U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

2016 BILLION-TON REPORT
Advancing Domestic Resources for a Thriving Bioeconomy

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# 2016 BILLION-TON REPORT

## Advancing Domestic Resources for a Thriving Bioeconomy

A Study Sponsored by U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

**Volume 1:**
Economic Availability of Feedstocks

July 2016

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for the
U.S. DEPARTMENT OF ENERGY

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## Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

energy.gov
eere.energy.gov
bioenergy.energy.gov
web.ornl.gov/sci/transportation/research/bioenergy/

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### DISCLAIMER

The authors have made every attempt to use the best information and data available, to provide transparency in the analysis, and to have experts provide input and review. However, the *2016 Billion-Ton Report* is a strategic assessment of potential biomass. It alone is not sufficiently designed, developed, and validated to be a tactical planning and decision tool, and it should not be the sole source of information for supporting business decisions. This analysis provides county by county estimates of the feedstocks at a selected cost, yet users should use associated information on the Bioenergy Knowledge Discovery Framework (bioenergykdf.net/billionton) to understand the assumptions and ramifications of using this analysis. The use of tradenames and brands are for reader convenience and are not, nor does their use imply, an endorsement by the U.S. Department of Energy or Oak Ridge National Laboratory.

The foundation of the agricultural sector analysis is the USDA Agricultural Projections to 2024. From the report, "projections cover agricultural commodities, agricultural trade, and aggregate indicators of the sector, such as farm income. The projections are based on specific assumptions about macroeconomic conditions, policy, weather, and international developments, with no domestic or external shocks to global agricultural markets." The *2016 Billion-Ton Report* agricultural simulations of energy crops and primary crop residues are introduced in alternative scenarios to the 2015 USDA Long Term Forecast. Only 2015-2024 Billion-Ton national level baseline scenario results of crop supply, price, and planted and harvested acres for the 8 major crops are considered to be consistent with the 2015 USDA Long Term Forecast. Additional years of 2025–2040 in the *2016 Billion-Ton Report* baseline scenario and downscaled reporting to the regional and county level were generated through application of separate data, analysis, and technical assumptions led by Oak Ridge National Laboratory and do not represent nor imply U.S. Department of Agriculture or U.S. Department of Energy quantitative forecasts or policy. The forest scenarios were adapted from U.S. Forest Service models and developed explicitly for this report and do not reflect, imply, or represent U.S. Forest Service policy or findings.

The biomass supply projections presented in this report are policy independent and estimate the potential economic availability of biomass feedstocks using specified market scenarios and guiding principles intended to be conservative and to reflect certain environmental and socio-economic considerations. For example, some principles aim to maintain food availability and environmental quality, including improved tillage and residue removal practices, exclusion of irrigation, and reserved land areas to protect biodiversity and soil quality. In this sense, this report (volume 1) and related analyses on environmental effects (forthcoming in volume 2) may differ from other efforts seeking to depict potential biomass demand and related market, environmental and land use interactions under business-as-usual or specific policy conditions.

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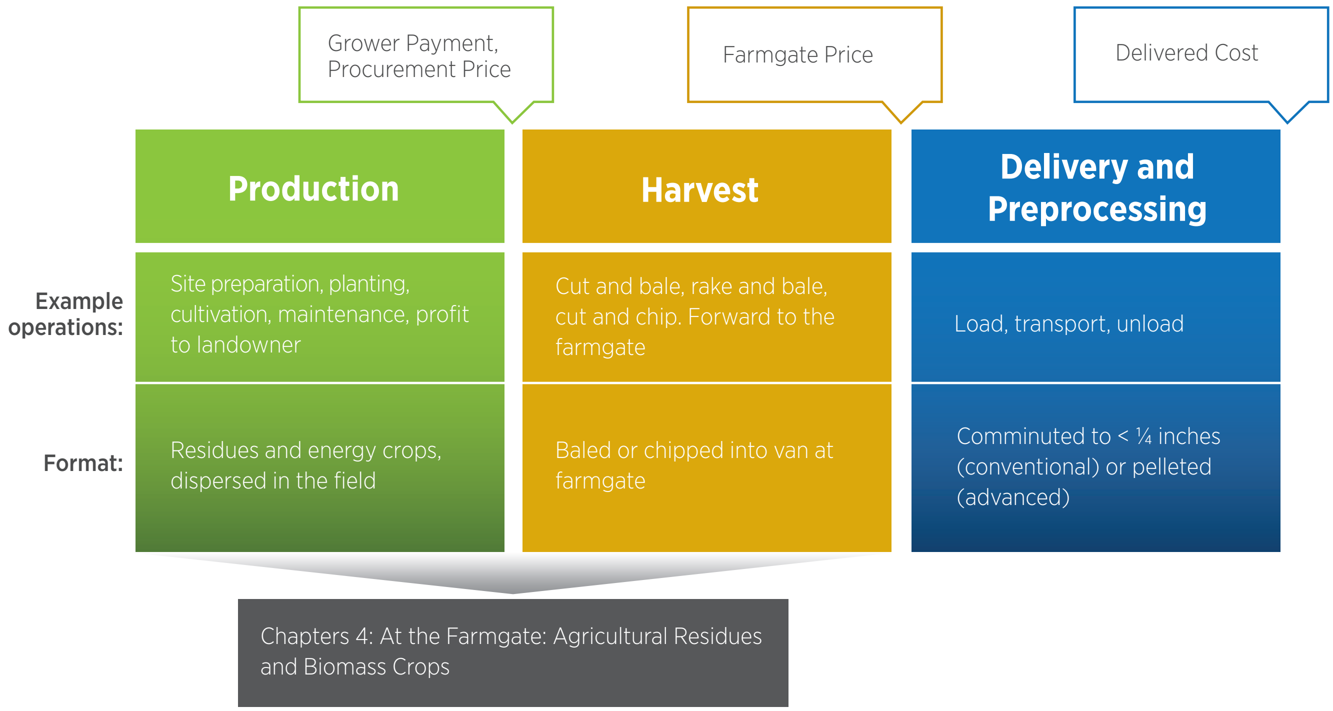
# 04 | At the Farmgate

Agricultural Residues and Biomass Energy Crops




## 4.1 Introduction

This chapter provides an updated assessment of the potential economic availability of biomass resources from agricultural lands reported at the farmgate. These farmgate results are in turn used in chapter 6, which characterizes these agricultural resources as delivered to potential biorefineries, along with the forestry resources and waste resources quantified in chapters 3 and 5, respectively.

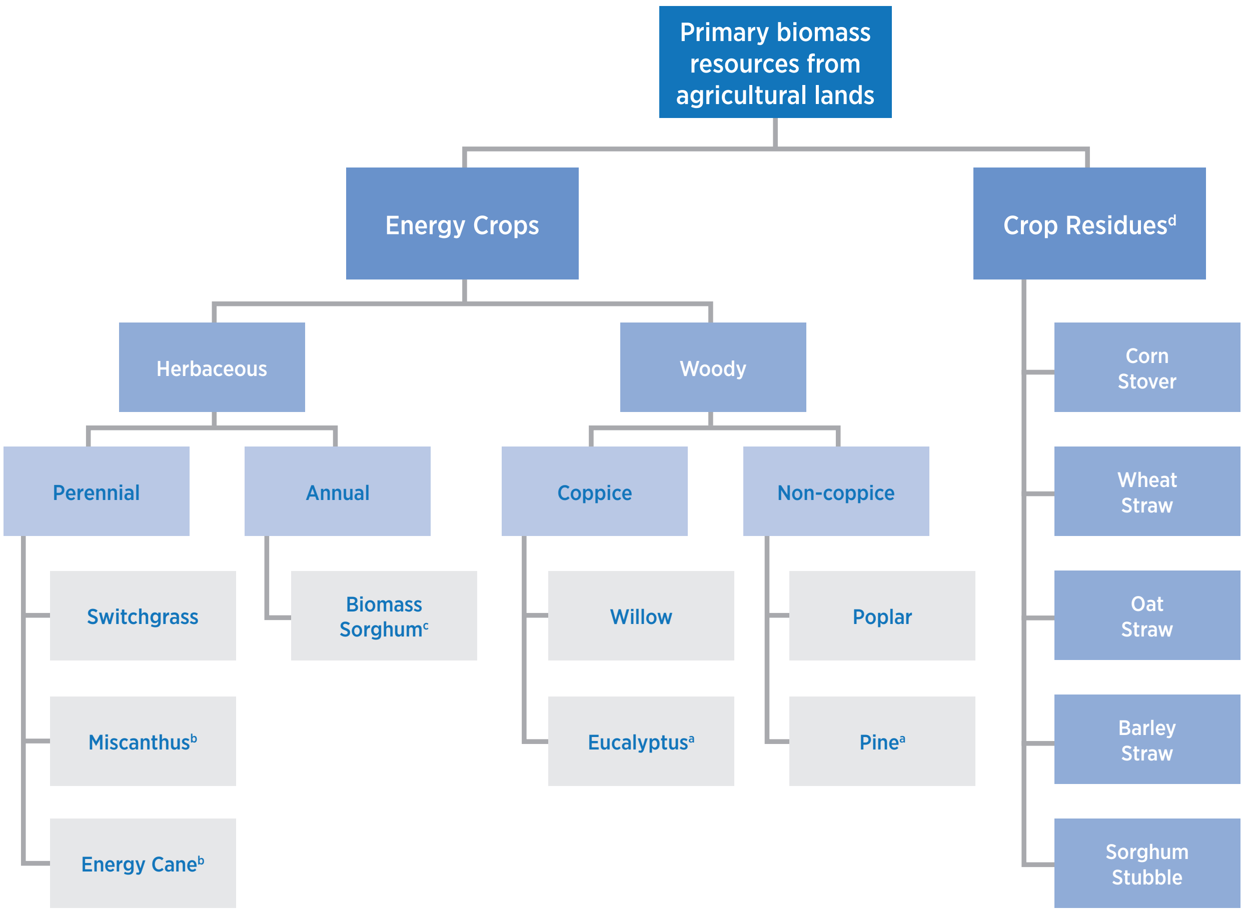
Resources evaluated in this chapter include crop residues and dedicated biomass energy crops (hereafter "energy crops") produced on agricultural land. Both of these biomass types can play a unique and important role in a national biofuels commercialization strategy. The 2011 *BT2* reported biomass resources from agricultural lands to be abundant, diverse, and widely distributed across the United States. The farmgate supplies reported here are derived using the same modeling approach as was used in the 2011 *BT2* but with updated input data and model enhancements (see appendix C.2).

Crop residues quantified here include corn stover, cereal (wheat, oats, and barley) straws, and sorghum stubble. These crop residues require no additional cultivation or land and represent near-term opportunity feedstocks. Most cellulosic biofuels commercialization strategies to date (of companies such as POET-DSM, Abengoa, and DuPont) have focused on agricultural residues, primarily corn stover. Secondary agricultural wastes, such as rice hulls, wheat dust, and sugar cane trash, are addressed in chapter 5.

Along with crop residues, dedicated energy crops are poised to complement the process to further commercialize biofuels, biopower, and bioproducts. These crops, such as switchgrass, miscanthus, and short-rotation woody crops, can improve supply security and help control feedstock quality characteristics. This can be achieved using energy crops alone or in combination with other feedstocks. Crop improvement programs are demonstrating energy crop yield gains and traits tailored to enhance conversion processes. Perennial energy crops can also complement the production of conventional crops, with potential for improved incomes and environmental benefits.

This chapter quantifies the potential availability of biomass feedstocks from primary agricultural residues and energy crops. Sources of each category evaluated are specified in figure 4.1.

**Figure 4.1** | Taxonomy of modeled biomass resources from agricultural lands




[a]Eucalyptus and pine are newly added feedstocks. They were generalized in the 2011 *BT2* as 8-year rotation, short-rotation woody crops under single-stem management.

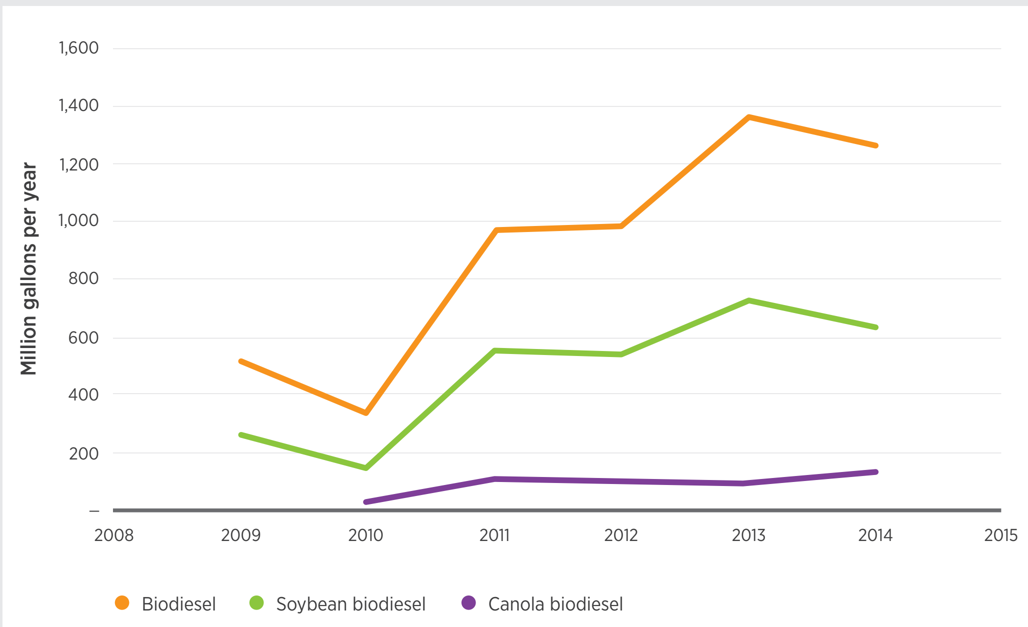
[b]Energy cane and miscanthus are newly added feedstocks to the billion-ton reporting. They were generalized in the 2011 *BT2* as perennial grasses, along with switchgrass.

[c]The 2011 *BT2* discussed several types of sorghum. For the purposes of this report, "biomass sorghum" depicts any variety developed for high biomass yields, and neither for grain nor sugar content. Budgets for biomass sorghum can represent biomass sorghum, forage sorghum, or sweet sorghum. Modeled yields represent either biomass or forage sorghum; the variety with the highest productivity in a certain region was used.

[d]Agricultural resources already used for biofuels or bioenergy, such as sugar cane bagasse, are reported in chapter 2.

## Text Box 4.1 | Oilseeds for Use in Biodiesel and Drop-In Renewable Jet Fuel

Oilseeds, primarily soybean and canola, are currently used as feedstocks for biodiesel production. In 2014, soybean made up 51% and canola made up 11% of the feedstocks used in U.S. biodiesel production (EIA 2015). Other oilseeds include non-edible industrial rapeseed, camelina, Ethiopian mustard (carinata), condiment mustard, pennycress, sunflower, and safflower. The EISA targets for biodiesel have mandated at least 1 billion gallons of biodiesel per year since 2012 and are set for 2.0 billion gallons in 2017. USDA's ten-year projections (2016–2025) for U.S. soybean plantings remain above 80 million acres; and as growth in both domestic use and export demand lead to increases in prices, much of the required increase in production will be satisfied with expected yield improvement (USDA 2016). Soybean oil used to produce biodiesel in the United States is projected to rise from 5.2 billion pounds in 2015/2016 to 5.7 billion pounds in 2020/2021 and later years, supporting the production of about 800 million gallons of biodiesel annually in the second half of the projection period. These projections reflect a growing biomass-based diesel use requirement through 2017 under the RFS, and additional demand for biodiesel and renewable diesel to meet a portion of the RFS's advanced biofuel requirement (USDA 2016).




**Source:** Data from EIA (2015).
**Note:** Data assume 7.5 pounds per gallon for soybean and canola biodiesel.

Oilseeds can also be used to produce drop-in renewable jet fuel and diesel products, most commonly using a hydroprocessed esters and fatty acids conversion process. The Federal Aviation Adminstration has a goal of 1 billion gallons of alternative jet fuel by 2018. In addition, the U.S. Navy and U.S. Air Force have alternative energy goals that include the use of alternative jet fuels (50% blends by 2022). Oilseeds could be used as feedstocks in helping to meet these goals, and certified jet fuels have been made from several oilseeds. Initial alternative jet fuel production has been primarily from woody biomass, municipal solid waste, and waste grease, so it is unclear what portion might be supplied by oilseeds.

The 2011 *BT2* included a range of energy crop categories, including perennial grasses, annual herbaceous crops, and single-stem and coppicing short-rotation woody crops. The current analysis adds more specificity, reflecting advancements and understanding in the management of energy crop options. The following are brief descriptions of energy crops included in this analysis. More detail on these crops is provided in the 2011 *BT2* section 5.1 (DOE 2011, 87–117) and in appendix C.

- **Agricultural residues**—Conventional crop residues including corn stover and wheat, barley, oats, and sorghum straw.
- **Biomass sorghum**—An annual herbaceous crop, currently grown in rotation throughout the Southeast and Great Plains for grains and forage. Biomass sorghum exhibits non-photoperiod sensitivity and drought tolerance.
- **Energy cane**—A perennial tropical grass with high yield potential across the Gulf South. Low-sugar, high-cellulose varieties (a hybrid of commercial and wild sugar cane species) can be established, managed, and harvested using existing sugar-cane industry equipment.
- **Eucalyptus**—A short-rotation woody crop ideal for Gulf States as well as Georgia and South Carolina.
- **Miscanthus**—A sterile triploid with low nutrient requirements and wide adaptability across cropland.
- **Pine**—A tree representing the major commercial tree crop in the South, with 32 million acres of plantations (Fox, Jokela, and Allen 2007). This crop can be adapted to grow in high density on agricultural land assuming 8-year rotations.
- **Poplar**—A short-rotation woody crop with great potential in the Lake States, the Northwest, the Mississippi Delta, and other regions.
- **Switchgrass**—A model perennial native grass, with wide range and potential distribution.
- **Willow**—A short-rotation woody crop assumed to be managed on a 20-year cycle and harvested at 4-year growth stages. It is being commercialized widely in the Northeast.

## 4.2 Approach to Quantifying Farmgate Resources from Agricultural Lands

To evaluate potential farmgate supplies of agricultural resources, this study employs the Policy Analysis System (POLYSYS), a policy simulation model of the U.S. agricultural sector (De La Torre Ugarte and Ray 2000). The POLYSYS modeling framework, which can be conceptualized as a variant of an equilibrium displacement model, was previously developed to simulate changes in economic policy, agricultural management, and natural resource conditions, and to estimate the impacts to the U.S. agricultural sector from these changes. An important component of POLYSYS is its ability to simulate how commodity markets balance supply and demand via price adjustments based on known economic relationships. POLYSYS is used to estimate how agricultural producers may respond to new agricultural market opportunities, such as new demand for biomass, while simultaneously considering the impact on other non-energy crops. POLYSYS was used to quantify potential biomass resources in the 2011 *BT2* and has been used in other agricultural and biofuels analyses (Ray et al. 1998a; Langholtz et al. 2014; Ray et al. 1998b; Langholtz et al. 2012; Lin et al. 2000; De la Torre Ugarte et al. 2006; Larson et al. 2010; De La Torre Ugarte et al. 2003).

POLYSYS anchors its analyses to the USDA-published baseline of yield, acreage, and price projections for the agriculture sector, which are extended from the USDA 10-year baseline projection period through 2040 for this analysis (Hellwinckel et al. 2016). Conventional crops currently considered in

POLYSYS include corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay, which together comprise approximately 90% of the U.S. agricultural land acreage. Conventional crops simulated for residues include corn, grain sorghum, oats, barley, and wheat (winter plus spring). Production costs associated with residue removal from these crops include replacement of embodied nutrients and per-acre harvest costs associated with shredding, raking, and baling (with a large square baler; see appendix C.3) and transportation to the field edge. Second-generation biofuel crops specified in figure 4.1 are also considered. Production costs associated with these herbaceous and woody energy crops include establishment, maintenance, and per-acre harvest costs (see tables C.3 and C.4 of appendix C.3).

See appendix C.1 for more information on the POLYSYS modeling framework, including land base[1] and other input assumptions.

### 4.2.1 Enhancements and Modifications from *BT2*

Although this analysis follows the same general methodology for estimating farmgate supplies as was reported in the 2011 *BT2*, several changes have been made in this analysis. The changes include updating input data, adjusting for inflation, harmonizing with current and projected operational technology, and minor corrections in the modeling framework. Updated data sets and revised technical assumptions used in this analysis are described in more detail in appendix C.2.

### 4.2.2 Model Inputs, Assumptions, and Constraints for Energy Crops

The following general constraints, assumptions, and inputs apply to all energy crops discussed in section 4.1:

- **Yield improvements**: Field trial data to date provide validation (Owens et al. 2016) for higher biomass yields in the future (see appendix C.1). Base-case and high-yield scenarios are two scenarios for yield improvements over time that may be achieved with a mix of improved management practices and crop genotypes. These assumptions were derived from a series of workshops in 2010 drawing on expert opinion (DOE 2009). In the 2011 *BT2*, the base-case scenario assumed 1% yield improvements per year, with high-yield scenarios adding 2%, 3%, and 4% yield improvements per year. Yield improvement assumptions in this analysis, ranging from 1% to 4%, are specified by scenario (see table 4.1).
- **Land-use constraints**: In addition to the constraint of available land, as established by the USDA baseline (USDA-OCE/WAOB 2015, see appendix C.1), there are annual constraints (5% of permanent pasture, 20% of cropland pasture, 10% of cropland) and cumulative constraints (40% of permanent pasture, 40% of cropland pasture, 10% of cropland) applied to the model regarding land that can be converted to energy crops. These constraints are also bound by the management-intensive grazing (MiG) constraint of 1.5 acres of MiG required for one acre of pasture converted to energy crops. Eligible pasture is defined as having greater than or equal to 25 inches of annual precipitation, which excludes irrigated pasture acres amounting to 47.1 million acres of land nationally (see appendix C, fig. C.1).
- **Budgets**: Energy crop budgets include establishment and maintenance, excluding land rent. (See 2011 *BT2* tables 5.3 and 5.4 [DOE 2011, 128–129] and appendix C.3 for a summary of crop budgets, as well as a discussion of land rent

[1] Our analyses are limited to the continental United States. Hawaii and Alaska were excluded because of a lack of conventional crops grown in these areas and in turn the inapplicability of our modeling approach to these states.

**Table 4.1** | Specified-Price Simulation Scenario Descriptions at County Scale

| Scenario name | | Short description | Tillage flexibility constraint | Energy crop yield improvements[a] | Conventional crop yield |
|---|---|---|---|---|---|
| **Base case (1%)** | BC1 | Cumulative base-case | 1 | 1% | Baseline for all crops[b] |
| **High yield (2%)** | HH2 | Cumulative high-yield run | 3 | 2% | High corn grain[c] |
| **High yield (3%)** | HH3 | Cumulative high-yield run | 3 | 3% | High corn grain |
| **High yield (4%)** | HH4 | Cumulative high-yield run | 3 | 4% | High corn grain |

[a]Energy crop yield improvements are applied as annual yield increases, compounded beginning in 2015 (see section 4.5 ).

[b]The base-case scenarios follow the USDA baseline projection (USDA-OCE/WAOB 2015) and demands, extrapolated to 2040 (see appendix C.1).

[c]High-yield scenarios use assumptions derived from the high-yield workshops (DOE 2009). The high-yield scenarios assume corn grain yield grows at a higher rate to achieve 265 bushels per acre in 2040 (national average) and allows greater farmer adoption of no-till management.

exclusion in appendix C.1.) Harvest costs in this report were added to the crop budgets to calculate the break-even cost of production at the farmgate.

See appendix C for more information on the yield modeling framework, as well as detailed budgets and land use assumptions and constraints.

### 4.2.3 Agricultural Residue Modeling Assumptions

Quantities of agricultural residues are based on estimates of total aboveground biomass produced as byproducts of conventional crops, which are then limited by sustainability and economic constraints. Total aboveground biomass residue produced (before sustainability, operational, and economic constraints) is calculated in POLYSYS based on a 1:1 harvest index or ratio of residue to grain for corn, and on a 1:1.57 ratio for barley, oats, sorghum, and wheat (spring and winter). There are many harvest options for residues; but for each crop, this study models and costs one machinery complement. For more information, see appendix C.1.

Crop residues provide important environmental benefits, such as protection from wind and water erosion, maintenance of soil organic carbon, and soil nutrient recycling. Thus, not all crop residues produced are sustainably available. Sustainably available removals are constrained to not exceed the tolerable soil loss limit of the USDA Natural Resources Conservation Service (NRCS 2016a; 2016b), and to not allow long-term reduction of soil organic carbon. The following models were used in this analysis: Revised Universal Soil Loss Equation 2 (USDA 2016), the Wind Erosion Prediction System (NRCS 2012), and the Soil Conditioning Index. County-level average retention coefficients are calculated for wind, rain, and soil carbon for each rotation and tillage combination by crop management zone (see Muth et al. [2013] for more details).

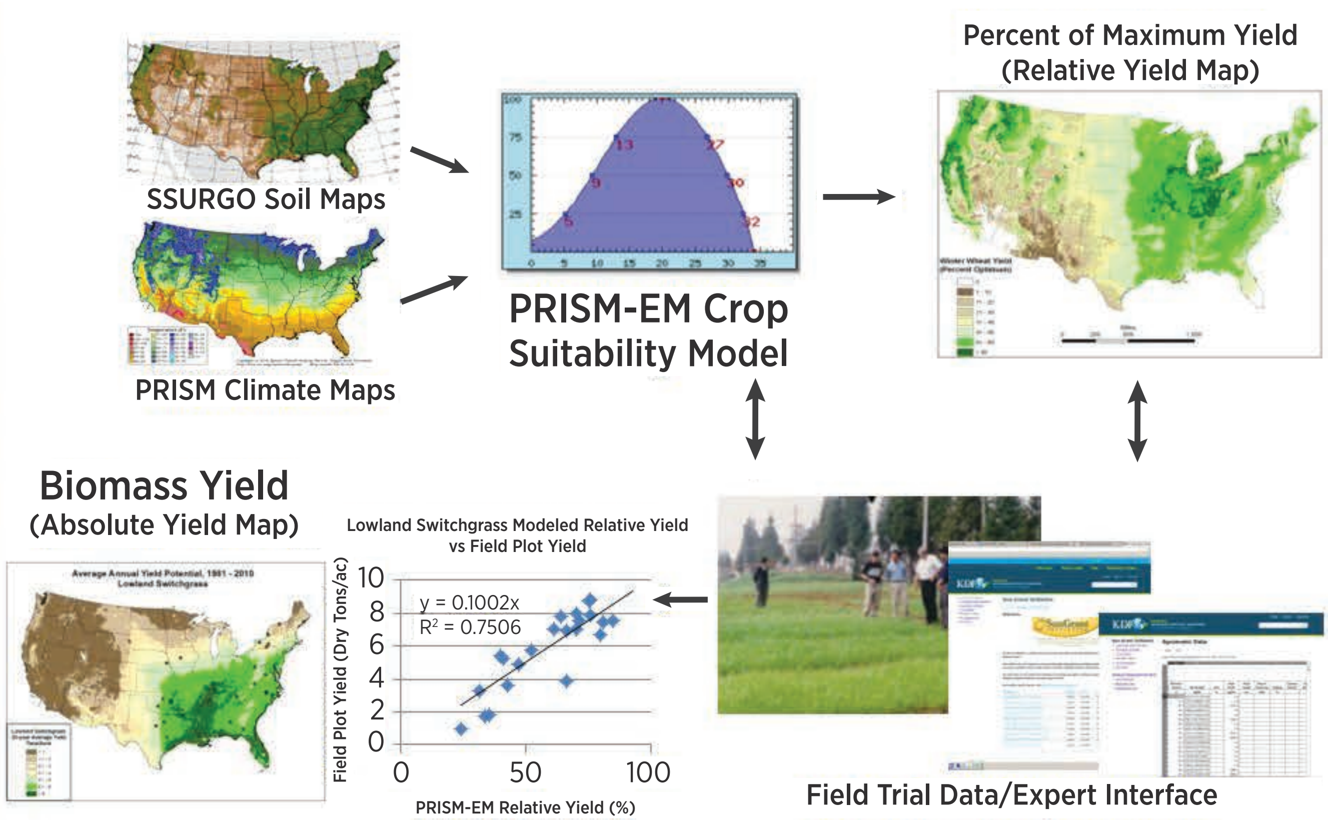
In the 2011 *BT2*, 100% of sustainably available agricultural residues were also assumed to be operationally available. In this report, operationally available residues are limited to 50% of total residue yield starting in 2015, increasing linearly to 90% of available residue yield in 2040, for each county.

Subsequently, collection of residues is assumed to be limited to operationally available removals or sustainably available removals, whichever is most limiting. This operational efficiency change was made to reflect the near-term technical challenges of harvesting variable levels of available field and sub-field residue, while acknowledging technological advancements in harvesting equipment in the long term that can be developed to mobilize greater proportions of the sustainable supply.[2]

### 4.2.4 Energy Crop Modeling Assumptions

Empirically modeled energy crop yields are new to this analysis. Energy crop yields were derived from modeling of crop yields based on data from the Sun Grant Regional Feedstock Partnership in coordination with the Oregon State University PRISM (Parameter-elevation Relationships on Independent Slopes Model) modeling group. Following six crop-specific

**Figure 4.2** | Crop yield mapping work flow using PRISM-EM with the Regional Feedstock Partnership




**Source:** Daly and Halbleib (2014), "Potential Yield Mapping of Dedicated Energy Crops," energy.gov/sites/prod/files/2014/11/f19/daly_biomass_2014.pdf.

**Note:** Acronyms from top left to bottom right are as follows: SSURGO = Soil Survey Geographic Database; PRISM = Parameter-elevation Relationships on Independent Slopes Model; PRISM-EM is an environmental suitability modeling framework.

[2] This constraint is not meant to capture willingness to participate in residue collection.

workshops, the data from more than 110 field trials were used to estimate county-specific per-acre yields based on 30-year historic weather data (fig. 4.2).

Modeled crop yield is generated with PRISM-EM (Halbleib, Daly, and Hannaway 2012) based upon PRISM biweekly climate variables including precipitation, minimum temperature, maximum temperature, and Soil Survey Geographic Database soil pH, drainage, and salinity. The process of creating potential yield begins with calibrating PRISM-EM model settings for crop-specific water use and temperature tolerance values (such as optimal temperature growth and water use efficiency). Initial calibrations for these functions are based on known relative tolerances for warm- or cool-season crops and whether they are grown as annuals or perennials. These functions are used with soil characteristics and historical weather patterns to generate "first-guess" average annual relative yield values (0%–100%). The relative values are regressed with average field trial yield values to create a transfer function that is used to estimate absolute yield. Since yield data are available for only a few years, in some cases PRISM-EM is run for the individual years that match those of the data; and the estimated yields are adjusted to reflect those under 1981–2010 thirty-year average climate conditions. The process of modeling relative yield and estimating absolute yield is done in an iterative fashion during face-to-face meetings with species experts, in which yield outliers from the regression function are examined and model calibrations modified as needed.

The field trial potential yield values are derived from plot-level data, which are averaged across top-producing and/or commercially recommended varieties (when available) or nutrient applications that reflect best management practices (BMPs) via pre-establishment soil sampling. In the former case, however, BMPs are assumed to have been applied to all variety trials. Note that small-scale test plot yields are typically much higher than field-level production values; therefore, small-plot values are reduced by 20% to account for this bias according to Knörzer et. al (2013). Additionally, the fidelity of soils data used in the model is limiting, and the process acknowledges that two identical soils in different locations may behave differently.

# 4.3 Scenarios

Consistent with the 2011 *BT2*, this *BT16* report introduces markets for biomass feedstocks as specified farmgate prices offered (≤\$40, ≤\$60 and ≤\$80 per ton).[3] These prices (\$2014) are adjusted for inflation and are applied to all counties for all years in the simulation period. The exception is for specified demand scenarios, in which POLYSYS targets specified levels of production and solves for the least-cost resource mix needed to meet the specified demand. The 2011 *BT2* reported potential county-level feedstocks as a function of price, year, and yield scenario ("base-case" with a 1% annual yield increase or one of three "high-yield" scenarios with a 2%, 3%, or 4% annual yield increase). In addition to a "baseline scenario" (BL0) that establishes initial and future crop supply and demand, we expand the number of scenarios and market simulations in this analysis to include the following:

## 4.3.1 Supplies at Specified Prices

Exogenous price simulations (hereafter "specified-price" simulations) introduce a farmgate price, and POLYSYS solves for biomass supplies that may be brought to market in response to these prices. In specified-price scenarios, a specified farmgate price is offered constantly in all counties over all years of the simulation. For example, at a ≤\$60 specified price, the resulting supply potential in 2040 is achieved by

[3] A broader range of offered prices (\$30–\$100 in \$5 increments) were simulated and are available online in the Bioenergy KDF.

### Text Box 4.2 | Observed Energy Crop Yield Improvements

The Regional Feedstock Partnership provided critical information related to potential yields of energy crops at locations across the country. Yields forecasted in the High-Yield Scenario workshops are becoming realized in the field. The development of poplar as an energy crop has advanced rapidly. Yields of the fastest-growing new poplar clones ranged from 1.3–1.6 times those of currently-available commercial clones, and they are capable of producing up to 8 tons per acre per year. As development of the poplar energy crop continues, it is estimated that gains in biomass yield of roughly 20% to 30% can be expected through each breeding cycle. Yield increases associated with new willow cultivars have typically ranged from 15% to 25%, with the yield of the top three cultivars across all research sites ranging from 1.3 to 6.3 tons per acre per year. Sorghum and energy cane cultivars have been identified that are capable of yields in excess of 8.9 and 20 tons per acre, respectively.

In addition to the identification of new high-yielding clones, fertilization and nitrogen addition were found to enhance yields dramatically in some crops. Switchgrass yields were improved by up to 88% with the addition of moderate amounts of fertilizer. In miscanthus field trials in Illinois, yields increased from 4.7 to 8.1 tons per acre with the addition of moderate amounts of nitrogen. In some locations, miscanthus yields were more than 8.9 tons per acre, especially with a moderate fertilizer treatment.

As energy crop development continues, higher-yielding cultivars can be expected, and continued improvement in agronomic practices will enable these energy crops to make significant contributions to the nation's energy portfolio.

the constant presence of a ≤$60 market price in all preceding years as well (2015–2039 for residues and 2019–2039 for energy crops). Constant prices allow farmers to respond by changing crops and practices gradually over time. Indeed, some biomass crops, such as poplars, require years to reach maturity. The same supply would not result from a sudden offer of ≤$60 solely in year 2040 but not in the preceding years. Specified price runs represent the potential if a national market were in place beginning in the near term and offering constant prices until 2040 (see text box 4.4). Consistent with the 2011 *BT2*, these simulations are for all feedstocks combined (i.e., energy crops were simulated to compete both with conventional crops and with other energy crops).[4]

## 4.3.2 Prices at Specified Production Targets

New to the billion-ton report series, exogenous demand simulations (hereinafter "production-target" simulations) introduce a national supply target, and POLYSYS solves for prices needed to realize the least-cost mix of biomass resources to meet that demand. This approach simulates markets that develop using least-cost resources first, producing higher-cost resources only when necessary to meet demand targets. In this sense, production-target simulations better represent current biofuels commercialization efforts, which capitalize on least-cost feedstock opportunities and lack the support of a commodity infrastructure for biomass delivery. Even production-target scenarios may somewhat overestimate actual supply paths because of the potential for some of the estimated production to be geographically dispersed and uneconomical to transport to biorefineries. The specified-production scenarios are outlined in table 4.2. Selected quantities and target years are chosen based on potential real-world scenarios (e.g.,

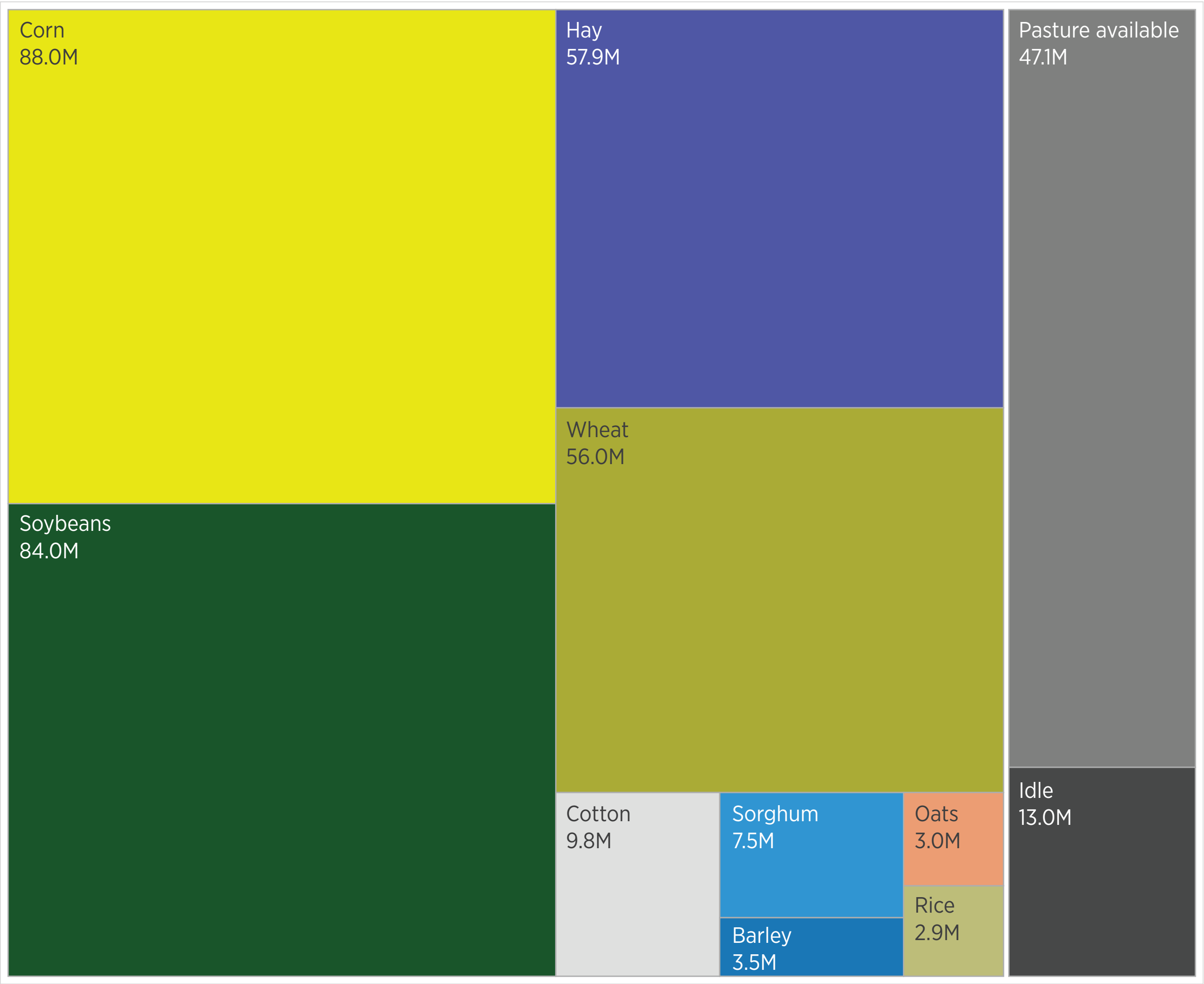
[4] In addition to specified-price simulations of all feedstocks combined, our simulations include feedstock-specific scenarios, which simulate each dedicated energy crop in the absence of the other energy crops, elucidating each energy crop's full potential if it is not competing with other energy crops. These specified-price simulations are further described in appendix C and are available online in the Bioenergy KDF.

RFS levels). These targets are slightly exceeded when POLYSYS solves for biomass supplies that will enter at simulated prices. Higher-quantity scenarios do not include earlier years (e.g., 2022) because of the time necessary to achieve these higher targets. These higher-quantity scenarios often bring prices exceeding offered prices under specified-price simulations at corresponding biomass levels because of delays in production of some high-yielding crops (e.g., no production of miscanthus in year 1). See appendix C.

## 4.4 Baseline (BLO) Results: Primary Agricultural Resources

To establish a baseline for comparison, we completed a simulation without offering any farmgate prices to energy crops or residues (i.e., continuation of the USDA baseline). The resulting planted acres are presented in figure 4.3 for the initial simulation year of

**Figure 4.3** | Baseline land use by conventional crops in 2015, idle land, and pasture available in 2015 (pasture available is 11% of the total pastureland)[5]




[5] Interactive visualization: https://bioenergykdf.net/billionton2016/4/8/tableau

2015. The available land base for this simulation and all others discussed below is described in appendix C with other agricultural land modeling assumptions.

# 4.5 Specified-Price Simulation Results

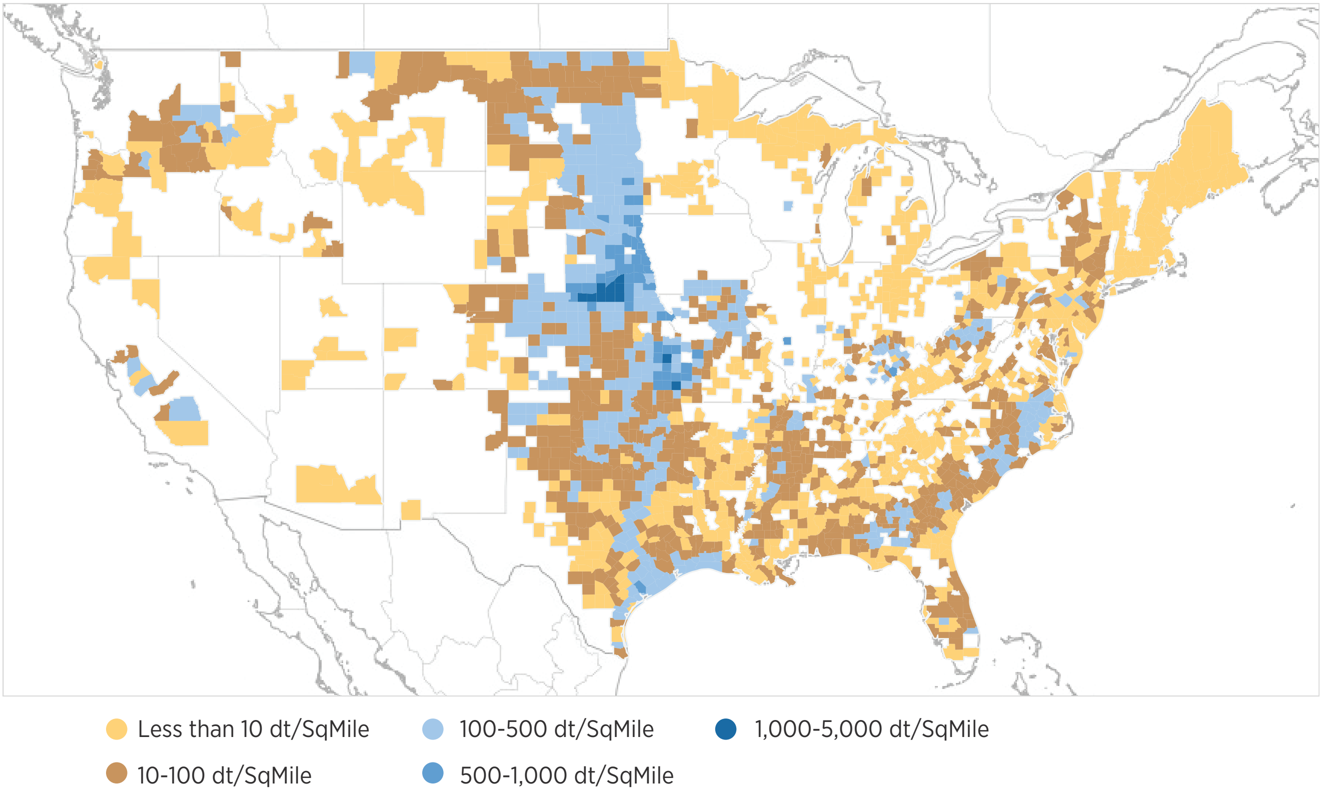
Two scenarios of specified-price simulations are highlighted in this report: a base-case scenario with a 1% yield increase annually and a high-yield scenario with a 3% annual yield increase. The simulations begin in 2015 with an offered farmgate price for primary crop residues only between 2015 and 2018 and long-term contracts for dedicated crops beginning in 2019, as discussed in appendix C. Expected mature energy crop yield grows at a compounding rate beginning in 2016 as specified by scenario. For example, woody crops planted in 2022 according to base-case yield growth assumptions would expect mature yield increase of 7.2% above the assumed base year value. For example, a county with a 2015 expected yield of 5 dry tons per acre mean annual increment (or 40 dry tons per acre at the end of an 8-year rotation) would have an expected yield if planted in 2022 of 5.36 dry tons per acre mean annual increment (or 42.9 dry tons per acre at the end of an 8-year rotation) when harvested in 2030. For the high-yield 3% scenario, the expected yield at planting is 6.1 dry tons per acre mean annual increment (or 49.2 dry tons per acre at the end of an 8-year rotation) when harvested in 2030. The yield growth assumptions are fixed after crops are planted such that yield gains do not apply to crops already planted, but new plantings do take advantage of the gains in expected yield growth.

## 4.5.1 Base-Case Scenario (1%)

Under this base-case scenario, at offered farmgate prices less than $35, supply is found to be available only from residues (96%–100% of total supply) and woody energy crops (0%–4% of total supply). At ≤$40, 30 million tons of total biomass resources from agricultural lands are available in 2017, consisting completely of residues because of the constraints discussed earlier, and 38 million tons by 2022, also completely from residues because of low offered prices and the high cost of energy crops under these base-case assumptions. The total reaches 59 million tons with both residues and energy crops in 2030 and 108 million tons in 2040, the final year of the simulation as displayed in figure 4.4. A total of 79% of this production is from residues in 2030 and only 54% in 2040, with herbaceous energy crops dominating the market in later years (11% in 2030, 31% in 2040) as planted acreage reaches maturity and is ready for harvest, along with some woody energy crops (11% in 2030 and 15% in 2040). In these later years and at these lower prices, herbaceous energy crops are coming primarily from switchgrass, with some miscanthus (a higher-yielding, but higher-cost crop). Less than one million tons of energy sorghum is coming into production by 2040. Woody energy crops contribute about half the total energy crop production in 2030 but decrease to 32% of energy crop production by 2040 as switchgrass production continues to rise with realized yield increases.

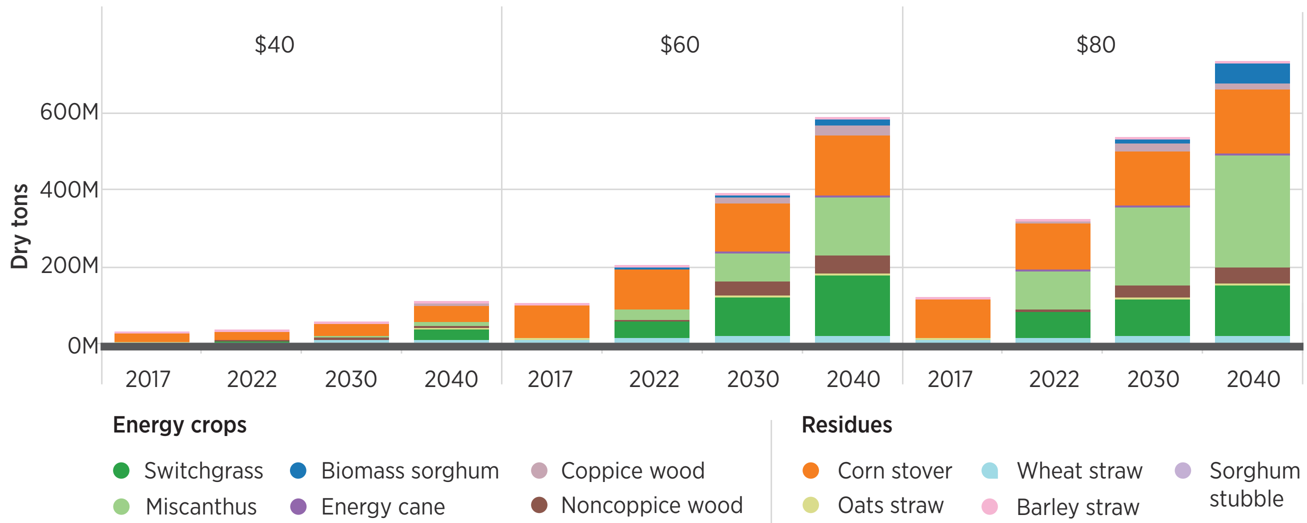
At a ≤$60 offered farmgate price, 104 million tons of residues are available in 2017 and 201 million tons of residues and energy crops in 2022. In later years, 388 million tons of residues and energy crops are available in 2030 and 588 million tons in 2040 from residues and energy crops. At this price point, 49% of total supply is available from herbaceous energy crops in 2030, increasing to 58% by 2040. Another 13% is available from woody energy crops in 2030, which decreases to 12% in 2040. Increasing the offered farmgate price further to ≤$80 yields 117 million tons of available residues in 2017. Herbaceous energy crops continue to dominate the market at this price point, with residues taking a smaller share of the 323 million tons of total potential feedstocks in 2022 than under a ≤$60 offered farmgate price scenario (fig. 4.5). In 2030 and 2040, the total energy

**Figure 4.4** | Production of residues and energy crops at an offered farmgate price of $40 in 2040 under a base-case (1%) scenario[6]




**Note:** dt/SqMile = dry tons per square mile.

**Figure 4.5** | Production of herbaceous and woody energy crops under ≤$40, ≤$60, and ≤$80 offered farmgate prices under a base-case (1%) scenario for select years[7]




[6] Interactive visualization: https://bioenergykdf.net/billionton2016/4/1/tableau

[7] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

crops and residues reach 537 and 734 million tons, respectively. This supply comprises 60% in 2030 and 67% in 2040 for herbaceous energy crops. Woody energy crops are limited to 10% of the market in 2030 and 8% in 2040, and residues make up the rest. The total potential availability of biomass feedstocks under the base-case scenario in selected years is outlined in figures 4.6, 4.7, and 4.8.

Under this base-case scenario at an offered farmgate price of ≤$40, land planted under dedicated energy crops begins at 0.9 million acres in 2022, advancing to 2.4 in 2030 and 9.4 in 2040. In comparison, at a higher offered farmgate price of ≤$60, the acres under production at the launch of energy crops (2019) are higher and accelerate at a faster pace: 21.4 million acres are planted in 2022, 42.4 million acres in 2030, and 64.4 in 2040. Similarly, at a ≤$80 offered farmgate price, the planted acres begin at 41.5 million acres in 2022 and grow to 62.1 million acres in 2030 and 80 million acres in 2040. Figure 4.9, which shows acres in production in selected years and prices under the base-case (1%) scenario, depicts two other crop categories: conventional crops (as discussed earlier, this includes eight crops shown in figure 4.3) and "other," which consists of pasture land[8] and idle land,[9] as well as land under production for energy crops. For example, other land covers 468.3 million acres in 2017 under a ≤$40 offered farmgate price and shrinks to 467.0 million acres in 2040. As we transition to a ≤$60 offered price with 303.6 million acres under production for conventional crops in 2017, for example, a total change of -28.1 million acres planted occurs for conventional crops by 2040. This gives way to energy crops coming into production during this timeframe on a total of 64.3 million acres across all land types (42% cropland, 4% cropland pasture, 54% permanent pasture) by 2040.[10] The distribution of land use under base-case assumptions for select years at $60 per ton farmgate prices is shown in table 4.3.

The energy crop category of land use depicted in figure 4.9 at the ≤$40 offered farmgate price consists primarily of coppice and non-coppice wood (0.9 million acres in 2022, 1.6 million acres in 2030, and 4 million acres in 2040) with some switchgrass and miscanthus entering in later years (e.g., 4.4 million acres of switchgrass in 2040). However, at higher offered prices, the use of land for these dedicated energy crops changes to primarily switchgrass and miscanthus (e.g., 13.7 million acres under production for these two crops at an offered farmgate price of ≤$60

## Text Box 4.3 | Constructing Supply Curves From Independent Exogenous Price Simulations

Each simulation of a different price is an independent model simulation. The mix of feedstocks supplied at each price will change based on the offered price. For example, when markets are offered at ≤$40 in 2019, farmers respond differently than if they were offered ≤$80 in 2019. Each price increase does not look back at the previous simulation (e.g., recursive dynamics) to determine land allocation due to existing programming of the model. Therefore, supply curves constructed from these separate simulations for individual or combined biomass crops shown later in this chapter may have anomalies (e.g., backward bends) for certain feedstocks.

[8] Pasture land excluded from POLYSYS land base includes 399.2 million acres out of 446.2 million acres total pasture (see appendix C.1 for more details).

[9] Idle land is fixed across all scenarios beginning at 12.3 million acres in 2015 and ending at 23.3 million acres in 2040 (see appendix C.1 for more details).

[10] Note: In a baseline scenario (BL0, a continuation of the USDA baseline), other land decreases, although less severe than the modeled change described in this scenario example.

**Figure 4.6** | Supply curves of potential production from major crop residues for select years under base-case assumptions

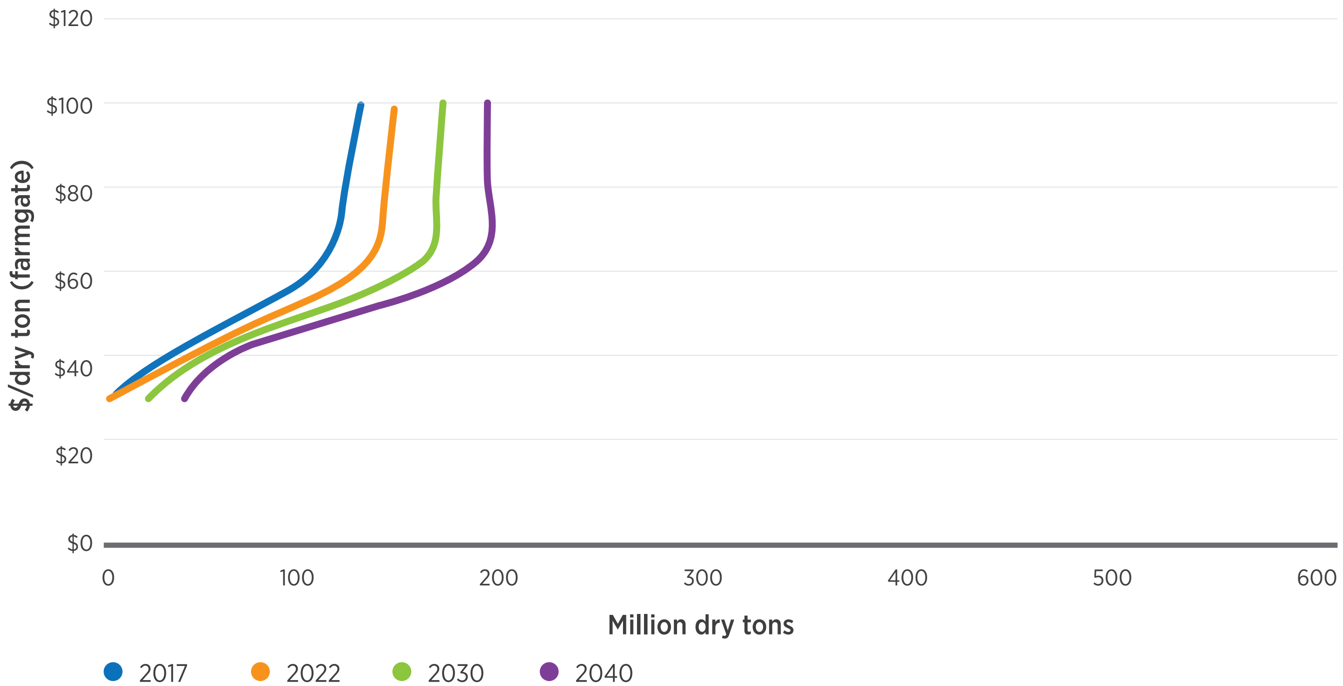



**Figure 4.7** | Supply curves of potential herbaceous energy crop production for select years under base-case assumptions

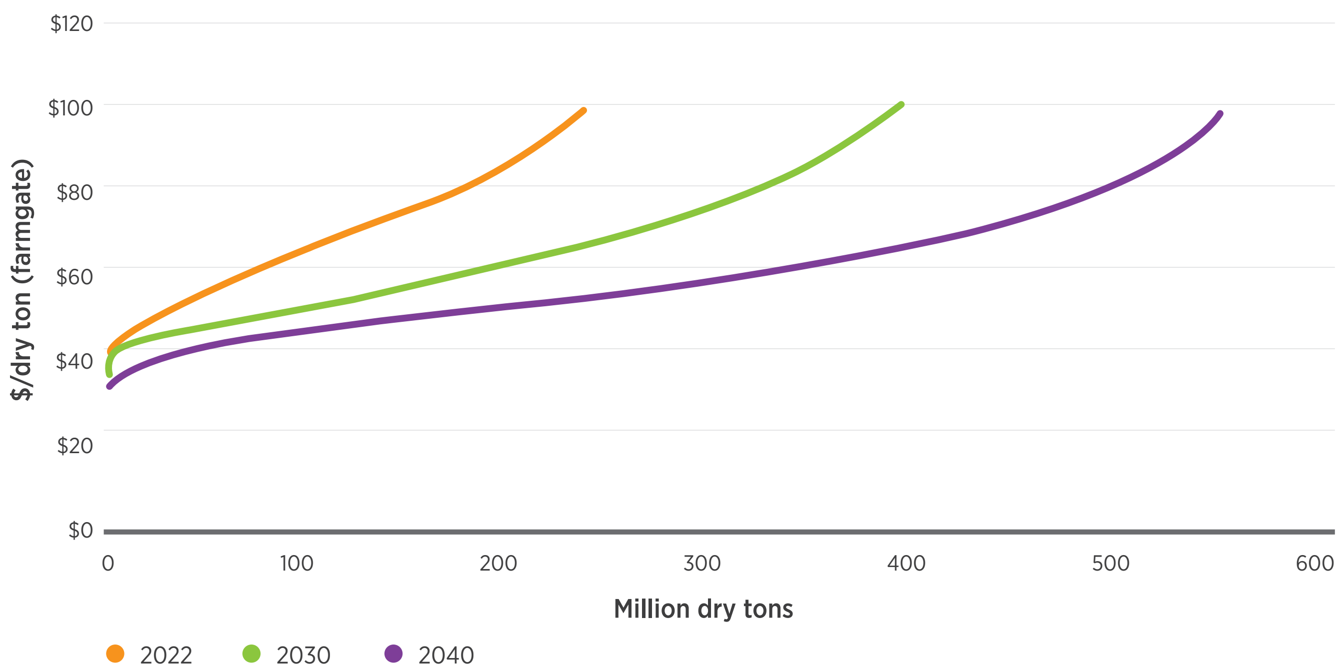
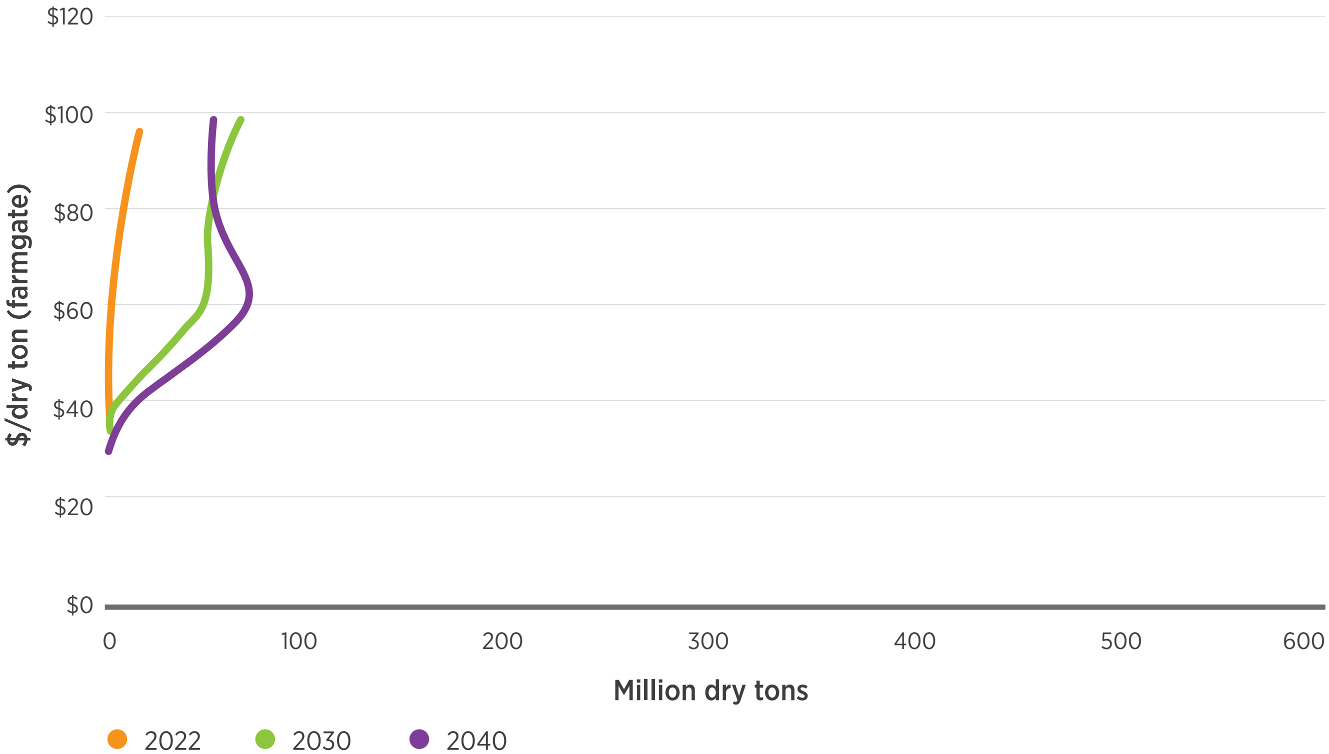


**Figure 4.8** | Supply curves of potential woody energy crop production for select years under base-case assumptions



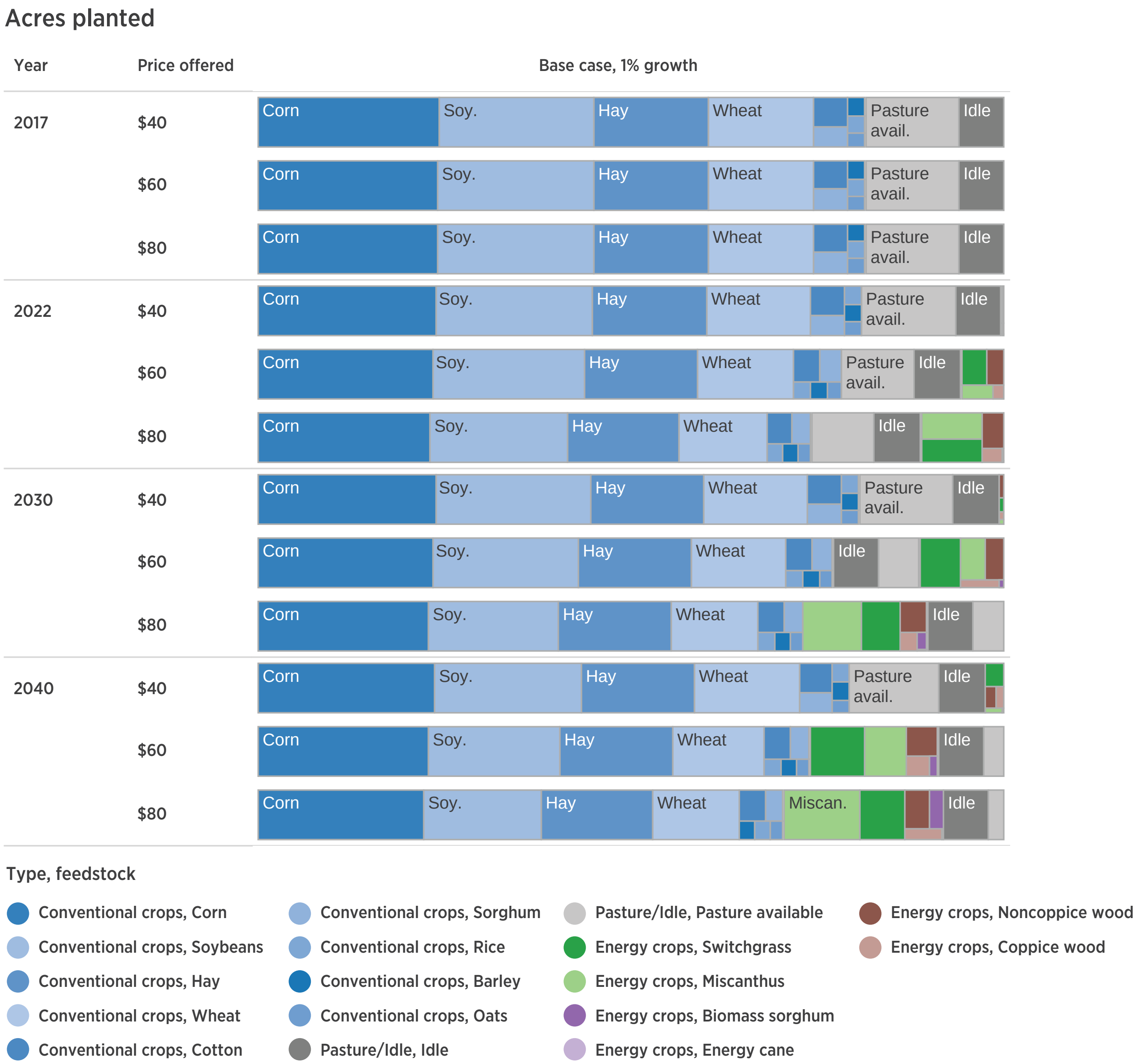

in 2022), which demonstrates the decreasing supplies at higher prices as depicted in figure 4.8 and text box 4.3. The share of coppice woody crops remains nearly constant at higher offered prices (e.g., in 2030: 3.2 million acres at ≤$60 versus 3.5 million acres at ≤$80), but more land comes into production for non-coppice (e.g., less than 7.9 million acres at ≤$60 and 8.5 million acres at ≤$80 in 2030) as depicted in figure 4.9. Biomass sorghum claims more area for production under the ≤$80 scenario, beginning at 130 thousand acres in 2022 and increasing to 5.1 million acres in 2040 as yield improvements begin to accumulate and make biomass sorghum more competitive, and as land is freed up from the transition of other energy crops out of production (e.g., as acres in switchgrass production end their rotation and are eligible for transitioning to another crop or land use). The ramp-up of planted acres, mirroring production as discussed earlier, is replicated and even compounded under the high-yield scenarios discussed below.

### 4.5.2 High-Yield Scenario (3%)

A high-yield scenario initiates a 3% yield improvement for all energy crops beginning in year 2016 as well as high-yielding corn and a high flexibility of tillage options to accommodate no-till adoption for agricultural residue generation. Figure 4.10 depicts the acres under production for selected years and prices for the high-yield scenario as well as the base-case scenario for comparison.

Total planted acres under energy crops after constraints are met encompass slightly more under this more aggressive scenario at an offered farmgate price of ≤$40 than under the base-case at this same price: 2.2 million acres in 2022, 9 million acres in 2030, and 38.5 million acres in 2040. Likewise, acres under production are higher at ≤$60 and ≤$80 offered farmgate prices: ≤$60 brings 28.3 million acres into production in 2022, 57.9 million acres in 2030, and 88 million acres in 2040; ≤$80 brings in 49.9 million

**Figure 4.9** | Total planted acres by crop type after constraints are met at select prices under base-case assumptions[11]

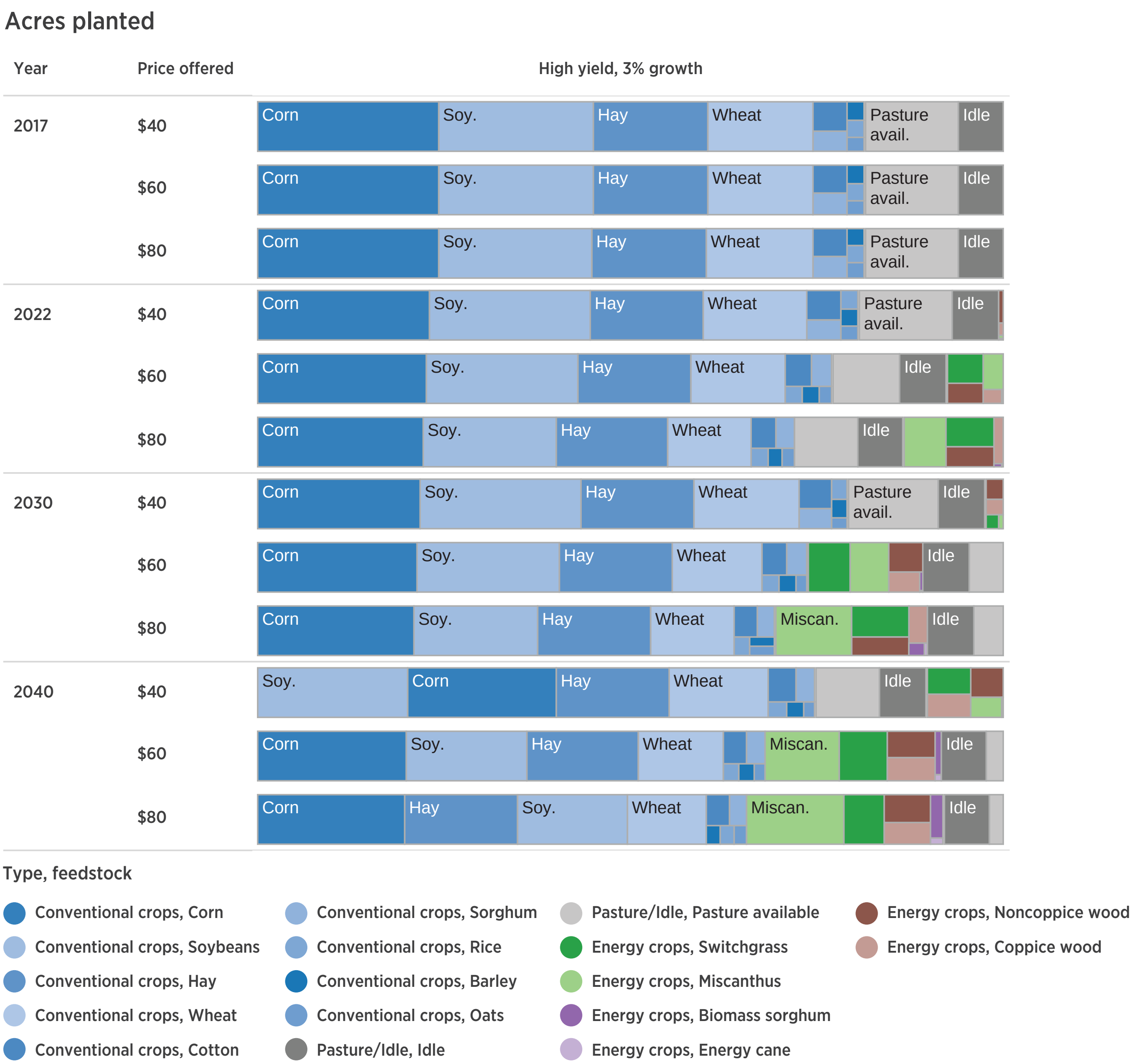



[11] Interactive visualization: https://bioenergykdf.net/billionton2016/4/6/tableau

**Table 4.3** | Distribution of Land Use Under Base-Case Assumptions for Select Years at ≤$60 Offered Farmgate Price

| Land use type | 2017 | 2022 | 2030 | 2040 |
|---|---|---|---|---|
| | Million acres | | | |
| **Energy crops land allocation (planted)** | N/A | 21.41 | 42.38 | 64.34 |
| Cropland allocation (planted) | N/A | 11.01 | 15.30 | 27.10 |
| Cropland used as pasture allocation (planted) | N/A | 1.11 | 2.20 | 2.48 |
| Permanent pastureland allocation (planted) | N/A | 9.29 | 24.88 | 34.76 |
| **Energy crops (harvested/fraction)** | N/A | 13.2/0.62 | 31.95/0.75 | 50.00/0.78 |
| **Corn (planted)** | 89.85 | 87.6 | 86.92 | 84.76 |
| Corn stover (harvested) | 47.68 | 50.36 | 54.63 | 56.53 |
| **Other crops with residues (planted)** | 65.79 | 59.72 | 59.08 | 56.91 |
| Other crops with residues (harvested) | 16.34 | 17.89 | 20.26 | 22.05 |
| **Percent of total U.S. cropland (325.6 million acres) allocated to energy crops** | N/A | 3.4% | 4.7% | 8.3% |
| **Percent of total U.S. pastureland (446.2 million acres) allocated to energy crops** | N/A | 2.3% | 6.1% | 8.3% |
| **U.S. major crops with residues (acreage), percentage harvested for biomass** | 155.60, 41.1% | 147.30, 46.3% | 146.00, 51.3% | 141.70, 55.5% |
| **Percentage of U.S. cropland contributing to biomass production (energy crops planted and residue harvested)** | 19.7% | 24.3% | 27.7% | 32.5% |

**Figure 4.10** | Total planted acres by crop type after constraints are met at select prices under high-yield (3%) assumptions[12]




[12] Interactive visualization: https://bioenergykdf.net/billionton2016/4/6/tableau

acres in 2022, 76.1 million acres in 2030, and 98.6 million acres in 2040. For comparison, under this aggressive scenario (high yield 3%, ≤$80), 303.6 million acres are in production for conventional crops in 2017; this decreases to 268.3 million acres in 2022 and finally by 2040 decreases to 244.3 million acres (a 20% reduction from 2017). The distribution of land use under high-yield assumptions for select years at $60 per ton farmgate prices is shown in table 4.4.

As depicted in figure 4.11 and consistent with constraints discussed earlier, in 2017, production of 30 million tons was simulated to be available from residues only at an offered farmgate price of ≤$40. The total available biomass resources associated with planted acres discussed earlier at an offered farmgate price of ≤$40 are simulated to be 2 million tons from energy crops in 2022, which was 5% of 44 million tons of total production. Compared with the base-case scenario, which had no energy crops entering at ≤$40 in 2022, the onset of energy crops at this low price demonstrates the impact that yield improvements (3% per year) have on the profitability of these crops. In 2030, 40 million tons from energy crops are available, and in 2040, 276 million tons from energy crops are available at an offered farmgate price of ≤$40. In this high-yield but low-price scenario, herbaceous energy crops and woody energy crops come into production in 2019 and reach a potential supply of 18 million tons for herbaceous energy crops and 22 million tons for woody energy crops in 2030. Later years see further increases to 170 million tons for herbaceous energy crops and 106 million tons for woody energy crops in 2040. Residues are capped at 83 million tons in 2040, which constitutes just 23% of total production; herbaceous energy crops dominate at 47% of total production.

At a ≤$60 offered farmgate price, 105 million tons of residues are available in 2017, and 245 million tons of biomass resources from agricultural lands are available in 2022 (55% residues, 42% herbaceous energy crops). The surge in herbaceous energy crops when the simulation transitions from ≤$40 to ≤$60 demonstrates the minimum profitability needed under these simulations for herbaceous crops. In later years, 554 million tons become available in 2030 (54% herbaceous energy crops, 15% woody energy crops, and 31% from residues) and 937 million tons in 2040 (64% herbaceous energy crops, 15% woody energy crops, and 21% residues) at ≤$60. A ≤$80 price yields 121 million tons of residues in 2017. In 2022, herbaceous energy crops begin to dominate the market at this higher price, comprising 59% of 394 million tons of total production in 2022. In 2030 and 2040, woody energy crops increase to 12% of total production: 85 million tons in 2030 and 125 million tons in 2040. The production of herbaceous energy crops continues to rise from 62% of total production (446 million tons) in 2030 to 68% of total production (729 million tons) available in 2040. Total production reaches 1.07 billion tons at a ≤$80 offered farmgate price in 2040, with just 20% (214 million tons) of this production coming from residues. The total potential availability of biomass feedstocks under the high-yield (3%) scenario at selected years is shown in figures 4.11, 4.12, 4.13, and 4.14.

## 4.5.3 Economic Impacts

Changes in crop prices, planted acres, and crop net returns compared to the 2015 base year are summarized in tables C-8 and C-9 of appendix C for the base-case and high-yield scenario at $60 per dry ton or less. Relative to the USDA projections, simulated results show a loss of crop acres to energy crops; 2040 crop prices relative to the baseline are generally higher in nominal terms but lower than near-term prices in real terms. For producers, the higher crop prices more than compensate for the loss in crop acres, as reflected in higher net crop returns relative to the base year. In the base case, the cross price elasticity of supply of corn when biomass prices increase from $40 to $60 is 0.7 in 2030 and 1.8 in 2040. This suggests the responsiveness of corn price to biomass

**Table 4.4** | Distribution of Land Use Under High-Yield Assumptions for Select Years at <$60 Offered Farmgate Price[13]

| Land use type | 2017 | 2022 | 2030 | 2040 |
|---|---|---|---|---|
| | (million acres) | | | |
| **Energy crops land allocation (planted)** | N/A | 28.3 | 57.87 | 87.95 |
| Cropland allocation (planted) | N/A | 15.39 | 27.8 | 48.95 |
| Cropland used as pasture allocation (planted) | N/A | 1.29 | 2.31 | 2.54 |
| Permanent pastureland allocation (planted) | N/A | 11.62 | 27.76 | 36.46 |
| **Energy crops (harvested/fraction)** | N/A | 17.11/0.60 | 41.63/0.72 | 64.12/0.73 |
| **Corn (planted)** | 90.36 | 84.55 | 79.67 | 74.33 |
| Corn stover (harvested) | 46.76 | 51.93 | 53.45 | 50.38 |
| **Other crops with residues (planted)** | 65.87 | 58.72 | 56.35 | 52.48 |
| Other crops with residues (harvested) | 19.41 | 23.37 | 28.02 | 29.51 |
| **Percent of total U.S. cropland (325.6 million acres) allocated to energy crops** | N/A | 4.7% | 8.5% | 15% |
| **Percent of total U.S. pastureland (446.2 million acres) allocated to energy crops** | 0% | 2.9% | 6.7% | 8.7% |
| **U.S. major crops with residues (acreage), % harvested for biomass** | 156.20, 42.4% | 143.30, 52.6% | 136.00, 59.9% | 126.80, 63% |
| **% of U.S. cropland contributing to biomass production (energy crops planted and residue harvested)** | 20.3% | 27.9% | 33.6% | 39.6% |

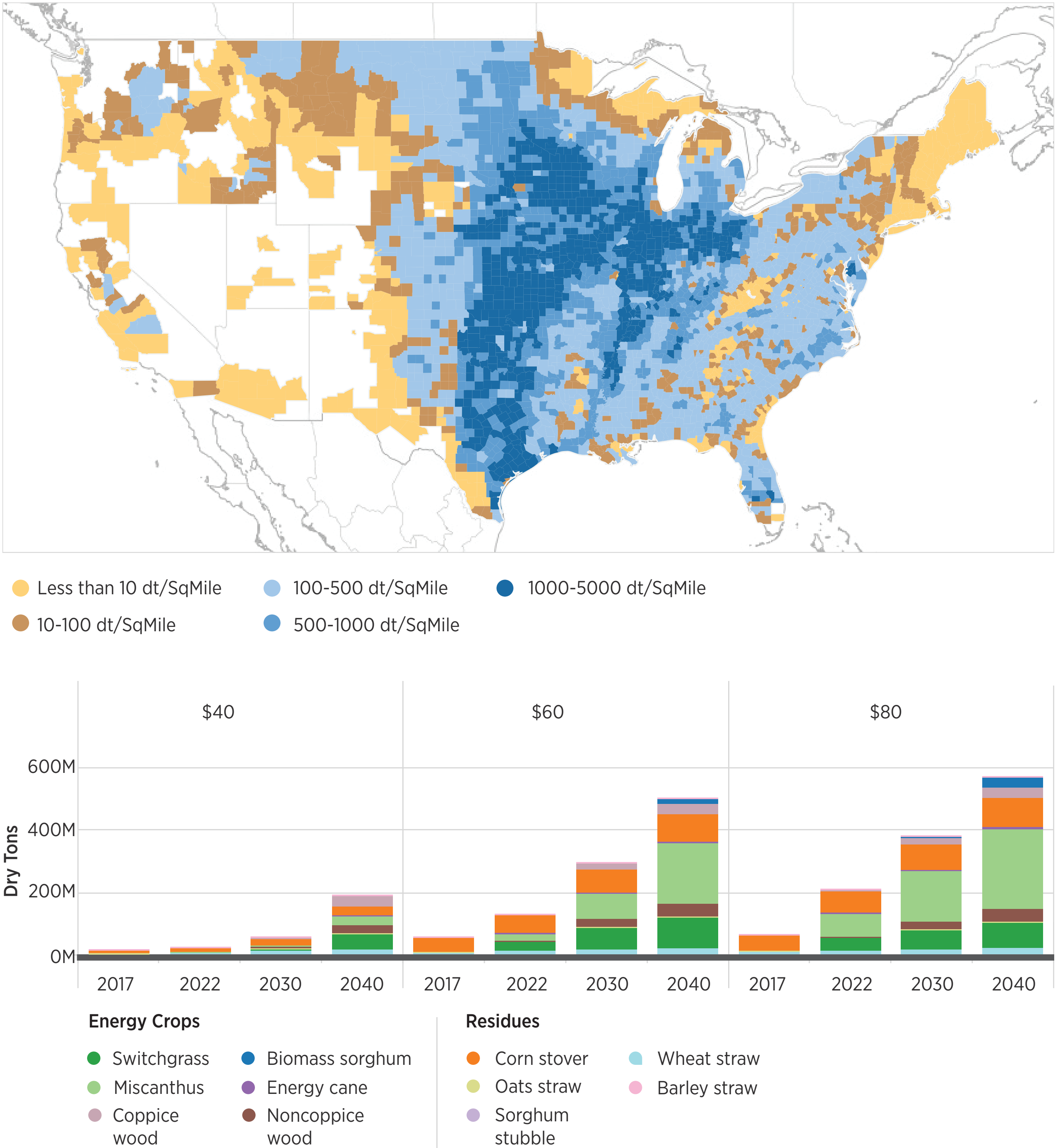
price is increasing over time. The price of corn is lower due to the excess grain produced under the 3% high-yield scenario.

Comparing the simulated results to the USDA projections shows only minor changes in total livestock production, beef cattle farm prices, and inventories of cattle. The key assumption is that increased forage productivity compensates for losses because of the presence of energy crops on pastureland.

Total net crop returns increase significantly under the USDA baseline scenario where crop residues are collected and energy crops produced. Total net returns from livestock production are unaffected. Overall, total net returns to major crops and livestock in the *BT16* base-case scenario increase by about $16.5 billion by 2040 compared to the extended baseline. Under the high-yield scenario, total net returns are nearly $14.5 billion higher by 2040.

[13] Interactive visualization: https://bioenergykdf.net/billionton2016/4/5/table

**Figure 4.11** | Production of residues and energy crops at an offered farmgate price of <u><</u>$60 in 2040 under a high-yield (3%) scenario[14]




[14] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

**Figure 4.12** | Supply curves of potential production from major crop residues for select years under high-yield (3%) assumptions

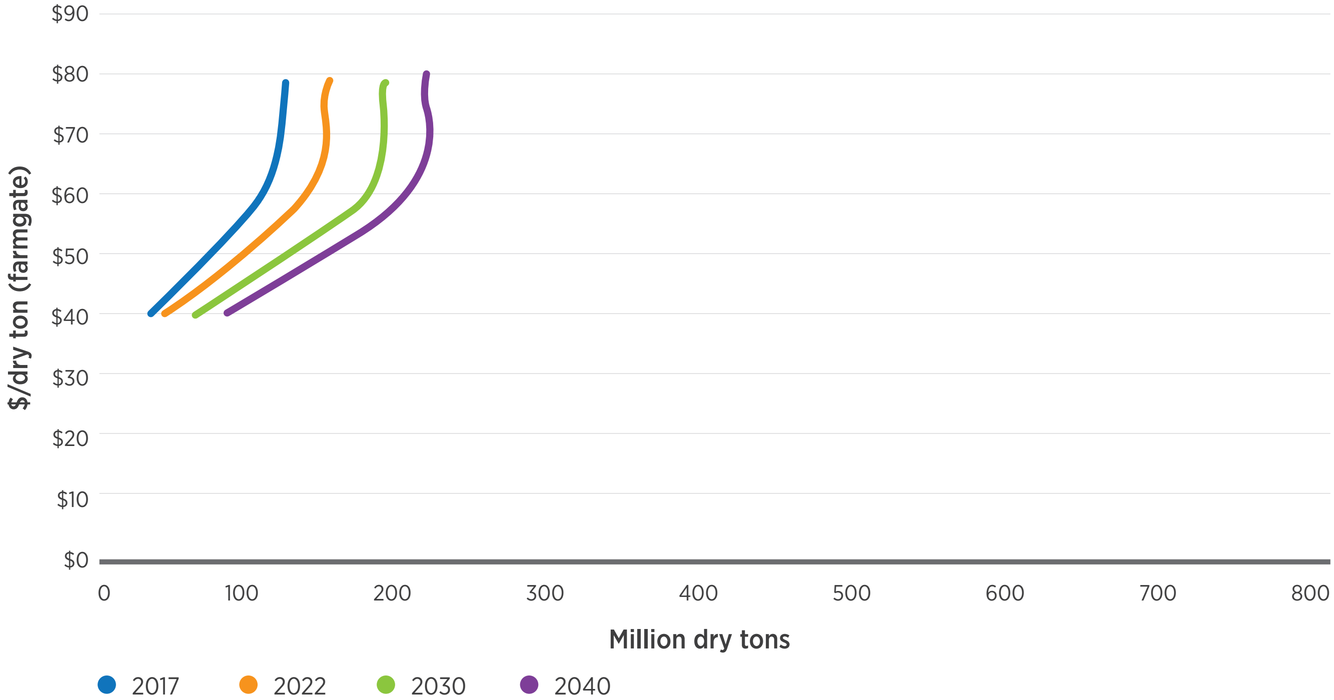



**Figure 4.13** | Supply curves of potential herbaceous energy crop production for select years under high-yield (3%) assumptions

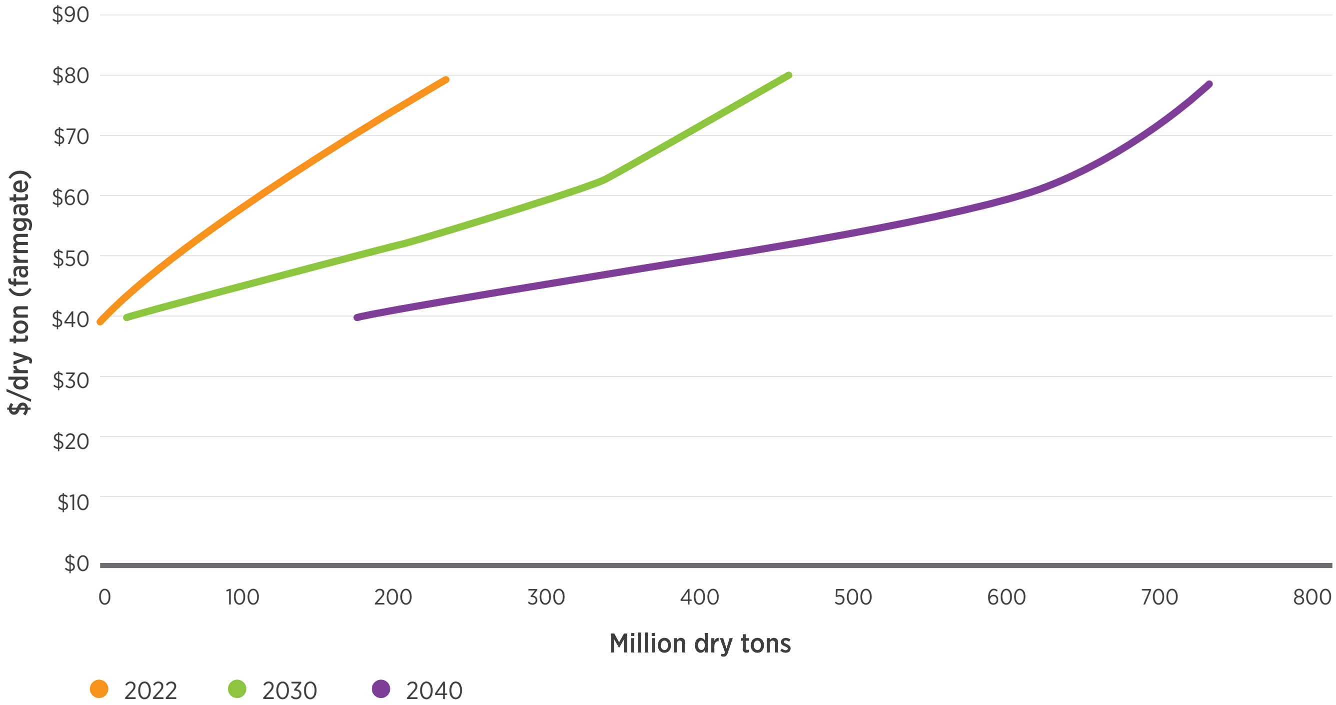
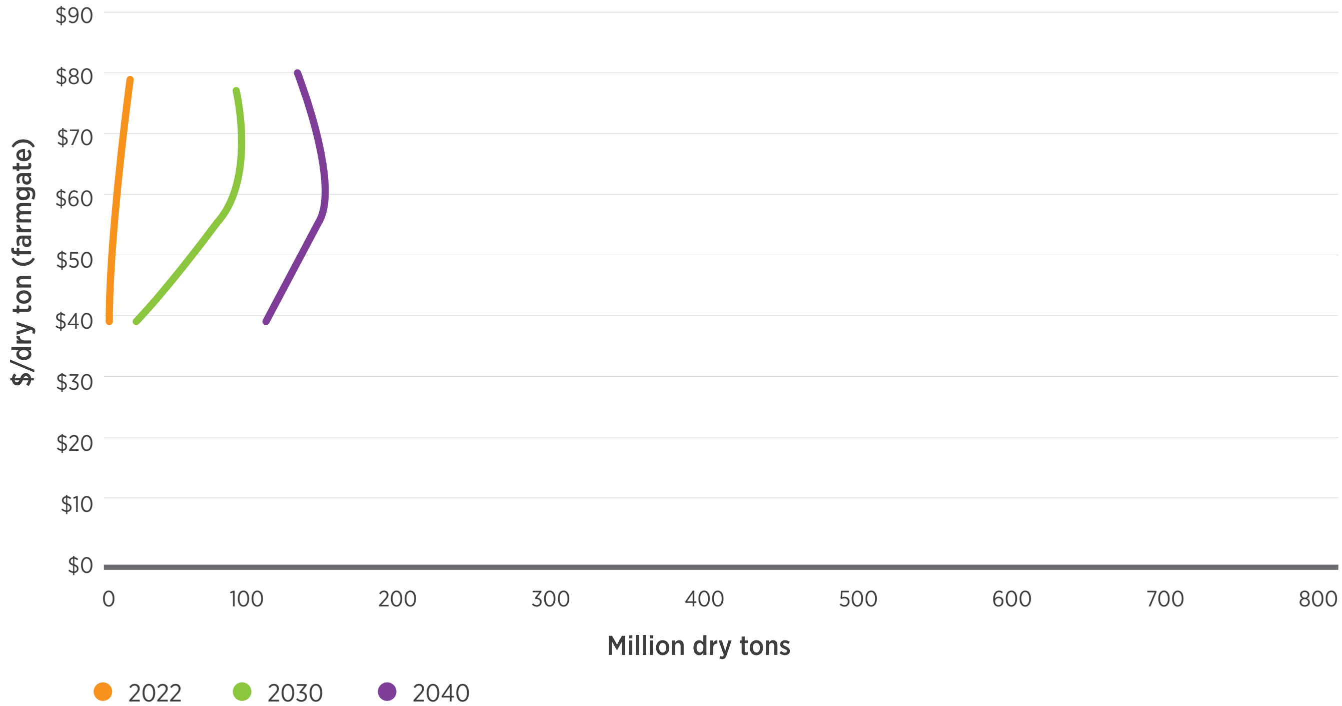


**Figure 4.14** | Supply curves of potential woody energy crop production for select years under high-yield (3%) assumptions




**Note:** Decreasing supplies at higher prices are due to transitions to herbaceous energy crops under these market scenarios.

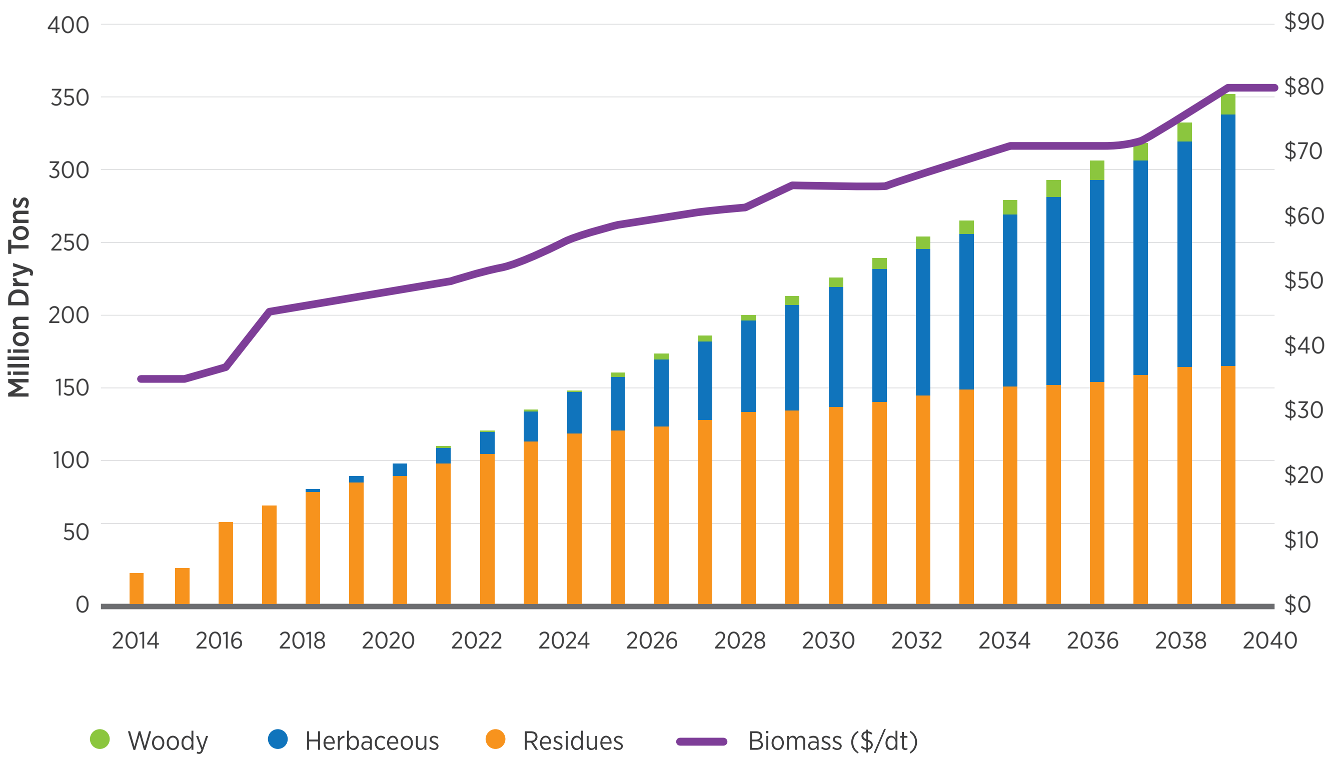
## 4.6 Prices at Specified Production

In modeling a production-target simulation (demand level 1 scenario[15]) of 250 million tons by 2022, the model solves for a $60 farmgate price in 2022 and is able to achieve 319 million tons of primarily residues (132 million tons) and miscanthus (93 million tons), with switchgrass (64 million ton), coppice woody energy crops (28 million tons), and some energy cane (1.5 million tons) as well. A farmgate price of $60 is again determined to be necessary to meet a national production target of 325 million tons (demand level 2 scenario) by 2022; but this follows several years of prices exceeding $100 that elicit production from miscanthus, which is then sustained for 15 years at lower prices due to rotation assumptions.[16] At that same production target, $83 is necessary for a target year of 2030 (350 million tons achieved). However, the later years of 2035 and 2040 yield slightly lower farmgate prices of $77 (346 million tons) and $80 (351 million tons), respectively. Increasing the production target to 500 million tons by 2040 yields a farmgate price of $79 necessary to achieve this production (606 million tons total, consisting of 176 million tons from residues, 215 million tons from miscanthus, 134 million tons from switchgrass,

[15] The demand-run scenarios simulate a gradual increase in demand and, in turn, feedstock price, over time.

[16] Once an herbaceous energy crop enters production, the entire rotation must be completed. In the case of miscanthus, this is for 15 years. See appendix C.1.

**Figure 4.15** | Feedstock supply composition and necessary farmgate price (nominal) under a demand scenario with 325-million-ton national production target by 2040




53 million tons from coppice, 27 million tons from non-coppice woody energy crops, and 0.4 million tons each from biomass sorghum and energy cane). Figure 4.15 shows the increasing farmgate price (to $71) and feedstock supply composition across the three major energy crop types as production steadily increases to meet the target demand of 325 million tons of national production in 2040.

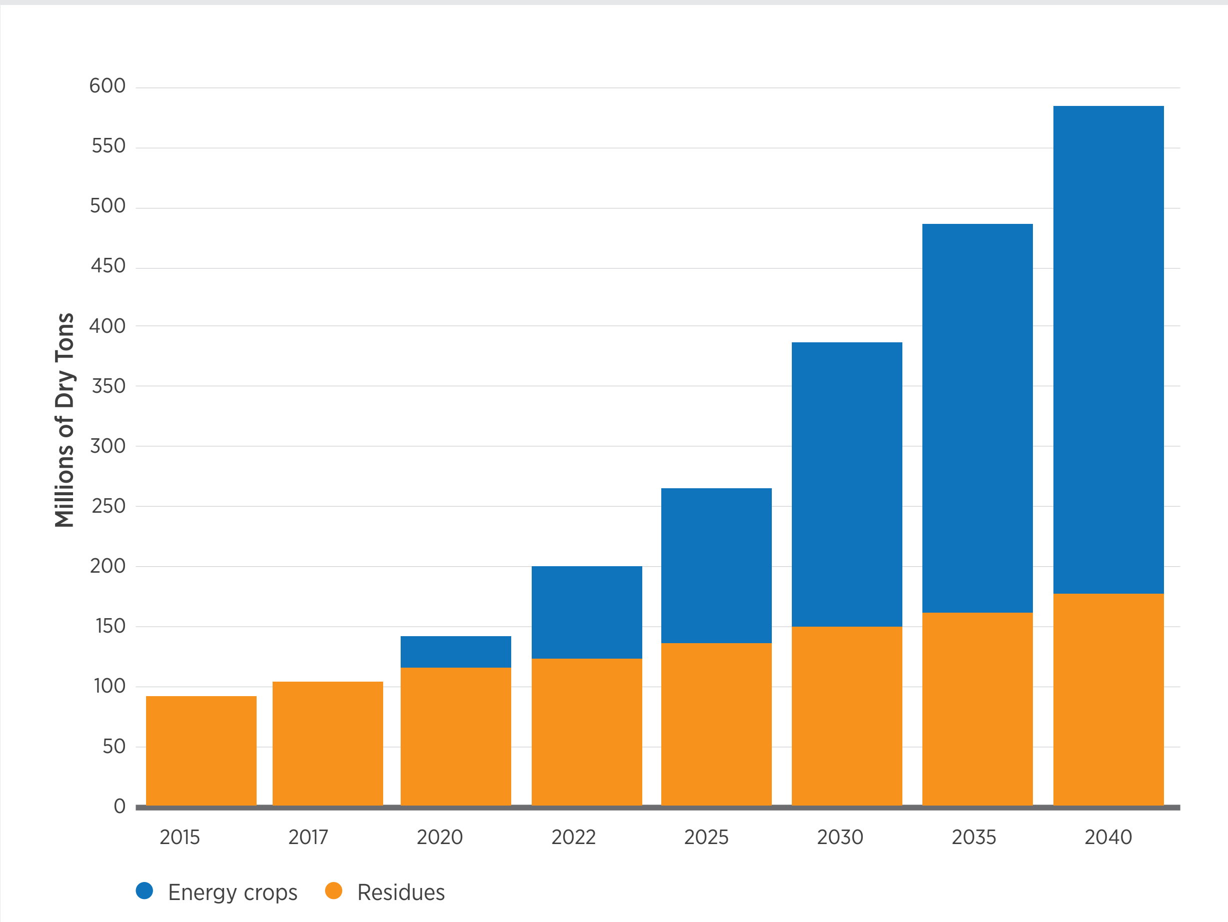
## 4.7 Discussion

Although model improvements and assumption refinements have been incorporated into this analysis, in general, the results presented for agricultural residues and biomass crops are consistent with the 2011 *BT2* results in feedstock supply composition (e.g., residues dominating in early years, herbaceous in later years). Compared with *BT2* results, this analysis shows a more conservative outlook for all energy crops: residues (e.g., because of new operational efficiency constraints; see appendix C.1), woody energy crops (e.g., due to adjusted costs and model improvements to allow for staggered plantings), and herbaceous energy crops (e.g., due to constraints applied on pasture conversion[17]). Figures 4.16, 4.17, 4.18, and 4.19 show supply curves at selected prices in year 2040 under the base-case and high-yield scenarios for comparison.

[17] Pasture land excluded from POLYSYS land base includes 399.2 million acres out of 446.2 million acres total pasture (see appendix C.1 for more details).

## Text Box 4.4 | Realizing Technical Potential With Sustained Market Demand

The biomass resources quantified in this report represent "technically available" potential resources (i.e., tons of resources that could be available at specified prices, if specified markets are provided; see fig. 8.1). Actual market availability of these potential resources is dependent upon future market demands defining the economic viability of their mobilization. While the assumption is that energy crops become "major crops" in 2019 for all scenarios (i.e., they compete with existing eight major crops and hay), it is anticipated that biomass crops continue to develop in local crop markets in the near term. In particular, future energy crops supply, which represents approximately 30%–40% of the potential billion-ton supply by 2040, is entirely dependent upon sustained market demand to incentivize energy crop deployment. For example, the specified price run of ≤$60 per dry ton in the baseline scenario indicates 411 additional million tons of energy crops are potentially available by 2040. This potential 2040 supply is in response to a simulation of a ≤$60 per dry ton price offered in all producing counties in all years between 2019 and 2040, with no limitation of what the market can consume. The response is a nearly linear progression of growth of biomass crops over time.




Potential supply of all energy crops and residues for selected years in the base-case scenario at $60 per dry ton.

**Figure 4.16** | Agricultural residues available across four exogenous price scenarios in the year 2035

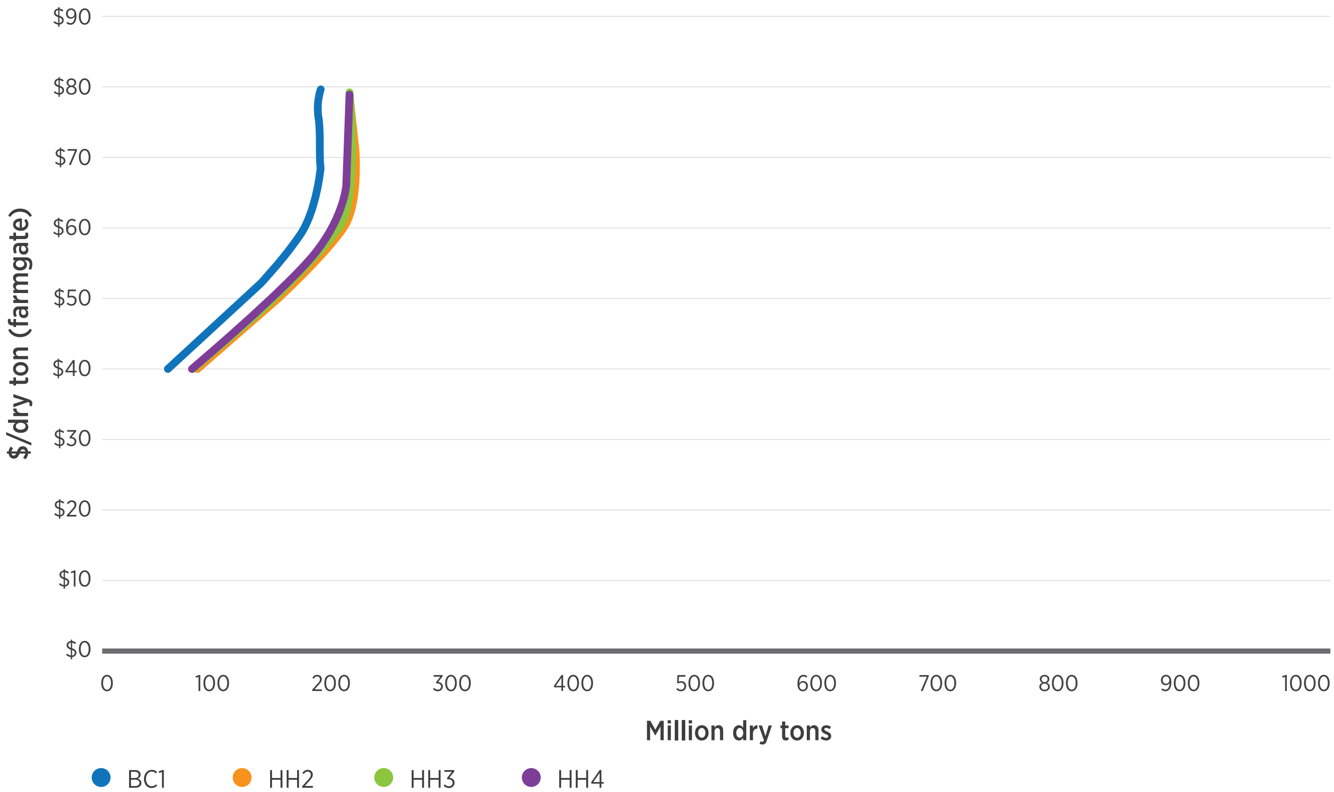



**Figure 4.17** | Herbaceous energy crops available across four exogenous price scenarios in the year 2035

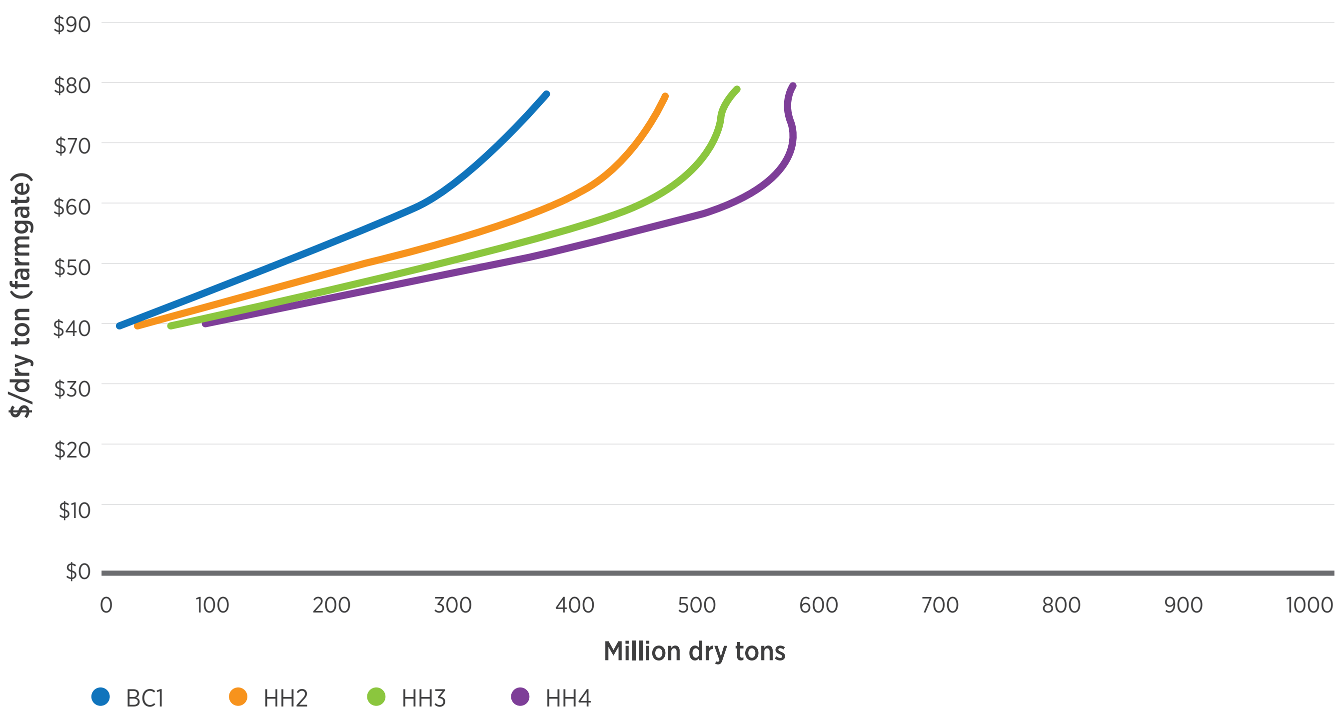


**Figure 4.18** | Woody energy crops available across four exogenous price scenarios in the year 2035

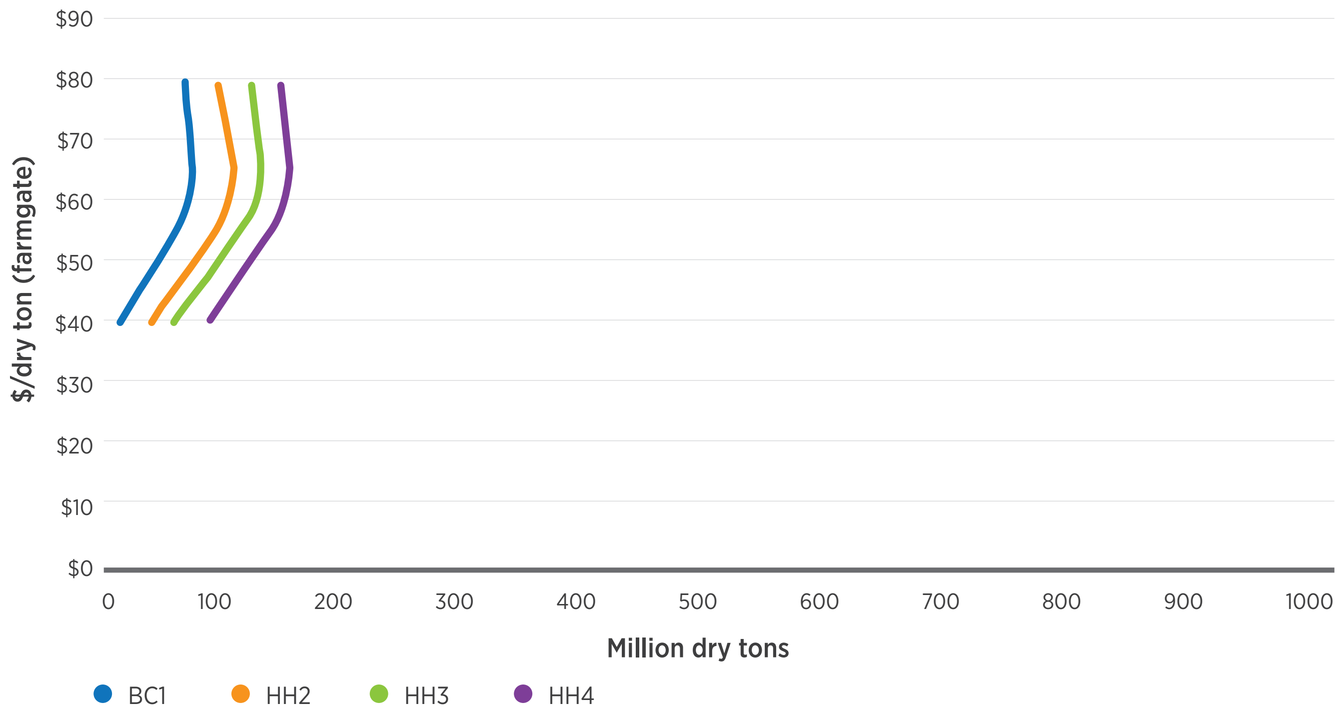
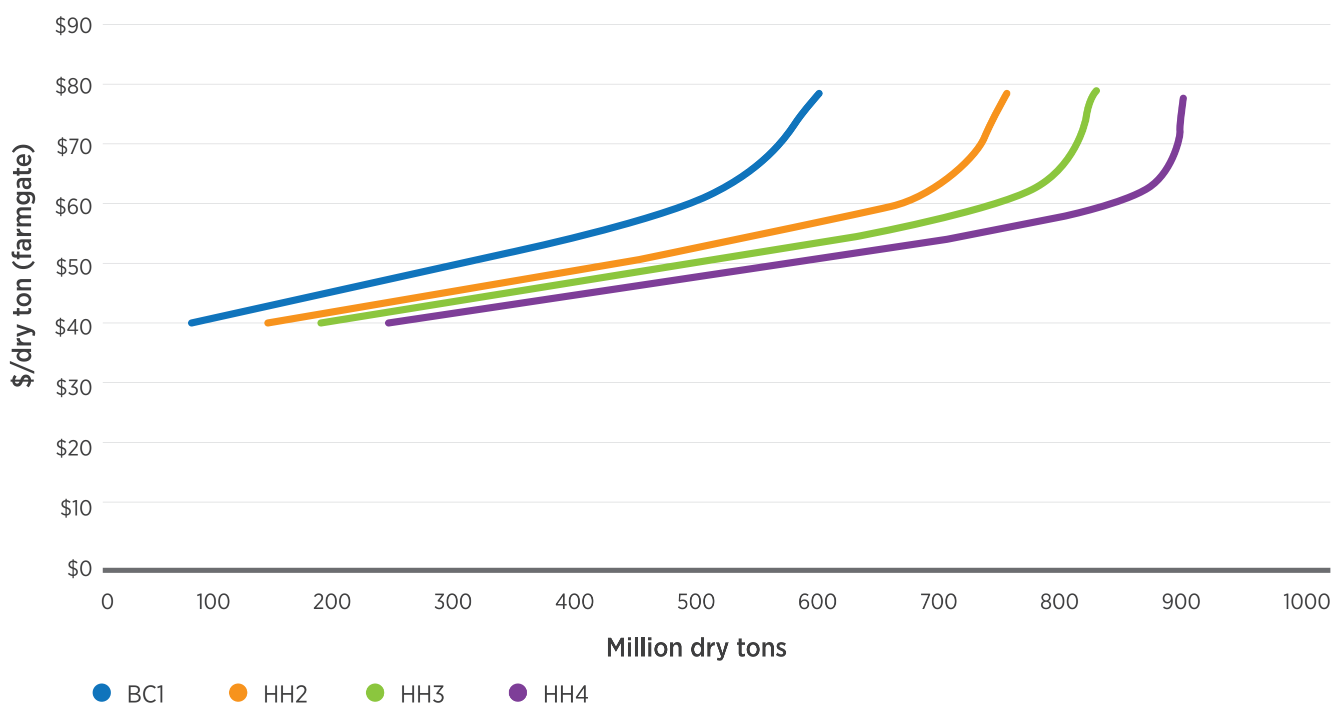
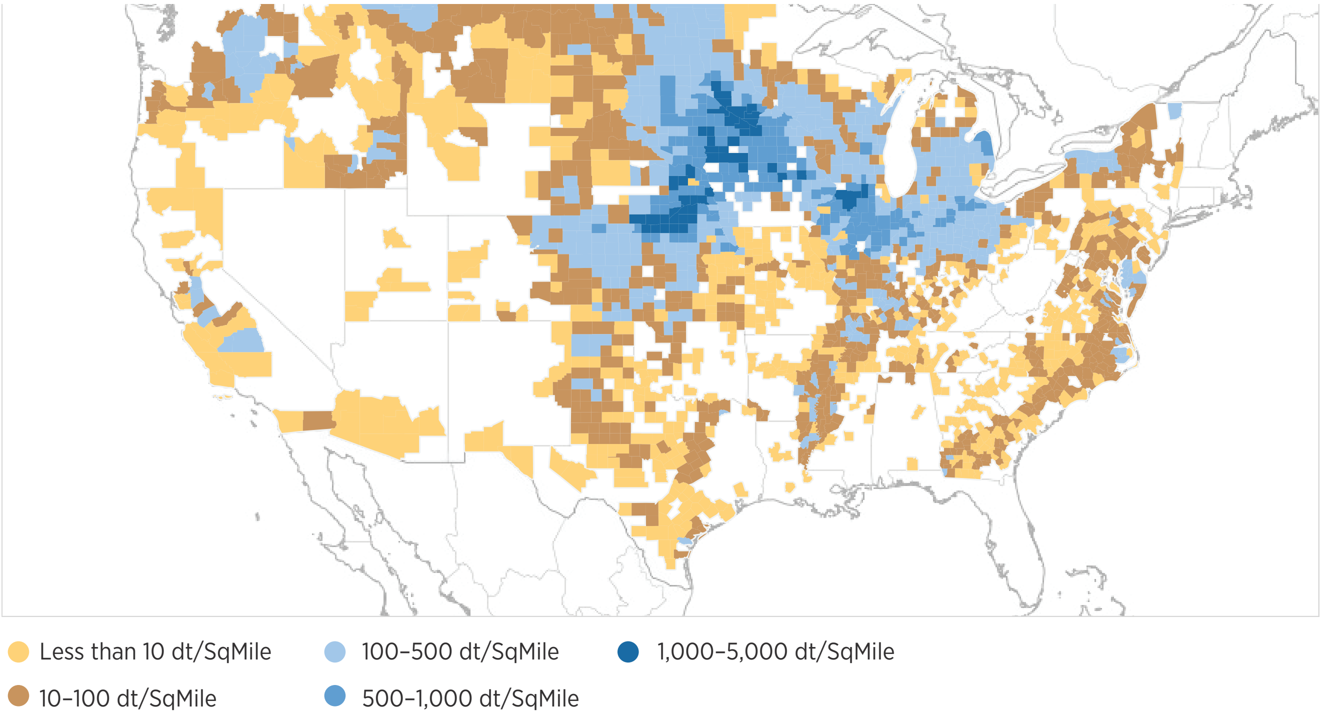


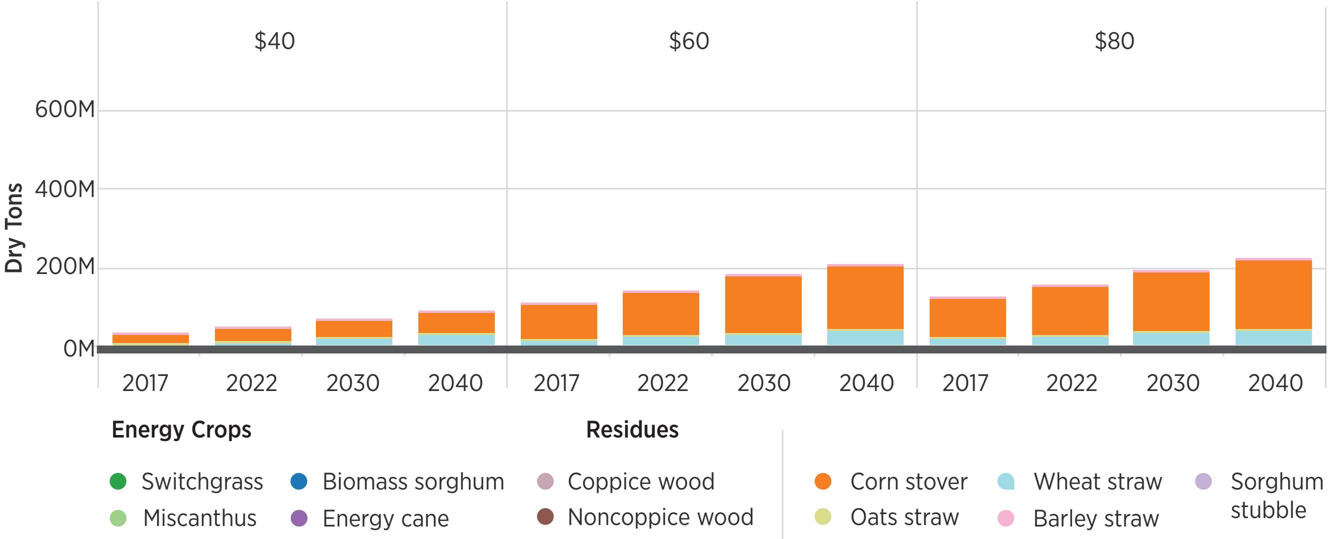

**Figure 4.19** | Total biomass resources from agricultural lands available across four exogenous price scenarios in the year 2035



Energy crop production is summarized in the state maps shown in figures 4.20, 4.21, and 4.22.[18] As depicted, the Corn Belt is again the principal area for production of residues. These figures consistently show dominance of the Great Plains in perennial grass. As discussed in the 2011 *BT2*, the dominance of perennial grasses in the Plains is due to the land availability as well as the relatively low profitability of current land uses. Cropland and pasture land are still found to be the two main land-use sources for energy crops.

**Figure 4.20** | Production from residues at <$60 offered farmgate price under a high-yield (3%) scenario[19]

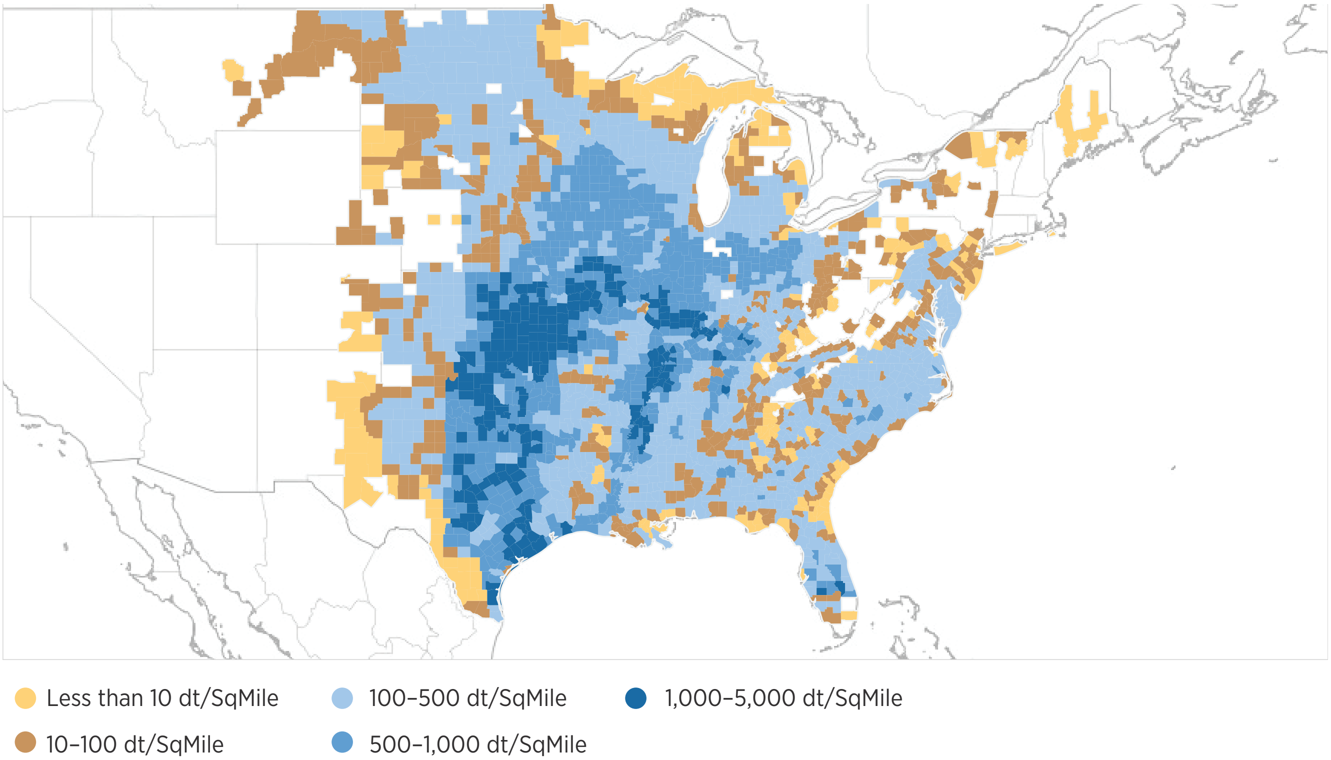


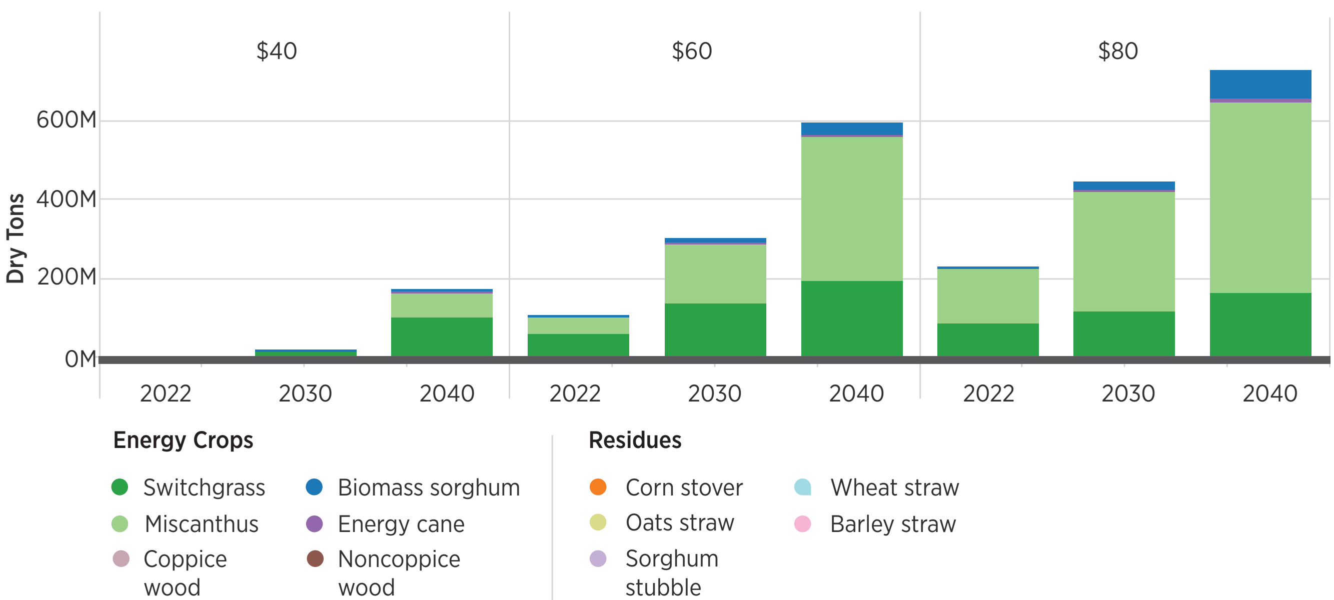




[18] We have highlighted a 3% scenario in these interactive visualizations, although any yield scenario can be selected.

[19] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

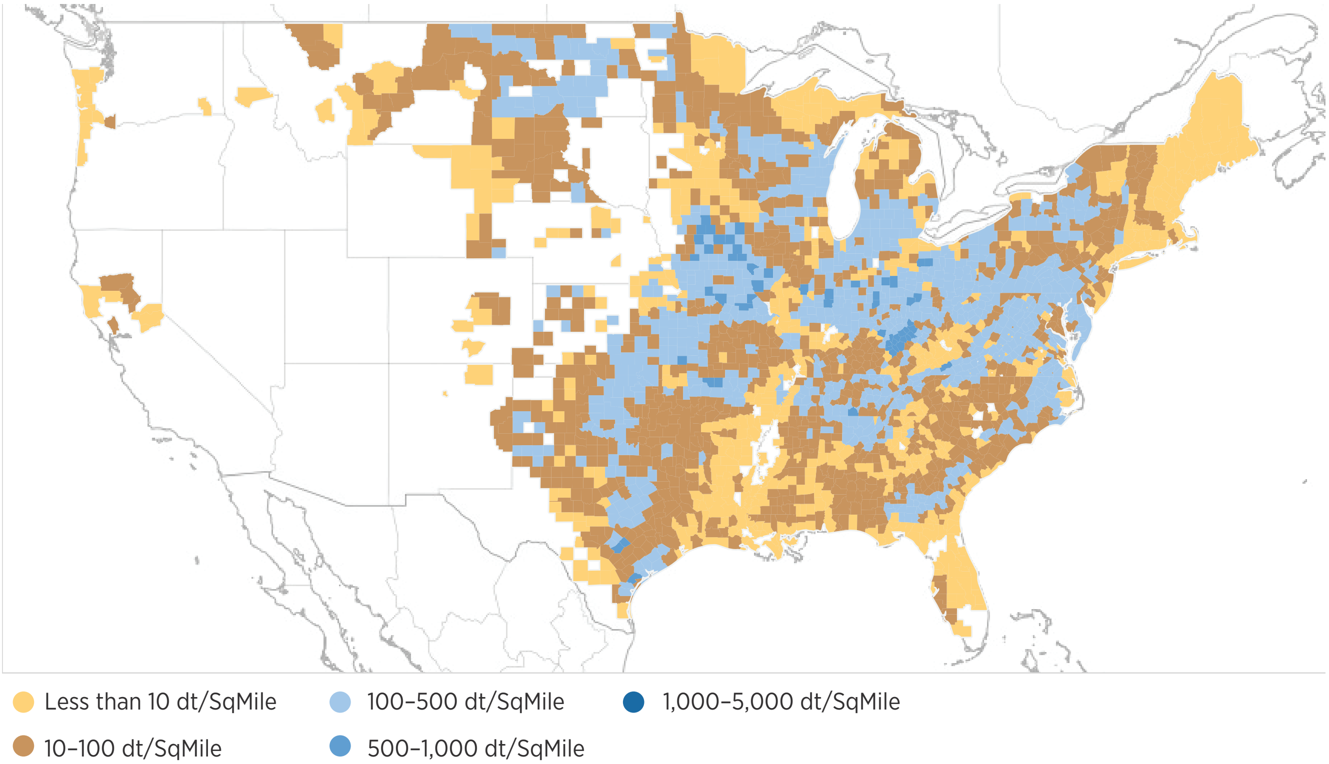
**Figure 4.21** | Production from herbaceous energy crops at ≤$60 offered farmgate price under a high-yield (3%) scenario[20]

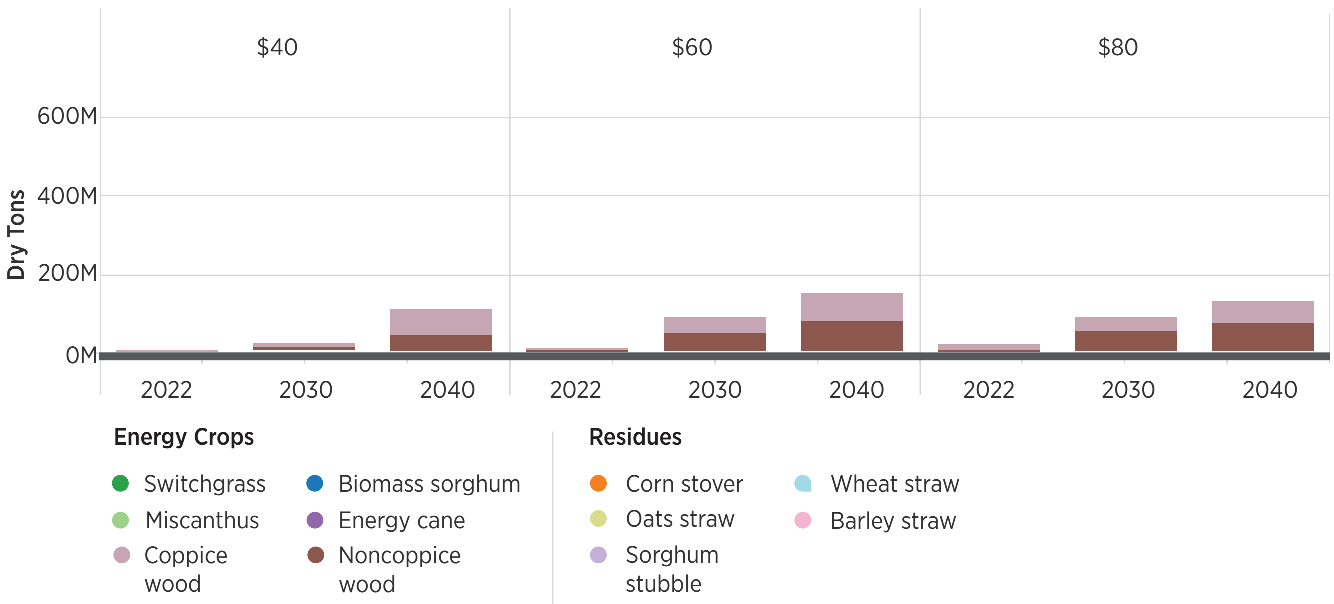



[20] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

**Figure 4.22** | Production from woody energy crops at ≤$60 offered farmgate price under a high-yield (3%) scenario[21]




[21] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

**Table 4.5** | Key Variables and Assumptions

| Assumptions | Pessimistic | Reference case | Optimistic |
|---|---|---|---|
| **Price scenario (offered farmgate price)** | $55 | $60 | $65 |
| **Yield scenario (ton acre[a] annual improvement)** | Base-case: 0%<br>High-yield: 2% | Base-case: 1%<br>High-yield: 3% | Base-case: 2%<br>High-yield: 4% |
| **Tillage flexibility (permitted tillage acreage changes by crop)** | Base-case: 0<br>High-yield: 2 | Base-case: 1<br>High-yield: 3 | Base-case: 2<br>High-yield: N/A |
| **Pastureland intensification (MiG land required to replace 1 acre of converted pasture land)** | 2:1 (i.e., 33% pasture available to convert) | 1.5:1 (i.e., 40% pasture available to convert) | 1:1 (i.e., 50% pasture available to convert) |
| **Operational efficiency (annual improvement in residue collection efficiency)** | 50% efficiency in initial year, increasing to 80% efficiency in final year | 50% efficiency in initial year, increasing to 90% efficiency in final year | 50% efficiency in initial year, increasing to 100% efficiency in final year |
| **Varying input costs (establishment, maintenance, and harvest) for all energy crops** | +10% | No change | -10% |
| **Land rental rates (per acre cash rental rates[a] included in crop production costs)** | Added | Not added | N/A |

[a]For more detail, see section 4.2.3 and appendix C.1.

# 4.8 Sensitivity Analysis of Key Assumptions

A sensitivity analysis was performed to evaluate the sensitivity of the feedstock supply in 2022, 2030, and 2040, at a simulated offered farmgate price of ≤$60, to the key variables outlined in table 4.5.

## 4.8.1 Results of Sensitivity Analysis

Figures 4.23, 4.24, 4.25, 4.26, 4.27, and 4.28 illustrate the sensitivity of feedstock supply to key variables in 2022, 2030, and 2040.

## 4.8.2 Offered Farmgate Price

As expected, the offered farmgate price is found to have the largest effect on total available biomass resources from agricultural lands in the initial years of the simulation (e.g., see year 2022 results in figs. 4.23 and 4.26). In these formative years and at the low prices, such as ≤$60 simulated here, supply is very sensitive to price changes. For example, a $5 drop in offered prices leads to a 38 million ton reduction in total supply in 2022 under a base-case (1%) scenario and a 60 million ton reduction under a high-yield (3%) scenario. Likewise, increasing the offered price by $5 yields 28 million tons more total supply in 2022 under the high-yield scenario and 32 million tons more under the base-case scenario.

**Figure 4.23** | Analysis of sensitivity of total supply in 2022 to key variables under a base-case (1%) ≤$60 offered farmgate price scenario

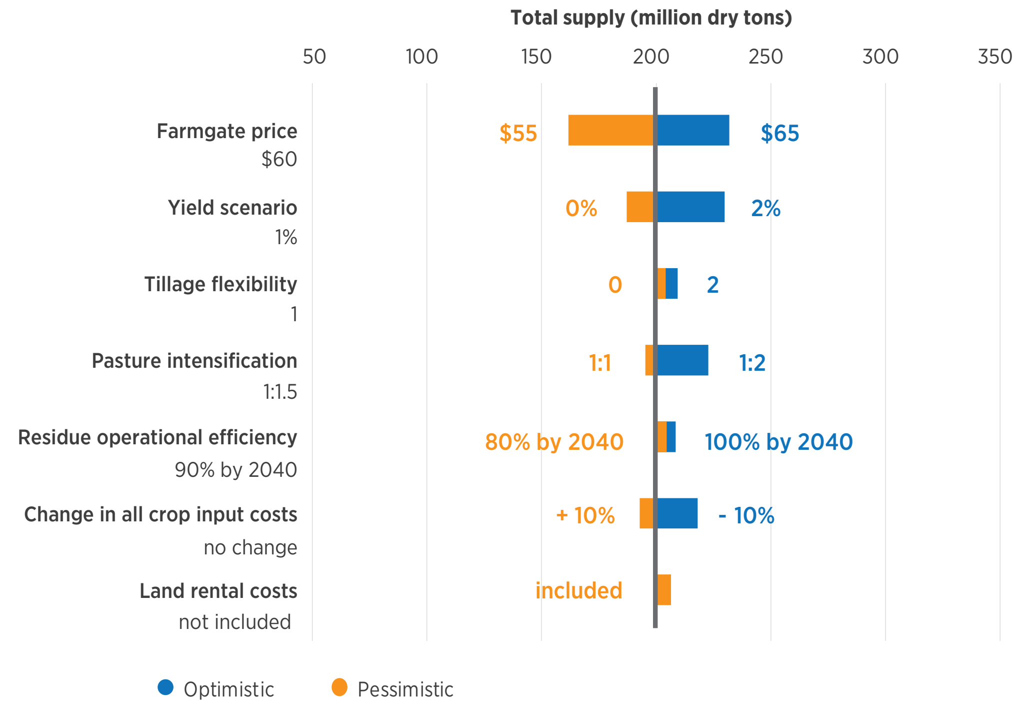



**Figure 4.24** | Analysis of sensitivity of total supply in 2030 to key variables under a base-case (1%) ≤$60 offered farmgate price scenario

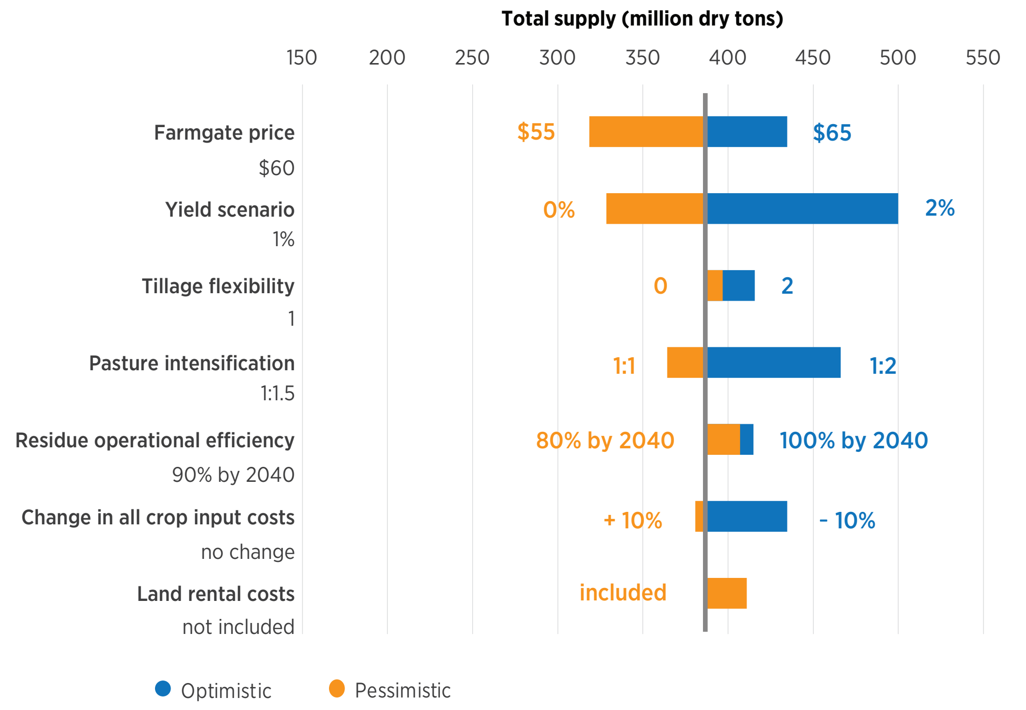


**Figure 4.25** | Analysis of sensitivity of total supply in 2040 to key variables under a base-case (1%) ≤$60 offered farmgate price scenario

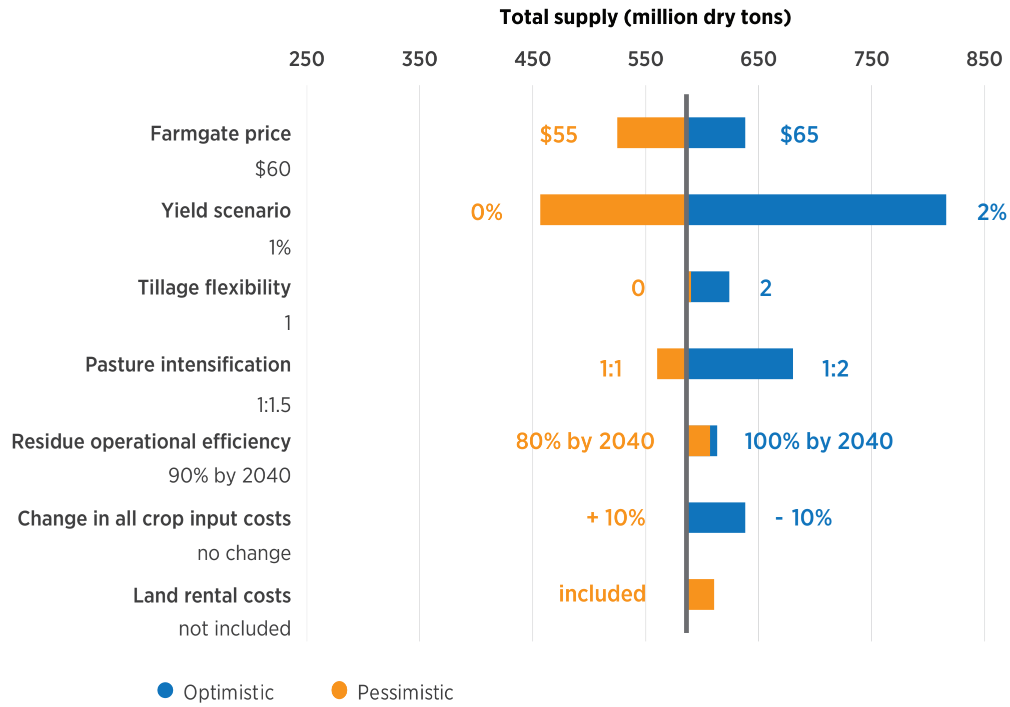



**Figure 4.26** | Analysis of sensitivity of total supply in 2022 to key variables under a high-yield (3%) ≤$60 offered farmgate price scenario

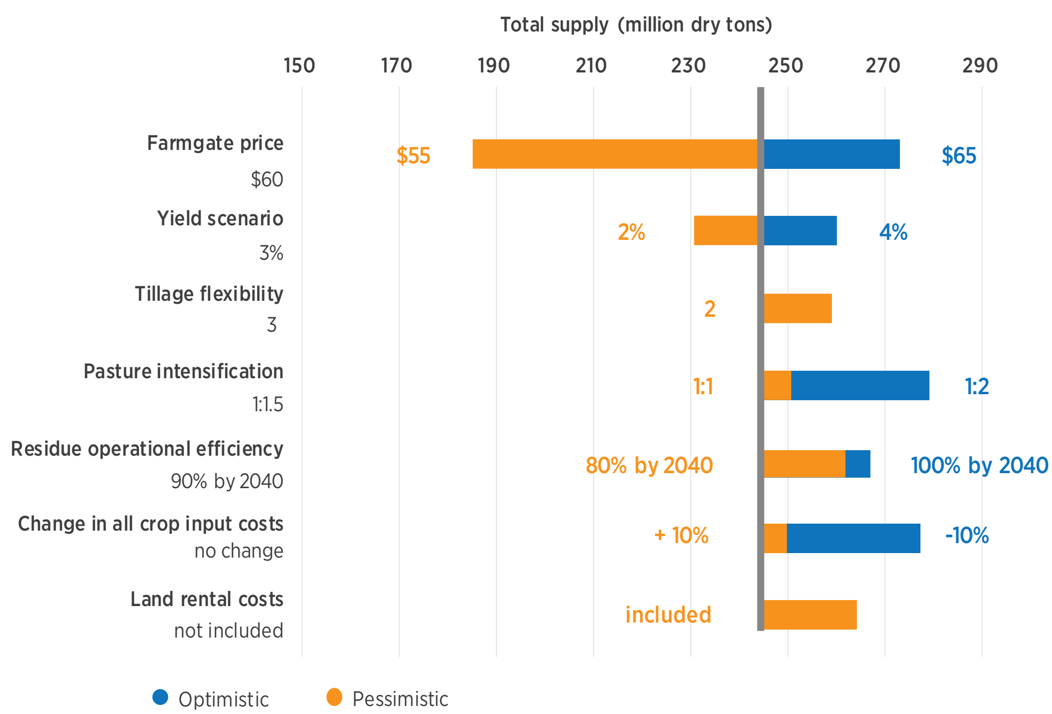


**Figure 4.27** | Analysis of sensitivity of total supply in 2030 to key variables under a high-yield (3%) ≤$60 offered farmgate price scenario

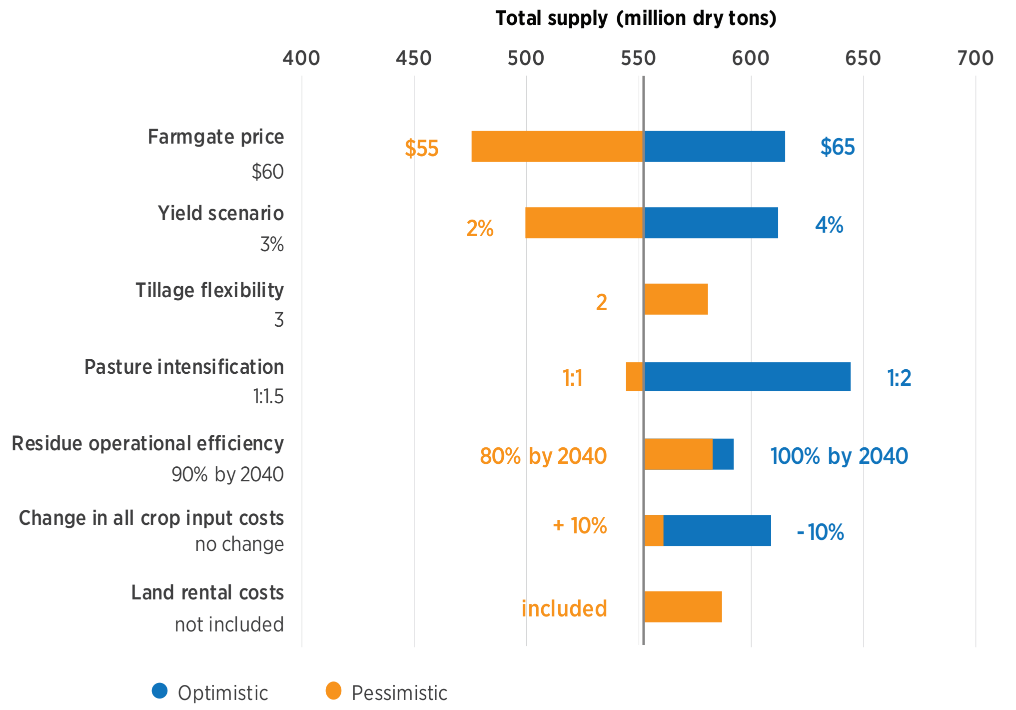
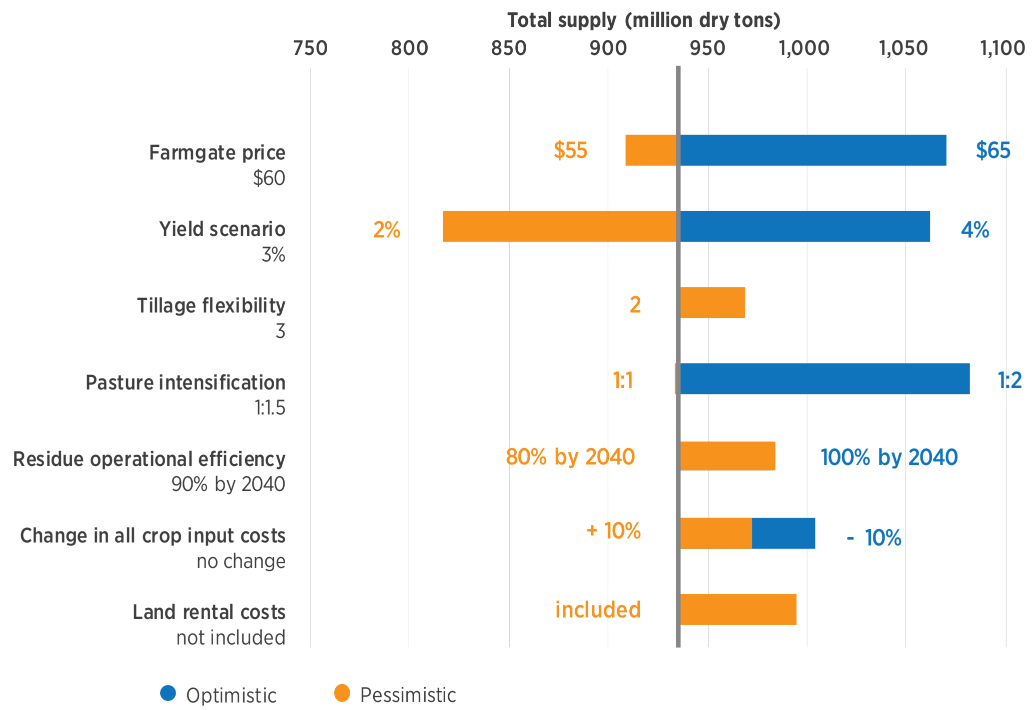



**Figure 4.28** | Analysis of sensitivity of total supply in 2040 to key variables under a high-yield (3%) ≤$60 offered farmgate price scenario



At these simulated prices, a decrease in the offered price has a larger effect on total supply under both scenarios in 2022 and 2030, and a larger effect in 2040 under the base-case scenario.

Under both scenarios and in all years, the reduction comes primarily from herbaceous energy crops, which are very sensitive to price changes at these lower price levels because of conversion of marginally profitable land[22] to higher-cost miscanthus. For example, miscanthus loses 32 million tons for the base-case and 50 million tons for the high-yield case under the pessimistic scenario (≤$55) compared with the reference case (≤$60) in 2030. For comparison, miscanthus gains 80 million tons in 2030 under the high-yield optimistic scenario compared with the reference case. Under this scenario, switchgrass is the second most responsive feedstock to the price changes, gaining between 8 and 18 million tons in each year highlighted in figures 4.26, 4.27, and 4.28. Residues—primarily stover, because it has a higher market share than wheat and other minor residues—also respond to the offered prices under the base-case scenario, with -6.5 to + 3.5 million tons in 2022, -6.3 to +4.7 in 2030, and -4.6 to +4.1 in 2040 compared with the reference case. In the high-yield scenario, residues are also heavily affected by price fluctuation, with a loss occurring under both the pessimistic and optimistic scenarios (e.g., -17 to -32 million tons in 2030 compared with the reference case). These reductions in the optimistic scenario are due to substitutions by energy crops (e.g., in 2022,[23] planted acres in corn and wheat are reduced by 4 million acres as miscanthus expands by 4.57 million acres), consistent with scenarios presented in text box 4.5.

### 4.8.3 Yield Scenario

Varying the yield rate[24] in this sensitivity analysis is also found to have a large effect on total available biomass resources from agricultural lands in 2030 and 2040. The initial year of 2022 did not show as much variability because energy crops are permitted to enter into production only beginning in 2019. In 2040, the range of simulated yield increases introduces a variability from -95 to +94 million tons around the reference case values for herbaceous crops under the high-yield scenarios and from -108 to +159 million tons for the base-case scenario.[25] These increases are attributable to a combination of factors, including greater land availability because less acreage is required to grow the same total biomass, as well as higher yields of dedicated energy crops that allow marginally productive crops to be economically viable. Likewise, under lower-yield scenarios, marginally productive crops are restricted by the economic constraints of the model (as discussed in the farmgate price sensitivity results). For example, the yield reduction between the high-yield (3%) reference case and the pessimistic scenario (2%), a 1% annual change, causes a significant decline in herbaceous crops (primarily miscanthus at a loss of 89 million tons) and woody energy crops (coppice crops primarily, which incur losses of 17 million tons) in

[22] Economic constraints imposed by the model do not allow planting without profitability. Lower-yielding acres under higher-cost crops such as miscanthus are therefore very sensitive to offered prices and yield scenarios, which can push them above or below this constraint.

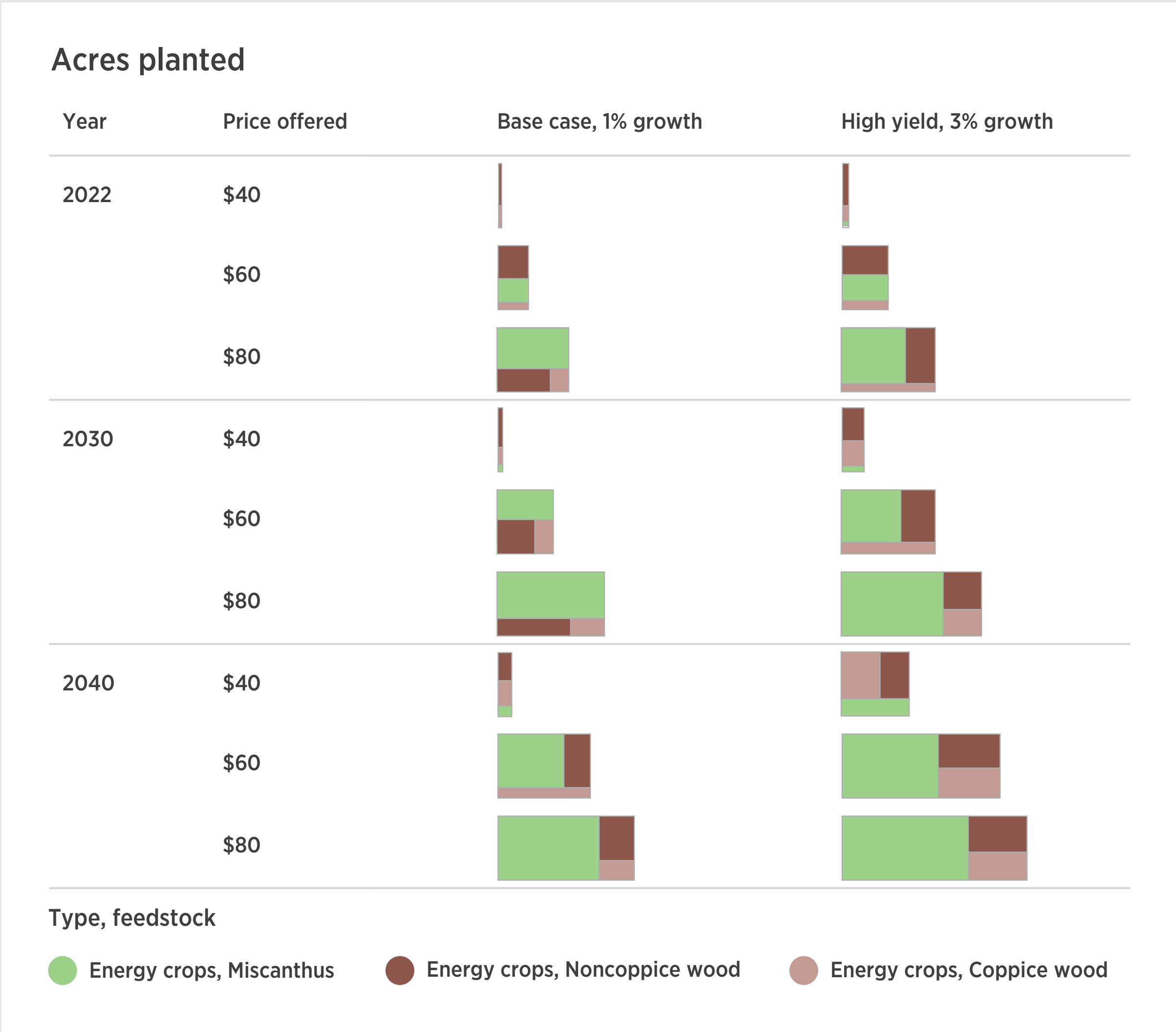
[23] Results by year such as this serve only as a snapshot and do not take into account switching between conventional crops that may occur in subsequent years.

[24] This compounding yield improvement is applied beginning in 2016 and affects energy crops that enter in 2019 by giving them an initial yield boost equal to four times the yield improvement percentage applicable under that scenario (e.g., 4 × 3% = 12% yield improvement in 2019).

[25] The base-case (1%) reference scenario is compared with an optimistic 2% high-yield scenario with a tillage flexibility of 1 for the base-case and 3 for the high-yield. See tillage flexibility discussion in section 4.8.4.

## Text Box 4.5 | Independent Model Simulations and Substitutions Among Crops As Prices Increase

Under the high-yield (3%) scenario, the transition from a $60 offered farmgate price to $80 intensifies the surge in higher-price but higher-yielding herbaceous crops such as miscanthus over woody energy crops; the latter actually decrease when production in 2040 is compared under the two simulations. This decrease in production of woody energy crops is shown as a bend in the supply curve under figure 4.14. Displacement of some woody energy crops can be seen in the following visualization of planted acres for the base-case (1%) and high-yield (3%) scenarios.




Tree map showing planted acres for miscanthus, coppice, and non-coppice woody energy crops under the base-case (1%) and high-yield (3%) scenarios across all highlight prices and years.

2040. Likewise, the gains that occur between the optimistic scenario (a 2% high-yield scenario) and the base-case (1%) scenario, a 1% annual change as well, are the result of herbaceous crops (again primarily miscanthus at a gain of 121 million tons) and woody energy crops (again coppice crops with a gain of 24 million tons) becoming more profitable and therefore entering the market to add more total supply.

### 4.8.4 Tillage Flexibility

The tillage flexibility constraint sets the maximum and minimum of tillage acreage changes for conventional crops. By varying the index levels in this simulation, we are simply controlling the level of intensity for switching between land management types: a higher value (e.g., 3) increases the percentage allowed to transition more rapidly than a lower value (e.g., 1) (see appendix C.1, “Agricultural Residue Modeling Assumptions,” for more details). Modifying the constraint to 2 under the pessimistic high-yield (3%) scenario actually allows for a gain in total supply at a given price, as seen in each tornado chart (figs. 4.26, 4.27, and 4.28). The sensitivity analysis demonstrates the interplay between conventional crop acreage and energy crops; as conventional crops are restricted, energy crops can sometimes respond favorably and actually increase supply by taking over some land in conventional crops. For example, when comparing a high-yield (3%) reference case with a tillage flexibility of 3 and a pessimistic scenario with a tillage flexibility of 2, the total change in agricultural lands for corn and wheat is a loss of 1 million acres in 2030. However, in that same year, herbaceous and woody energy crops gain 1 million acres each. Under the base-case reference scenario with a tillage flexibility index of 1, we simulate a $\pm$1 index: tillage flexibility at 0 in a pessimistic scenario and at 2 in an optimistic scenario. Similar to the high-yield case, the response by herbaceous crops in 2030 (+7.8 million tons) and by woody crops in 2040 (+6.8 million tons) actually causes an increase in total production under the pessimistic tillage flexibility assumption in 2030 and 2040, with a minimal change in production for residues (-5 to +1.8 million tons). In 2030 and 2040, the change between the optimistic (tillage flexibility index of 2) and the base-case reference scenario, however, is more dramatic: a +17.7 to +18.3 million ton change in residues, +10.8 to +15.7 dry ton change in herbaceous energy crops, and -0.2 to +4.7 change in woody energy crops. The total gains in production under both the pessimistic and optimistic base-case (1%) scenarios are shown in figures 4.23, 4.24, and 4.25.

### 4.8.5 Pastureland Intensification

The third and most important assumption analyzed in this sensitivity analysis is a constraint on the amount of land in MiG that is assumed to be capable of replacing the forage production displaced by one acre of pasture converted to energy crops (see table 4.3, section 4.2.2, and appendix C.2). Similar to the yield scenario analysis, the initial year 2022 does not show as large a variance around the reference scenario as do later years because of the restriction on energy crops that does not release until 2019 and their interaction with pasture land. Results for years 2030 and 2040 show a -22 million ton to +94 million ton variance around the reference case value for the base-case scenario and a -1.4 to +147 million ton variance under the high-yield scenario (3%). These results demonstrate the importance of available pasture acreage to the economic viability of these energy crops. For example, under an optimistic simulation, miscanthus gains 81 million tons of production for a high-yield (3%) scenario and 20 million tons under an optimistic base-case (1%) simulation compared with their respective reference cases in 2040. Switchgrass is also highly responsive, with a gain of 37 million tons in 2040 under an optimistic base-case (1%) scenario. Non-coppice woody crops also respond to the optimistic simulation under the base-case (1%) scenario in 2040 with a gain of 14.6 million tons of production.

## 4.8.6 Operational Efficiency

As discussed in appendix C, the modeling conducted under this report limits the operationally available residues that can be collected (operational efficiency constraint). Harvestable yield is the lesser of sustainable removable yield and operational efficiency as described in appendix C and figure C.3. In this sensitivity analysis, this constraint is varied to increase linearly to 80% of available residues in 2040 under a low-quantity scenario (pessimistic) and to 100% of available residues in 2040 under a high-quantity scenario (optimistic). This constraint is found to have an effect of between +4.9 and +28.3 million tons compared with the reference scenario in the base-case scenario. Under the high-yield scenario, a change of between +17.2 and +49 million tons occurs under the pessimistic and optimistic scenarios compared with the reference case. There is a loss in residues (e.g., 39 million tons in 2030 under the high-yield scenario) as expected with a pessimistic operational efficiency constraint, but this is offset by gains in other crops (e.g., 97 million tons of woody energy crops in 2030 under the high-yield scenario). This added total production in a pessimistic scenario is depicted in all of the sensitivity analysis figures above.

## 4.8.7 Varying Energy Crop Input Costs by ±10%

Varying the input costs for all energy crops is shown to have an effect on total supply of between -6 and +70 million tons under the high-yield (3%) scenario and -7 and +52 million tons under the base-case scenario. Miscanthus shows the most sensitivity to optimistic input costs of any crop assessed in this sensitivity analysis in 2022 and 2030 under the high-yield (3%) scenario. For example, reducing the input costs for all crops by 10% allows miscanthus to produce an extra 147 million tons in 2030. The second most responsive crop to optimistic cost changes is switchgrass (e.g., 112 million tons of extra production in 2030 under the high-yield scenario). These two crops contribute to a total gain of 279 million tons of herbaceous energy crops in 2030 under this optimistic high-yield (3%) scenario. Under the base-case (1%) scenario, the effects are more pronounced for non-coppice woody crops (e.g., a loss of 12.3 million tons under a pessimistic scenario in 2030) and for energy sorghum (e.g., a gain of 6.9 million tons in 2030 under an optimistic scenario), although miscanthus remains highly responsive (e.g., a gain of 10 million tons in 2030 under an optimistic scenario). These variations are consistent with the yield scenario and farmgate price sensitivity analyses above and reinforce the importance of the economic constraints applied in POLYSYS to total supply.

## 4.8.8 Land Rent

A standard approach in agricultural analysis is treatment of fixed and variable costs differently. Fixed costs relate to those invariant to production (also known as sunk costs) and assumed constant across cropping choices. Examples of fixed costs include overhead, taxes, insurance, and rent. Variable costs include those related to specific production practices based upon crop choice, such as seeding rates, diesel use, and labor that vary by management recommendation. The rental rate of cropland is included in these sensitivity scenarios based upon feedback from feedstock supply stakeholders and to provide a scenario that matches the crop costs used for enterprise costing purposes.

In all cases, the inclusion of cropland rent increases the amount of biomass produced in out-years relative to the references case. While the assumption raises crop costs across the board, additional production costs indirectly benefit high-cost/high-yield crops for two reasons: First, because of increased cost of production, low-cost/low-yield crops that would have been first to enter the landscape are now disadvantaged and become unprofitable. Secondly, high-cost/high-yield crops (such as miscanthus) are given preference over all other crops because of positive

**Table 4.6** | Summary of Base-Case and High-Yield Scenarios, Energy Crops and Agricultural Residues

| Feedstock | ≤$40 | | | | ≤$60 | | | | ≤$80 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2022 | 2030 | 2040 | 2017 | 2022 | 2030 | 2040 | 2017 | 2022 | 2030 | 2040 |
| **Base-case scenario (1% annual growth)** | | | | | **Million tons** | | | | | | | |
| **Crop residues** | 30 | 37 | 46 | 58 | 104 | 123 | 149 | 176 | 117 | 137 | 163 | 188 |
| **Herbaceous** | N/A | 0 | 6 | 34 | N/A | 74 | 190 | 340 | N/A | 177 | 321 | 491 |
| **Woody crops** | N/A | 1 | 6 | 16 | N/A | 3 | 50 | 71 | N/A | 10 | 53 | 56 |
| **Total** | **30** | **38** | **59** | **108** | **104** | **201** | **388** | **588** | **117** | **323** | **537** | **734** |
| **High-yield (3% annual growth)** | | | | | | | | | | | | |
| **Crop residues** | 30 | 42 | 63 | 83 | 105 | 135 | 174 | 200 | 121 | 148 | 184 | 214 |
| **Herbaceous** | N/A | 1 | 18 | 170 | N/A | 104 | 298 | 594 | N/A | 230 | 446 | 729 |
| **Woody crops** | N/A | 1 | 22 | 106 | N/A | 7 | 83 | 142 | N/A | 16 | 85 | 125 |
| **Total** | **30** | **44** | **103** | **358** | **105** | **245** | **554** | **936** | **121** | **394** | **716** | **1068** |

**Note:** Totals may differ because of rounding.

net returns when land rent is added. In all cases, the increase of biomass is due to a larger share of miscanthus on the landscape than the reference case.

# 4.9 Summary and Future Research

## 4.9.1 Summary

The residues and herbaceous and woody energy crops reported are found to be economically available under imposed constraints. At a farmgate price of ≤$40 – ≤$80, the supply under a specified-price simulation has a range of between 30 million tons and 734 million tons under a baseline scenario and up to 1.068 billion tons under a high-yield scenario of 3% (see tables 4.6, 4.7, and 4.8). Supply potentials vary by year, with a greater supply potential occurring in later years of the simulations as energy crops are established and return higher yields.

Similarly, the production-target simulations of between 250 and 500 million tons yield a range of farmgate prices between $60 and $114, with some peak prices of $150 (maximum allowed under simulation) occurring in years when demand cannot be met because of crop rotations (see appendix C.4, "Energy Crop Feedstock-Specific Assumptions"). Timing for these specified supplies is key: allowing multiple years for a ramp-up of energy crops (establishment and improved yields) keeps prices low in these simulations. A range of available feedstocks are able to meet the specified demand or specified price. These feedstocks vary over time as yield and land uses change. For example, herbaceous energy crops

**Table 4.7** | Summary of Base-Case and High-Yield Scenarios, Agricultural Residues

| Feedstock | ≤$40 | | | | ≤$60 | | | | ≤$80 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2022 | 2030 | 2040 | 2017 | 2022 | 2030 | 2040 | 2017 | 2022 | 2030 | 2040 |
| **Base-case scenario (1% annual growth)** | | | | | | **Million tons** | | | | | | |
| **Corn stover** | 24 | 30 | 36 | 44 | 89 | 106 | 129 | 154 | 102 | 119 | 142 | 166 |
| **Wheat straw** | 6 | 8 | 9 | 12 | 13 | 16 | 19 | 21 | 15 | 17 | 19 | 20 |
| **Sorghum residue** | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Oat residue** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Barley residue** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| **Total** | **30** | **37** | **46** | **58** | **104** | **123** | **149** | **176** | **117** | **137** | **163** | **188** |
| **High-yield (3% annual growth)** | | | | | | | | | | | | |
| **Corn stover** | 23 | 30 | 40 | 52 | 87 | 111 | 141 | 161 | 100 | 122 | 150 | 176 |
| **Wheat straw** | 7 | 12 | 21 | 29 | 17 | 23 | 31 | 37 | 19 | 25 | 32 | 36 |
| **Sorghum residue** | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| **Oat residue** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Barley residue** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| **Total** | **30** | **42** | **63** | **83** | **105** | **135** | **174** | **200** | **121** | **148** | **184** | **214** |

**Note:** Totals may differ because of rounding.

enter into production at lower prices, and increase over time and as prices increase beyond an offered price of $60. Coppice woody energy crops begin to come into production at lower prices as well, with more modest gains as prices increase. Crop residues remain an important feedstock under both the base-case and high-yield scenarios.

## 4.9.2 Future Research

With regard to biomass resource assessment, future research is needed in a variety of areas:

- Periodic updates are needed to keep pace with advances in agricultural innovation (e.g., crop development and management strategies) and constantly changing agricultural markets (i.e., commodity crop demand changes due to macroeconomic variables).
- The international market for bioenergy and bioproducts affects the domestic biofuel industry through competitive forces. Future research should account for demand fluctuations arising from policy shifts domestically and abroad, as

**Table 4.8** | Summary of Base-Case and High-Yield Scenarios, Energy Crops

| Feedstock | ≤$40 | | | | ≤$60 | | | | ≤$80 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2022 | 2030 | 2040 | 2017 | 2022 | 2030 | 2040 | 2017 | 2022 | 2030 | 2040 |
| **Base-case scenario (1% annual growth)** | | | | | **Million tons** | | | | | | | |
| **Switchgrass** | N/A | 0 | 4 | 27 | N/A | 46 | 107 | 161 | N/A | 71 | 100 | 137 |
| **Miscanthus** | N/A | 0 | 2 | 7 | N/A | 28 | 79 | 160 | N/A | 104 | 203 | 293 |
| **Biomass sorghum** | N/A | 0 | 0 | 1 | N/A | 0 | 4 | 19 | N/A | 1 | 18 | 58 |
| **Energy cane** | N/A | 0 | 0 | 0 | N/A | 0 | 0 | 0 | N/A | 0 | 1 | 2 |
| **Non-coppice** | N/A | 0 | 4 | 9 | N/A | 0 | 33 | 45 | N/A | 0 | 34 | 41 |
| **Coppice** | N/A | 1 | 2 | 7 | N/A | 3 | 17 | 26 | N/A | 10 | 19 | 15 |
| **Total** | **N/A** | **1** | **12** | **51** | **N/A** | **78** | **239** | **411** | **N/A** | **186** | **374** | **547** |
| **High-yield (3% annual growth)** | | | | | | | | | | | | |
| **Switchgrass** | N/A | 1 | 13 | 101 | N/A | 58 | 133 | 189 | N/A | 81 | 115 | 163 |
| **Miscanthus** | N/A | 1 | 5 | 65 | N/A | 45 | 157 | 370 | N/A | 146 | 308 | 483 |
| **Biomass sorghum** | N/A | 0 | 0 | 4 | N/A | 1 | 7 | 31 | N/A | 2 | 21 | 71 |
| **Energy cane** | N/A | 0 | 0 | 1 | N/A | 0 | 1 | 5 | N/A | 1 | 3 | 12 |
| **Non-coppice** | N/A | 0 | 10 | 41 | N/A | 0 | 44 | 75 | N/A | 0 | 48 | 70 |
| **Coppice** | N/A | 1 | 12 | 65 | N/A | 7 | 38 | 67 | N/A | 16 | 37 | 55 |
| **Total** | **N/A** | **2** | **40** | **276** | **N/A** | **110** | **380** | **736** | **N/A** | **246** | **531** | **853** |

**Note:** Totals may differ because of rounding.

well as price effects arising from changes in imports and exports from international sources.

- Following the introduction of specified-demand scenarios discussed in this analysis, attention should shift from potential biomass availability under hypothetical market simulations to expected biomass availability under expected market conditions. Finally, attention should similarly shift from potential farmgate supplies to potential delivered supplies, as discussed in chapter 6 of this report.

With regard to strategies to improve the economic availability of sustainable biomass, the sensitivity analyses in this chapter indicate key areas of opportunity, primarily market development (i.e., farmgate price) and energy crop yield improvement.

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