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The updated billion-ton resource assessment

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ABSTRACT

This paper summarizes the results of an update to a resource assessment, published in 2005, commonly referred to as the Billion-Ton Study (BTS). The updated results are consistent with the 2005 BTS in terms of overall magnitude. The 2005 BTS projected between 860 and 1240 Tg of biomass available in the 2050 timeframe, while the Billion-Ton Update (BT2), for a price of 66 $ Mg^{-1}, projected between 994 and 1483 Tg in 2030. For the BT2, forest residue biomass potential was determined to be less owing to tighter restrictions on forest residue supply including restrictions due to limited projected increase in traditional harvest for pulpwood and sawlogs. Crop residue potential was also determined to be less because of the consideration of soil carbon and not allowing residue removal from conventionally tilled corn acres. Energy crop potential was estimated to be much greater largely because of land availability and modeling of competition among various competing uses of the land. Generally, the scenario assumptions in the updated assessment are much more plausible to show a "billion-ton" resource, which would be sufficient to displace 30% or more of the country's present petroleum consumption and provide more than enough biomass to meet the 2022 requirements of the Renewable Fuel Standard.

1. Introduction

The 2005 Billion-Ton Study (2005 BTS), was an estimate of "potential" biomass within the contiguous United States based on numerous assumptions about current and future inventory, production capacity, and technology [1]. The main conclusion of the study was that U.S. agriculture and forest resources have the capability to sustainably produce one billion dry tons of biomass annually (910 Tg) – enough to

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displace approximately 30% of the country's 2003 petroleum consumption of 1.2 km^3 y^{-1}. In this paper, the results of an update to the 2005 BTS in 2011, referred to hereafter as the Billion-Ton Update (BT2), are discussed [2]. The BT2 asked the question: Given better modeling of environmental constraints (e.g., soil erosion, soil carbon) can a billion dry tons (910 Tg) of biomass be produced in the United States and how much at varying prices? The BT2 improved upon the BTS by providing:

- Estimates of prices and available quantities (i.e., supply curves) for primary feedstocks;
- A more rigorous treatment and modeling of resource sustainability; and
- A county-by-county inventory of primary feedstocks.

Further, the update emphasizes the 2012 through 2030 time period coincident with implementation of Energy Independence and Security Act of 2007 (EISA) [3] and U.S. Department of Energy (DOE) initiatives rather than on updating the mid-century projection results in the original study. The BTS included biomass that was currently being used for energy production because it counted toward the billion-ton goal. In the update, currently consumed biomass resources, such as wood residues and pulping liquors used in the production of forest products, are treated separately to avoid confusion with the unused potential. These and other major differences between the 2005 BTS and the BT2 are summarized in Table 1. The update focuses on the larger primary biomass resources available for additional energy production at different prices and locations across the continental United States. Many of the more significant unused secondary residues and tertiary wastes as well as the currently used resources are evaluated and included in the study. However, in this paper these feedstocks are only discussed briefly. Further, this paper presents only the national results. County-level supply assessment results, visualization tools, model to optimize biomass supply chains, as well as other related information and data, are available on the Bioenergy Knowledge Discovery Framework web site [4]. Note that while the paper title "The Updated Billion-Ton Resource Assessment," the title refers to a billion short tons or 910 Tg of biomass.

2. Estimating the forest and agriculture resource potential

The BT2 focuses on estimating county-level feedstock supply curves for all major primary cropland and forest resources. These supply curves include costs to acquire or produce the resource and costs for collecting or harvesting the resource and moving it to the field edge or forest roadside ready for transport. The estimates in the BT2 are minimum farmgate or forest roadside prices and do not represent the total cost or the actual available tonnage to a biorefinery or conversion facility. There will be additional costs to preprocess, handle, store, and transport the biomass to a facility for conversion into fuel or power. The estimates include losses to the farmgate or roadside (assumed to be 10%), but do not include losses due to continued handling, additional processing, storage, and material degradation. More than one Mg from the estimates will be required to have one Mg ready to process at a biorefinery, with the amount depending on many variables in the supply chain and final conversion technology. In addition, the biomass will be in varied forms and may not be directly comparable at a biorefinery in either cost or conversion efficiency.

The primary forest resources include logging residues and fuel treatment thinnings, which are assumed collected as part of an integrated harvest operation and are summarized in the assessment as composite operations; other removal residues from land clearing and cultural operations (e.g., precommercial thinnings); thinnings from other forestland

Table 1 – Major differences between the 2005 BTS and the 2011 BT2.

- Separation of "used" and "potential" feedstocks. In the 2005 BTS, feedstocks currently used for energy production or could be shifted from another market to energy production were counted in the biomass potential. In the update, the currently used biomass is clearly delineated from the potential.
- The BT2 covers the 2012 through 2030 period instead of the 2025 to 2050 focus of the 2005 BTS.
- County-level agricultural environmental sustainability requirements include:
  - Cost assumptions include compliance with statutes, regulations, and BMPs.
  - Assumed the use of acceptable management practices.
  - Explicitly modeled crop residue retention, tillage, and crop rotation to provide erosion protection and maintenance of soil organic carbon.
  - Modeled nutrient replacement, crop rotation, and reduced tillage practices to ensure long-term site productivity.
- FIA plot-level forestry environmental sustainability requirements include:
  - Cost assumptions include compliance with statutes, regulations, and BMPs.
  - Assumed the use of acceptable management practices.
  - Little to no road building.
  - Operations are restricted if the slope is above 80%.
  - Used gradient retention of biomass based on ground slope.
- Energy crop sustainability requirements include:
  - Cost assumptions include compliance with statutes, regulations, and BMPs.
  - Assumed the use of acceptable management practices.
  - No conversion of forest lands.
- Energy crop potential is modeled at a county-level using an agricultural policy simulation model (POLYSYS).
- High-yield scenario for agricultural resources assumes changes in corn yield, changes in tillage, and several scenario growth rates for energy crop yields.
- Estimates of energy crop potential in the 2005 BTS and 2011 BT2 assume that demands for food, feed, and exports continue to be met.

(i.e., non-commercial timberland, forestland incapable of producing 0.57 m^3 of industrial wood under natural conditions); and some conventionally sourced pulpwood. Potentially available agricultural residues include corn stover, small grain residue (wheat, barley, and oats), and grain sorghum stubble. Energy crops considered in the update include perennial herbaceous crops, such as switchgrass; short rotation woody crops (SRWC), such as hybrid poplar, willow, and southern pine; and energy sorghum as a representative annual herbaceous crop. Secondary process residues and tertiary wastes are included in summaries, but only briefly discussed in this paper.

Supply curves for these primary resources are estimated under two scenarios: baseline and high-yield. For agricultural resources, the baseline utilizes the 2009 USDA 10-year projections for major food and forage crops [5]. The 10-year projections are then extended to 2030 using population trends and a linear extrapolation of the last three years of the forecast. The baseline represents current trends in agriculture in terms of crop yields. In these projections, average corn yield increases annually at a rate slightly more than 1%. The baseline scenario also assumes a continuation in the trend toward reduced tillage and no-till away from conventional tillage. Energy crop yields are assumed to increase at a rate of 1% per year, reflecting learning or experience gained in planting and growing energy crops and limited gains that can be obtained through breeding and selection of improved varieties. For forest resources, the 2007 Forestry Resource Planning Act (RPA)/Timber Product Output (TPO) with a 2012 to 2030 timeframe is utilized [6,7]. Baseline yields for energy crops are within observed test plot yields. No low-yield scenario was run.

To help inform assumptions about crop yields in the high-yield scenario, workshops were held for corn, herbaceous energy crops, and woody crops and in these workshop experts for these crops made estimates projecting future yields [8]. In the high-yield scenario, higher corn yields and a much larger fraction of crop acres in reduced and no-till are assumed. These are assumptions and show what the potential contribution of corn could be with changes in tillage practices and a higher rate of increase in corn yields. The projected annual increase in corn yield is about double that in the baseline scenario or nearly 2% over the simulation period. Other conventional crops (wheat, soybeans, sorghum, oats, and barley) are modeled with the same yield as in the baseline. Energy crop yield increases are modeled at annual rates of 2%, 3%, and 4% in plantings in subsequent years. The annual yield increase reflects not only learning or experience gained in planting and growing energy crops, but also more aggressive implementation of breeding and selection programs. Forestry in the high-yield scenario is the same as the baseline as these residues are contingent on the demand for pulpwood and sawlogs based on the RPA projections of timber harvests.

The remainder of this section summarizes the approaches used to estimate supply curves for forest residues, crop residues, and energy crops. Included in this discussion is environmental sustainability and associated restrictions imposed on forest and agricultural residue removal and energy crop production.

2.1. *Forest residues*

In the BT2, primary forest residue biomass has three main sources. The largest source of residue biomass is a composite of two estimates, consisting of 1) the removal of a portion of logging residue that is generated during the harvesting of timberlands for sawlogs and pulpwood and 2) the prospective removal of excess biomass from fuel treatment and thinning operations [9]. The woody biomass could be removed in either of these two ways, and to avoid double counting, estimates are made for each type of harvest separately and then a 50:50 mix of the two are assumed to be how this common resource is harvested. These thinning operations are designed to reduce risks and losses from catastrophic fires and improve forest health by removing merchantable whole trees and excess small trees to the roadside. The tops and branches of the merchantable trees, cull trees, and excess small trees would be used for bioenergy applications. The merchantable tree components would be used for pulpwood and sawlogs depending on size and species. Both of these residue estimates were considered separately in the 2005 BTS, but in this update estimates are made assuming that there will be a transition from leaving logging residues behind to removing them as part of an integrated harvesting operation that meets market demands for sawlogs and pulpwood as well as provide biomass for energy. Merchantable harvest was limited to the amount projected in the base case for the Forest Service 2005 RPA Timber Assessment update [6] and thus biomass from integrated harvesting operations was determined from projections in the 2005 RPA update. Because of the most recent economic recession harvest declined, so estimates made represent biomass supplied from integrated operations when harvest returns to prerecession levels. Projections for housing starts for 2015 are approaching prerecession levels.

There are two other potential primary residue resources considered: (1) thinnings from other forestlands (i.e., non-commercial timberland) to remove excess biomass to reduce fire hazards and (2) other removals. Residue harvesting operations for (1) are similar to the timberland operations except that all of the removed trees would be used for bioenergy as other forestlands by definition do not produce merchantable trees suitable for sawlogs or pulpwood. Other removals (2), as identified by the Forest Service, includes wood from cut or killed growing stock, silvicultural operations such as pre-commercial thinnings, and the conversion of timberland to non-forest uses including croplands, roads, and urban development. The final primary resource considered in the update is conventionally sourced wood, which is defined as separate, additional operations to provide pulpwood-sized roundwood for bioenergy applications.

Estimates were primarily derived from or modeled using USDA Forest Service databases. Logging residue estimates and other removals are available from the Timber product output (TPO) database [7]. The TPO consists of a number of county-level data variables that provide timber product harvested, logging residues, other removal residues, and wood and bark residues generated by primary forest product processing mills. Data used to simulate fuel treatment operations were obtained from the Forest Inventory Analysis (FIA) plot data [10–12]. Future projections are based on the 2005 RPA assessment [6].

2.1.1. Composite operations — integration of logging and fuel treatment thinnings

It is assumed that logging residues that would be used for bioenergy are generated in whole-tree harvesting operations where trees are felled and then skidded or forwarded to a landing area where they are delimbed and topped. Whole-tree harvesting results in the accumulation of slash or residue at the forest landing or roadside where it can be chipped and loaded directly into trucks. Estimated logging residue supply curves are assumed to only have two cost components — stumpage (i.e., feedstock acquisition) and chipping. Costs for felling and skidding are assumed borne by the primary product either sawlogs or pulpwood. Further, the supply curve analysis assumes the logging residue is collected concurrently with sawlogs or pulpwood as opposed to leaving the residue on-site to dry and be removed in a subsequent and likely more costly operation.

For privately-owned timberland, stumpage is assumed to begin at 4.40 $ Mg^{-1} and increase to 90% of published pulpwood stumpage prices when 100% of the available logging residue is used. [Note that all units of biomass are on a dry basis (i.e., 0% moisture)] The low entry price is based on a token payment in the likelihood that the biomass is only removed to meet other landowner objectives, such as reducing site preparation costs or fire risks. The higher prices are the result of demand increasing or supply decreasing to the point that biomass is almost competitive with pulpwood. Stumpage is assumed to vary by region and species. In this update, stumpage ranges from 14.70 to 17.00 $ Mg^{-1} for hardwoods and 17.30 to 30.40 $ Mg^{-1} for softwoods. Chipping costs, the other component in the logging residue supply curve, are determined by the Fuel Reduction Cost Simulator (FRCS) model [13]. This model was modified and expanded for this update to cover the U.S. North and South, as well as the West [14]. Chipping costs average about $14 Mg^{-1} nationwide and are slightly higher in the West and slightly lower in the South due to differences in labor and fuel costs.

Leaving forest residues on harvest sites provides a number of environmental benefits. They contribute nutrients and organic matter to soils, regulate water flows and limit soil erosion, and create habitat and enhance biodiversity [15]. In the U.S., much effort has gone into training timber-harvesting operators and designing equipment to minimize ecological impacts [16]. Studies have shown how to minimize such impacts through use of buffer zones, leaving adequate biomass residue, and nutrient management programs. Usually, cautionary actions are taken to minimize soil disturbance, prevent soil or machine fluids from entering streams and other water bodies, avoid sites with steep slopes and high elevation, protect sensitive areas, and meet prescribed biodiversity and habitat requirements, like leaving foliage, roots, parts of tree crown mass, and downed/standing dead trees. The update assumes 30% of logging residue (i.e., leaves and needles, non-merchantable trees, standing and dying trees are left in the field, and parts of tops and branches at the forest landing) are left on site in the field to address these potential concerns. The 30% residue left in the is based on the literature and harvest guidelines (e.g., Maine, Missouri, Pennsylvania, Wisconsin — see p. 23 of [1]) that indicate that retaining 30% of the residues on slopes less than 30% is a reasonable and conservative estimate of material needed to be left to maintain productivity and for ecological purposes. Biomass taken to the landing is either made into logs or chipped and blown into a chip van. Very little of harvested wood that is processed is left at the landing.

The fuel treatment thinnings component of the composite operations was modeled using FIA plot data. The FIA plots were subjected to a set of screening criteria. First, FIA plots on administratively reserved forestlands were excluded. These are lands excluded from timber production by legislative statute and include wilderness and National Parks. Second, inventoried roadless areas were excluded. These are USDA Forest Service lands identified as possibly qualifying for wilderness or other conservation protections. Third, FIA plots considered too wet for treatment operations were excluded. Fourth, any FIA plots that required the building of roads more than a half mile to gain access to the timberland were excluded.

Decades of fire prevention and suppression efforts across the United States, especially in western areas, have led to overstocked stands and an accumulation of fuels that are increasing the risk of catastrophic fire. Estimates of biomass amounts were made by simulating an uneven-age treatment in overstocked stands in all fire regime classes. The treatments were assumed to occur on a 30-year cycle. Thinning is used to reduce density, open up the stands, and improve resiliency to fire and pests. Uneven-aged thinning removes trees across all age classes. This type of harvesting provides bioenergy feedstocks at a reduced cost because biomass is removed in combination with the removal of larger trees for pulpwood and sawlogs. Otherwise, harvest costs would be considerably more if fuel treatment operations were focused solely on smaller-sized trees. The uneven-aged thinning simulation was done on all FIA plots where the plot stand density index (SDI) was greater than 30% of a maximum SDI for that given forest type [17].

Uneven-aged thinnings are simulated, and estimates are made of the amounts of biomass, pulpwood, and sawlogs that are removed. Beginning with 2.5 cm diameter breast high (dbh) trees, a treatment successively removes fewer trees from each larger diameter class where the removals bring the SDI down to 30% of the identified maximum SDI value for that stand type. For the North and South, biomass removals include all wood from trees 2.5–12.7 cm dbh and tops and branches of trees greater than 12.7 cm dbh, except for wood left for retention purposes. For the West, biomass removals include all wood from harvested trees 1–17.8 cm dbh and tops and branches of trees greater than 17.8 cm dbh. It is assumed that all of the small-tree biomass can be extracted to roadside, but only 80% of the volume in tops and branches of larger trees will make it to roadside because of breakage.

Biomass retention for logging residues assumed 30% of the biomass remains on-site to account for erosion, soil nutrients, biodiversity, soil-organic carbon, and long-term soil productivity. For fuel treatment thinning operations, biomass retention levels were determined by FIA plot slope as follows:

if slope is less than 40%, then 30% of residue is left onsite; if slope is greater than 40% but less than 80%, then 40% of the residue is left onsite; and if slope is greater than 80%, then no residue is removed.

As with the logging residues, the limbs, branches, tops, and cull components of merchantable trees have a chipping cost and a stumpage cost. Felling and transport to roadside costs are borne by the merchantable sawlogs and pulpwood. However, the small, non-merchantable trees and dead trees have harvest and skidding costs in addition to chipping and stumpage costs. The small tree harvest costs were estimated by the FRCS model [13,14]. The FRCS estimates the cost of providing biomass at roadside by whichever is the least expensive of three alternative harvesting systems: 1) ground-based, whole-tree harvesting with mechanized felling; 2) ground-based, whole-tree harvesting with manual felling; or 3) cable-yarding of whole trees that have been manually felled. Cable-yarding is used in the model only when the average ground slope is between 40% and 80%.

2.1.2. *Other primary residues — other removals and other forestland thinnings*

Other forestlands are defined as incapable of producing industrial wood under natural conditions because of a variety of adverse site conditions, ranging from poor soils, lack of rainfall, and high elevation. Many of these woodlands (low-stature or sparse forests) are in the western states and are overstocked, especially with stands of pinyon pine and juniper. As with the fuel reduction thinnings on timberland, removal of the excess biomass could greatly reduce catastrophic fire hazards. FIA data were used to identify overstocked western woodlands.

The conversion of timberland to non-forest land uses (cropland, pasture, roads, urban settlements, etc.) and precommercial thinning operations generates a relatively significant amount of forest residue biomass. These “other removals,” especially from land-clearing operations, usually produce different forms of residues and are not generally as feasible or economic to recover. From land clearing operations a mixture (hodgepodge) of woody material is generated depending on what is standing on the site cleared. In the update, it was assumed only half of the residues available could be recovered. The 50% recovery level, transportation costs, and market prices used to derive stumpage prices for this diverse material are based on expert opinion. The diversity of materials from land clearing make it extremely difficult to model and is why expert opinion is relied upon. Amounts of other forest removals, by county, were obtained from the TPO database for 2007 [7].

2.1.3. *Secondary and tertiary sources of forest residues and wastes*

2.1.3.1. *Mill residues*. Quantities of wood and bark residue from milling operations (by county) for the update were obtained from the TPO database for 2007 [7]. It was assumed that only unused mill residues would be available for new bioenergy uses. For secondary processing mills neither the Forest Service nor any other federal agency systematically collects residue and waste data. One of the few estimates of the amount of secondary mill residue available was developed by Rooney [18] and subsequently revised by Fehrs [19]. Fehrs estimated that about 14 Tg are generated annually, with about 40% of this potentially available and recoverable. The remaining fraction is used to make higher-valued products, is used onsite to meet some energy needs (such as heat for drying operations), or is not available for other reasons.

2.1.3.2. *Urban wood wastes*. The two major sources of urban wood residues are the woody components of municipal solid wastes (MSW) and construction and demolition (C&D) waste wood. In 2007, 209 Tg of MSW were generated [20]. About 54% of the total quantity generated was discarded in municipal landfills. The remainder was either recycled, made into compost, or combusted for energy recovery. Containers and packaging are the single largest component of MSW, totaling some 64 Tg, or 31%, of the total. Durable goods are the second largest portion, accounting for 25% of total MSW generated. Yard trimmings are the third largest portion and account for about 27 Tg, or 13%, of the total.

The other principal source of urban wood residue is C&D debris. C&D wood waste is generated during the construction of new buildings and structures, the repair and remodeling of existing buildings and structures, and the demolition of existing buildings and structures [21]. These materials are considered separately from MSW because they come from many different sources. These debris materials are correlated with economic activity (e.g., housing starts), population, demolition activity, and the extent of recycling and reuse programs. Estimated availability of urban wood wastes are based on a set technical coefficients developed by McKeever [21] that took into consideration quantities recycled or combusted for energy recovery, and quantities contaminated and not suitable for recovery [2].

2.1.4. *Conventional pulpwood*

If pulpwood-sized material is used as biomass for bioenergy, it will most likely be obtained from 1) “additional harvests” of pulpwood-sized trees and biomass together in thinning operations that are in addition to the previously discussed thinnings and 2) from a shift of pulpwood being cut for current uses into uses for bioenergy (i.e., “pulpwood supply”). In the update, both are referred to as conventionally sourced wood because the pulpwood-sized trees are usually harvested for conventional products, such as paper and panels. To ensure sustainability in the additional harvests, pulpwood harvests were restricted to only removing the annual growth and not reducing inventory. When using pulpwood to supply bioenergy, the shift of current pulpwood use to bioenergy was restricted to 20% of the 2006 pulpwood harvest because of restrictions in the analysis on the underlying assumptions about the response to changing prices. Generally, pulpwood starts to be supplied for bioenergy at current pulpwood stumpage prices, and harvest costs increase as the price that buyers are willing to pay increases. Pulpwood can either come from additional harvesting operations that specifically harvest pulpwood for bioenergy (possibly more expensive than current integrated harvesting) or from a shift in pulpwood use from current users to bioenergy producers. The assumptions are explained in detail in Perlack and Stokes [2].

2.2. Agricultural crop residues and energy crops

Supply curves for crop residue collection and energy crop production were estimated using POLYSYS, an agricultural policy model [22]. POLYSYS includes four interdependent modules – crop supply disaggregated to each of the 3110 counties in the continental United States (i.e., excluding Alaska and Hawaii), national crop demand and prices, national livestock supply and demand, and agricultural income [22]. The model is tied to the USDA 10-year agricultural sector projections [5]. The projections include production and consumption for agricultural commodities, agricultural trade and exports, commodity prices, and aggregate indicators of the sector, such as farm income and food prices. In POLYSYS, these projections were extended 12 years to 2030 by extrapolating crop yields, exports, and population. The land base used for the update includes 1,010,000 km^2 planted to the eight major crops, 250,000 km^2 of land in hay production, 90,000 km^2 of cropland used as pasture, and 470,000 km^2 of non-irrigated permanent pasture. Land enrolled in the Conservation Reserve Program (CRP) is another potential source of land. However, the USDA projections assume acreage enrolled in the CRP remains close to the legislated maximum of 130,000 km^2. The update also makes this same assumption about the availability of CRP for commodity and energy crop production.

Crop residue supply curves were estimated for corn, wheat, grain sorghum, oats, and barley by accounting for residue production (a function of crop yield, grain moisture, and residue to grain ratio), residue retention to keep erosion within tolerable soil loss levels and maintain soil carbon, and residue production costs consisting of a fixed per ton grower payment plus collection costs per dry Mg of removed residue. For cotton and rice, two of the three other major crops in POLYSYS, residues were estimated separately. Cotton and rice production are assumed to be fixed (i.e., the quantity to be supplied by the model is specified and does not vary) and therefore the quantities of residues can be estimated without the use of the POLYSYS model. An average soybean crop produces about 2.6 Mg ha^{-1} of residue. Soybean residue is fragile and is best left undisturbed after harvest. For soybeans, it was assumed there is no residue available because all of the residue is needed for preventing soil erosion [23]. The version of POLYSYS used in this updated assessment includes three energy crop options—a perennial grass, short-rotation woody crops, and an annual energy crop. The grasses and non-coppice woody crops (e.g., poplar, pine) were evaluated for 10- and 8-year rotations, respectively. The rotation length for the coppice woody crops (e.g., willow) was 20 years with a 4-year cutting cycle. In POLYSYS, supplies of crop residues were estimated simultaneously with energy crops since they must compete for land and any changes in land use affects estimated quantities.

2.2.1. Agricultural crop residues

Crop residues protect soils and control erosion from water and wind, retain soil moisture, maintain soil organic matter, provide nutrients, enhance soil structure, and improve crop yields [24]. Determining how much residue can be sustainably removed must take into account these factors. Building from the work presented by Wilhelm et al. [25], the amount of agricultural residue that can potentially be collected was subject to two modeled constraints in the update. First, residue removal cannot exceed the tolerable soil loss limit as recommended by the USDA's Natural Resource Conservation Service (NRCS). Second, residue removal cannot result in long-term loss of soil organic matter as estimated by the Revised Universal Soil Loss Equation (RUSLE2) and the Wind Erosion Prediction System (WEPS). Both of these programs incorporate a soil quality index referred to as the soil conditioning index (SCI) and are employed by NRCS to help guide farmers and landowners in making their conservation plans [26–28]. In general, both programs are designed to provide estimates of soil erosion and other pertinent soil tilth parameters due to types of crops, rotations, field management practices (e.g., tillage), and field topography.

The baseline erosion and carbon levels for each crop are yield dependent and were calculated through 2030 to determine retention coefficients. These estimated retention coefficients act as binding constraints in the POLYSYS model. For acres under reduced-till cultivation, the organic matter sub-factor of the SCI and for acres under no-till, the combined SCI was used to determine how much residue could be removed. Due to the concern about residue removal and long-term soil fertility, removing residue from conventionally tilled acres was not allowed and residue can only be collected on acres under reduced- and no-till tillage. The map shown in Fig. 1 displays no-till sustainable retention coefficients (expressed as a fraction of stover that must remain on the field to meet sustainability requirements) for year 2030. Areas in dark green (in web version) indicate high levels of potential stover removal, and areas in dark brown (in web version) indicate much of the stover must be retained onsite. Similar results are generated for other years up to 2030, as well as for reduced tillage.

The amount of crop residue produced depends on the crop yield and the ratio of residue to grain or harvest index (HI). The amount that can be sustainably removed is governed by the

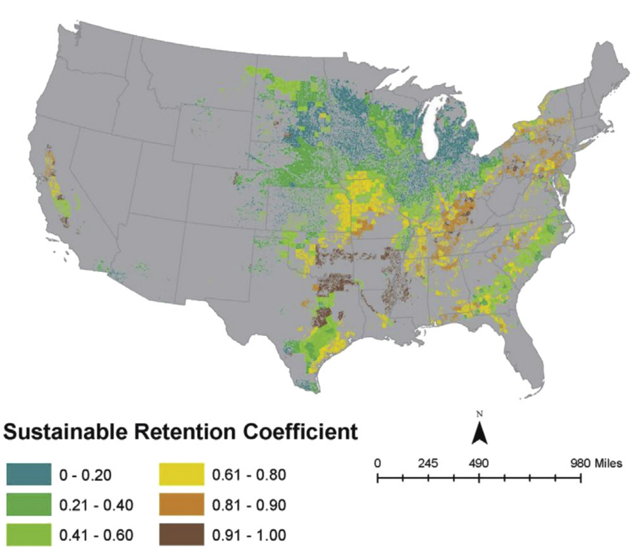

Fig. 1 – Estimated retention coefficients for no-till managed corn in year 2030 (fractions indicating how much of residue must be left on the field).

retention coefficients, which were estimated from application of RUSLE2 and WEPS models incorporating the SCI and tillage [23]. The amount that can be physically removed depends on the combined efficiency of the collection equipment (e.g., shredders, rakes, balers). And the amount that can be economically removed depends on grower payments, collection costs, and prices offered for the feedstocks. In the estimation of crop residue supply curves, costs have two components – a grower payment and the residue collection costs.

Grower payments were estimated by valuing the removed nutrients and organic matter and adding a profit. The nutrient value is a product of fertilizer prices and the amount of nutrients in the removed residue. There are many nitrogen sources, with prices varying considerably among these sources. Anhydrous ammonia is the least expensive and generally applied to corn, while ammonium nitrate tends to be the most expensive. The sources of most phosphorus are diammonium phosphate (DAP) and monoammonium phosphate (MAP). For potassium, muriate of potash is used almost exclusively. Data from Nielson [29], Lang [30], Gallagher et al. [31], Schechinger and Hettenhaus [32], and Fixen [33] were used to estimate an average nutrient composition of removed corn stover. Nutrient values for stover on a dry basis were nitrogen 14.8 kg Mg^{-1}, P_2O_5 (phosphorus) 2.6 kg Mg^{-1}, and K_2O (potassium) 13.6 kg Mg^{-1}.

Corn producers surveyed indicated that they desire to receive a return for their corn stover over and above the nutrient replacement value of their residue. A return of 11 $ Mg^{-1} above the value of nutrients and organic matter was assumed based a review of published sources [30,32,34,35], and summarized on pages 61 and 62 of [2]. Based on Lang [30] an additional 1 $ Mg^{-1} was added to account for the value of the residue for organic matter and other nutrients. The valuation of the removed nutrients, organic matter, and return result in an average grower payment of 28.70 $ Mg^{-1} of removed corn stover and 27.60 $ Mg^{-1} of removed wheat straw (using 2006–2009 average regional fertilizer prices). Grower payments were lowest in the Northern and Southern Plains and highest in the Pacific Northwest. For the Corn Belt, the grower payment was about the same as the national average. The variability among regions is low.

Corn stover collection costs were estimated over a relatively large yield range and three equipment configurations depending on how much residue removed. These equipment configurations included: 1) turning off the combine's spreader and baling the windrow using a large round baler; 2) after combining, raking and baling the resulting windrow using a large round baler; and 3) shredding after combining, raking the shredded biomass, and baling the resulting windrow using a large rectangular baler. Low-yield residue collection is most cost-effective by simply turning off the combine spreader and baling the windrow. For wheat and other small grain residue, whose residue yields are generally lower than corn but dry, collection involves turning off the combine's spreader and baling the windrow using a large round or rectangular baler. There may be some problems with higher moisture corn stover, but this is something the three corn stover-to-ethanol facilities opening in the United States in 2014 will have to deal with. Shredding and raking are used when large amounts of residue are removed. Estimated collection costs up to the field edge are about 23, 20, and 15 $ Mg^{-1} for yields of 2.2, 3.4, and 5.6 Mg hm^{-2}, respectively. Small grain straw collection costs are very similar over the same residue yields [2].

2.2.2. *Energy crops*

POLYSYS allocates available land in each county to the competing crops, including energy crops based on the maximization of revenues above variable costs of production. Energy crops can displace conventional crops if they are more profitable. In the case of pastureland (permanent pasture and cropland pasture), if the land is east of the 100th meridian, in POLYSYS, conversion to perennial grasses and woody crops is allowed only if lost forage can be made up by intensifying pasture production. For counties west of the 100th meridian it was assumed that rainfall is limiting crop production and that if higher yields are to be achieved, irrigation would have to be used, and that irrigation water would not be available for biomass crops. Counties east of the 100th meridian were assumed to have sufficient rainfall to replace lost forage through intensification. That is, POLYSYS assumed it is possible to have no loss of forage production, if it is cost effective to convert the pasture to energy crops, given the following assumed costs. Intensifying cropland currently used as pasture will cost 124 $ hm^{-2} the first year and an additional 25 $ hm^{-2} in subsequent years. For permanent pasture, first-year costs were assumed to be 247 $ hm^{-2} and 37 $ hm^{-2} in following years. First-year costs are for additional investments, such as fencing. Costs in subsequent years are for pasture management. Energy crops must overcome these additional costs plus the pasture rental rate to come into production.

A set of restraints was used to limit the amount of land switching to new energy crops in a given year. These restraints were imposed to simulate the relative inelastic nature of agriculture in the near-term. These restraints include:

- 5% of permanent pasture can convert to energy crops each year. The total amount of permanent pasture in a given county that can convert to energy crops was limited to 50% (i.e., assumed doubling of forage through intensification)
- 20% of cropland pasture can convert to energy crops each year. The total amount of cropland pasture in a given county that can convert to energy crops was limited to 50% (same assumption as permanent pasture)
- 10% of cropland can convert to energy crops each year. The total amount of cropland in any given county that can convert to switchgrass or woody energy crops was limited to 25%. This restraint serves to maintain crop diversity.
- Energy sorghum, the annual energy crop, was restricted to planting on non-erosive cropland and assumed to be part of a mulitcrop rotation.

In POLYSYS, energy crop production costs include seed or planting stock, fertilizer, herbicide, insecticide, machinery services, custom operations, fuel and lube, repairs, handling, paid labor, and technical services. Factor input costs are specific to broad farm production regions due to regional differences in labor rates, fertilizer prices, and other inputs. Energy crop production inputs, assumptions, and prices are summarized in Tables 2 and 3, for herbaceous and woody crops, respectively. Inputs and assumptions were developed based on extension service crop guidelines, when available, for southern pines best management practices, and expertise of the authors based on experimental field data and input from researchers studying energy crops. Harvest costs for the herbaceous crops were estimated similarly to crop residues and are a function of removed quantity. Woody crop harvest costs assumed conventional equipment and averaged about 22 $ Mg^{-1}. For willow, harvest costs were estimated at about 16.50 $ Mg^{-1}. Tables 2 and 3 also show the assumed energy crop yields by USDA production region. These are summary ranges of crop yields by county in each region.

2.2.3. *Secondary agricultural produces and other wastes*

These include animal manure, rice straw, cotton field residues, orchard and vineyard prunings, cotton gin trash, rice hulls, sugar cane field residues, wheat dust, and animal fats. Rice straw, cotton field residues, cotton gin trash, sugar cane field residues, and wheat dust increase over time following the USDA baseline projections for their primary products. Estimates for production of orchard and vineyard prunings, manure, and fats are done independently of other estimates and are based on work by Nelson [36]. More detailed information on how these estimates are calculated can be found on pages 77–84 in Perlack and Stokes [2].

3. Results and discussion

The updated billion-ton study made a clearer distinction between currently used biomass resources, such as use of corn grain for ethanol and use of pulping liquors for heat and power production, and potential resources available for additional and new energy production. The currently used resources are summarized below and followed by a summary discussion of the potential forest and agricultural biomass resources.

3.1. *Currently used biomass resources*

Currently utilized biomass resources are 4% of U.S. primary energy consumption, or 194 Tg (Table 4). These resources are utilized in all sectors – residential, commercial, industrial, electric utility, and transportation. Biomass resource use has been gradually increasing since the early 2000s, primarily because of greater use of corn grain for ethanol. The overall trend is projected to continue, and by 2030 utilization is projected to be nearly 300 Tg. Forest sources account for 60–70% of currently utilized resources. The two largest single categories are fuelwood, which is directly combusted for heat in the residential and commercial sectors and for power production in the electric utility sector, and ethanol from starch, primarily corn grain. In 2010 about 35% of the corn crop was used to produce ethanol, and this percent has been around 40% in 2011 and increased to 45% in 2012 because of reduced corn production due to drought. In the update, the projected estimate of the amount of ethanol produced from starch was assumed to be limited to the equivalent of 57 Gl, which is the maximum allowed to contribute to the Renewable Fuel Standard (RFS) under the Energy Independence and Security Act of 2007 (EISA) mandates [3]. The amount of corn grain shown in Table 4 is the portion of the corn that is consumed to make ethanol and excludes the distillers dried grains feed by-product that is recovered and fed to livestock.

Table 2 – Summary of production inputs and costs for perennial and annual grasses.

Item	Units	Northeast	Appalachia	Southeast	Delta	Corn belt	Lake states	So. & No. Plains
Perennial grasses								
Stand life	Years	10	10	10	10	10	10	10
Productivity	Mg ha^{-1}	9.0–16.8	11.2–21.3	7.8–21.3	6.7–15.7	9.0–15.7	7.8–11.2	4.5–14.6
Establishment								
Seed	$ kg^{-1}	22	49	49	49	22	22	49
Planting	Kg ha^{-1}	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Replants	percent	25	25	25	25	25	25	25
Phosphorus	P_2O_5 (kg ha^{-1})	45	45	45	45	45	45	45
Potassium	K_2O (kg ha^{-1})	90	90	90	90	90	90	0
Lime	Mg ha^{-1}	2.2	4.5	4.5	4.5	2.2	2.2	0
Total establishment costs	**$ ha^{-1}**	**620**	**840**	**840**	**740**	**570**	**570**	**420/570**
Maintenance years								
Reseeding	year applied	2	2	2	2	2	2	2
Nitrogen	Kg ha^{-1}	58–110	73–139	52–139	44–102	58–102	52–73	29–94
Phosphorus	P_2O_5 (kg ha^{-1})	45	45	45	45	45	45	45
Potassium	K_2O (kg ha^{-1})	90	90	90	90	90	90	0
Harvest costs	$ Mg^{-1}	17.40–20.70	16.10–18.60	15.70–20.50	16.50–22.50	17.20–20.30	19.40–21.70	17.30–31.30
Annual energy crops								
Productivity	Mg ha^{-1}	13.4–18.4	13.4–19.5	13.4–20.2	13.4–20.2	15.0–20.2	n/a	14.6–20.2
Production costs	$ ha^{-1}	720	690	690	670	690	n/a	490
Harvest costs	$ Mg^{-1}	10.60–14.60	9.60–14.00	9.20–14.80	9.10–13.70	9.40–12.70	n/a	9.30–13.00

Notes: Discounted average costs of production ($ Mg^{-1}) for perennial grasses are 41–58 in the Northeast; 38–53 in Appalachia; 38–68 in the Southeast; 43–72 in the Delta; 42–57 in the Corn Belt; 50–62 in the Lake States. 34–72 in the Northern and Southern Plains. Costs assume a discount rate of 6.5% and include all variable costs exclusive of land rent. Discounted average cost of production for annual energy crops range from 38 to 80 $ Mg^{-1}.

Table 3 – Summary of production inputs and costs for woody crops.

Item	Units	Poplar	Pine	Eucalyptus	Willow (coppiced)
Rotation	Years	8	8	8	4 (5 harvests)
Spacing	m^3	5.6	5.6	5.6	7.5
	trees ha^{-1}	1793	1793	1793	14,326
Productivity	Mg ha-$year^{-1}$	7.8–13.4	11.2–12.3	13.4	11.4
Growing range	Region	Northeast, lake states, northwest, corn belt, plains	Southeast	Sub-tropics	Northeast and lake states
Establishment–year 1					
Cuttings	$ $tree^{-1}$	0.12	0.10	0.10	0.12
Planting	$ $tree^{-1}$	0.09	0.09	0.09	0.02
Replants	percent	5	5	5	0
Moldboard plow	–	1-time	1-time	1-time	1-time
Disk	–	1-time	1-time	1-time	1-time
Cultivate	–	2-times	2-times	2-times	2-times
Total kill herbicide	No. applications	1-time	1-time	1-time	1-time
	a.i. (kg ha^{-1})	1.68	1.68	1.68	1.68
Pre-emergent herbicide	No. applications	1-time	1-time	1-time	1-time
	a.i. (kg ha^{-1})	1.68	1.68	1.68	1.68
Phosphorus	P_2O_5 (kg ha^{-1})	0	90	0	0
Establishment costs	$ ha^{-1}	770	690	770	2770
Maintenance years					
Cultivate – year 2	–	2-times	2-times	2-times	1-time
Cultivate – year 3		1-time	1-time	1-time	None
Pre-emergent herbicide – year 2	No. applications	1	1	1	1
	a.i. (kg ha^{-1})	1.68	1.68	1.68	1.68
Lime – year 3	Mg ha^{-1}	1.12 (0 in northwest)	2.24	2.24	2.24
	year applied	–	year 3	year 3	–
Nitrogen – years 4 and 6	Kg ha^{-1}	101	101	101	112
	year(s) applied	3, 6	2, 4, 6	4, 6	4
Phosphorus – year 3	P_2O_5 (kg ha^{-1})	17–45	45	17	–
Potassium – year 3	K_2O (kg ha^{-1})	17–56	45	28	–
Maintenance costs – year 2	$ ha^{-1}	150	260	250	74
Maintenance costs – total years 3–8	$ ha^{-1}	410–550	500	490	250
Harvest costs	$ Mg^{-1}	20.80–22.30	22.00	22.00	16.50

Notes: Productivity for coppiced managed systems is expected to be about 15% higher after first coppice. "a.i." is active ingredient. Discounted average costs of production for poplar, pine, and willow are 44–58, 46–49, and 42–50 $ Mg^{-1}, respectively. Costs assume a discount rate of 6.5% and include all variable costs exclusive of land rent.

3.2. *Potential forest biomass and waste resources*

The composite operations, which have two components – logging residues and thinnings, are the single largest source of potential forest biomass. The estimated supply curves for these individual components are depicted in Fig. 2. The logging residue supply curve shows 43 Tg y^{-1} potentially available at a roadside price of about 44 $ Mg^{-1} or less. All produced logging residues after accounting for sustainability are available at this price. About 30% of this logging residue is available at roadside costs of less than 22 $ Mg^{-1} and nearly all of it at less than 33 $ Mg^{-1} [2]. The curve is relatively flat since it includes just chipping costs and stumpage. The largest supplies are where pulpwood and sawlog harvests are the greatest, namely the Southeast, Northwest, and Lake States. Over time, these estimates increase somewhat due to slightly higher projected timber harvests [6].

The second component of the composite operations, fuel treatment thinnings on timberlands, is also shown in Fig. 2. Nearly 40 Tg are potentially available for collection. About 37% of this total is estimated to be available at roadside costs of 33 $ Mg^{-1} or less. More than half is available at 44 $ Mg^{-1} and nearly 75% of the total resource at 66 $ Mg^{-1} or less. This supply curve is not nearly as flat as the logging residue supply curve due to the higher costs of felling and removing the small trees.

A 50/50 weighting of the logging residue and thinnings supply curves is used to form the composite operations supply curve shown (Fig. 2). It is difficult to estimate the pace of transition from current operations represented by logging residue estimates to thinning based estimates. We assume a 50% transition toward thinning operations where simulated thinnings would provide half of the harvest needed to meet sawlog and pulpwood needs. The other half of harvest would be done in a conventional way and generate logging residue, a portion of which can be removed for bioenergy. The conceptual transition from leaving the biomass as logging slash to removing it when the merchantable timber is harvested is likely to occur in response to the development of biomass markets. The composite supply curve for the years 2012, 2017, 2022, and 2030 show most of the supply, 32 to 33 Tg y^{-1} is available at a roadside price of 44 $ Mg^{-1} or less and only an

Table 4 – Current and projected use of currently used biomass resources.

Feedstock source	2012	2017	2022	2030
	Tg			
Forest resources				
Fuelwood[a]	34	65	87	96
Mill residues	29	34	35	38
Pulping liquors	41	47	49	53
MSW sources[b]	13	18	18	18
Total forest	**117**	**165**	**190**	**205**
Agriculture resources				
Ethanol[c]	69	80	80	80
Biodiesel[c]	2	4	4	4
MSW sources	6	10	10	10
Total agriculture	**77**	**93**	**93**	**93**
Total forest and agriculture	**194**	**259**	**283**	**298**

[a] Fuelwood includes the residential commercial sector as well as biomass consumed by the electric utility industry in dedicated biomass plants and co-firing applications.
[b] MSW sources are allocated to forest (65%) and cropland (35%) based on EIA [37].
[c] Ethanol and biodiesel are based on EISA mandates 2022 production of 60.6 GL of biofuels and 3.8 GL of biodiesel. Ethanol assumes corn grain at 15.5% moisture content, and 417 L Mg^{-1}. For ethanol, it takes about 116 Tg to make 56.8 GL of ethanol (the EISA cap on grain-based ethanol starting in 2015). However, only 80 Tg are consumed in making the ethanol. The remainder (36 Tg) is distiller's grain and is excluded from the total. Current consumption of biodiesel is 43% from soybeans and 57% from other sources, including animal fats and waste oils. The proportion of sources of future feedstocks will vary and are assumed to have an average conversion rate of 0.9 kg of oil/fats L^{-1} of biodiesel.

additional 3 to 4 Tg becomes available as price increases to 66 $ Mg^{-1}.

Table 5 summarizes these composite operations as well as the other forest residue and waste biomass potential. Over a price range of 44–66 $ Mg^{-1}, forest residue and waste biomass potential is 72–92 Tg in the 2012 to 2030 time period. At the highest price estimate of 66 $ Mg^{-1}, the available biomass from composite operations is about 33 Tg annually in 2012. By 2030, these quantities increase by just a few million dry Mg. Although not shown in Table 5, higher roadside prices do not bring in much additional biomass. The additional biomass at a price of $100 dry Mg^{-1} is about 2 Tg. The thinnings portion of the composite operations estimates is for all land ownerships and includes federal lands, even though they do not currently qualify under the Renewable Fuel Standard. Removal of the federal lands has little effect on the total biomass availability, ranging from 4 to 6 Tg, over the period 2012 to 2030 and a range of prices from 44 to 66 $ Mg^{-1}. It should be noted that the supply quantities shown for the primary resources already account for the biomass that is retained onsite for sustainability purposes.

By comparison, treatment thinnings on other forestlands are considerably smaller and higher cost. By definition, these other forestlands do not produce commercial-sized pulpwood or sawlogs, so the cost of removing the other forestland thinnings with a preponderance of small trees is borne fully by the biomass harvesting operation, unlike for composite operations. An assumption used in the analysis, based on the expertise of BT2 contributing authors, was that about 50% of the identified biomass (2.9 Tg) requiring removal could be harvested at a price of 66 $ Mg^{-1} and the full amount of 5.8 Tg at a roadside price of 77 $ Mg^{-1}. For other residue removals, there is little price data available for these types of feedstocks. Assumptions were made based on the expertise of the BT2 contributing authors concerning recovery and prices to derive the stumpage values. Specifically, one-third of the available quantity (4 Tg) was assumed to be available at 22 $ Mg^{-1} (roadside) and the entire recoverable amount of 11 Tg at 33 $ Mg^{-1} (roadside).

For the unused primary mill residue, it was assumed that these residues can be purchased at the mill for 22 $ Mg^{-1} or less, which is comparable to the disposal cost if there are no markets available. Of course, delivered prices would be much higher, especially for secondary mill residue where facilities are small, dispersed, and operate seasonally. Slightly more than 80% of the mill residue shown in Table 5 is from

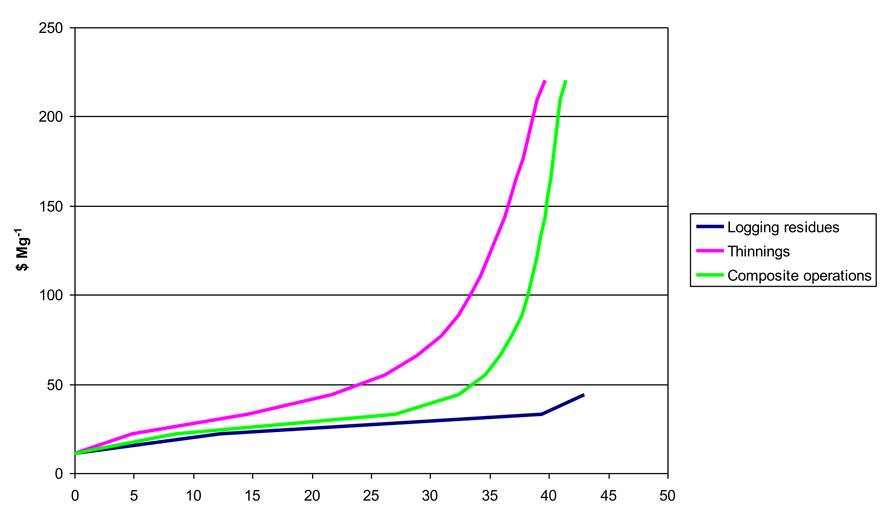

Fig. 2 – Estimated total U.S. supply curves for logging residues, fuel treatment thinnings on timberlands, and composite operations in year 2012.

Table 5 – Forest residues and waste resources.

Year	2012			2017			2022			2030		
Feedstock ($ Mg^{-1})	44	55	66	44	55	66	44	55	66	44	55	66
	Tg											
Composite operations[a]	33	35	36	33	35	37	33	36	37	34	36	37
Treatment thinnings – Other forestland	0	0	2.9	0	0	2.9	0	0	2.9	0	0	2.9
Other residue removals	11	11	11	11	11	11	11	11	11	11	11	11
Conventional pulpwood to energy	0	0.1	1.4	0	0.1	1.5	0	0.1	1.6	0	0.1	1.7
Mill residue (primary & secondary)	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Urban wood waste – C & D	13	20	20	13	21	21	14	21	21	14	22	22
Urban wood waste – MSW	8.3	9.1	9.1	8.6	9.1	9.1	9.1	10	10	9.1	10	10
Total	72	82	88	73	83	89	74	85	90	76	87	92

Notes: No high-yield scenario was estimated for the forest residues and waste resources. Forest residues come from existing timberlands, and there is no obvious way to increase volumes other than reducing fractions left behind to meet environmental sustainability, which is not recommended.

[a] The estimate assumes a 50:50 mix of logging residues and fuel treatment thinnings on timberlands. Individual logging residue and treatment thinnings estimates can be found in Ref. [2].

secondary processing mills. It was assumed that any residue associated with increased future demand for primary and secondary wood products would be offset by greater mill efficiencies and a continued increase in the use of this material for by-products.

In the BT2, about 8 Tg of urban wood wastes from MSW sources were estimated as potentially collectable at a roadside price of 44 $ Mg^{-1} or less. The updated estimates of C&D debris wastes total about 20 Tg at a roadside price of 66 $ Mg^{-1} or less. They are slightly higher than the 2005 BTS estimates because

Table 6 – Estimates of agricultural residues, waste resources, and energy crops.

Year	2012			2017			2022			2030		
Feedstock ($ Mg^{-1})	44	55	66	44	55	66	44	55	66	44	55	66
	Tg											
Baseline scenario												
Agricultural crop residues												
Corn stover	17	66	77	29	84	96	38	98	109	59	117	127
Wheat, oats, barley, sorghum residue	7.0	19	23	8.3	22	26	9.7	26	30	14	31	36
Other crop and processing residues[a]	19	19	19	21	21	21	22	22	22	23	23	23
Animal manures	11	26	27	12	31	32	15	37	39	18	51	54
Total agricultural residues	**54**	**130**	**147**	**70**	**158**	**175**	**84**	**183**	**200**	**113**	**222**	**240**
Energy crops												
Perennial grasses	–	–	–	2.7	37	82	11	70	171	27	117	231
Woody crops	–	–	–	0.0	0.8	5.3	0.0	36	77	0.1	61	114
Annual energy crops	–	–	–	0.6	3.4	4.5	1.6	6.6	8.9	3.8	13	17
Total energy crops	–	–	–	**3.4**	**41**	**92**	**12**	**113**	**256**	**31**	**190**	**363**
Total baseline scenario	**54**	**130**	**147**	**73**	**199**	**266**	**96**	**295**	**456**	**145**	**413**	**602**
High–yield scenario												
Agricultural crop residues												
Corn stover	65	130	139	120	180	189	145	206	212	200	239	246
Wheat, oats, barley, sorghum residue	10	30	36	12	35	39	13	37	41	16	40	44
Other crop and processing residues[a]	19	19	19	21	21	21	22	22	22	23	23	23
Animal manures	11	26	27	12	31	32	15	37	39	18	51	54
Total agricultural residues	**105**	**205**	**221**	**165**	**266**	**281**	**195**	**302**	**314**	**258**	**353**	**367**
Energy crops												
Perennial grasses				10–32	61–96	111–140	39–90	138–245	230–306	52–183	217–368	289–419
Woody crops				0–0.1	1.7–10	9.3–15	0.1–4.8	71–107	132–192	3.8–41	116–180	188–285
Annual energy crops				1.5–3.1	5.0–6.2	6.3–8.5	3.7–8.2	8.0–10	9.9–13	6.7–13	11–16	13–20
Total energy crops				**12–35**	**68–113**	**126–163**	**43–103**	**217–362**	**317–511**	**62–237**	**343–565**	**490–725**
Total high–yield scenario	**105**	**205**	**221**	**176–200**	**334–379**	**407–444**	**238–298**	**519–665**	**685–826**	**320–495**	**696–918**	**857–1092**

[a] Other crop and processing residues include rice field residue, rice hulls, cotton field residues, cotton gin trash, sugarcane field residues, wheat dust, and orchard and vineyard prunings.

of changes in population and economic activity. All urban wood waste estimates account for contamination, recycling, reuse, and energy recovery. These estimates are based on publications from and the methodologies within EPA [20] and McKeever [21,38].

Conventional pulpwood to energy, which includes separate, additional operations or shifts of current pulpwood supply to energy was included in the updated assessment. However, only after prices are higher than 66 $ Mg^{-1} does conventionally sourced pulpwood start making significant contributions. In 2012, at 66 $ Mg^{-1} at roadside, the estimated pulpwood supply from additional harvest or shifts from current users is 1.4 Tg y^{-1}. At a roadside price of 88 $ Mg^{-1}, the amount of pulpwood for use as biomass is 16 Tg y^{-1}.

3.3. *Agricultural crop residues and energy crops*

3.3.1. *Agricultural residues and waste resources*

Crop residues from corn and other grains have the potential to contribute substantial resources (Table 6). The largest quantities of agricultural residues and wastes are crop residues from the major commodity crops. They range from 24 to 73 Tg between 2012 and 2030 at a farmgate price of 44 $ Mg^{-1} (Table 6). Corn has the potential to contribute substantially more residue than other grains, accounting for 70% or more of the total crop residue. As can be seen in Table 6, price is an important determinant in how much residue can be collected over time. As crop yields increase in the future, available residues increase. The total resource for corn and other grains ranges from 24 Tg in 2012 at 44 $ Mg^{-1} to 163 Tg in 2030 at 66 $ Mg^{-1}.

Under the high-yield scenario, estimated corn stover is considerably larger because of greater amounts of corn acreage in no-till and reduced-till cultivation as well as considerably higher grain yields. The results show a potential to double the quantity of collectable corn stover as well as increase residue from wheat and the other grains. By 2022, there is sufficient stover to produce a significant fraction of biofuels required from cellulosic sources. At the price of 66 $ Mg^{-1}, crop residues (from corn, wheat, barley, oats, and sorghum) increase to 290 Tg by 2030. The impact of the high-yield scenario can be seen in Fig. 3. Supply curves are shown for the baseline for four different baseline scenario years and for the 2030 high-yield scenario. Yield increases and additional acreage in reduced- and no-till cultivation shift the baseline scenario and high-yield stover supply curves over time.

Other crop and processing residues (rice field residues, rice hulls, cotton field residues, cotton gin trash, wheat dust, and orchard and vineyard prunings are made exogenously to the POLYSYS model runs and are based on current production and trends from the USDA 2009 10-year projections (for cotton, and rice) and Nelson [5,36]. Other crop and processing residues (excluding manure) in the aggregate are in the range of 19–23 Tg depending on the year and price (44–66 $ Mg^{-1}), with orchard and vineyard prunings, cotton field residue, and rice straw being the largest individual components (Table 6). Collectible animal manure production ranges from 11 Tg in 2012 at 44 $ Mg^{-1} to 54 Tg in 2030 at 66 $ Mg^{-1}. In total, the agricultural processing residues and wastes range from about

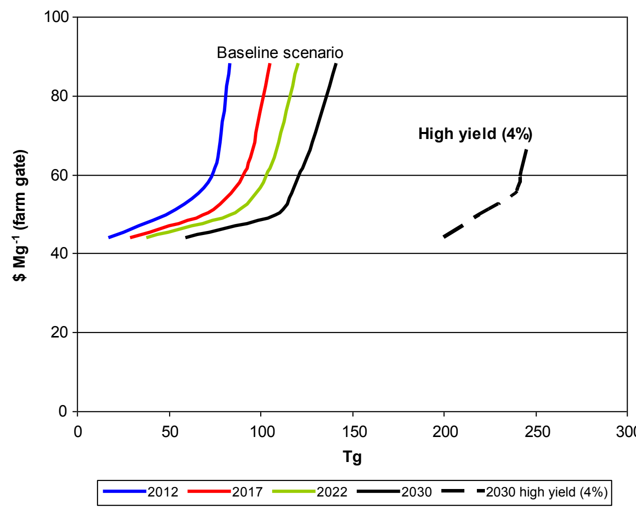

Fig. 3 – Estimated supply curves for corn stover under the baseline scenario for selected years and high-yield scenario for year 2030.

30 to 76 Tg over the 18-year simulation period. In addition to what is listed in Table 6, there are fats and grease that are not shown because their price is above 66 $ Mg^{-1}. These fats and greases amount to 20 to 22 Tg. Combining all of the agricultural residues and wastes totals about 113 Tg at 44 $ Mg^{-1} or less by 2030. An additional 109 Tg become available at 55 $ Mg^{-1} farmgate price. More than 90% of the collectable residue and waste is available at prices below 55 $ Mg^{-1}. All secondary agricultural processing and other wastes are the same under the high-yield scenario.

3.3.2. *Energy crops*

Energy crops are planted starting in 2014 and by 2017 perennial grasses have the potential to make substantial contributions (Table 6). In the baseline, the yield increase is 1% per year. At the lowest simulated farmgate price (44 $ Mg^{-1}), energy crop production reaches 13 Tg by 2022 and 31 Tg by 2030. Higher simulated prices make energy crops much more competitive with commodity crops and pasture. At the highest simulated price of 66 $ Mg^{-1}, 256 Tg of energy crops are potentially available by 2022, increasing to 363 Tg by 2030. These results are for the baseline scenario, which assumes an annual increase of 1% in yield due to learning or experience in planting energy crops and limited gains attained through breeding and selection of better varieties and clones.

The high-yield scenario assumes energy crop productivity increases are modeled at three levels – 2%, 3%, and 4% annually. These gains are assumed to be due not only to experience in planting energy crops, but also to more aggressive implementation of breeding and selection programs. Total potential energy crop supplies increase significantly from 363 to 490 Tg at the 2% annual growth rate to nearly 726 Tg at the 4% growth rate by 2030, assuming a 66 $ Mg^{-1} simulated price. Fig. 4 shows the estimated supply curve under the baseline scenario for three selected years and the estimated 2030 supply curve for the high yield scenario assuming energy crop yields increase at 4% in subsequent plantings. As can be seen from the supply curves, a higher rate

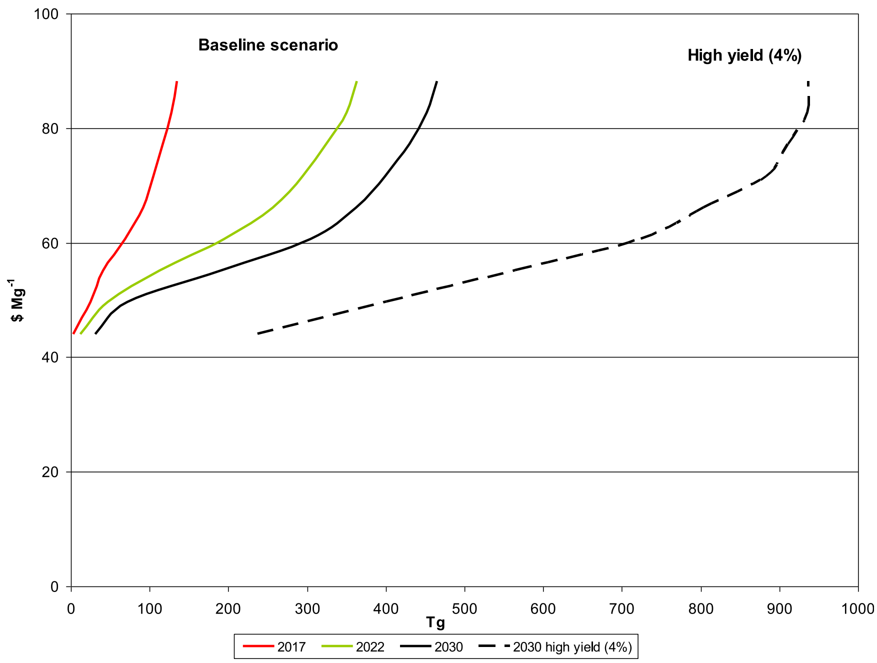

Fig. 4 – Estimated supply curves for energy crops under the baseline scenario for selected years and high-yield scenario for year 2030.

of yield increase leads to significantly higher energy crop production over time.

The large-scale planting of energy crops will entail significant changes among commodity crops and conversion of pastureland to energy crops, provided forage can be made up through pasture intensification. At the highest simulated farmgate price of 66 $ Mg^{-1}, 90,000 to 120,000 km^2 of cropland and 160,000 to 200,000 km^2 of pasture shift into energy crop production, depending on the baseline or high-yield scenario (Fig. 5).

3.4. *Overall potential*

The BT2 shows significant amounts of biomass to be available at present and increasing over time. No single category of biomass dominates, but resources that are not currently used to any large extent (energy crops, agricultural residues and wastes, and forest residues and wastes) make up the majority of available resources. In the baseline at 66 $ Mg^{-1}, these three categories contribute 547 and 696 Tg (or 66% and 70% of total resources) in 2022 and 2030, respectively (Fig. 6).

4. Summary and conclusions

The 2011 BT2 updates and improves on the 2005 BTS. A significant difference between the two is that the 2005 BTS had no cost restrictions. The 2011 BT2 improves on the BTS in that environmental sustainability is more comprehensively and rigorously modeled, the POLYSYS model is used to estimate

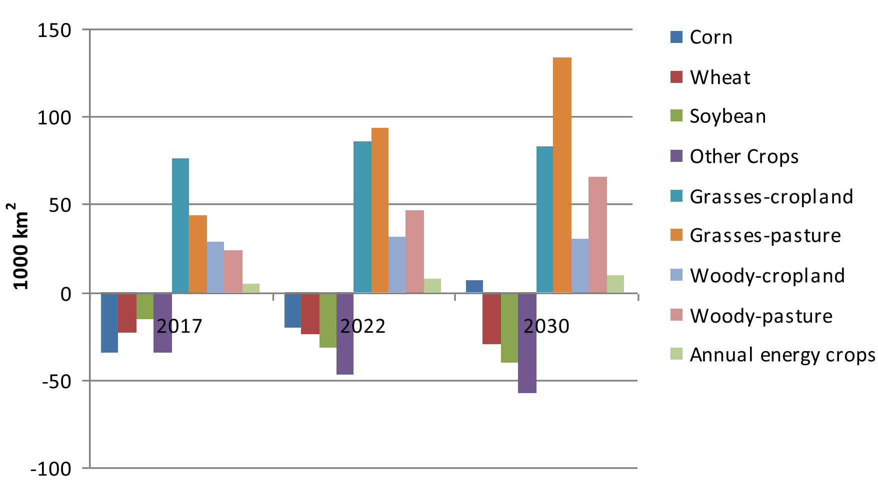

Fig. 5 – Cropland shifts from commodity crops and pasture to energy crops.

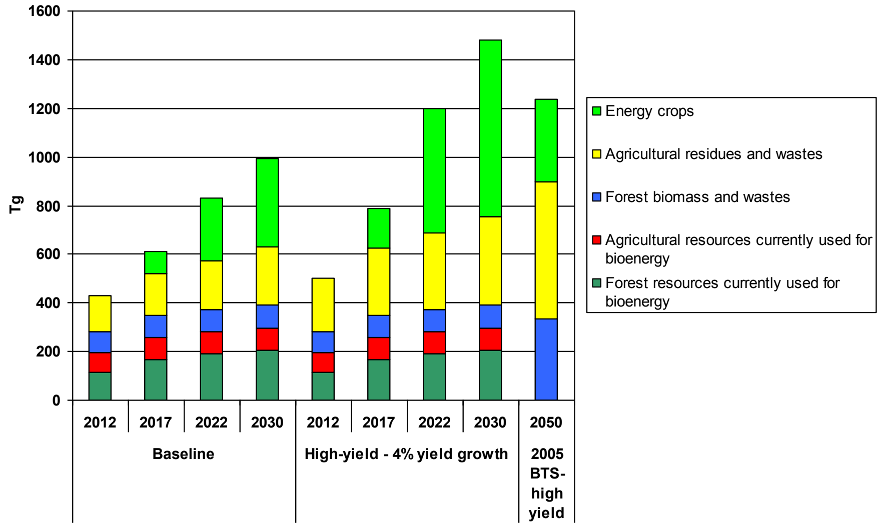

Fig. 6 – Total resources available at 66 \$ Mg^{-1} in the BTU compared to the high-yield scenario from the 2005 BTS.

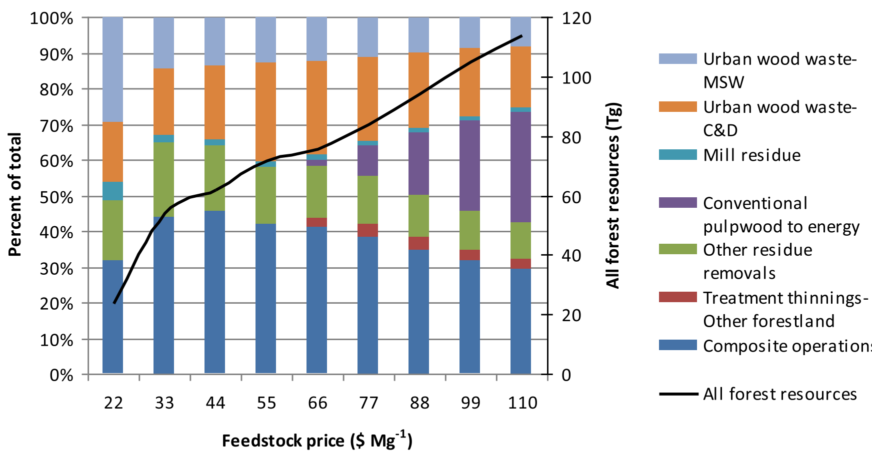

Fig. 7 – Year 2022 forest resource supply curve and feedstock proportions at roadside prices of 22–110 \$ Mg^{-1}.

supply curves for energy crops, and most resources are estimated at the county level. Costs in the BT2 are estimated at the farm-gate or forest landing for energy crops, crop residues, and resources from the forest and additional costs will be incurred in transporting and processing of the biomass and in losses during further handling and storage.

The 2011 BT2 shows that large quantities of biomass are available while meeting food, livestock feed, industrial, and export demands. There are two sets of estimates, baseline and high yield. Estimated supplies in 2030 range from 1.0 (baseline) to 1.5 (high yield, 4% energy crop yield increase) Pg at 66 \$ Mg^{-1}. Excluding currently used biomass, the range is to

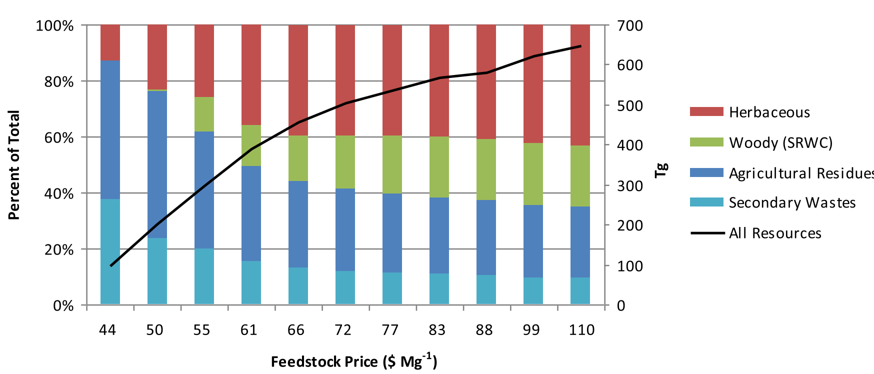

Fig. 8 – Year 2022 agricultural resource supply curve and feedstock proportions at farmgate or roadside prices of 44–110 \$ Mg^{-1}.

0.7 to 1.2 Pg at 66 $ Mg^{-1}. Resources from Federal lands are only a minor constituent of the total at about 5–7 Tg. The BT2 is consistent with the 2005 BTS in terms of the magnitude of the resource potential, on the order of 1 Pg. Total available resources increase over time as yields increase. No single category of resources dominates. Price has a significant effect on estimated supplies (Figs. 7 and 8).

In 2022 the Renewable Fuel Standard (RFS) requires 136 GL of renewable fuels, but allows only 57 GL to come from corn ethanol and requires 3.8 GL to come from biomass-based biodiesel. At a minimum 76 GL of fuel will be required from cellulosic biofuels in 2022. Excluding currently used resources, in 2022 in the baseline, 540 Tg are estimated available at a farm-gate/forest–landing price of 66 $ Mg^{-1}, which at 355 L Mg^{-1}, only about 10% of the resources, 56.4 Tg, would be needed to meet this requirement. At higher yield growth (3%) only 7% of the estimated supply is needed to meet the 2022 RFS requirement. Feedstock availability is not a constraint to meeting the RFS requirement.

The bottom line of the BT2 is that large quantities of biomass (>1 Pg) are available.

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