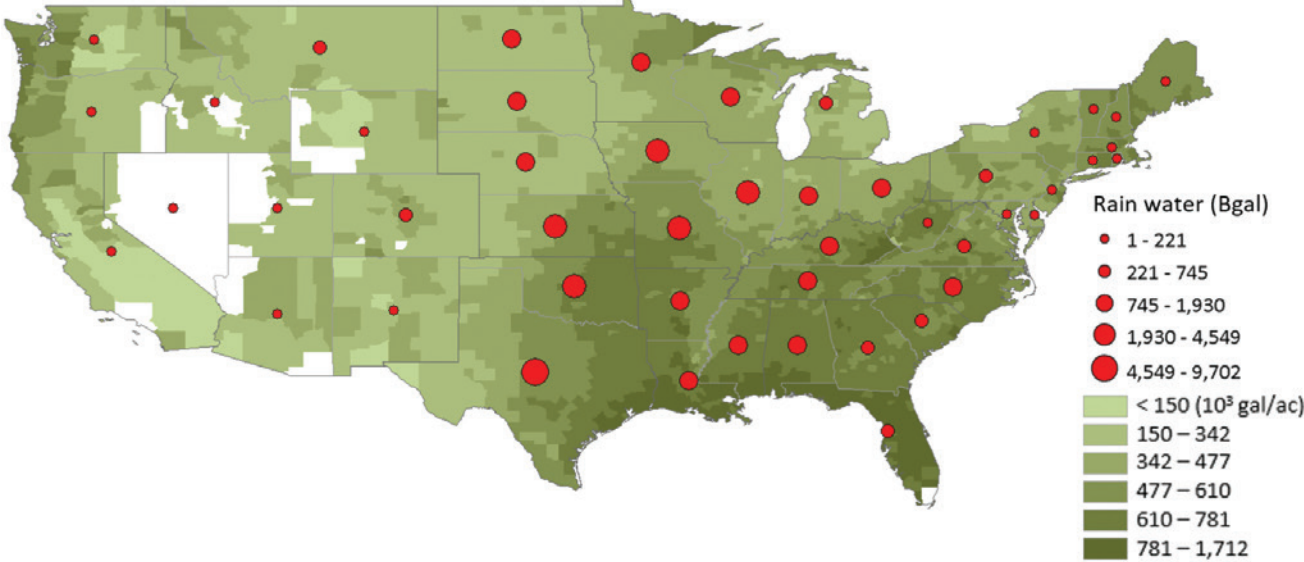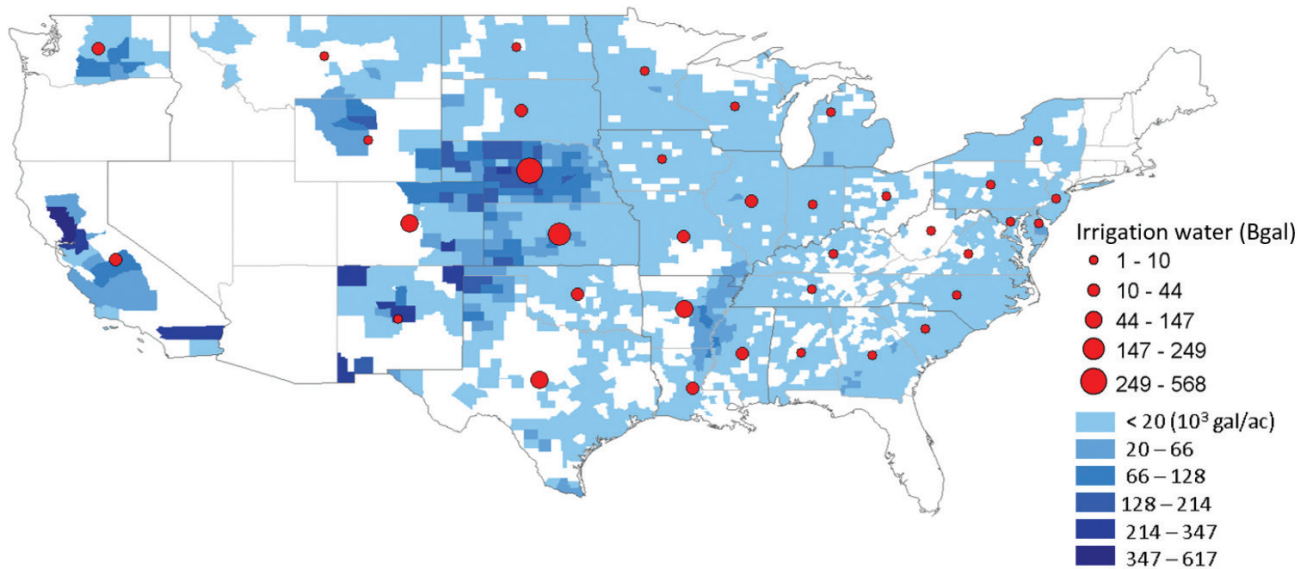

Rain water (Bgal)
- 1 - 221
- 221 - 745
- 745 - 1,930
- 1,930 - 4,549
- 4,549 - 9,702
- < 150 (10^3 gal/ac)
- 150 – 342
- 342 – 477
- 477 – 610
- 610 – 781
- 781 – 1,712

Figure 8.12 | Irrigation requirements for biomass feedstock production under scenario HH3&HH 2040. Gal/ac is gallon per acre of biomass. Bgal is billions of gallons.

ern Plains, Appalachia, Northwestern, and Cornbelt regions. Total irrigation water consumption would decrease to 1.0 trillion gallons from the 1.4 trillion gallons in the BC1&ML 2017 scenario.
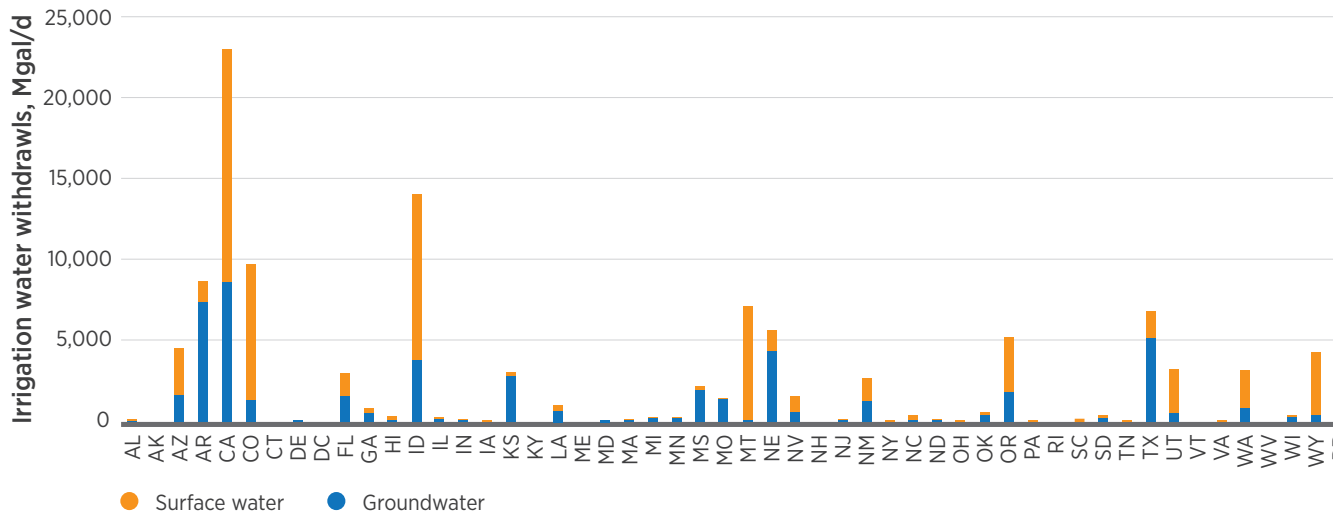
8.3.2 Impact on Groundwater Irrigation

The U.S. agriculture sector withdrew 41.98 trillion gallons of fresh water for irrigation in 2010 (Maupin et al. 2014), which accounts for 38% of freshwater withdrawal for all uses. About 43% of the total irrigation water comes from groundwater sources (figure 8.13). In 2010, 18 trillion gallons of groundwater were withdrawn for irrigation. Geographically, 83% of U.S. irrigation withdrawal took place in the 17 conterminous western states. Surface water was the primary source of water in the western states, with the exception of Kansas, Oklahoma, Nebraska, Texas, and South Dakota, where groundwater was the main option.

The Ogallala Aquifer provides 20% of irrigation water to agriculture crops and cattle produced in the United States (Maupin et al. 2014). The counties in the High Plains withdrew a total of 5.8 trillion gallons from the Ogallala Aquifer for agricultural crop irrigation in 2010. (The western states that use groundwater for irrigation are mostly in the High Plains region.) The Ogallala Aquifer is facing depletion—the rate of water withdrawal far exceeds water replenishment. The area-weighted, average water-level changes in the aquifer were an overall decline of 15.4 feet from predevelopment to 2013, and a decline of 2.1 feet from 2011 to 2013. Total water in storage in the aquifer in 2013 declined 36.0 million acre-feet from 2011 to 2013. (McGuire 2014).

In 2011, the USDA Natural Resources Conservation Service (NRCS) launched the Ogallala Aquifer Initiative (OAI) to reduce aquifer water use, improve water quality, and enhance the economic viability of croplands and rangelands in Colorado, Kansas, Oklahoma, Nebraska, New Mexico, Texas, South Dakota, and Wyoming.[5] OAI aims to reduce water withdrawal

[5] See http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/programs/initiatives/?cid=stelprdb1048809.

Figure 8.13 | Agriculture irrigation water withdrawals in the United States (Maupin et al. 2014)

and extend the life of the aquifer by implementing multiple conservation measures. One of the strategies is converting operations to dryland farming, which is defined as the non-irrigated cultivation of crops. This strategy is consistent with one of the sustainability principles in *BT16*: the production of non-irrigated biomass.

We analyze the impact of the *BT16* scenarios on groundwater use. The *BT16* feedstock production scenarios incorporate land management changes from irrigated land to non-irrigated land for biomass production. The feedstock portfolio changes from mostly starch-based material (scenario BC1&ML 2017) to mostly cellulosic-based material (scenario HH3&HH2040), and rain-fed acreages are increased in the latter scenario. Overall, irrigation water requirements could decrease significantly for each ton of feedstock grown in the United States if it replaces irrigated crops. As a result, groundwater consumption for irrigation in this region would decrease because irrigation water accounts for about 30% of ground water withdrawal from the Ogallala aquifer (McGuire et al. 2000). We compared groundwater irrigation for feedstock production in the High Plains between scenarios BC1&ML 2017 and HH3&HH 2040. On the basis of relative volume of the surface- and groundwater for irrigation in each state, we estimated the irrigation consumption for each county in the Ogallala Aquifer under both biomass production scenarios. As indicated in figure 8.14, irrigation water use for feedstock production would decrease in the 2040 scenario, compared to the 2017 scenario. The annual requirement for groundwater-based irrigation could be reduced from 720 billion gallons (Bgal) (scenario BC1 2017) to 540 Bgal (scenario HH3 2040), which is a savings of 179 Bgal in the High Plains. This quantity translates to 3.9% of the 5.8 trillion-gallon irrigation withdrawal from the Ogallala Aquifer in 2010 (assuming 80% of the water withdrawal is consumed). The reduction in groundwater irrigation in Ogallala counties is primarily due to reduced corn acreage for feedstock. A transition from irrigated-feedstock to non-irrigated feedstock could contribute to groundwater resource conservation. This would be consistent with federal and regional efforts to slow the depletion of the Ogallala Aquifer.

Figure 8.15 presents county-level irrigation con-

Figure 8.14 | Annual county-level groundwater consumptive use for feedstock irrigation under scenarios BC1&ML 2017 and HH3&HH 2040 in the High Plains Region

BC1&ML 2017   HH3&HH 2040

Groundwater Irrigation (Mgal)

- 1 - 600
- 601 - 1700
- 1701 - 3200
- 3201 - 4700
- 4701 - 6800
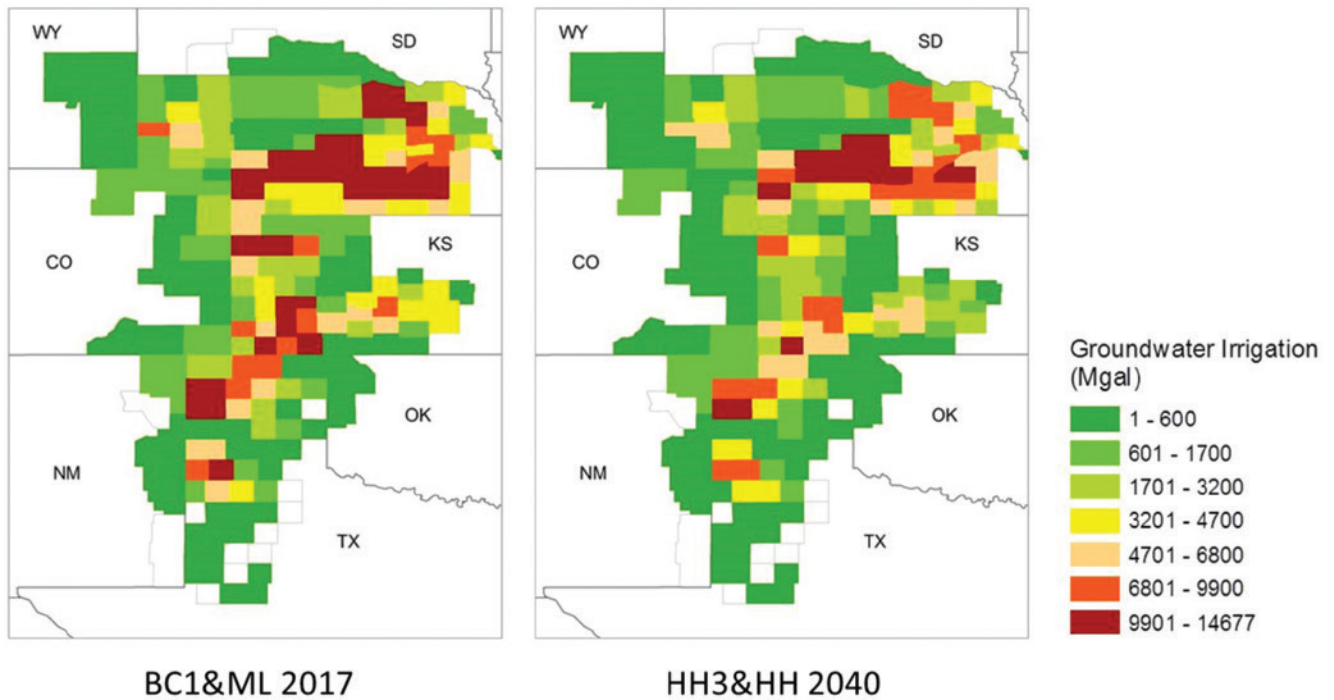- 6801 - 9900
- 9901 - 14677

Figure 8.15 | County-level irrigation consumption, state surface water and groundwater fraction for biomass feedstock production under scenario HH3&HH 2040, and the reductions of irrigation from scenario BC1&ML 2017 to scenario HH3&HH 2040 in the conterminous United States
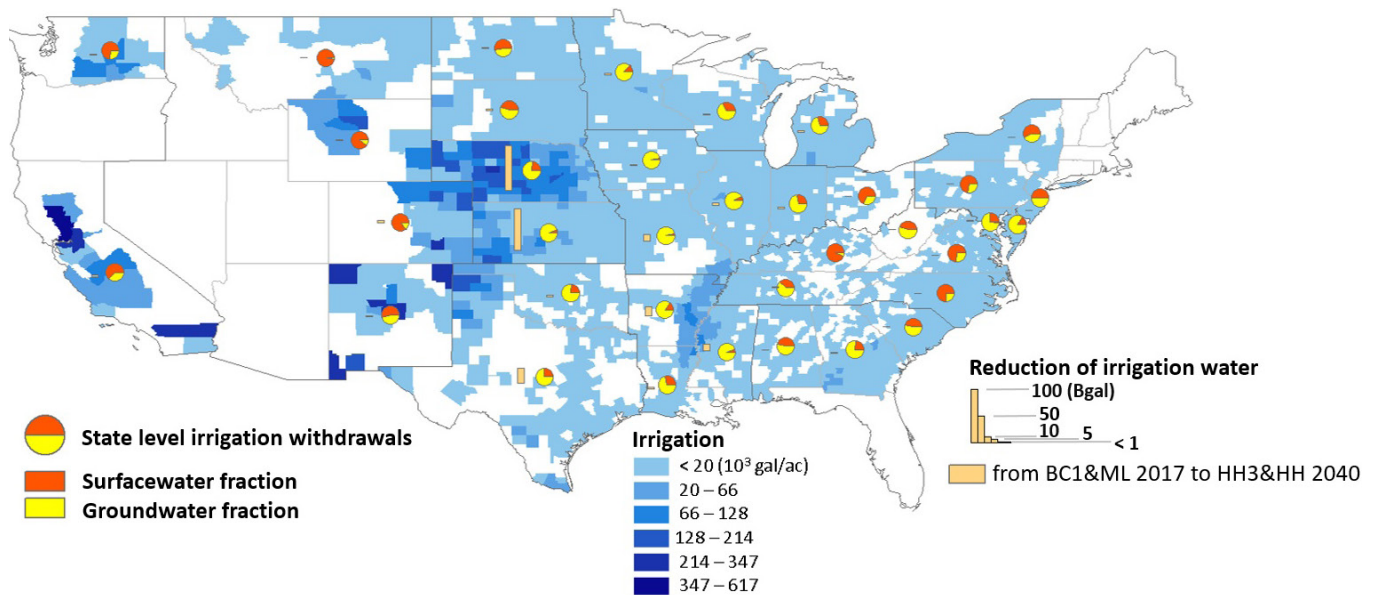

State level irrigation withdrawals
Surfacewater fraction
Groundwater fraction

Irrigation
- < 20 (10³ gal/ac)
- 20 – 66
- 66 – 128
- 128 – 214
- 214 – 347
- 347 – 617

Reduction of irrigation water
- 100 (Bgal)
- 50
- 10
- 5
- < 1

from BC1&ML 2017 to HH3&HH 2040

Table 8.4 | Groundwater Irrigation Consumption in Arkansas, Kansas, Nebraska, and Texas under Different Future Scenarios (billion gallons)

States	BC1 2017	HH3 2040	Change
Arkansas	65.0	47.2	17.9
Kansas	223.1	144.9	78.2
Nebraska	413.9	330.0	83.9
Texas	105.4	78.3	27.1
Sum	807.5	600.5	207.0

sumption, potential irrigation decreases from scenario BC1&ML 2017 to scenario HH3&HH 2040, and the surface- and groundwater fractions for each state. The key states that would benefit most from the potential biomass production scenarios are Nebraska and Kansas, followed by Texas and Arkansas. Compared with scenario BC1&ML 2017, annual groundwater irrigation would be 84 billion gallons less in Nebraska and 78 billion gallons less in Kansas in scenario HH3&HH 2040. The groundwater savings in Texas

and Arkansas would be 27 billion gallons and 18 billion gallons per year, respectively, for the 2017 to 2040 period. Together, the four states could decrease 207 billion gallons of groundwater for irrigation (table 8.4).

Nationally, a total of 276 billion gallons that would otherwise be used for groundwater-based irrigation could be saved by transitioning from scenario BC1&ML 2017 to scenario HH3&HH 2040. Of the national total volume of irrigation water, 75% is

Figure 8.16 | Irrigation water footprint in the transition to cellulosic dominant feedstock mix for biomass production
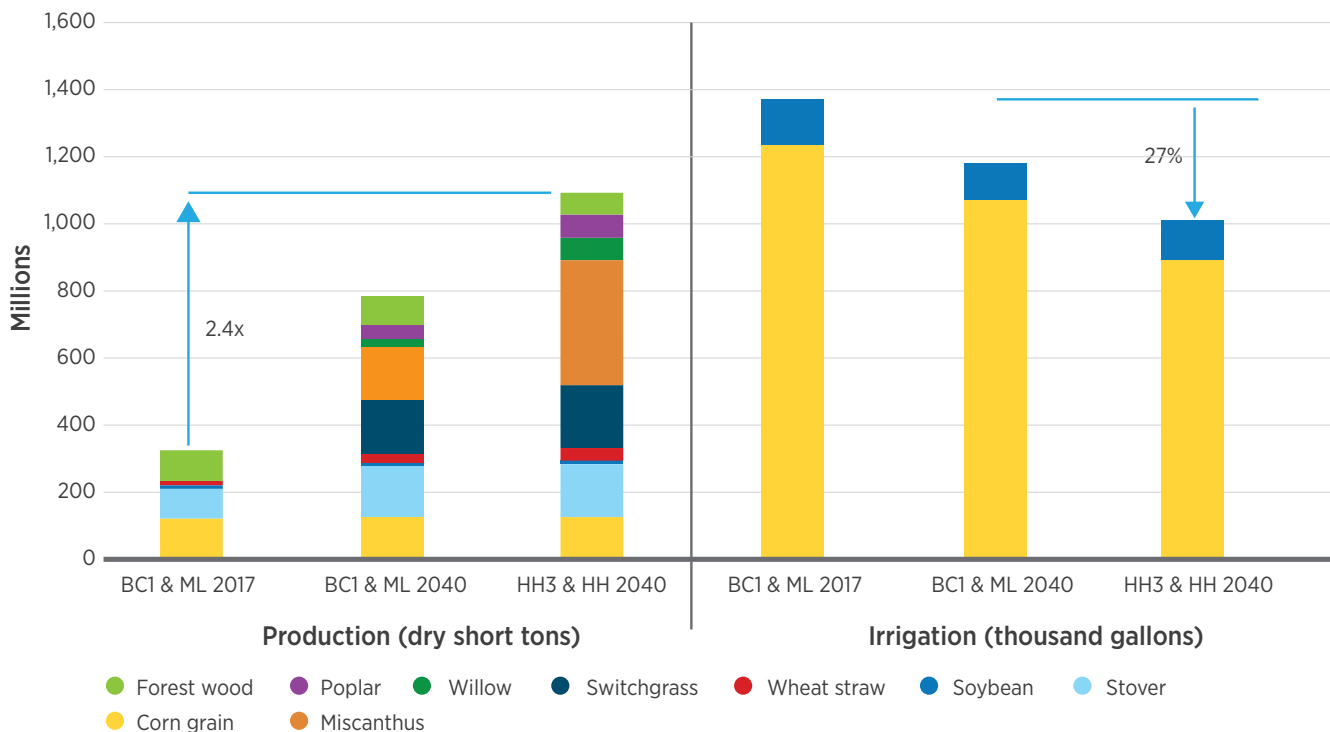
attributed to the four states (Nebraska, Kansas, Texas, and Arkansas). Figure 8.16 shows a comparison of feedstock production volume and irrigation volume when scenarios progressed from BC1&ML 2017 to HH3&HH 2040. We found that from scenario BC1&ML 2017 to scenario HH3&HH 2040, biomass production could increase by a factor of 2.4, while irrigation water consumption from both surface and groundwater could decrease by 27% in the contiguous United States (figure 8.16).

8.4 Uncertainties and Future Work

Uncertainties are associated with these estimates, as in all analyses, because of incomplete data sources and assumptions made in developing the future scenarios. This study calculates the irrigation water demand of biomass crops and forest biomass, not the actual irrigation water volume withdrawn. In practice, irrigation operations often have water use variation—causing over- or under-irrigation. In particular, over-irrigation can affect regional water budgets and constrain resource use. The USDA NRCS has developed several tools to address this problem (USDA NRCS 2012), and many states have programs in place to provide guidance for irrigation management (USDA NRCS 2016).

The irrigation efficiency is a key factor related to water use. The U.S. Geological Survey reported that the number of acres irrigated by using water-efficient sprinklers and micro-irrigation systems continues to increase and accounted for 58% of all irrigated lands in 2010. The adoption of these new irrigation systems is believed to have contributed to an overall decrease in irrigation in 2010 (Maupin et al. 2014). Regionally, the level of adoption of advanced irrigation technology varies. In addition, the local availability of water resources also limits the ability of irrigation operations to fully meet the demand for crop water. Irrigation withdrawal monitoring data and technology

adoption data for 2015, which were not available at the time of this work, would be an excellent source to enhance the analysis.

A number of methods have been proposed to estimate crop ET in the past few decades. The method adopted for this study (see appendix 8-A) is the American Society of Civil Engineers standard, which has been the dominant method used in the United States, with some variations. Mass-based allocation methods for attributing consumption of irrigation water to different parts of the plant (grain and residue) are available for additional analyses. Results generated from other methods may vary slightly compared to those of this study because of differences in approach and parameters. Therefore, it is highly desirable to conduct a full uncertainty analysis in the future.

Finally, this study represents an estimate of water consumption under specific future scenarios and their attendant assumptions based on available data, knowledge, and models. Further regional analysis to examine the water availability would be helpful, especially in water-stressed areas. A full water footprint analysis, accounting for water required in the biofuel-production life cycle, would provide a more complete picture of water consumption.

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Appendix 8-A

8A.1 Crops

Consumptive water use is quantified for the production of feedstocks (crops, grasses, short-rotation woody crops [SRWCs], and forest wood) by estimating evapotranspiration (ET). A large number of empirical methods have been developed over the last 50 years to estimate ET from different climate variables (Jensen and Allen 2000). The Penman-Monteith method (Allen et al. 1998) was standardized by the American Society of Civil Engineers' (ASCE's) Environmental and Water Resources Institute (EWRI) (ASCE-EWRI 2005), as illustrated in great detail by Howell and Evett (2004) and Allen et al. (2005a). In this study, the water footprint of agricultural crops adopts the so-called two-step Penman-Monteith method in which the crop ET is estimated by the Penman-Monteith reference ET method and crop coefficient (Jensen 1968; Allen et al. 2005b; Evett et al. 2000). The method has been widely used for nearly half a century and is relatively robust (Jensen 2010; Allen and Robison 2007). The Penman-Monteith method determines the reference ET of a crop using the following equation.

Equation 8.1:

$$ET_0 = \frac{[0.408\Delta(R_n - G)] + \gamma \frac{900}{T + 273} u_2(e_s^o - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where:

ET_0 = reference ET rate (mm d^{-1}),

Δ = slope of the saturated vapor pressure curve $\delta e^o/\delta T$,

e^o = saturated vapor pressure (kPa),

T = daily mean air temperature (°C),

R_n = net radiation flux (MJ m^{-2} d^{-1}),

G = sensible heat flux into the soil (MJ m^{-2}d^{-1}),

γ = psychrometric constant (kPa °C^{-1}),

e_s^o = mean saturated vapor pressure (kpa),

e_a = mean daily ambient vapor pressure (kPa), and

u_2 = wind speed (m s^{-1}) at 2 m above the ground.

The crop-specific ET value is calculated from the reference ET and crop coefficients (Kc) at monthly intervals at each location and summed to annual crop ET. The water sources that support plant growth can be rainfall stored in the root zone, rainfall in the canopy layer, and/or irrigation. The quantity of rainfall available for the crops is described by the effective precipitation variable. Effective precipitation, which accounts for rainfall available for crop consumptive use, is obtained by applying the definition and method proposed by the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS) (Kent 1972; USDA NRCS 1997). Thus, the crop ET provided by rainfall is calculated each month by using equation 8.2, and these values are summed to find the annual value.

Equation 8.2:

$$Crop\ ET\ provided\ by\ rainfall = ETc, IF\ ETc < Eff\ prcp, else\ Eff\ prcp$$

Where:

ETc = calculated crop ET (mm/month) and

Eff prcp = effective rainfall (mm/month).

The consumptive irrigation water requirement is estimated from the precipitation deficit, which represents the quantity of water beyond effective rainfall needed to sustain the growth (Allen and Robison 2007). The precipitation deficit is obtained by the differential of crop ET and effective rainfall at each monthly step, as shown in equation 8.3.

Equation 8.3:

$$Precipitation\ deficit = 0, IF\ ETc < Eff\ prcp, else\ ETc - Effprcp$$

$$Consumptive\ irrigation\ water\ requirement = Precipitation\ deficit$$

The monthly crop-consumptive, irrigation-water requirement is obtained from the calculated monthly precipitation deficit together with crop area. These monthly values are summed to find the annual irrigation demand.

8A.2 Perennial Grasses

To estimate actual evapotranspiration (AET) from perennial grassland, using the Penman-Monteith reference ET, ET losses from three major components are considered: (1) rain captured and evaporated from the grass canopy (Ecan), (2) vegetation transpiration (TP), and (3) evaporation from soil (Es). This study defines the sum of these three components as the AET of grasslands. Key parameters are adopted from the SWAT. The AET and its three components are computed in monthly steps by incorporating 30-year monthly input data for average climate (temperature, precipitation, solar radiation, humidity, and wind speed).

Equation 8.4:

$$ET_0 = \max\left(0.01, \frac{\left[\frac{\Delta \times Rn + \gamma \times (1710 - 6.85 AvgT) \times (es - ea)/r_a}{\Delta + \gamma \times \left(1 + \frac{r_c}{r_a}\right)}\right]}{\lambda} \times SunD\right)$$

The input parameters in equation 8.4 are defined as follows:

Δ = slope of saturated vapor pressure,

Rn = net solar radiation (MJ m^{-2}/day^{-1}),

γ = psychrometric constant (kPa °C^{-1}),

$es - ea$ = difference in vapor pressure (kPa),

r_c = canopy resistance (s m^{-1}),

r_a = aerodynamic resistance (s m^{-1}),

λ = latent heat of vaporization (MJ kg^{-1}), and

$SunD$ = number of sunny days = day count in a given month – RainD.

Rain captured and evaporated from grass canopy (E_{can}):

Equation 8.5:

$$E_{can} = if\ AvgT < 0, 0,\ else$$

$$if\ ET_0 < 0.0004 \times LAI \times 1000 \times RainD, ET_0, else$$

$$0.0004 \times LAI \times 1000 \times RainD$$

Where:

$AvgT$ = average monthly temperature (°C), using monthly maximum and minimum temperature as inputs;

ET_0 (mm month^{-1}) = reference ET (mm month^{-1}); and

LAI = leaf area index, estimated from vegetation height (Hc, in cm) in a given month.

$RainD$ = average raining days in a given month.

Equation 8.6:

$$LAI = 1.5 \times LN(Hc) - 1.4$$

Vegetation transpiration (TP):

Equation 8.7:

$$TP = if\ LAI \leq 3, (ET_0 - E_{can}) \times LAI/3, else\ ET_0 - E_{can}$$

The calculation of E_{can} is completed by linking the estimates of plant LAI, ET_0, and E_{can} on a monthly basis.

Evaporation from soil (E_s):

Equation 8.8:

$$E_s = min\left[E'_{s\ adj}, 0.8 \times (W_s - P_w)\right]$$

Where:

E_s = quantity of water evaporated from soil (in mm),

$E'_{s\ adj}$ = adjusted evaporated demand (in mm),

W_s = water content in the soil layer (in mm), and

P_w = wilting point (in mm).

The value of W_s fluctuates over time because of variability of ET, and Pw is defined by the local soil type. Together with the water content and wilting point, the evaporated demand (E'_s) can be adjusted ($E'_{s\ adj}$):

Equation 8.9:

$$E'_{s\,adj} = E'_s \times \exp\left(\frac{2.5(W_s - F_c)}{F_c - P_w}\right) \quad if \quad W_s < F_c, else\ E'_{s\,adj} = E'_s$$

Equation 8.10:

$$E'_s = E''_s \times \left[\frac{100}{100 + \exp(2.374 - 0.00713 \times 100)} - \frac{10 \times 0.95}{10 + \exp(2.374 - 0.00713 \times 10)}\right]$$

Equation 8.11:

$$E''_s = \min\Bigg[(ET_0 - E_{can}) \times \exp\left(-5 \times 10^{-5} \times M_{grass}\right),$$

$$\frac{(ET_0 - E_{can}) \times \exp\left(-5 \times 10^{-5} \times M_{grass}\right) \times (ET_0 - E_{can})}{(ET_0 - E_{can}) \times \exp\left(-5 \times 10^{-5} \times M_{grass}\right) + TP}\Bigg]$$

$$E''_s = 0, \quad if\ AvgT < 0\ or\ ET_0 - E_{can} = 0$$

Where:

Fc = field capacity (in mm) and

M_{grass} = the plant coverage (kg ha^{-1}) on the soil.

The water content in the soil compartment at start of month (t) is then computed as equation 8.12.

Equation 8.12:

$$W_{s\,t+1} = W_{s\,t} + Prcp_t - AET_t$$

Equation 8.13:

$$Pw \le W_{s\,t+1} \le Fc$$

$$Ws_0 = Pw + 0.15(Fc - Pw)$$

The monthly AET values for grasses are summed to an annual value.

8A.3 Wood from Forests

Estimates of ET for wood from forests are based on the same principles as the estimates for perennial grasses, SRWCs, and crops. Again, the reference ET is determined by using the Penman-Monteith equation (Allen et al. 1998). ET equations for hardwood and softwood are adopted from previous studies (Sun et al. 2011; Tang et al. 2006; Irmak and Whitty 2003; Oishi et al. 2008; Ford et al. 2011). The hardwood ET calculation uses the accumulation method, which considers evaporation from the soil and the tree canopy, as well as transpiration from the canopy. The total ET is expressed as the sum of water lost from each component. Sun et al. (2011) proposed a method that estimates forest ET on a monthly basis by using tree leaf area index (LAI), precipitation (P), and the Penman-Monteith reference ET as inputs. Using this method, a study compared results with field data and

showed improved ET estimates for softwood (Chiu and Wu 2013). ET calculations for SRWCs are based upon their categorization as either hardwood (poplar and willow) or softwood (pine).

Hardwood Evapotranspiration, AEThw

- *Soil Evaporation*

The equation for soil evaporation is as follows

Equation 8.14:

$$E_{sd} = 0.0123 \times \Delta\varepsilon^{1.3003} \times 48 \times \frac{M_D \times D_L}{24}$$

Where:

E_{sd} = daily soil evaporation in mm/month,

M_D = number of days of a given month.

D_L = daytime length in a given day of a year (h), and

$\Delta\varepsilon$ = vapor pressure deficit (kPa).

$$D_L = \left[24 \times \frac{ACOS\left(1-\left\{1-\tan\left(LAT_{county} \times \frac{PI}{180}\right)*\tan\left[\left(23.439 \times \frac{PI}{180}\right) \times \cos\left(PI \times \frac{MD_{mid}}{182.625}\right)\right]\right\}\right)}{PI}\right]$$

Equation 8.15:

$$\Delta\varepsilon = 0.6108 \times \left(EXP\left\{17.27 \times \frac{2.24 + 0.49 \times (Tmax + Tmin)}{[2.24 + 0.49 \times (Tmax + Tmin)] + 237.3}\right\}\right.$$
$$\left. - EXP\left(17.27 \times \frac{Tmin}{Tmin + 237.3}\right)\right)$$

Tmax and *Tmin* are the maximum and minimum monthly temperature in °C.

- *Canopy Transpiration*

The tree canopy transpiration (mm month^{-1}), E_{tc}, is determined by equation 8.16.

Equation 8.16:

$$E_{tc} = 2.17 \times [1 - EXP(-2.27 \times \Delta\varepsilon)] \times M_D \times \frac{D_L}{24}$$

- *Evaporation of the Intercepted rain*

Evaporation of the intercepted rain is the part of water loss that is equal to the portion of precipitation intercepted by the tree canopy. The equation can be described as follows:

Equation 8.17:

$$E_{ic\ ann} = (0.083\ P_{ann} + 0.036\ n) \times 25.4$$

Where:

$E_{ic\ ann}$ (mm yr^{-1}) is the annual precipitation (P_{ann} in. yr^{-1}) intercepted by tree canopy, and n is the number of rain events in the growing season.

To downscale the annual value to the monthly basis ($E_{ic\ m}$), $E_{ic\ ann}$ is weighted by monthly tree leaf area index (LAI).

Softwood ET, AET$_{sw}$

Equation 8.18:

$$AET_{sw} = 11.94 + 4.76 \times LAI + ET_0 \times (0.032 \times LAI + 0.0026 \times P + 0.15)$$

Where P (mm/month) is the monthly precipitation.

Equation 8.19:

$$P = 0.001013 \times \frac{P_{elv}}{0.622 \times (2.501 - 0.002361 \times AvgT)}$$

Where P_{elv} is the air pressure in kPa determined by a county's average elevation.

Equation 8.20:

$$P_{elv} = 101.3 - 0.01152 \times Elv + 0.544 \times 10^{-6} \times Elv^2$$

Where *Elv* is the county's average elevation.

8A.4 References

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