

Global and regional potential for bioenergy from agricultural and forestry residue biomass

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Abstract As co-products, agricultural and forestry residues represent a potential low cost, low carbon, source for bioenergy. A method is developed for estimating the maximum sustainable amount of energy potentially available from agricultural and forestry residues by converting crop production statistics into associated residue, while allocating some of this resource to remain on the field to mitigate erosion and maintain soil nutrients. Currently, we estimate that the world produces residue biomass that could be sustainably harvested and converted into nearly 50 EJ yr⁻¹ of energy. The top three countries where this resource is estimated to be most abundant are currently net energy importers: China, the United States (US), and India. The global potential from residue biomass is estimated to increase to approximately 50–100 EJ yr⁻¹ by mid- to late- century, depending on physical assumptions such as of future crop yields and the amount of residue sustainably harvestable. The future market for biomass residues was simulated using the Object-Oriented Energy, Climate, and Technology Systems Mini Climate Assessment Model (O^{bj}ECTS MiniCAM). Utilization of residue biomass as an energy source is projected for the next century under different climate policy scenarios. Total global use of residue biomass is estimated to be 20–100 EJ yr⁻¹ by mid- to late- century, depending on the presence of a climate policy and the economics of harvesting, aggregating, and transporting residue. Much of this potential is in developing regions of the world, including China, Latin America, Southeast Asia, and India.

Keywords Bioenergy · Biofuels · Alternative energy · Renewable energy · Sustainable energy · Residue biomass · Climate policy · Integrated assessment

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1 Introduction

Currently, the world consumes nearly 500 EJ of primary energy annually (BP 2008). Eighty-six percent of this energy is in the form of fossil fuels (EIA 2007) (coal, petroleum, and natural gas), resulting in over 8.5 Gt C yr⁻¹ of carbon dioxide (CO₂) emissions (Marland et al. 2009). As global supplies of fossil resources tighten and concerns about climate change mount, interest is growing in biomass energy as a means to replace some part of the energy portfolio currently occupied by fossil fuels. The response to the energy and climate challenges will require a dramatic restructuring of the global energy portfolio, with bioenergy likely to play an increasing role.

Recent years have witnessed a dramatic expansion of bioenergy production, particularly biofuels for the transportation sector, motivated by efforts to increase domestic energy supplies, boost rural agricultural economies, and to reduce greenhouse gas (GHG) emissions by replacing fossil fuels (Kojima and Johnson 2005; Shapouri et al. 2002; Turhollow and Perlack 1991). Between 1997 and 2007, United States (US) ethanol production [almost exclusively from fermenting corn (*Zea mays* L.)] increased by a factor of five (EIA 2008); in the European Union (EU), biodiesel production has increased by a factor of ten (EBB 2008). Total global bioenergy consumption (including fuel wood and traditional biomass) is estimated to have increased by 70% during 1950–2000 (Fernandes et al. 2007).

In the face of such rapid growth, some have expressed concern over the aggressive expansion of bioenergy production, pointing to many potential negative consequences. Land and resource constraints create economic pressure between the various anthropogenic uses of biomass, the so-called six f's (fuel, food, feed, feedstock, fiber, and fertilizer) (Rosillo-Calle 2007). Estimates of food price increases due to increased bioenergy demand have been from 2% to 12% (Ranses et al. 1998) to over 100% (Johansson and Azar 2007). In addition, expansion of biomass production can potentially lead to increases in the conversion of natural areas to agricultural use (Righelato and Spracklen 2007; Wise et al. 2009) and losses in biodiversity (Raghu et al. 2006). Others have expressed concern that the intensification of agriculture that would result from the expanding US bioenergy economy would bring much of the Conservation Reserve Program (CRP) land back into production, leading to a loss of wildlife habitat (Bies 2006). Fargione et al. (2008) recently introduced the idea of a "carbon debt," which occurs when virgin lands, particularly in tropical regions, are converted into bioenergy plantations. Expansion of crops into marginal lands could also exacerbate soil erosion (Kort et al. 1998), increase consumption of water resources (Berndes 2002), and increase nutrient run-off and eutrophication of riparian and aquatic systems (Hill et al. 2006). Furthermore, a number of life-cycle studies have shown that the energy yield (particularly with corn-based ethanol) tends to hover near a break-even balance when accounting for the energy consumed in the production and processing biofuel energy crops (Shapouri et al. 2002).

These drawbacks can be assuaged to some degree by utilizing residue biomass; byproducts of practices already taking place. Current research in bioenergy potential has focused primarily on developing novel, dedicated cropping systems and assessing the potential of dramatically expanding energy crop agriculture [see, for example (Hanegraaf et al. 1998)]. In contrast, less research is being conducted in utilizing residue biomass, though this resource is already produced. Sources of residue biomass include agriculture residue (stalks, stover, chaff, etc.), forestry residue (tree tops, branches, slash), and mill residue (sawdust, scraps, pulping liquors). Utilization of biomass residues allows for the same land and production practices to produce multiple products, reducing both the resource inputs and the demand for land associated with producing dedicated energy crops.

Considering the global magnitude of agriculture and forestry production, residue biomass is potentially a large and under-utilized resource. However, estimates of the magnitude of future residue biomass utilization vary widely (by as much as a factor of five) due to challenges in accurately defining the resource, the high degree of heterogeneity in feedstock sources, the uncertainties in its technical availability and sustainable recoverability, and challenges in determining the economic viability of residue biomass utilization (Rosillo-Calle 2007). Ultimately, utilization of residue biomass is an economic decision, influenced by competing crop and energy prices as well as the price of carbon. The difficulty in tracking the various biomass residue streams led Gillingham et al. (2007) to model residue biomass by calibrating to 1990 values and allowing total production to grow as a function of Gross Domestic Product (GDP) in a study that examined the future potential for bioenergy with respect to projected land and energy demand. Other studies have taken a more detailed approach by assuming some fraction of availability for various residue streams to estimate potential global supply of biomass; Fischer and Schratzenholzer (2001) estimated the 2050 potential for bioenergy from agricultural residues to be 35 EJ yr⁻¹, with another 100 EJ yr⁻¹ from forestry (which includes both forestry residues and purpose-grown forest biomass), based on mean biomass productivity rates and global land cover. In a review of several studies, Hoogwijk et al. (2003) estimated the potential for modern primary energy from biomass residues to range between 30 EJ yr⁻¹ and 108 EJ yr⁻¹ by 2050; about 14 EJ yr⁻¹ are produced currently, largely from mill residues. Of note here is that the range for total modern (as opposed to traditional) biomass utilization (which includes dedicated energy crops) varies widely from 33 EJ yr⁻¹ to 1,135 EJ yr⁻¹, depending on assumptions about the availability of land for biomass crop production. In a hypothetical future scenario where all available cropland is used to produce food and fiber, or where converting virgin land for biomass crop incurs a unacceptable carbon debt (Fargione et al. 2008), then residue biomass could provide the major feedstock for expanding bioenergy production. The objectives of this study are to quantify and characterize the current potential supply of residue biomass, and to model the utilization this resource in the 21st century.

2 Methods

2.1 Current available residue biomass

The framework for projecting the potential for residue biomass functions in two parts. First, the maximum available sustainable supply of biomass residue is estimated based on crop and forestry production statistics and crop-specific parameters. To determine the maximum available supply of biomass residue, national agricultural and forestry production statistics were obtained from the Food and Agriculture Organization of the United Nations (FAO) database (FAOSTAT 2008a, b). For each crop, the harvest index, water content, and residue energy content were estimated from various sources. In addition, for each crop, we estimated an residue retention value- the amount of residue needed to mitigate soil loss and preserve soil nutrients. Taken together these allow an estimate of the total potential supply of residue biomass.

Second, to project the future production of residue biomass, a market is simulated to estimate the fraction of the maximum sustainable supply of residue biomass that would be collected and utilized. The utilization of residue biomass is simulated and projected with an integrated assessment model for the next century for 14 aggregated regions of the world.

The total amount of residue produced is estimated using harvest index (HI_{dry}) statistics, which represent the dry mass ratio of the harvested crop to the total aboveground biomass, taken from the Environment Policy Integrated Climate (EPIC) model inputs (Williams 1990). For root crops, such as sugar beet (*Beta vulgaris* L.), the harvested crop is below ground biomass, and thus these crops can have reported harvest indices greater than one. The harvest index, HI_{root} , is adjusted by the following equation for root crops:

$$HI_{root} = \frac{HI_{dry}}{HI_{dry} + 1}$$

Additionally, for orchard and tree crops, we define the harvest index to be the ratio of the harvested crop mass to the sum of the masses of the harvested crop mass and pruned material. Forest and mill parameters were estimated from Perlack et al. (2005) and from a report to the US Department of Energy National Renewable Energy Laboratory by the Antares Group (1999).

Because crop and forestry production statistics are reported on a wet mass basis, the harvest index is adjusted to account for the mass of water in the crop by the following formula:

$$HI_{wet} = \frac{HI_{dry}}{\text{water content} \cdot (HI_{dry} - 1) + 1}$$

This adjustment allows the determination of residue biomass ratio (dry basis) for every crop in the FAO database by inversion of the HI_{wet} value. The useful form is the *Residue Ratio*, which when multiplied by crop production, gives the total amount of aboveground crop residue:

$$\text{Residue Ratio} = (HI_{wet}^{-1} - 1)$$

Not all residue is logistically harvestable, however. Moreover, additional residue biomass must remain uncollected to sustain soil nutrients and to prevent erosion. While soil nutrient levels and erosion are a function of local topography, climate, soil, and management practices, here we assume a *Residue Retention* parameter, general crop-specific values in terms of mass of residue per unit area to remain on the field.

$$\text{Residue Biomass Available} = \text{Production} \cdot \text{Residue Ratio} - (\text{Residue Retention} \cdot \text{Harvested Area})$$

The initial values for *Residue Retention* parameter are calculated by taking a percentage of the total available residue based on the mean global 1990 and 2005 FAO yield statistics (FAOSTAT 2008a) and the *Residue Ratio* given above. These crop-specific values are then kept constant for all locations and time periods. This allows for greater amounts of residue to be harvested as yields increase, and less residue to be harvested if agriculture expands into marginal land that is more susceptible to soil and nutrient loss. Though historically, harvest indices and the residue ratio has decreased with time through judicious breeding and genetic modification (Sinclair 1998), we assume here that these values will not change much in the future, as the maximum harvest index is limited by nitrogen availability (Sinclair 1998) and some amount of plant structure is necessary to support the food portion of the crop.

For major grain and oil crops [corn, wheat (*Triticum aestivum*), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rapeseed (*Brassica napus* L.), etc.] we assume that the residue retention is 70% of the calculated total available residue (a maximum residue harvest rate of

30%) (Graham et al. 2007; Wilhelm et al. 2007). Likewise, it is assumed that for pruned crops [grapes (*Vitis* spp.), oranges (*Citrus* spp.), tree nuts, etc.] 99% of the estimated residue is recoverable (1% is retained), and for root crops [potatoes (*Solanum tuberosum* L.), sugar beets, etc.]—where the entire plant is harvested—95% of the residue is recoverable (5% retained). For rice (*Oryza sativa*), and all other miscellaneous crops (fruits, vegetables, etc.), it is assumed that 75% of the residue is recoverable (25% retained). These percentages are then converted to crop-specific mass values based on the mean global average 1990 and 2005 production and harvested area statistics in the FAO database (FAOSTAT 2008a) (Table 1). For forests, the residue retention value is estimated to be 20 Mg ha⁻¹ (Table 1), based on recommendations to maintain fungi and soil organic matter; this number is at the upper range recommended by Graham et al. (1994) and the lower range of that recommended by Harvey et al. (1981). As a point of reference, 20 Mg ha⁻¹ would be approximately 25% of the estimated aboveground biomass residue from a 40-year clear cut rotation of Japanese Cedar (*Cryptomeria japonica*) with average productivity (Nishizono et al. 2005). In practice, the residue retention values will vary depending on local climate, soil, topography, and management practices (Gregg and Izaurralde 2010), and therefore these values represent only global averages.

Finally, the net energy content (lower heating values) of residue biomass is estimated on a dry mass basis for each crop (Goswami et al. 2000; Tyagi 1989). For all crop and forest parameters, missing values are estimated by using values for similar crops where data are available.

The maximum supply of agricultural residues is thus a function of crop-specific attributes, crop production, and harvested area. For forestry, two residue streams are considered: timber harvesting residue (tree tops, slash, and branches), and mill residue (wood scraps, sawdust, and recovered pulping liquors). As with agricultural crops, the harvest index, milling efficiencies, wood energy content, and residue retention values are used to estimate the total potential supply of forestry residues (Table 1). Specifically, for a given region and given crop type, the total amount of biomass is estimated by the following formulation:

Maximum Residue Biomass Energy Available

$$= [\text{Production} \cdot \text{Residue Ratio} - (\text{Residue Retention} \cdot \text{Harvested Area})] \cdot \text{Energy Content}$$

Table 1 Summary of input parameters. Presented here are weighted global means; regional values vary based upon the mix of crop and timber production within groups

Residue source	Residue ratio (dry residue mass/wet crop mass)	Residue retention (Mg ha ⁻¹)	Residue energy content (MJ kg ⁻¹)	Curve exponent <i>b</i>	Midprice (2,005\$)
Wheat	1.49	2.81	16.22	10.83	2.08
Rice	0.99	0.94	13.55	10.83	2.08
Corn	0.74	2.20	16.86	10.83	2.08
Other Grain	1.02	1.09	15.20	10.83	2.08
Oil Crops	1.28	1.26	13.26	10.83	2.08
Sugar Crops	0.28	1.24	15.21	10.83	2.08
Misc Crops	0.38	0.38	8.17	10.83	2.08
Timber	0.33	20.00	18.93	7.024	2.48
Mill	0.30	0.00	20.00	3.439	1.46

This formula is used for agricultural, forestry, and mill residue, though for mill residue the residue retention parameter is zero. This formula is employed for all crop types, forestry, and mills, for all countries in the FAO database.

2.2 Future role of residue biomass

To estimate the future role for this resource, the economic dimension is added and the previous parameter estimates are aggregated into 14 world regions (Fig. 1) and seven crop types by using a weighted mean of the 1990 and 2005 FAO (2008a) crop production statistics (Table 1). The economics of harvesting residue biomass is simulated using data generated for the EIA NEMS (Energy Information Administration National Energy Modeling System), a model developed by the US Department of Energy to forecast US energy markets (supply, demand, prices, etc.) in order to inform energy policy decisions (EIA 2003). The input data for the EIA NEMS estimates the amount of biomass energy produced per NEMS coal region in the US given a price for bioenergy. The cost curve data represent the cost for harvesting, aggregating and delivering residue biomass, assuming the maximum economic distance of transportation to be 50 miles (80 km) from farm gate to processing plant. Transport costs, which are included in the cost curves, are assumed to be between \$10 and \$13 (2005\$) per short ton (\$11 Mg^{-1} and \$14 Mg^{-1}) (EIA 2006). For mill wastes, the maximum economic travel distance is 100 miles (160 km) (EIA 2006). Cost of transport for these wastes is calculated stepwise for 25, 50, 75, and 100 miles (40, 80, 120, 160 km) with the price being \$0.26 per short ton–mile (\$0.17 $\text{Mg}^{-1} \text{ km}^{-1}$) (the national average freight shipping rate) and adjusted by state transportation indices (EIA 2006). Furthermore, the EIA assumes that there is no trading across different US coal districts when deriving the point data (EIA 2006). Separate EIA NEMS cost curve data are available for agricultural residue, forestry residue, and mill residue. Moreover, the EIA NEMS projected cost curves evolve through time as biomass harvesting is assumed to become less expensive.

For this study, the regional EIA NEMS cost curves are aggregated into a single set of data points for the entire US, by calculating the mean of estimated residue biomass production at each cost increment. These data points are then converted to relative

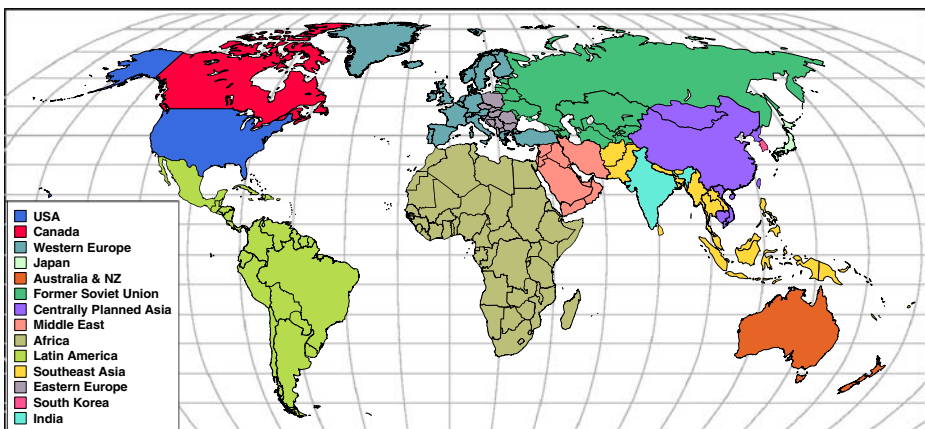


Fig. 1 Map of aggregated world regions for the O^bJECTS MiniCAM

proportions of the maximum production. A logistic curve is fit to these point data and is defined by the following equation:

$$p = \frac{price^b}{Midprice^b + price^b}$$

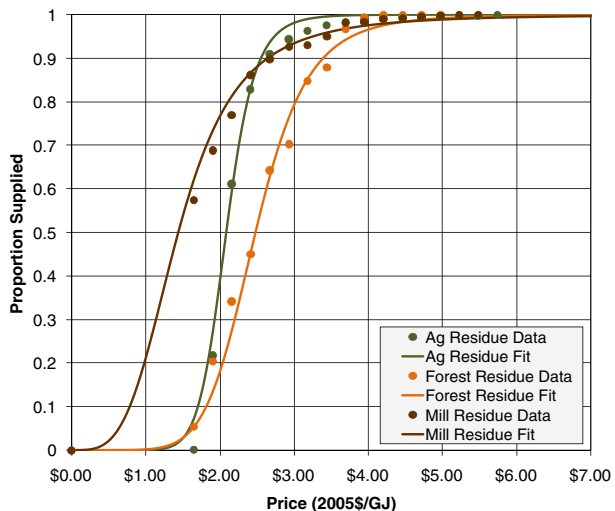
where p is the dimensionless proportion, varying from 0 to 1, of the *maximum residue biomass energy* that is supplied to market. The *price* is the independent variable and represents the equilibrium price for biomass energy in 2005 US dollars per GJ. The curve is defined by the *Midprice*, the price where half of the total available is demanded, and b , an exponent controlling the steepness of the curve. Distinct curves are created for agricultural residue, forestry residue, and mill residue (Fig. 2). However, for this study, it is assumed that there is no regional variability or evolution in the curves and prices for residue biomass; the same curves are used for all 14 regions of the globe and all time steps, though they are scaled to the total available residue supply for each region and time period.

To harvest crop or forest residue, there will be a collection cost and a point where the price for the residue makes collection of residue profitable. Because no global market for residue biomass currently exists (though there has recently been some international trade of wood pellets), there is a lot of uncertainty concerning the form of the cost curve for the future residue biomass market. The NEMS model estimates a steep cost curve: there is small range of prices between very little residue biomass and the near maximum theoretical amount of residue biomass being supplied the market (Haq and Easterly 2006). The sensitivity of the modeling results to these assumptions, which are admittedly uncertain, is examined below.

In future years, the NEMS cost curves evolve with expanding biomass production; however, for purposes of this study, only the initial cost curve is used since we directly account for expanding residue biomass production by modeling future agriculture and forestry production with an integrated assessment model, the Object-Oriented Energy, Climate, and Technology Systems Mini Climate Assessment Model (O^{bj}ECTS MiniCAM).

Global and regional supply and demand for energy from residue biomass is modeled with the O^{bj}ECTS MiniCAM, a modular, object-oriented, partial equilibrium, integrated economic model that simulates long term changes in energy markets, land use, and

Fig. 2 Cost curves for residue biomass from agriculture, forestry, and mills. Data from EIA NEMS (2003). See Table 1 for curve fit parameters



greenhouse gas emissions over the next century under various GHG stabilization climate policy scenarios. Development of the general model structure can be found in Edmonds et al. (2004) and is based on Edmonds and Reilly (1985). The model operates on 15-year time steps from 1990 to 2095 for 14 aggregated regions of the world (Fig. 1), and uses current aggregated economic, demographic, energy consumption, agricultural, forestry, and land use data to calibrate the historical years of 1990 and 2005. For each region, the model estimates GDP based on assumptions about labor productivity and then estimates energy demand by end use. The model is designed to simulate, under various carbon markets, the integrated interactions between energy production (coal, petroleum, natural gas, nuclear, solar, geothermal, hydro, wind, biomass, and future exotic energy sources), energy transformation (e.g., refining, electricity production, hydrogen production), energy end use (buildings, industry, transportation), agricultural production (corn, wheat, rice, other grains, oil crops, sugar crops, fiber crops, fodder crops, miscellaneous, and biomass crops), forestry and forest production (both for managed and unmanaged forestland), rangeland and animal production, as well as land allocation dynamics. The O^{bj}ECTS MiniCAM employs the Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC), a simple climate model, which balances equations for sources and sinks of carbon across six reservoirs (ocean, atmosphere, and four terrestrial types) and estimates a range of feedbacks based on modeled temperature changes (Wigley 1993). Both the O^{bj}ECTS MiniCAM and MAGICC have been used in numerous IPCC reports to develop emissions and climate scenarios.

The projected global economic development and population growth pathways are from Clarke et al. (2007), a scenario similar to the IPCC B2 scenario from the Special Report on Emissions Scenarios (SRES) (Nakićenović et al. 2000). This scenario features a continuously growing population (leveling off at about 9.5 billion people by the end of the century), and intermediate economic growth (Clarke et al. 2007). Global policy GHG stabilization pathways are based on Wigley et al. (1996) and are designed to optimally reach the target atmospheric CO₂ concentration by the end of the century. For this study, the O^{bj}ECTS MiniCAM is used to simulate the future market for residue biomass under both a reference scenario and a policy scenario that reaches 450 ppm atmospheric concentration of CO₂ by the end of the century.

3 Results and discussion

3.1 Current available residue biomass

In 2005, if all sustainably collectable residue were converted to energy, it could have supplied nearly 50 EJ to the global energy market (Table 2), roughly half the annual energy consumption of the US. Table 2 gives the leading countries in terms of total potential residue biomass available in 2005, as well as its source. Major agricultural producers such as China, India, and the US, top the list, each with the potential to produce about 5 EJ yr⁻¹ or greater from this resource.

The relative size of the 2005 potential resource by continent is shown in Figs. 3, 4, 5, 6, 7, and 8, though the scales change between figures. In Africa, the majority of the current potential residue biomass is primarily in forestry and mill residues, and miscellaneous crops (Fig. 3). Nigeria, Ethiopia, and Egypt represent the countries within Africa with the largest estimated amount of residue biomass available, with Egypt the only country in Africa with significant grain residue. China and India are the main countries in Asia with respect to

Table 2 Potential residue biomass energy for 2005 (EJ). Listed countries could produce over 1 EJ yr⁻¹ of bioenergy from current residue biomass

Residue source	Wheat	Corn	Rice	Other grain	Oil crops	Sugar crops	Misc crops	Forest	Mill	Total
China	1.31	0.76	2.07	0.10	0.92	0.41	0.45	0.35	0.77	7.13
United States	0.49	2.39	0.12	0.15	0.53	0.13	0.10	0.47	1.07	5.44
India	0.45	0.00	1.31	0.08	0.28	1.10	0.24	0.64	0.77	4.86
Brazil	0.00	0.01	0.13	0.02	0.20	1.97	0.30	0.51	0.59	3.73
Indonesia	0.00	0.02	0.57	0.00	1.53	0.14	0.22	0.21	0.24	2.93
Malaysia	0.00	0.00	0.02	0.00	1.72	0.01	0.01	0.06	0.05	1.87
Canada	0.20	0.08	0.00	0.13	0.18	0.00	0.05	0.24	0.49	1.36
France	0.65	0.11	0.00	0.18	0.13	0.02	0.04	0.07	0.14	1.33
Nigeria	0.00	0.00	0.02	0.10	0.32	0.00	0.47	0.15	0.16	1.23
Germany	0.43	0.03	0.00	0.26	0.14	0.02	0.02	0.06	0.12	1.08
Global total	5.58	4.16	6.51	2.01	7.41	6.17	3.89	5.14	7.85	48.71

residue biomass availability (Fig. 4). This biomass is primarily in the form of wheat stalks and rice stalks in China and sugarcane bagasse and rice stalks in India. Oil palm residue from Indonesia and Malaysia is also substantial potential residue biomass resource (Fig. 4). In Europe, wheat straw is the major component to residue biomass, except in northern Europe and the Russian Federation where forest and mill residue potentially plays a larger role (Fig. 5). France, Germany, and the Russian Federation are the countries with the greatest amount of residue biomass in Europe (Fig. 5). In North America, the US is the leading country in terms of the size of the residue biomass resource, primarily in the form of corn stover, and mill residue (Fig. 6). In Canada, the forests and mills provide a larger proportion of residue biomass and in Mexico sugarcane bagasse is a larger potential resource than the US (Fig. 6). Sugarcane bagasse is also the dominant source of residue biomass in Australia, the leading producer of residue biomass in Oceania (Fig. 7), though the amount of residue available in Oceania is considerably smaller than that of other continents. Residue biomass in South America is also dominated by sugarcane bagasse, primarily in Brazil (Fig. 8).

In the 21st century, as global population expands and demand for food and forest products increase, the potential residue biomass supply is expected to also increase. Increasing global crop production is expected to occur through increasing crop yields on current agricultural land, and through bringing more land into production. Assumptions about the future trends of crop yields and agricultural expansion affect the cost and the total future sustainable supply of this resource.

3.2 Future role of residue biomass

To project future scenarios, the price for biomass is computed based on total energy demand and the prices for competing sources of energy. Under a climate policy scenario, fossil energy sources become more expensive; thus demand and price for biomass increase. In the policy scenario, the total available supply of residue biomass (~84 EJ yr⁻¹) is projected to be utilized as energy by mid- to late-century (Fig. 9b and d). In the reference scenario, with no price of carbon, much of the residue biomass is still utilized as energy demand and

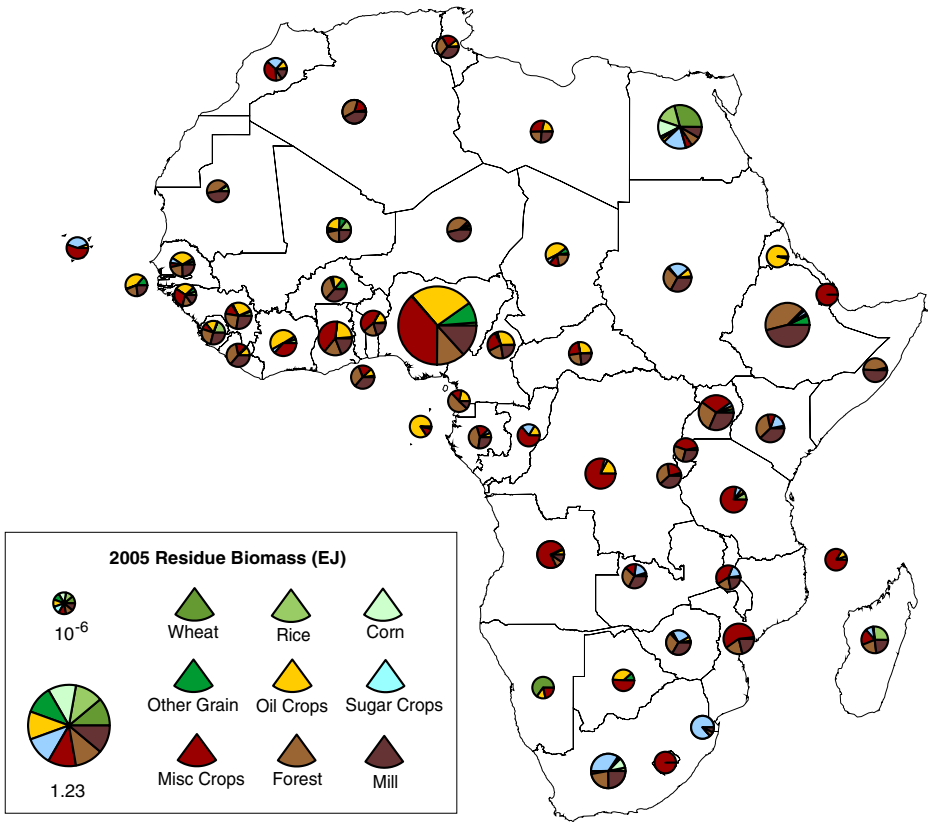


Fig. 3 Potential bioenergy from residue biomass sources, Africa, 2005

energy prices increase, reaching a projected global output of approximately 75 EJ yr^{-1} (Fig. 9a and c).

Centrally Planned Asia (China), Latin America, Southeast Asia, and India have the highest residue biomass production; each of these regions could produce over 10 EJ yr^{-1} from this resource, particularly under a climate policy scenario (Fig. 2b). Though the composition of the residue varies from region to region (China and Southeast Asia are projected to produce more rice straw, Latin America is projected to produce more timber residue, etc.), globally, mill residues represent the largest utilized resource, followed by oil crops, wheat, sugar crops, rice, miscellaneous crops, corn, forest, then other grains (Fig. 2c and d).

Given the cost curve and assumed price structures, residue biomass, which requires no additional land to produce, is more economically competitive than dedicated biomass crops [e.g., switchgrass (*Panicum virgatum*) or hybrid poplar (*Populus spp.*)]. For example, in the 450 ppm CO_2 atmospheric concentration policy scenario, residue biomass meets nearly all the current biomass energy demand, over two-thirds by mid century, and still over half by the end of the century. Dedicated biomass becomes economical at higher biomass prices when the maximum global output of residue biomass approximates 90 EJ yr^{-1} . Dedicated biomass is projected to contribute an additional 65 EJ yr^{-1} of energy by the end of the century, but is generally more expensive if land carbon is incorporated in the price of production as assumed in these scenarios (Wise et al. 2009).

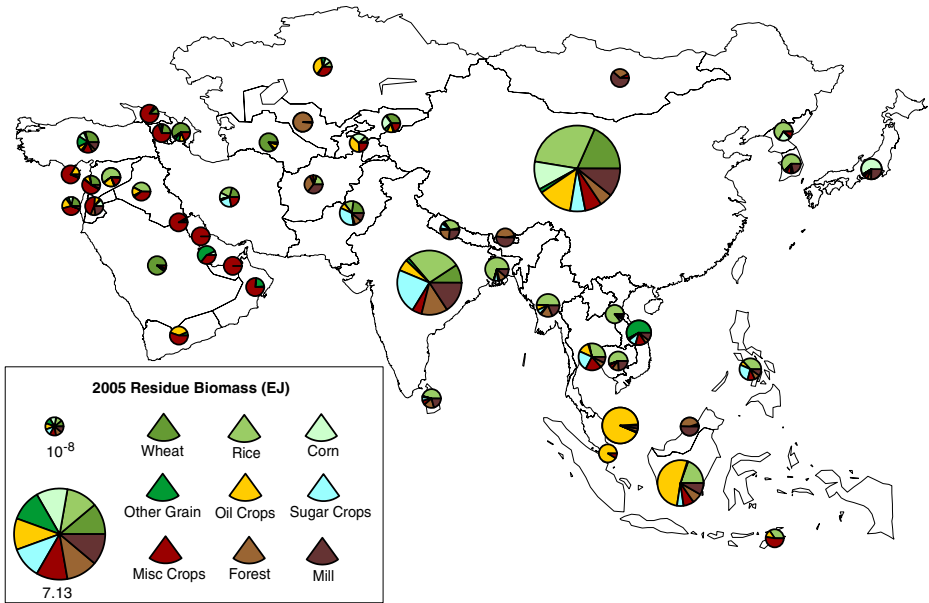


Fig. 4 Potential bioenergy from residue biomass sources, Asia, 2005

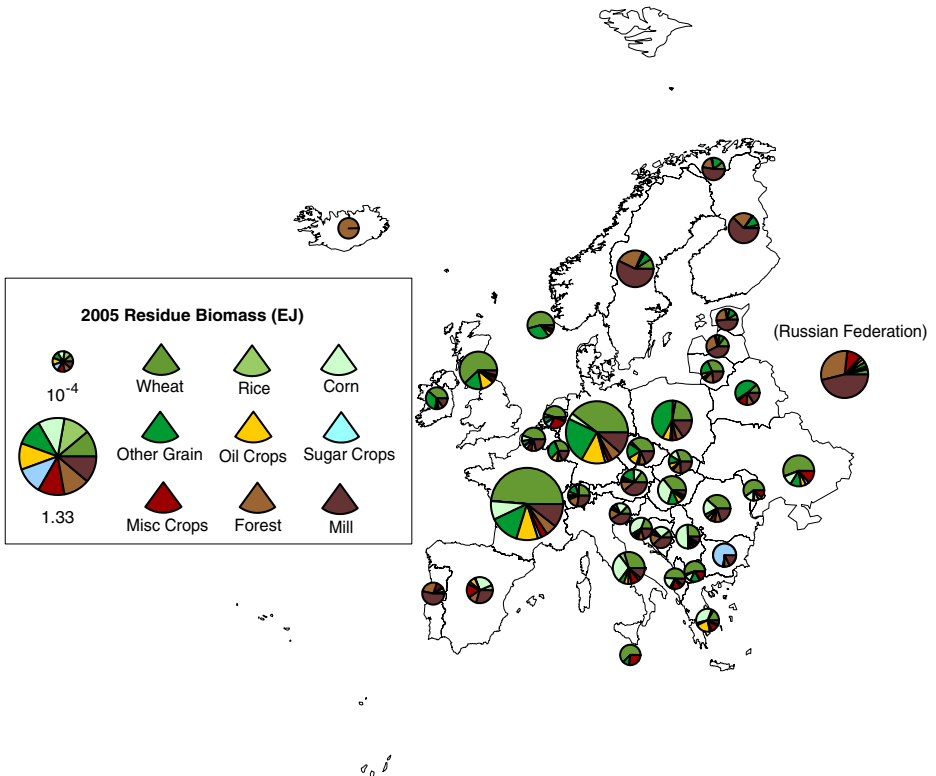


Fig. 5 Potential bioenergy from residue biomass sources, Europe, 2005

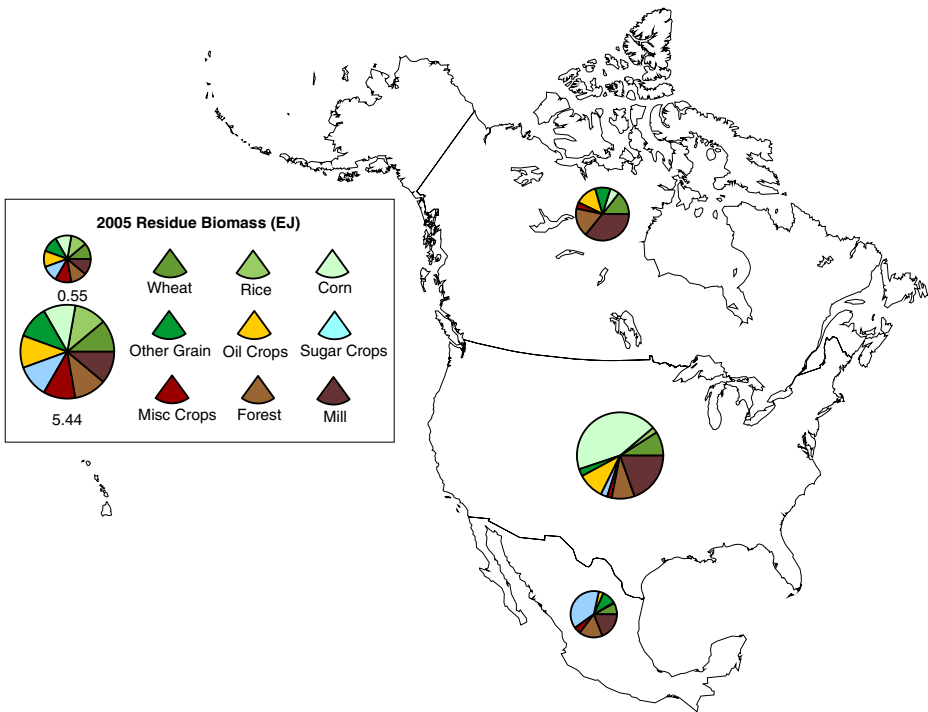


Fig. 6 Potential bioenergy from residue biomass sources, North America, 2005

While this resource requires little new technology to produce (it is already available as a co-product of farming and forestry), full utilization will depend on technological and economic optimization of processing mixed streams of biomass feedstocks. This could include co-firing for electricity, pyrolysis and gasification (perhaps with biochar returned to the soil), or conversion of cellulose to ethanol. Figures 3, 4, 5, 6, 7, and 8 suggest that biomass processing facilities would receive feedstocks from seasonally consistent sources and thus the engineering processes may be optimized for the local feedstocks and energy markets (i.e., liquid fuels, electricity, etc.).

4 Sensitivity analysis

The limiting factors for supply of residue biomass feedstock are both physical and economic. Physical factors include assumptions about future agricultural and forest productivity, and the amount of residue that must be left on the field to mitigate soil erosion and maintain soil nutrients (the residue retention parameter). Economic factors include the cost of collection, aggregation, and transport—captured by the *Midprice* parameter—and assumptions about the shape of the cost curve (*b*) as parameterized in the equations. Because no large-scale energy market currently exists that demands residue biomass, projection of future utilization depends on assumptions about these initial conditions. Therefore, a series of sensitivity tests were conducted to determine the effect these parameters have on the projected utilization or residue biomass.

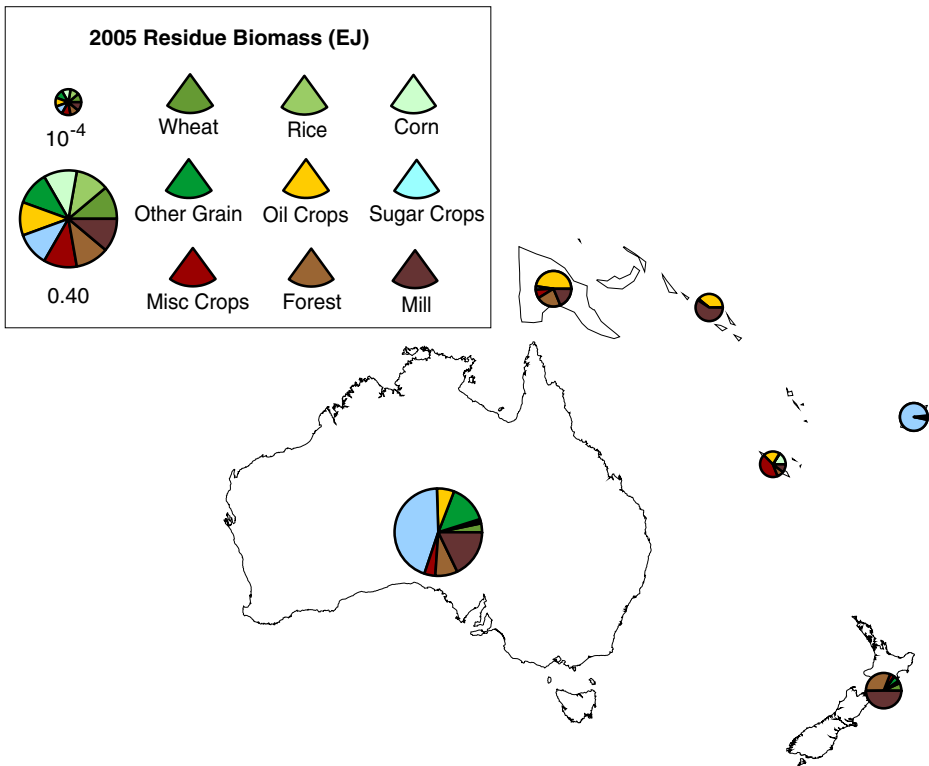


Fig. 7 Potential bioenergy from residue biomass sources, Oceania, 2005

The largest uncertainty for projecting the amount of energy from residue biomass in the future rests in assumptions about future crop productivity. The default scenarios assume modest increases in agricultural yields for the rest of century, in line with historical increases in crop yields. This reference scenario is based on a FAO report that projects crop yield change to 2030, and assumes yields improve at a slightly faster rate in the developing world, and retain the historical yield increase rate for the developed world. After 2030, we assume the yield changes converge to 0.25% by 2050 for all crops in all regions. Two other scenarios were tested, one in which agricultural yields were held steady at current levels (no yield increases), and one assuming advanced technological developments that increase crop yields dramatically (approximately double the reference rate) in the next century. Assumptions about future agricultural yields have a large impact on residue availability, more so than the presence of a climate policy (Fig. 10a). More residue is expected to be supplied under the reference scenario with high or default yield assumptions than the policy scenario with a low yield assumption (Fig. 10a). This is because as yields increase, more residue becomes available (Fig. 10b). Thus, more residue can be supplied to as an energy feedstock (Fig. 10a). This effect could be more pronounced than modeled here, because if there is more residue available per area, per mass collection costs would likely decrease and the cost curve would change accordingly. The magnitude of the yield effect is non-linear, however, because if future yields are high for all crops, there would be more agricultural land available to grow dedicated biomass, it would be less expensive to produce (because of

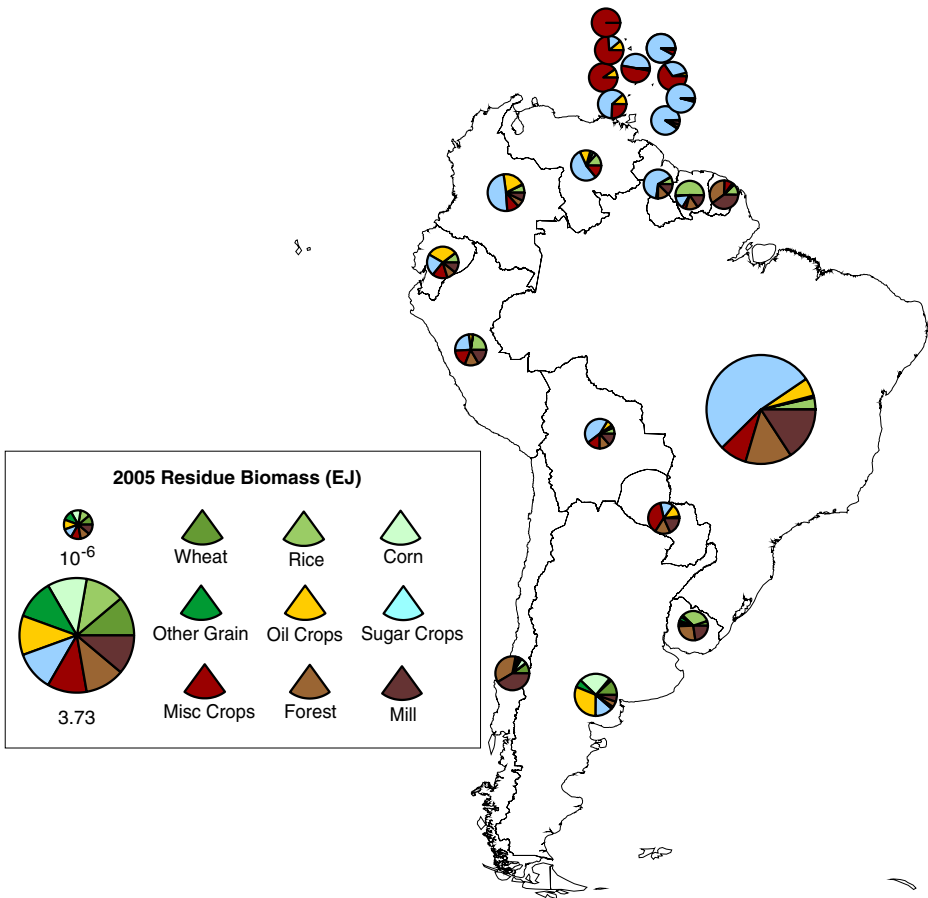


Fig. 8 Potential bioenergy from residue biomass sources, South America, 2005

higher yields), and would therefore be more competitive with residue biomass by the end of the century.

On the other hand, if yields do not increase much in the future, agriculture must expand into less fertile land to produce more food for the growing world population. In this scenario, residue is spread out over larger areas, a higher proportion of the residue must remain on the field to mitigate erosion and less residue biomass is projected to be supplied as an energy feedstock.

The residue retention parameter was also tested by altering the initial default values by 50% and 200%. More stringent residue retention requirements reduce the amount of residue supplied. Varying the residue retention parameter by 50–200% of the default value has about a 35% effect on the global residue supplied by the end of the century (Fig. 10c), and little effect on the projected price (Fig. 10d). Because the various streams of residue are substitute goods, the market demands more residue from sources that do not have strict residue retention requirements, such as rice stalks and mill residue. On the other hand, high residue retention requirements significantly reduce the amount of residue available from dry field crops such as corn, wheat, and other grains (Fig. 11a). Forest residue is almost unavailable if the residue retention parameter is 40 Mg ha^{-1} (200% the default value in

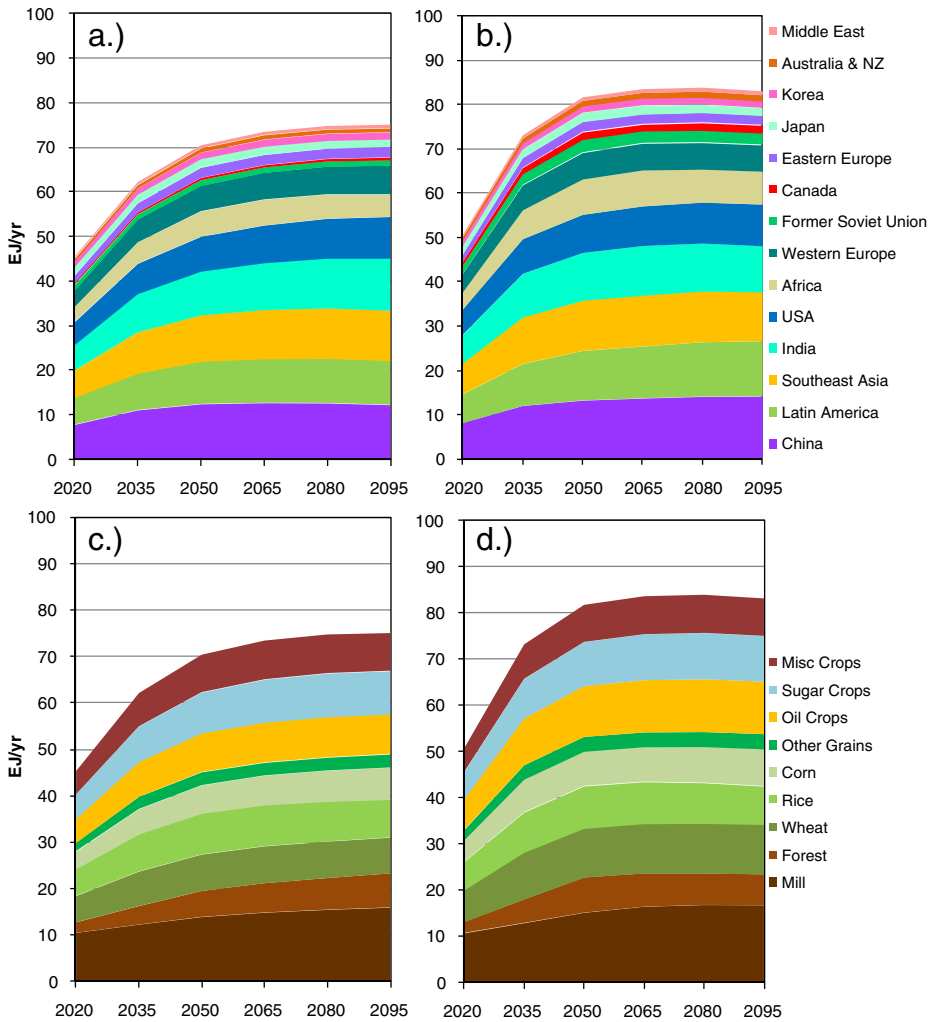


Fig. 9 Projected residue biomass energy utilization for the next century. **a** Spatial distribution of residue projected biomass energy distribution, reference scenario (no climate policy). **b** Spatial distribution of projected residue biomass energy distribution, policy scenario (450 ppm atmospheric concentration of CO₂). **c** Composition of projected global residue energy utilized, reference scenario. **d** Composition of projected global residue biomass energy utilized, policy scenario

Table 1), though evidence suggests that this would be counter-productive to ecosystem health (Harvey et al. 1981). As a result, high residue retention requirements do not affect regions such as Southeast Asia, Korea and Japan (which have a larger proportion of residue in the form of rice, mill, and non-field oil crops) as much as the US, Canada, Eastern Europe and the Former Soviet Union (which have a larger proportion of residue in the form of dry grains and forestry) (Fig. 11b). In the model, residue retention only affects the maximum potential residue supply for each crop; no feedbacks are modeled between unsustainable residue retention, yield, collection price, and chemical inputs. If, for example, unsustainable residue removal were to reduce crop productivity, then the residue retention

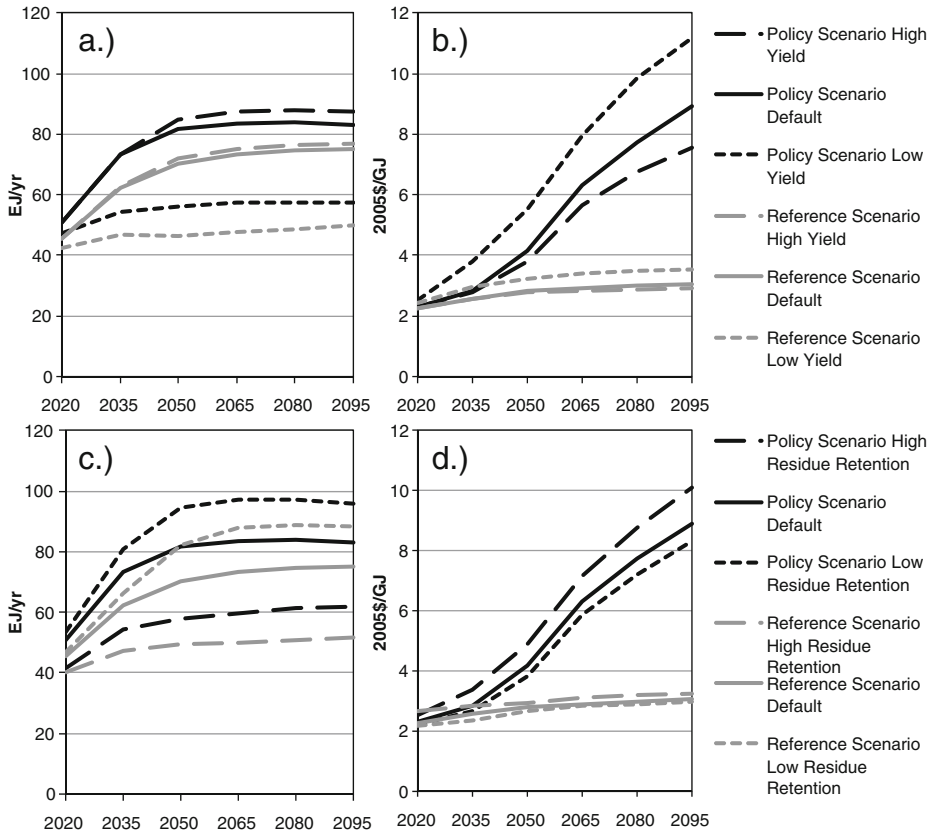


Fig. 10 Sensitivity test of physical parameters. **a** Projected residue biomass energy in scenarios where future agricultural productivity is varied from high yield, default yield (continued historical yield increases) and low yield (no increases from current observed yields). **b** Projected biomass price for agricultural productivity scenarios. **c** Projected residue biomass energy in scenarios where the *residue retention* values are varied from 150% of default values to 50% of default values. **d** Projected biomass price for *residue retention* scenarios

variable could have a much larger effect on global residue supply, as seen in Fig. 10a and b when assumptions about future crop yields were varied.

In terms of the economic assumptions, the *Midprice*, which would represent the average cost of collecting, processing and delivering this resource. Changes in this parameter will either advance (in a scenario where the *Midprice* values are 50% of the default values) or delay (in a scenario where the *Midprice* values are 200% of the default values) the utilization of biomass residue (Fig. 12a). This variable makes little difference in the projected total supply delivered by the end of the century, except in the reference scenario with high *MidPrice* (Fig. 12a). In that scenario, the equilibrium price for residue biomass never gets above the *Midprice* (Fig. 12b) and most of the biomass demand is met by dedicated biomass crops. Under the high *Midprice* scenario without a climate policy, most residue biomass is too expensive to collect, and only a meager amount is supplied to the market, primarily from less expensive mill residue. Thus, the reference scenario is more sensitive to the *Midprice* variable than the policy scenario, because the under the policy scenario, where premiums on carbon-intensive fuels drive up the price for all fuels, the

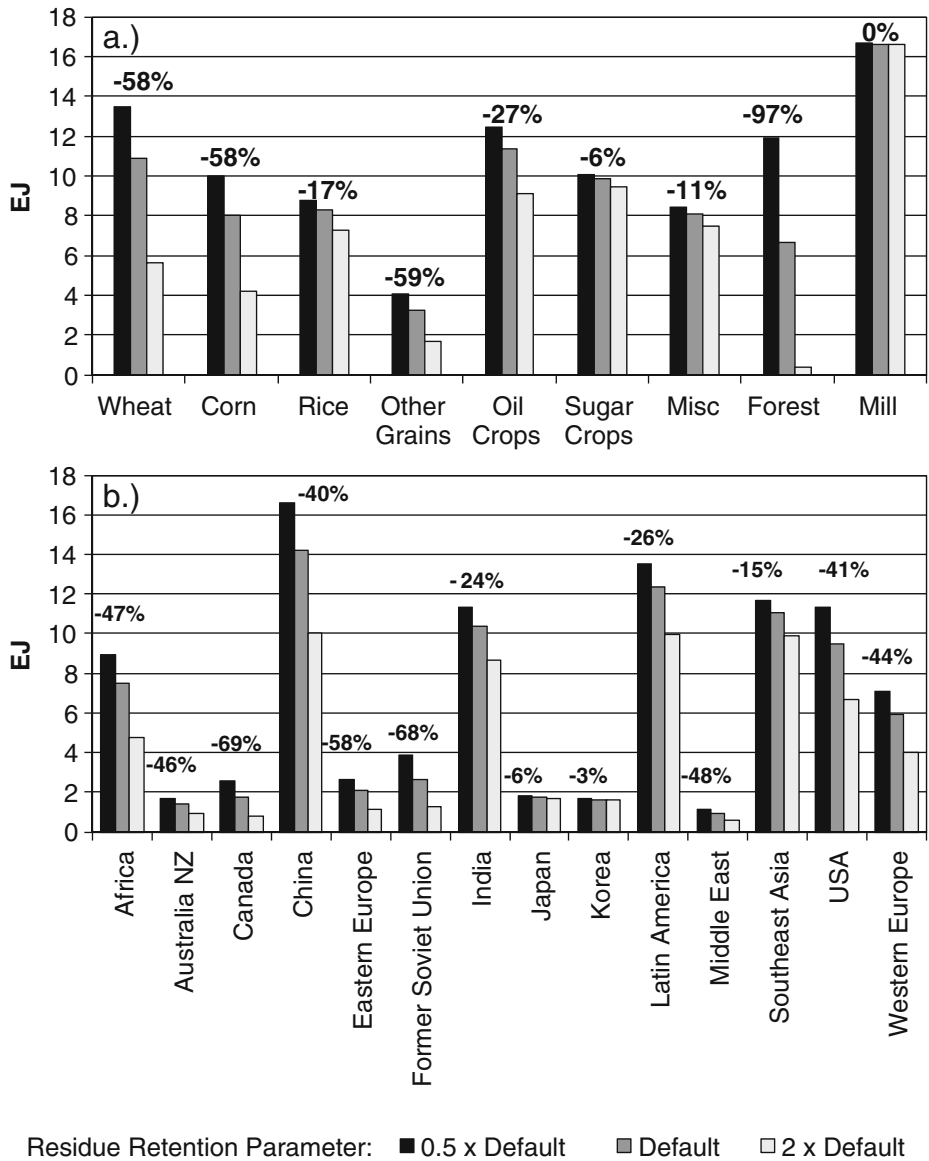


Fig. 11 The effect of varying the residue retention parameter (from 50% the default value to 200% the default value) on consumption of residue biomass energy by **a** region, and **b** resource. Default residue retention values are crop specific and given in Table 1. A climate policy scenario was used and end of century (2095) values were compared to closely approximate a situation where maximum potential residue biomass available is utilized. Percentages represent the difference between the high and low values

equilibrium price is high enough to accommodate a high value for the *Midprice*. In other words, the presence of a climate policy is able to drive the price for biomass high enough (because to the carbon premium added to fossil fuels) to maximize the supply despite a higher cost for residue collection and processing.

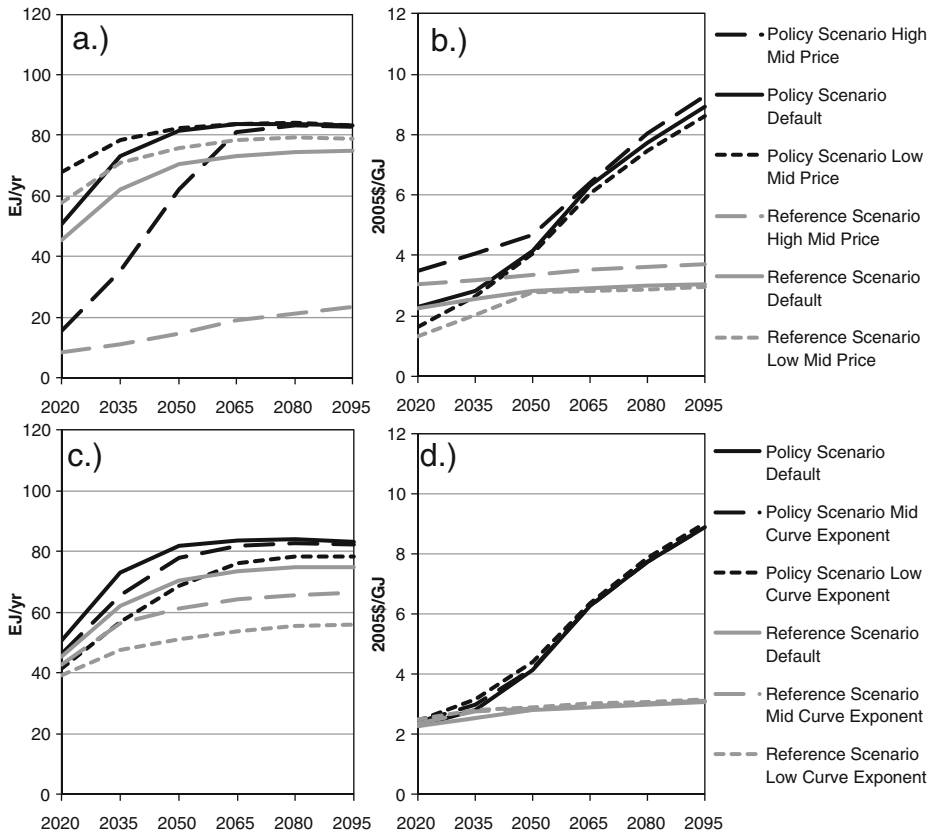


Fig. 12 Sensitivity test of economic parameters. **a** Projected residue biomass energy in scenarios where *Midprice* values are varied from 50% of default values to 200% of default values. **b** Projected biomass price for *Midprice* scenarios. **c** Projected residue biomass energy in scenarios where the curve exponent, *b*, values are varied from 150% default values to 50% default values. **d** Projected biomass price for curve exponent scenarios

The EIA NEMS model assumes a steep cost curve (high elasticity of supply) (EIA 2003; Haq and Easterly 2006), so once the price increases slightly beyond the *Midprice*, the supply of residue biomass is maximized, and as the price continues to rise beyond this point, dedicated biomass crops are necessary to meet demand. Reducing the curve exponent (*b*) to 25% and 50% the default values has a similar effect to increasing the *Midprice*, in that it takes longer to maximize the utilization of residue biomass (Fig. 12c). Altering the curve exponent has little effect on the price of biomass (Fig. 12d), but it allows for a more gradual development of both residue biomass and dedicated biomass crops.

5 Conclusions

Our global analysis of crop and forestry statistics indicates that approximately 50 EJ yr⁻¹ of residue biomass is currently available on a sustainable basis. The principal source of uncertainty in this estimate is the amount of residue that needs to be left behind to reduce soil erosion. The potential supply of residue biomass increases over the 21st century to

perhaps twice the current figure, as the scale of agricultural and forestry activities expand to meet the food and fiber needs of a more affluent and larger world population. In addition to residue retention constraints, the future potential supply of residue biomass depends on the degree to which agricultural yields increase. An increase in yields has a twofold impact on residue supply: increased product yields imply increased residue production, and increased yields mean that more residue per unit area can be sustainably removed without a large increase in erosion and impacts on crop productivity.

The amount of biomass that is used depends on the cost of collecting and processing residues, the cost of competing energy technologies, and any environmental incentives. We find that, residue biomass is projected to be increasingly used by mid- to late- century for bioenergy production. In the reference scenario, between 20–75 EJ yr⁻¹ of residue biomass is projected to be produced globally. This wide variation, for a reference scenario without climate policy, is due to differences in both economic assumptions regarding the cost of residue collection, and physical assumptions regarding the total amount of sustainable residue available. In climate policy scenarios, where a premium is paid for carbon-free energy such as residue biomass, nearly all of the potential residue biomass resource is used for energy with projected use increasing to 60–100 EJ yr⁻¹ globally. Assumptions about collection costs have little impact later in the century on policy scenarios as costs for residue biomass become low relative to alternatives. The primary uncertainty in policy scenarios are the assumptions on residue retention requirements and future agricultural productivity.

The International Energy Agency (IEA) (2006) estimates that 45 EJ of primary solid biomass was consumed globally in 2005, of which 70% is consumed in the residential sector, primarily in developing countries. It is not clear how much of this is sustainably produced biomass as defined here; it is likely that much, if not the majority, of the biomass used in developing countries is from unsustainable collection and deforestation. The projections presented here, therefore, imply a large increase in the fraction of sustainable residue biomass that is used for energy purposes. This near-term increase is a consequence of the steep shape of the default cost curve used here. In the near-term, the utilization of residue biomass is likely to be highly sensitive to the cost of collection and processing. The cost curves used in this study are specific to the US and further research in this area would be valuable to better elucidate the near-term trajectories for residue biomass consumption.

In the long-term, however, we find that collection and processing costs have little impact once the carbon price, the premium that is paid for carbon-free energy, increases under a climate policy. This is because the carbon price is controlled by the marginal cost of mitigation, that is the cost of the most expensive option that has been put into place. Residue biomass is a low-cost option that is utilized early once climate policy is put into place. At this point, the primary determinants of residue biomass supply are changes in agricultural productivity and constraints imposed due to residue retention for erosion control. For this study a generic crop-specific formulation of residue retention for erosion control in terms of Mg ha⁻¹ of residue retained in the field was applied. This may prove to be overly simplistic, and a further elaboration of the tradeoffs in terms of soil nutrients, crop yields, and erosion that come with the removal of crop residues is needed.

Removal of residue will reduce the carbon entering the soil, though this can be alleviated to some extent with conservation management practices (Gregg and Izaurralde 2010). Furthermore, even if no residue is harvested, the majority of the residue carbon is returned to the atmosphere (Huggins et al. 2007). On the whole, while long-term soil carbon could be reduced in agricultural land, net emissions to the atmosphere will be reduced if residue biomass energy is used in place of fossil energy.

Given the potential for bioenergy from residue biomass, further research is needed as to how to most sustainably harvest this resource, and how to most efficiently convert it to energy. Certainly a number of logistical and technological challenges will need to be addressed. Inter-annual variability in local residue production will need to be buffered by appropriate storage and transport systems, coupled with national and international biomass markets. The ability to use residue from different sources interchangeably at the end-use, would also help buffer local variations in supply, although this is likely easier to achieve for combustion and gasification technologies than for biologically-based technologies such as cellulosic ethanol conversion. Assessing the potential for energy from residue biomass given the economic conditions and the climate policy landscape is essential to forming prudent decisions about our future energy portfolio. Our finding that residue biomass is likely to be heavily utilized under a climate policy implies that policies need to be in place to ensure that residue removal is conducted in a sustainable manner.

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References

- Antares Group I (1999). Biomass residue supply curves for the United States (Update), Report for the U.S. Department of Energy and the National Renewable Energy Laboratory. Landover, MD
- Berndes G (2002) Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. *Glob Environ Change* 12:253–271
- Bies L (2006) The biofuels explosion: is green energy good for wildlife? *Wildl Soc Bull* 34(4):1203–1205
- BP (2008) Statistical review of world energy, <http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622>
- Clarke LE, Edmonds JA, Jacoby HD, Pitcher HM, Reilly JM, Richels RG (2007) Scenarios of greenhouse gas emissions and atmospheric concentrations; and review of integrated scenario development and application. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington
- Edmonds J, Reilly J (1985) *Global energy: assessing the future*. Oxford University Press, Oxford
- Edmonds JA, Clarke J, Dooley J, Kim SH, Smith SJ (2004) Stabilization of CO₂ in a B2 world: insights on the roles of carbon capture and storage, hydrogen, and transportation technologies. *Energy Econ* 26:517–537
- Energy Information Administration (EIA) (2003) The national energy modeling system: an overview 2003. U.S. Department of Energy (D.O.E.), Washington
- Energy Information Administration (EIA) (2006) Model documentation renewable fuels module of the national energy modeling system. Office of Integrated Analysis and Forecasting, Coal and Electric Power Division, Department of Energy, Washington
- Energy Information Administration (EIA) (2007) Table 1.8: World consumption of primary energy by energy type and selected country groups. Department of Energy, Washington, <http://www.eia.doe.gov/iea/wecbtu.html>
- Energy Information Administration (EIA) (2008) Monthly oxygenate report, form EIA-819. Department of Energy, Washington, http://www.eia.doe.gov/oil_gas/petroleum/data_publications/monthly_oxygenate_telephone_report/motr.html
- European Biodiesel Board (EBB). (2008). Statistics—the EU biodiesel industry. Bruxelles, Belgium, <http://www.ebb-eu.org/stats.php>
- FAOSTAT (2008a) Production statistics: crops (Publication). Retrieved October 8, 2009, from Food and Agriculture Organization of the United Nations (FAO): <http://faostat.fao.org/site/567/default.aspx>

- FAOSTAT (2008b) Production statistics: forests (Publication. Retrieved October 8, 2009, from Food and Agriculture Organization of the United Nations (FAO): <http://faostat.fao.org/site/381/default.aspx>
- Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science* 319:1235–1238
- Fernandes SD, Trautmann NM, Streets DG, Roden CA, Bond TC (2007) Global biofuel use, 1850–2000. *Glob Biogeochem Cycles* 21:GB2019. doi:10.1029/2006GB002836, 1–15
- Fischer G, Schrattenholzer L (2001) Global bioenergy potentials through 2050. *Biomass Bioenergy* 20:151–159
- Gillingham KT, Smith SJ, Sands RD (2007) Impact of bioenergy crops in a carbon dioxide constrained world: an application of the MiniCAM energy-agriculture and land use model. *Mitig Adapt Strat Glob Change*. doi:10.1007/s11027-11007-19122-11025
- Goswami DY, Kreith F, Kreider JF (2000) Principles of solar engineering, 2nd edn. Taylor & Francis, Philadelphia
- Graham RT, Harvey AE, Jurgensen MF, Jain TB, Tonn JR, Page-Dumroese DS (1994) Managing coarse woody debris in forests of the Rocky Mountains. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden
- Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL (2007) Current and potential U.S. corn stover supplies. *Agron J* 99:1–11
- Gregg JS, Izaurrealde RC (2010) Effect of crop residue harvest on long-term crop yield, soil erosion and nutrient balance: trade-offs for a sustainable bioenergy feedstock. *Biofuels* 1(1):69–83
- Hanegraaf MC, Biewinga EE, Van der Bijl G (1998) Assessing the ecological and economic sustainability of energy crops. *Biomass Bioenergy* 15(4/5):345–355
- Haq Z, Easterly JL (2006) Agricultural residue availability in the United States. *Appl Biochem Biotechnol* 129–132:3–21
- Harvey AE, Jurgensen MF, Larsen MJ (1981) Organic reserves: importance to ectomycorrhizae in forest soils of Western Montana. *For Sci* 27(3):442–445
- Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *PNAS* 103(30):11206–11210
- Hoogwijk M, Faaij A, Van der Broek R, Berndes G, Gielen D, Turkenburg W (2003) Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy* 25(2):119–133
- Huggins DR, Allmaras RR, Clapp CE, Lamb JA, Randall GW (2007) Corn–soybean sequence and tillage effects on soil carbon dynamics and storage. *Soil Sci Am J* 71(1):145–154
- International Energy Agency (IEA) (2006) Renewables information with 2005 data. OECD/IEA, Paris
- Johansson DJA, Azar C (2007) A scenario based analysis of land competition between food and bioenergy production in the US. *Clim Change* 82:267–291
- Kojima M, Johnson T (2005) Potential for biofuels for transport in developing countries. United Nations Development Programme/World Bank: Energy Sector Management Assistance Programme (ESMAP), Washington
- Kort J, Collins M, Ditsch D (1998) A review of soil erosion potential associated with biomass crops. *Biomass Bioenergy* 14(4):351–359
- Marland G, Boden TA, Andres RJ (2009) Global, regional, and national CO₂ emissions. In: Trends: a compendium of data on global change (vol. doi:10.3334/CDIAC/00001). Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, http://cdiac.ornl.gov/trends/emis/overview_2006.html
- Nakićenović N, Alcamo J, Davis G, de Vries B, Fenham J, Gaffin S et al (2000) Special report on emissions scenarios: a special report of Working Group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Nishizono T, Iehara T, Kuboyama H, Fukuda M (2005) A forest biomass yield table based on an empirical model. *J For Res* 10:211–220. doi:10.1007/210310-210004-210133-210318
- Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC (2005) Biomass as a feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Laboratory, Oak Ridge
- Raghu S, Anderson RC, Daehler CC, Davis AS, Wiedenmann RN, Simberloff D et al (2006) Adding biofuels to the invasive species fire? *Science* 313:1742
- Ranses A, Hanson K, Shapouri H (1998) Economic impacts from shifting cropland use from food to fuel. *Biomass Bioenergy* 15(6):417–422
- Righelato R, Spracklen DV (2007) Carbon mitigation by biofuels or by saving and restoring forests? *Science* 317:902
- Rosillo-Calle F (2007) Overview of biomass energy. In: Rosillo-Calle F (ed) The biomass assessment handbook. Earthscan, London, pp 1–25

- Shapouri H, Duffield JA, Wang M (2002) The energy balance of corn ethanol: an update. United States Department of Agriculture (USDA), Office of the Chief Economist, Office of Energy Policy and New Uses, Washington
- Sinclair T (1998) Historical changes in harvest index and crop nitrogen accumulation. *Crop Sci* 38(3):638–643
- Turhollow AF, Perlack RD (1991) Emissions of CO₂ from energy crop production. *Biomass Bioenergy* 1(3):129–135
- Tyagi PD (1989) Fuel from wastes and weeds. Batra Book Service, New Delhi
- Wigley TML (1993) Balancing the carbon budget. Implications for projections of future carbon dioxide concentration changes. *Tellus* 45B:409–425
- Wigley TML, Richels R, Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO₂ concentrations. *Nature* 379:240–243
- Wilhelm WW, Johnson JME, Karlen DL, Lightle DT (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. *Agron J* 99(6):1665–1667
- Williams JR (1990) The erosion productivity impact calculator (EPIC) model: a case history. *Phil Trans Roy Soc London* 329:421–428
- Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R et al (2009) Implications of limiting CO₂ concentrations for land use and energy. *Science* 324:1183–1186