# *Assessing Sustainable Bioenergy Feedstock Production Potential by Integrated Geospatial Analysis of Land Use and Land Quality*

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**BioEnergy Research**

ISSN 1939-1234

Bioenerg. Res.
DOI 10.1007/s12155-015-9618-x


Springer

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# Assessing Sustainable Bioenergy Feedstock Production Potential by Integrated Geospatial Analysis of Land Use and Land Quality

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**Abstract** Development of viable bioenergy economies will require large increases in biomass feedstock production. Improved methods are needed to quantify production potential based on land availability, land suitability, biomass yield, and cost. We developed such a method and applied it throughout New York State. While maintaining existing forest and agricultural production, we quantified additional sustainable biomass production potential using geospatial and yield modeling that integrates remotely sensed and survey data for land cover, soil type, climate patterns, and crop yields and then applied multiple sustainability constraints. Nearly 680,000 ha with varying quality was found to be available and suitable for new biomass production. Predicted yields ranged from 7.8 to 18.3 Mg/ha for short-rotation willow and 6.9–16.3 Mg/ha for perennial grasses for a total production potential of 8.2 Tg/year. Increased forest harvest could produce an additional 4.3 Tg/year of hardwood and 1.6 Tg/year of softwood. In total, an additional 14.2 Tg/year of biomass for bioenergy could be produced while maintaining existing agricultural and forest production. This new biomass, before processing, would contain energy equivalent to 7.4 % of 2012 New York energy use (3.4 % if converted to ethanol).

**Keywords** Biomass · Bioenergy · Biofuel · Sustainability · Switchgrass · Willow · Corn · Maize · NCCPI · Forest biomass · Land use change · GIS · Energy · Perennial · Warm season grass · New York State

**Abbreviations**

| | |
|---|---|
| DEM | Digital elevation model |
| ESRI | Environmental Systems Research Institute |
| GHG | Greenhouse gas |
| GIS | Geographic information system |
| K | Potassium |
| LULC | Land use/land cover |
| Mg/year | Megagram/year (assume dry matter unless otherwise stated) |
| MRLC | Multi-Resolution Land Characteristics |
| NCCPI | National Commodity Crop Productivity Index |
| NY | New York |
| N | Nitrogen |
| NLCD | National Land Cover Database |
| P | Phosphate |

## Introduction

Comprehensive analysis of reliable, affordable, and sustainable feedstock production potential is necessary to plan and locate bioenergy production facilities and supply chains while maintaining existing production of food, feed, fiber, and fuel. While biomass production potential has been analyzed at the national scale [1], there is a need for more detailed analyses at regional, state, and local scales to more accurately develop

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**Electronic supplementary material** The online version of this article (doi:10.1007/s12155-015-9618-x) contains supplementary material, which is available to authorized users.

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Published online: 03 May 2015

local bioenergy economies. Specifically, a comprehensive analysis of land availability, land suitability, potential productivity, and feedstock production cost is required. In generating bioenergy products, it is critical to apply appropriate constraints to ensure long-term sustainable production and reduce adverse impacts on environmental services, recreation, and other land uses. We performed such an analysis for New York State (NYS).

Potential for biomass comes from three major categories: (1) collecting residues (non-harvested biomass from existing crop and forest harvests), (2) increasing harvest of existing hardwood and softwood from forests, and (3) growing new dedicated bioenergy crops on available land.

Crop residues and forest biomass can be harvested from existing land management systems. The main crop residues in NYS are maize stover and small-grain straw while wood residues come from logging (e.g., tree tops) and wood processing facilities (e.g., milling). From existing forests, increasing harvest of both hardwood and softwood includes both commercial and non-commercial species. Commercial species as defined by the United States Department of Agriculture Forest Service (USDA-FS) are "tree species currently or prospectively suitable for industrial wood products; excludes species of typically small size, poor form, or inferior quality" [2]. Since 1999, annual harvest of logs has decreased from 3.1 million to 2.2 million cubic meters (1.1 million Mg) while pulpwood and chip harvest have been variable with no strong trends [3]. To note, total net growth of "growing stock" in forests is approximately 9 Tg/year. Growing stock is harvestable material for traditional wood products; it does not include all forest material. Overall, forest biomass is growing approximately three times faster than it is being harvested.

New biomass crops include herbaceous annuals (e.g., sorghum), herbaceous perennials, and short-rotation woody crops that could be grown on current agricultural land or other non-forest lands currently in perennial herbaceous cover. We chose only perennials because of their minimal environmental impact. Specifically, vegetation is present throughout the year with perennial root systems that reduce planting inputs, erosion, nutrient loss to surface and ground water while promoting carbon storage in soil and improving soil health. We focus on two representative perennial feedstocks (1) warm season perennial grasses such as switchgrass (*Panicum virgatum*, henceforth "grass" or WSG) and (2) willow varieties managed as a coppiced short-rotation woody crop (*Salix* sp., henceforth "willow"). Substantial research elsewhere in the USA [4, 5] and ongoing in NY demonstrates that grasses, under good management and using current hay equipment, can produce high yields [6]. Likewise, research and demonstration at multiple sites in NY have shown that willow can produce high yields under good management [7].

To quantify realistic and sustainable yields from potentially available lands, we used geospatial data on land use/land cover (LULC) and soil characteristics combined with historical data on crop yields and forest inventory to quantify the amount of land potentially available for feedstock production. Using the area potentially available for biomass production, we estimated potential yield of selected bioenergy feedstock and determined total sustainable feedstock potential from new and existing sources. This assessment for development of a cellulose-based bioenergy industry is a comprehensive and timely analysis of available resources within a context of competing uses of a finite landbase. Scalable to other regions, this approach incorporates multiple land use and sustainability goals that constrain expansion of biomass feedstock production. The result is a comprehensive estimate of sustainable bioenergy production and its associated production costs for bioenergy development throughout a large region of mixed agricultural, forest, and developed land uses.

## Materials and Methods

To establish a baseline of production, we analyzed 2007 agricultural production data from the National Agricultural Statistics Service [8] and forest data from New York Department of Environmental Conservation [9]. These agricultural and forestry products were converted to a dry matter basis using standard moisture contents and conversion factors.

There were six overall steps in our analyses for 2020 feedstock production potential: (1) determine amount of available residue from existing crop practices, (2) determine potential increased sustainable harvest of wood from existing forests, (3) determine area of cropland that could become available due to dairy system efficiency and crop yield increase by 2020, (4) determine area of land in perennial herbaceous cover that is suitable and available for herbaceous and woody feedstock production, (5) geospatially model potential future yield of grass and willow based on soil and climatic data and historical crop yields, and (6) develop enterprise budgets to quantify sustainable feedstock production costs in 2020.

Several major constraints on potential land used for producing bioenergy feedstocks were applied in order to address sustainability concerns. First, no conversions between forest land and farm land are considered. Second, protected lands (e.g., wetlands, forest preserves) and significant acreage used for equine activities are not considered. Third, existing crop and forest products are maintained. Fourth, annual harvest rate of forest does not exceed the growth rate. Fifth, steeply sloping lands (≥15 %) are removed due to equipment and safety limitations, fields smaller than 2 ha are removed to assure harvesting efficiency, and only about half of suitable and potentially available lands in herbaceous cover will be used for feedstock production (the remainder used by landowners for other purposes such as recreation, hunting, etc.). Further information on sustainability constraints follows in subsequent sections and is summarized in Table S-1.

### Crop Residues

Significant crop residues include maize stover and small-grain straw. It was assumed that small-grain straw was used for livestock bedding and not available for bioenergy. Maize stover was estimated based on grain yields and harvest index of 0.5 (ratio of grain to aboveground biomass). Across a range of soil types, yields, and management practices in the USA, approximately one quarter of stover was estimated to be collected at an affordable cost [10]. Due to New York-specific logistical challenge of wet ground during late-season harvest, we reduced this value further to 12.5 %. This is conservative with respect to maintaining soil quality considering that approximately half of the maize acreage is currently harvested for silage, thus returning little stover to the soil. Furthermore, tillage has been found to have a greater effect on soil quality than does stover harvest, and under reduced tillage, stover can be harvested sustainably over the long term [11].

### Increased Harvest of Existing Forest Stocks

First, technically available woody biomass from timberland in each county was determined. “Timberland” is “forest land producing or capable of producing crops of industrial wood (more than 1.4 $m^3$/hectare) and not withdrawn from timber utilization” [12] which excludes land in parks and protected areas. “Technically available” is the amount of woody biomass that is available, accessible, and within limits of sustainable yield from timberland [12] and includes the categories: merchantable biomass, non-commercial species, recoverable logging residues, and other removals. None of the 3.6 Tg of wood products harvested from forests was considered available. We estimated that additional forest biomass could be harvested sustainably based on previously published methods [12] for each county using data from USDA-FS Forest Inventory and Analysis (USDA-FIA, conducted from 2002 to 2006) [2] and Timber Products Output (USDA-TPO, conducted in 2007) [13]. Sustainable harvest means that multiple biophysical and social criteria were included to assure that harvest could be maintained indefinitely without degrading the resource and that not all lands would be harvested based on landowner preferences (see Table S-1). For example, not all forestland was included (e.g., preserve land such as the Adirondacks and other areas were excluded). Wood harvest was not allowed to exceed net annual growth rate within each county; 100 % of net annual growth rate of merchantable timber and 3 % of biomass of non-commercial timber were assumed to be harvested. To address concerns of nutrient losses from woody debris removal, 35 % of logging residues were left on site [14] for nutrient and biodiversity purposes. To maintain critical habitat, dead trees were not considered available (tree mortality estimated to be slightly over 2.7 Tg/year).

Third, we limited landowner adoption by estimating the fraction of technically available biomass that could potentially be available for bioenergy using a sustainable yield management (SYM) model [15] (correlates road density with expert forester prediction of landowner adoption of sustained yield management for each township). The SYM model was used to determine the proportion of timberland in a township that would support forest management now and into the future. The county-level SYM factor was a weighted average of township SYM factors as a proportion of total land area of each county. County SYM factors were then applied to previously estimated “technically available” forest biomass for each county.

### Active Agricultural Land That May Become Available Due to System Efficiencies

If crop yields increase over time, the same total crop production could be produced on less land in the future; this land could be used for increasing biomass production. We performed regression analysis of historical trends in crop yield (maize silage, soybean, wheat) from 1989 to 2007 [8] and extrapolated these trends into the future to predict increases in crop yields by 2020 (Eqs. S1–S3).

If milk yield per cow increases over time, even though feed intake increases to support the increased milk production, baseline energy to sustain a cow remains the same. Therefore, fewer cows are required and a greater proportion of dairy feed goes to producing milk. Thus, the same amount of milk production requires less land to produce feed. Projections for the future NY herd suggest that existing milk production may be maintained, but there may not be markets for increased production [16]. Therefore, increases in dairy system efficiency would make additional crop and hay land available for other uses. We performed regression analysis of historic milk production and extrapolated the trend into the future to predict how much milk would be produced per cow in 2020. Based on increased efficiency of milk production, we calculated the area of land that could be available in 2020 while maintaining milk production at 2007 levels (Eq. S-4 and Fig. S-1).

### Available Land for Development of Perennial Biomass

To calculate amount of land that could be available in coming decades for dedicated grass and willow bioenergy feedstocks, we created raster maps with the sum of crop, pasture, grass/hay land, and shrub/scrubland (Table S-2). We assumed no net conversion of land between forest and non-forest. Then, we calculated the fraction of this land that would be biophysically suitable for feedstock production. Suitable land was defined as (i) slope less than 15 %, (ii) individual field area greater 2 ha, and (iii) land not in Federal ownership or State-protected lands. These steps are described below.

Land cover data were obtained from the National Land Cover Database [17] (NLCD) produced by the Multi-Resolution Land Characteristics (MRLC) Consortium [18, 19]. Data were aggregated to a 100 m×100 m grid from the original 30 m×30 m grid. This NLCD grid was then reclassified to nine major land use classes to determine spatial locations of crop, non-forest (grass/herbaceous, pasture/hay, and shrub/scrub), forest, and a small amount of "other" (unclassified) land areas.

A slope factor of 15 % was applied to remove steeply sloping lands unsuitable for typical farm equipment. Required tiles of 7.5-min elevation data from USDA NRCS Geospatial Data Gateway [20] were imported into ArcGIS (Environmental Systems Research Institute (ESRI)) and merged, reprojected, and processed to 100 m×100 m grid. This digital elevation model (DEM) was used for calculating slope gradient (in percent) for each grid cell.

Land in State and Federal ownership was removed using a revised January 2005 feature map obtained from the National Atlas of the USA [21]. Data were reprojected and converted to 100 m×100 m grid.

Smaller fields are not suitable for large-scale commercial feedstock production operations, so we removed contiguous areas smaller than 2 ha as follows. Binary grids of land cover (perennial herbaceous and cropland), slope gradient, and protected land were combined by means of raster overlay. Analyses were performed separately for land in cropland and perennial herbaceous rasters. Each cell of each raster was rated with overall National Commodity Crop Productivity Index (NCCPI) values [22]. Then, both rasters were reclassified into ten NCCP I classes. These two rasters were then converted to vector format. Polygons of suitable land with a size ≥2 ha were selected.

Areas of cropland and perennial herbaceous land were summed for each county. Area of cropland or perennial herbaceous land in use [23] was subtracted to calculate total amount of land (idle cropland, grass/hay land, and shrub/scrub categories) that was both suitable and potentially available for feedstock production for each county. As not all equine activities fall under the definition of a farm according to the Census of Agriculture, we removed non-farm equine area from pasture, hay, and grassland categories based on equine land use estimates from a statewide survey [24]. To this resulting pasture, hay, and grassland land area, we used the same landowner adoption factor (SYM model) described above.

**Projected Yield and Production of Dedicated Bioenergy Crops**

The NCCPI integrates important soil characteristics and climate conditions influencing crop yield into a single index that can be calculated for nearly all agricultural soil types at nearly all locations [22]. Thus, this index provides a robust yet tractable means of predicting crop yield throughout large regions. NCCPI values range from 0 to 1, with 0 indicating no productivity and 1 indicating highest productivity. The NCCPI values for land throughout NY are shown in Fig. S-2. We used draft NCCPI for maize to predict yield of maize, warm season perennial grasses, and willow. Grasses and willow were the chosen perennials because they can provide (1) high yields, (2) valuable wildlife habitat and cover throughout the year, (3) root systems that store carbon and nutrients in soils as they are not plowed or planted annually, (4) reduced erosion, and (5) reduced leaching and volatilization of N which contributes substantially to water quality issues and GHG emissions due to volatilization of $N_2O$.

The NCCPI was not used directly to predict potential maize, grass, and willow yields. Instead, we calculated average NCCPI for maize on all crop land in each county and used it as a predictor of average historical yields at the county scale. From National Agricultural Statistics Service (NASS), average maize grain yield was calculated for all counties in the conterminous USA from 1998 to 2007, selecting only counties with <5 % irrigation and NCCPI value on cropland >0.05. The resulting regression equations predict yield in 2020 (Eqs. S-5 and S-6).

Despite major differences between maize and switchgrass cropping systems, above-ground yields are remarkably similar [25]. Based on switchgrass yield data from other locations on lower-quality lands (with lower yields) [26, 27] and data from trials in NY [6], we assume that in coming decades, switchgrass yields on many soils in Northeastern USA will be similar to aboveground biomass yields of maize (grain + stover). Therefore, we adapted the maize yield model to represent aboveground biomass of grasses. Adjustments were made to account for aboveground biomass from grain yield data and to account for reduced yields during the first 3 years of a projected 10-year grass stand life (Eq. S-7).

Using many experiments conducted at a number of sites in NY, we developed a database of willow yield data along with management and site information. For the most frequently planted clone (SV1), annualized yields for first rotation ranged from 6 to 12 Mg/ha/year. At one site with second-rotation data, yields increased 19 %. Assuming that second-rotation yields will increase by a similar proportion for other sites, these yields are very similar to those predicted for perennial grasses. Therefore, we adapted the perennial grass model to represent willow yield adjusted to 22-year willow stand life with reduced yield during the first 3 years (Eq. S-8).

In our analysis for perennial feedstock production, suitable land came from two main categories: (1) idle, abandoned, and transition lands (shrub and scrub) and (2) improved efficiency of existing crop productivity and milk production. We accounted for competing uses (e.g., equine) and logistical limitations (e.g., slope >15 %). For our analysis, we assumed an approximately even split of area between grass and willow, slightly favoring grass on higher-quality lands, so these lands could be converted to food crops if necessary. We also allocated wetter lands to willow, as willow can maintain better yields on wetter soils than grasses.

### Cost of Feedstock Production

Cost of producing a bioenergy feedstock depends on many factors, including level of management and yield. In all cases, base prices were for 2007. We then used average consumer price index [28] increase from 2007 to 2014 to extrapolate estimated prices in 2020. For maize stover, we updated a published estimate of production cost [10]. For softwood and hardwood production, we developed estimates based on range of market prices paid by commercial wood chip consumers (if it were the sole product harvested, it would likely cost more but could be higher or lower depending on specific management practices).

Switchgrass and willow are not widespread crops in NY, so existing market prices could not be used to develop production cost estimates. For willow, we used the Eco-Willow model to estimate production costs over a 22-year stand life [7]. However, in order to make estimates more consistent among feedstocks, we adjusted estimates from the Eco-Willow model to reflect the same variable land rent values used for grass feedstocks, described below.

For grass, we developed an enterprise budget for production costs based on high-intensity hay production including funds for labor, management activities, land rental, inputs, machinery, and other costs. Cost estimates were developed as a function of yield so that we could estimate costs for any yield level. For most items, data for agricultural inputs were adapted from Agricultural Prices Summary [29] and farm operation rates were obtained from Machinery Custom Rates [30].

## Results

We calculate that 12.9 Tg/year of herbaceous and forest biomass is harvested. Of this, 3.6 Tg/year is harvested from existing forest stocks while 9.3 Tg is from agriculture [23]. Agricultural biomass includes 3.9 Tg/year of forage/hay grown on nearly 809,000 ha, 3.5 Tg/year of maize silage, and 1.5 Tg/year of maize grain each grown on approximately 200,000 ha. Remaining agricultural products (including vegetables, fruit, soybean, sorghum, sunflower, and other grains) amount to 0.34 Tg/year (Fig. 1).

### Crop Residues

Small-grain straw is highly valued for livestock bedding and so was assumed unavailable for bioenergy feedstock. Maize stover is a potential feedstock but provides value to soil surfaces by preventing rain splash, reducing erosion, and returning organic matter to soil [10, 31]. We estimate that 1.5 Tg/year of stover is produced from maize harvested for grain. To maintain soil quality, we conservatively estimate just 12.5 % of this 1.5 Tg/year or 0.19 Mg/year stover will be available as a sustainable feedstock (Fig. 1).

### Increased Harvest of Existing Forest Stocks

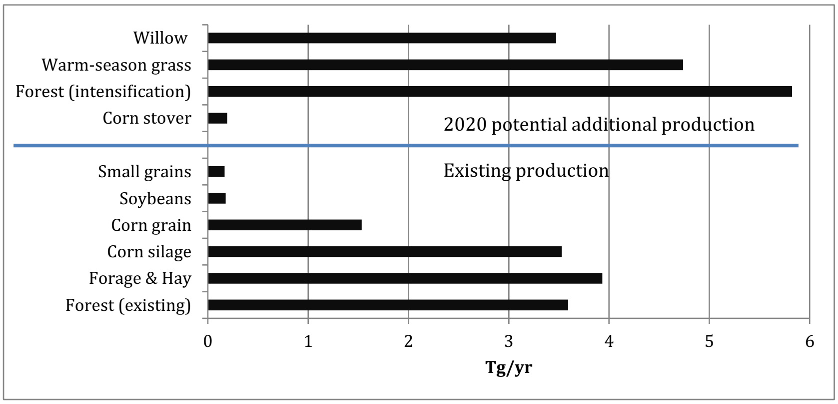
Most forest land is in private ownership (77 %), and 90 % of this privately owned land (4.7 million ha) is classified by USDA-FS as timberland. Most of the remaining forest is classified as "reserved," meaning that it is not available for timber production. Existing commercial harvest included 1.1 Tg/year of logs (2.2 million $m^3$), 0.5 Tg/year of pulpwood, and 0.5 Tg/year of wood chips [9]. Additionally, we estimate that 1.4 Tg/year of non-merchantable timber was harvested for firewood (Sloane Crawford, NYSDEC, 2009, personal communication). Thus, various industries harvest 3.6 Tg/year of NY forest biomass (see Table 1, numbers slightly different due to rounding).

Based on forest inventory data from USDA-FS, there are 7.5 million hectare of forest land in NY and 6.4 million hectare of timberland. From this, estimates of "technically available" forest biomass indicate that an additional 8.1 Tg/year could be harvested. Using the SYM model to estimate likelihood of landowner adoption, the proportion of timberland that would likely be harvested varied among counties from 0 to 90 %, with an average of 49 %. After applying the SYM model to the technically available biomass in each county, we estimate that approximately 5.8 Tg/year of woody biomass could be available for production of bioenergy (Table 1). This material would be 73 % hardwoods (4.3 Tg/year) and 27 % softwoods (1.6 Tg/year). Of these materials, 54 % would be merchantable timber, 32 % non-merchantable timber, and 14 % logging residues. This material is in addition to existing harvest (Table 1 and Fig. 1).

### Agricultural Land Made Available from Crop Yield Increases and Dairy System Efficiency by 2020

As crop yields increase over time, the same total production can be produced on less land in the future making a fraction of active agricultural land available for additional agricultural or bioenergy feedstock production. We estimate that increased

**Fig. 1** Potential additional biomass production (Tg/year) in New York. Additional materials for forest and corn stover come from use of existing stover and forest stocks. Willow and grass are grown on lands identified as available after many social, environmental, and logistical factors have been eliminated and are roughly split between these two crops for landowners with different objectives (see Table 2)




yields of four crops (maize grain, maize stover, soybean, wheat) will release 97,364 ha for other uses by 2020 while maintaining existing crop production. Additionally, land made available from increased dairy system milk production efficiency will release 51,380 ha of hay land and 64,617 ha of row crops (Table 2). Combined, these lands total 213,361 ha. Adding idle cropland (127,457 ha), lands made available by improved use of existing agricultural land total 340,819 ha.

## Available Land for Development of Perennial Biomass

From the 1,866,636 ha in miscellaneous herbaceous cover (pasture, grass, and hayland), we subtracted 794,245 ha for existing agricultural use and 323,099 ha for equine use (Table S-2). Equine use is important because 399,425 ha of land is used for horses [24] and 323,099 ha of this land is not on farms as defined by USDA (Table S-2). After removing land due to small field size, excessive slope, etc., the technically available land in miscellaneous herbaceous (352, 480 ha), and shrub/scrub (285,084 ha) categories, we further applied a 55 and 51 % landowner adoption factor (using SYM for applicable counties, assuming that landowners might wish to manage for other priorities such as hunting or aesthetics). We estimate that 339,248 ha of land is suitable and potentially available from miscellaneous herbaceous (194,985 ha) and shrub/scrub (144,264 ha); this land is not used for food or feed production (Table 2).

## Projected Yield and Production of Dedicated Bioenergy Crops

Combining miscellaneous herbaceous lands (194,985 ha), shrub/scrub (144,264 ha), idle cropland (127,457 ha), and land acquired from increased agricultural production efficiency (213,361 ha), a total of 680,067 ha of varying quality could be available for new biomass production (Table 2). The amount of land currently in herbaceous or shrub/scrub cover is substantial and likely represents a variety of current land uses. Much of this land is likely economically marginal for agricultural production [32] and would eventually revert to forest without occasional mowing. In our analysis, we project that approximately half of owners of such lands might participate in bioenergy feedstock production. If a higher or lower proportion of owners participate, it would directly affect the total biomass production potential.

Soil type characteristics affect potential yields for bioenergy feedstocks. In general, crop land is higher quality than non-cropland and will produce more perennial biomass per acre. Land cover was quantified using NLCD, and productivity was quantified based on NCCPI for each county. The suitable and available land area, yield, and cost of willow

**Table 1** Potential sustainable biomass harvest from existing NYS forest stocks

| Forest use | Merchantable timber (Mg/year) | Non-merchantable timber (Mg/year) | Logging residue (Mg/year) | Total (Mg/year) |
|---|---|---|---|---|
| Existing harvest | 1,088,616[a] | 1,959,509[b] | 544,308[c] | 3,592,433 |
| Potential additional harvest | | | | |
| Hardwoods | 2,218,765 | 1,444,483 | 602,318 | 4,265,565 |
| Softwoods | 917,597 | 419,646 | 222,561 | 1,559,804 |
| Total | 4,224,978 | 3,823,638 | 1,369,187 | 9,417,802 |

[a] 2.2 million cubic meters from timber

[b] Estimate of 0.54 million megagram from pulp plus 1.42 Mg million from firewood

[c] Chips from residues

**Table 2** Potential land availability for perennial feedstock development by existing land use/land cover (LULC) categories

| Land use | Land area (ha) | Technically available[b] (ha) | Landowner adoption (%) | Available area estimate (ha) |
|---|---|---|---|---|
| Cropland | 1,068,903 | | | |
| Idle | | 127,457 | 100[a] | 127,457 |
| Available due to increased crop productivity[c] | | 97,364 | 100[a] | 97,364 |
| Available due to increased dairy efficiency | | 64,617 | 100[a] | 64,617 |
| Pasture hay and grass | 1,866,636 | | | |
| Available due to increased dairy efficiency | | 51,380 | 100[a] | 51,380 |
| Misc. herbaceous land[e] | | 352,480 | 55[d] | 194,985 |
| Shrub and scrub | 355,383 | 285,084 | 51[d] | 144,264 |
| Total | 3,290,922 | 978,384 | 70 | 680,067 |

[a] We assume that currently active cropland will convert 100 % to biomass if financially viable because the farm is active and would make a choice to produce as much as possible on a farm in a given year

[b] After removing federal lands, slope, and plots <2 ha

[c] Increased efficiency of maize grain and silage, soy, and wheat in the State

[d] According to SYM modeling [15]

[e] To avoid double counting, we subtracted area associated with horses on farms from the total area dedicated to horses in the State for a total 323,098 ha of equine land area not on farms and also not available for biomass (Table S-2)

and grass for each productivity class are summarized in Table 3. While yields are similar for grass and willow feedstocks, it is clear that better quality lands have higher production per hectare and therefore lower cost for producing a ton of biomass as well as altering the radius (and transportation costs) of the energy-shed for a processing facility.

## Cost of Feedstock Production

If all 680,067 ha of suitable and available land was used for bioenergy feedstocks, approximately 8.2 Tg/year could be produced. Cost of producing a bioenergy feedstock depends on many factors including management and yield and is summarized in Fig. S-3. For maize stover, we updated a published estimate of production cost [10] to reflect agricultural production costs in 2020, resulting in an estimate of $77/Mg. For softwood and hardwood production, we developed estimates for 2020 based on range of market prices ($56–$85/Mg) paid by commercial wood chip consumers and we estimated that equal amounts would be within this range. These costs represent the fact that much woody biomass harvest will occur simultaneously with harvest of higher-value timber (if it were the sole product harvested, it would likely cost more but could be higher or lower depending on management). These estimated costs are generally higher than those estimated for 2022 by US Department of Energy (USDOE); specifically, the lower end of our range corresponds to the higher end of the range by USDOE [1]. Depending on soil quality, and thus yield, costs in 2020 ranged from $45 to $80/Mg for willow and $90 to $105/Mg for grass (Table 3). However, due to different amortization lengths, willow (22 years) and grass (10 years) production costs are not directly comparable (willow costs would be much higher with a 10-year stand life). These costs are higher than those estimated by USDOE for 2022, but the USDOE costs do not include fixed costs that are included in our estimates; thus, they are not directly comparable. Our estimates for grass are lower than current grass hay prices and the same as grass hay costs in NYS during 2004 to

**Table 3** Predicted available acreage by the National Commodity Crop Productivity Index (NCCPI) with associated warm season grass (WSG) and willow yield and cost in 2020

| NCCPI index | 0–0.1 | 0.1–0.2 | 0.2–0.3 | 0.3–0.4 | 0.4–0.5 | 0.5–0.6 | 0.6–0.7 | 0.7–0.8 | 0.8–0.9 | 0.9–1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Hectares (×1000) | 18.6 | 75.1 | 58.3 | 75.9 | 96.6 | 122.4 | 120.2 | 70.4 | 36.7 | 5.8 |
| WSG (Mg/ha) | 6.9 | 8.0 | 9.0 | 10.1 | 11.1 | 12.2 | 13.2 | 14.2 | 15.3 | 16.3 |
| WSG ($/Mg)[a] | $105 | $99 | $95 | $94 | $93 | $92 | $92 | $91 | $90 | $90 |
| Willow (Mg/ha) | 7.8 | 9.0 | 10.2 | 11.3 | 12.5 | 13.7 | 14.8 | 16.0 | 17.2 | 18.3 |
| Willow ($/Mg)[a] | $80 | $70 | $63 | $58 | $55 | $53 | $50 | $48 | $46 | $45 |

[a] Grass and willow cost curves were done by two different methods with different amortization periods of 10 years (grass) and 22 years (willow)

2007, thus may not be too high for 2020 prices, even with increased efficiency of production.

## Discussion

Development of new bioenergy industries can help meet future energy needs, reduce reliance on imported fossil fuels, increase rural income, and reduce greenhouse gas emissions if the industry develops in economically and environmentally sustainable ways. Since biomass will be produced and consumed in specific locations depending on local biophysical factors and infrastructure, development of an appropriately sized bioenergy industry requires a spatially explicit assessment of feedstock production potential. We analyzed geospatial data on land use and land cover to quantify location, area (Table 2), and quality (Table 3) of land that could be available for feedstock production. This analysis accounted for competing land uses (Table S-2), protected areas, existing levels of agricultural and forest production (Table 1), other uses of rural land, and ownership choice to produce bioenergy feedstocks. We developed enterprise budgets to estimate 2020 production costs of each feedstock across the landscape with varying climate and soil characteristics (Fig. S-3). Lastly, a series of sustainability factors were used to constrain estimated production (Table S-1).

The national "Billion Ton Update Report" assessed thinnings and logging residues to total 2.7 Tg/year in NY for 2030 [1]. However, our results indicate that 8.1 Tg/year is technically available from existing forests (54 % of NY landbase), but sustainability, land owner decision, and competing use factors limit this to 5.8 Tg/year. Still, this amount is more than double the national estimate for NY. Additionally, we determined that of the agricultural land (23 % of the land area), 971, 000 ha was technically available with 680,067 ha suitable for bioenergy crops by 2020. This area could produce an additional 8.2 Tg/year. This amount is also more than double the Billion Ton Update Report estimate of 3.4 Tg/year [1]. Together, agricultural and forest energy feedstocks could produce an additional 14.2 Tg/year with aggressive policy support. This represents a doubling of existing harvest levels of forest and crop products totaling 12.9 Tg/year (Fig. 1). Our assessment is important because it accounts for the variable land use and land quality within the region and provides a quantitative methodology for reducing the total production potential to account for multiple social, biophysical, and economic constraints.

For example, to maintain certain social considerations, there was no conversion between forest land and farm land and no protected lands (e.g., wetlands, forest preserves) are considered. Total production from existing crops and forest is maintained while forest harvest rate does not exceed growth rate within any county. Notably, for social constraints based on landowner choices, only about half of suitable and potentially available lands in herbaceous cover will be used for feedstock production, with the remainder used by landowners for other purposes (e.g., other crops, recreation, wildlife, aesthetics etc.). Trends extrapolated into the future for dairy productivity were calculated based on past trends and resulted in an estimated 1.3 % increase annually from 2007 to 2020 (from 8706 to 10,210 kg milk/cow/year). Notably in 2013, NY dairy cows are already averaging 10,024 kg milk/cow/year (NASS 2013) which is 6.6 % higher than what would be calculated for 2013 using our regression equation (Table S-3). Similarly, NY NASS reports for 2013 indicate that the 2013 crop yields (excepting maize silage) are 0.4–13 % higher than anticipated by regression analysis (see Table S-3). Our estimation of available land from crop and dairy efficiency is thus likely an underestimate of available land in 2020 due to increased production.

Further, this model restricts potential production in the short term to ensure long-term productivity and environmental concerns by implementing significant sustainability constraints (Table S-1). For forests considered harvestable, these restrictions included (1) leaving 35 % of tree tops and branches on site for nutrient and biodiversity purposes; (2) prohibiting harvest of standing dead trees to maintain critical habitat; and (3) harvesting only an average of 49 % of the area to address concerns related to site conditions, road density, and landowner preferences. As the region was mostly deforested 100 years ago, this analysis relies on active professional management of forests that will build a healthy diverse forest system that improves forest conditions for future timber harvests, wildlife habitat value, and other purposes. For agricultural land, we subtracted competing uses (e.g., equine) and added acres made available by increased production efficiency. We eliminated lands with >15 % slope for erosion and harvest practicality and areas less than 2 ha because they are too small for efficient commercial management. We assumed planting of roughly equal amounts of grasses and willow for their different landowner adoption goals (aesthetics, return on investment, level of maintenance, time commitment) and high yields (reducing loss of soil and nutrients while creating valuable wildlife habitat compared to annuals).

Lastly, this model identified economically viable feasibility for cultivating and harvesting these potential resources. The lowest cost feedstocks are maize stover, willow, and hardwood and softwood from existing forests (Fig. S-3). Cost estimates for hardwood and softwood are based on range of prices paid for industrial volumes of wood chips, rather than a stand-alone enterprise of just biomass for biofuel harvesting. Thus, they may be lower and not directly comparable to the costs estimated for grass and willow. However, because wood chip costs are based on historical market prices, they may also include additional costs that are not included in enterprise budgets. Actual prices will depend on the balance of these countervailing factors, the scale of the demand, and future markets for roundwood. As mentioned previously, our cost estimates for wood chips are generally lower than those estimated by the USDOE [1]. As grass and willow feedstocks are not currently produced commercially on large areas, cost estimates reflect current knowledge but are not directly comparable with each other. Specifically, willow was amortized over a projected 22-year stand life while grasses were amortized over a 10-year stand life resulting in a large influence on annual price. A smaller difference occurred because the grass model applies P and K based on calculated nutrient removal rates by harvested feedstock while the willow model does not include P and K fertilizers.

Despite these differences in assumptions, a few generalizations can be made about costs on agricultural land. First, with substantial fixed costs, crop yield strongly influences feedstock cost per unit weight (Table 3). For example, costs per megagram willow were about 50 % higher on lower-quality lands. Assuming that highest-quality land will be used first, these results indicate that as any bioenergy industry grows, production cost for feedstocks may increase due to increasing use of lower-productivity land.

As the landbase is finite, changes in practices will ultimately result in changes in competing uses. For example, wood harvest has been declining, so landowners may cull their low-grade wood for bioenergy in the short term to improve forest stands for high-value timber. As energy becomes more expensive, both low-value products such as cull wood for bioenergy and high-value products such as hardwood sawlogs could increase in value as builders choose high-carbon-sequestering wood over high-greenhouse-gas-emitting concrete and high-energy-consuming steel. Managing forests for both high-value timber and for bioenergy feedstocks may provide multiple benefits and multiple income streams to landowners.

In contrast, limited alternative uses of grass and willow feedstock necessitate consistent demand by bioenergy conversion facilities for a landowner to commit those acres to a biomass crop [33]. Operators of such facilities as well as feedstock producers might benefit from long-term contracts [34, 35] to sustain landowner commitment, production, and financial viability. Grass is likely to be attractive to producers because it is a familiar crop, uses standard farm equipment, is visually similar to existing grasslands, has a quicker return on investment, and converts easily to other crops if desired. Willow is likely to be attractive for its lower inputs and maintenance, flexibility in harvest time, lower production cost per ton when amortized over a 22-year stand life, and chemical and structural similarity to forest feedstocks. Willow might provide a stable feedstock supply for the life of the stand as a landowner is unlikely to change cropping systems before financial gains of willow are garnered.

## Conclusion

NYS harvests 12.9 Tg/year of biomass for food, feed, fiber, and fuel. Of the 3.2 million hectare of cropland, hayland, and shrub/scrub, 20 % was found to be suitable and potentially available for growing dedicated bioenergy crops for an additional 8.2 Tg/year from dedicated bioenergy crops. Thus, bioenergy from agriculture (including stover residue for 8.4 Tg/year) would be a 90 % increase in existing harvest. Sustainable intensification of forest management and harvest would result in 5.8 Tg/year of additional biomass that could be harvested annually; this is a 1.6-fold increase from existing harvest of 3.6 Tg/year. In total, this comprehensive analysis accounting for existing and competing land uses and sustainability constraints estimates the potential for a doubling in biomass potential from both agriculture and forest lands. There are many options for converting this new biomass feedstock production into usable energy. The total estimated potential production (14.2 Tg/year) has an energy equivalent of 275 million gigajoule before processing, representing 7.4 % of the 2012 energy consumption (3.7 billion GJ [36]) in the State. This assessment was a critical component of a larger effort to determine potential production of liquid biofuels in NYS. Using that study, processing this 14.2 Tg/year of biomass in second-generation cellulosic plants would create 6 billion gallons of ethanol [37] (420 L ethanol/Mg biomass). This total would displace 17 % of the projected 2020 NYS motor gasoline (729 million GJ [36] at 0.4 % increase by EIA projections [38] from 2012 use) and recycle nearly 2 billion dollars in the economy [37]. In summary, doubling total biomass production in New York to produce ethanol could displace 3.4 % of recent energy use by the State.

**Acknowledgments** This analysis was part of a larger study examining the potential for liquid biofuel production [37].

**Funding** This study is funded in part by the New York State Energy Research and Development Authority (NYSERDA), New York State Department of Environmental Conservation (NYSDEC), New York Department of Agriculture and Markets, and United States Department of Agriculture Cooperative State Research, Education and Extension Service (USDA-CSREES) special research grants FP2003-06052 and FP2004-06061.

**Author's Contribution** The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

## References

1. United States Department of Energy (US DoE). U.S. Billion-Ton Update: biomass supply for a bioenergy and bioproducts industry (2011). Perlack RD and Stokes BJ (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN

2. United States Department of Agriculture Forest Service (USDA-FS): Forest Inventory and Analysis (FIA) Website. www.fia.fs.fed.us/
3. Crawford S (2011) New York State Industrial Timber Harvest Production and Consumption Report—2010. New York State Department of Environmental Conservation. Forest Utilization Program, Albany
4. Parrish DJ, Fike JH (2005) The biology and agronomy of switchgrass for biofuels. Crit Rev Plant Sci 24(5–6):423–459
5. Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson CA, Wullschleger SD (2010) Empirical geographic modeling of switchgrass yields in the United States. Glob Chang Biol Bioenergy 2(5): 248–257
6. Mayton H, Hansen J, Crawford R, Crawford J, Viands D (2011) Field-scale yield of switchgrass under varying nitrogen management treatments in New York State. ASA Annual Meeting, San Antonio, TX, 16–19 October 2011. http://a-c-s.confex.com/scisoc/2011am/webprogram/Paper64926.html
7. Buchholz T, Volk TA (2011) Improving the profitability of willow crops—identifying opportunities with a crop budget model. Bioenergy Res 4:85–95
8. National Agricultural Statistics Service (NASS) Website. www.nass.usda.gov/Statistics_by_State/New_York/index.asp
9. Crawford S (2008) New York State Industrial Timber Harvest Production and Consumption Report-2007. New York State Department of Environmental Conservation - Forest Utilization Program. Albany, NY
10. Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL (2007) Current and potential U.S. corn stover supplies. Agron J 99:1–11
11. Moebius-Clune BN, van Es HM, Idowu OJ, Schindelbeck RR, Moebius-Clune DJ, Wolfe DW, Abawi GS, Thies JE, Gugino BK, Lucey R (2008) Long-term effects of harvesting maize stover and tillage on soil quality. Soil Sci Soc Am J 72:960–969
12. Castellano PJ, Volk TA, Herrington LP (2009) Estimates of technically available woody biomass feedstock from natural forests and willow biomass crops for two locations in New York State. Biomass Bioenergy 33(3):393–406
13. United States Department of Agriculture Forest Service (USDA-FS): Timber Products Output (TPO) Website. http://fia.fs.fed.us/program-features/tpo/
14. Evans AM, Perschel RT (2009) An assessment of biomass harvesting guidelines. Forest Guild, Santa Fe
15. Vickery BW, Germain RH, Bevilacqua E (2009) Urbanization's impact on sustained yield management as perceived by forestry professionals in central New York. Forest Policy Econ 11:42–49
16. LaDue E, Gloy B, Cuykendall C (2003) Future structure of the dairy industry: historical trends, projections, and issues. R.B. 2003–01; http://dyson.cornell.edu/research/researchpdf/rb/2003/Cornell_Dyson_rb0301.pdf
17. National Land Cover Data (NLCD) Website (2001/2006). www.epa.gov/mrlc/nlcd-2006.html
18. Multi-Resolution Land Characteristics (MRLC) Consortium Website. www.mrlc.gov/
19. Homer C, Dewitz J, Fry J, Coan M, Hossain N, Larson C, Herold N, McKerrow A, VanDriel JN, Wickham J (2007) Completion of the 2001 National Land Cover Database for the conterminous United States. Photogramm Eng Remote Sens 73:337–341
20. United States Department of Agriculture, Natural Resources Conservation Service, Geospatial Data Gateway Website. http://datagateway.nrcs.usda.gov
21. National Atlas of the United States of America Website. http://nationalatlas.gov/atlasftp.html
22. Dobos RR, Sinclair HR Jr, Hipple KW (2008) User Guide National Commodity Crop Productivity Index (NCCPI) Version 1.0, 2008. United States Department of Agriculture: Natural Resources Conservation Service, National Soil Survey Center, Lincoln
23. Census of Agriculture Website. www.agcensus.usda.gov/
24. Ropel S, Smith B (2007) New York equine survey 2005. New York Agricultural Statistics Service, Albany
25. McLaughlin SB, Kiniry JR, Taliaferro CM (2006) Projecting yield and utilization potential of switchgrass as an energy crop. Adv Agron 90:267–297
26. Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. Proc Natl Acad Sci U S A 105:464–469
27. Perrin R, Vogel K, Schmer MR, Mitchell R (2008) Farm-scale production cost of switchgrass for biomass. BioEnergy Res 1:91–97
28. United States Department of Labor, Bureau of Labor Statistics, Consumer Price Index (CPI Detailed Report, Data for January 2015), http://www.bls.gov/cpi/cpid1501.pdf
29. National Agricultural Statistics Service (NASS). Agricultural Prices 2007 Summary. http://usda01.library.cornell.edu/usda/nass/AgriPricSu//2000s/2008/AgriPricSu-07-31-2008_revision.pdf
30. National Agricultural Statistics Service (NASS). 2008 Machinery Custom Rates. www.nass.usda.gov/Statistics_by_State/Pennsylvania/Publications/Machinery_Custom_Rates/custom08.pdf
31. Wilhelm WW, Johnson JME, Karlen DL (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. Agron J 99(6):1665–1667
32. Richards BK, Stoof CR et al (2014) Reporting on marginal lands for bioenergy feedstock production—a modest proposal. BioEnergy Res 7(3):1060–1062
33. Paulrud S, Laitila T (2010) Farmers' attitudes about growing energy crops: a choice experiment approach. Biomass Bioenergy 34:1770–1779
34. Larson JA, English BC, Lambert L (2007) Economic analysis of the condition for which farmers will supply biomass feedstocks for energy production. Agricultural Marketing Resource Center. www.agmrc.org/media/cms/2007UTennProjDeliverable_9BDDFC4C2F4E5.pdf
35. Tiller K (2011) Tennessee case study in full-scale development and integration of switchgrass feedstocks with biorefinery operations: Genera Energy and UT Biofuels Initiative. Ind Biotechnol 7(5): 357–364
36. Energy Information Administration (EIA) website for New York. www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/tx/use_tx_NY.html&sid=NY
37. Wojnar Z (2010) Renewable fuels roadmap and sustainable biomass feedstock supply for New York. New York State Energy Research and Development Authority Report 10–05. www.nyserda.org/publications/renewablefuelsroadmap/default.asp
38. Energy Information Administration (EIA) Analysis & Projections, Annual projections to 2040, May 2014. http://www.eia.gov/analysis/projection-data.cfm#annualproj