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Identification of Land and Potential Production of Willow Biomass Crops Using a Multi-Criteria Land Suitability Assessment

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Abstract: The New York State (NYS) Climate Act aims for net-zero emissions across all economic sectors by 2050, with renewable biofuels playing a key role in this transition. Approximately half of the biomass required for these biofuels is expected to come from purpose-grown sources like willow. To address this demand, we assessed land availability and biomass production potential for willow using a GIS-based fuzzy logic Land Suitability Assessment (LSA) model under three land scenarios: (1) including all cropland, (2) excluding conventional crops, and (3) excluding any cropland. Our findings show that NYS has the potential for between 1.07 and 1.59 million ha for willow cultivation, capable of producing 14.0 to 20.6 million dry Mg of biomass annually. Grassland/pasture accounts for 32–51%, and herbaceous cover for 32–48% of the potential areas. Between 33% and 53% of the area identified was in parcels that were 2–20 ha in size. These results highlight the considerable potential for purpose-grown biomass in NYS, supporting the state's decarbonization goals and renewable energy transition.

Keywords: New York; potential land assessment; spatial analysis; willow; woody biomass feedstock

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1. Introduction

The scoping plan was created to provide pathways to reach the greenhouse gas (GHG) reduction and other targets in the 2019 Climate Leadership and Community Protection Act (CLCPA, also known as the Climate Act) of New York State (NYS). The plan outlines various actions within three scenarios (Strategic Use of Low Carbon Fuels (SULCF), Accelerated Transition Away from Combustion (ATAC), and beyond 85% reduction. Each of these scenarios highlights a substantial shift towards renewable energy sources such as solar, offshore, and onshore wind while improving energy conservation and developing a climate-focused bioeconomy. In this context, various biomass feedstocks are identified and recommended for use in producing renewable biofuels as alternatives to fossil fuel-intensive fuels currently in use [1].

The three proposed pathways in the scoping plan advocate for the adoption of low-carbon fuels, such as renewable distillate, renewable jet fuel, renewable natural gas, and hydrogen. The projected demand for biofuels and bioenergy in the scoping plan (without accounting for conversion losses) ranges from ~9.61×10^{13} GJ (91 TBtu) (ATAC scenario) to ~3.32×10^{14} GJ (315 TBtu) (SULCF scenario) by 2030 and from ~1.32×10^{14} GJ (125 TBtu) to ~3.64×10^{14} GJ (345 TBtu) by 2050 (Table S1). The highest individual target is set in the SULCF projects the use of purpose-grown biomass to produce ~5.91×10^{13} GJ (56 TBtu) of renewable diesel by 2030 (Figure S1) [2].

Purpose-grown biomass, also known as dedicated energy crops, refers to non-food, annual, and perennial (short-rotation) plants primarily cultivated for energy production while also providing various ecosystem services [3]. These crops play a crucial role in strategies to reduce greenhouse gas emissions, as they contain recently sequestered atmospheric carbon and can serve as sources of low-carbon or negative carbon feedstocks for bioenergy and bioproducts [4–6]. Examples of these herbaceous and woody plants include switchgrass (*Panicum virgatum*), willow (*Salix* spp.), poplar (*Populus* spp.), miscanthus (*Miscanthus giganteus*), which are considered renewable feedstocks for various bioenergy applications [7–11].

Among these, shrub willow stands out as a woody perennial energy crop with high yields, rapid growth, and the ability to resprout vigorously after each harvest. Its genetic potential remains largely untapped, and its chemical composition and energy content are comparable to hardwood tree species, allowing these two feedstocks to be blended for a more stable and reliable supply [12,13]. Shrub willow cultivation offers numerous environmental benefits, including soil management and erosion reduction [12,14–16], habitat provision for wildlife [17,18], biological pest control [19], nutrient management [20], and phytoremediation [21,22].

Achieving the 2030 target of producing 5.91×10^{13} GJ (56 TBtu) of energy from purpose-grown biomass in the SULCF scenario would require an annual production of around 6.73 million dry Mg of biomass (Figure S1) [2,23,24]. Based on the previously estimated average yield of 9.1 dry Mg/ha-yr for the region [24], 0.74 million hectares (ha) of land would be required to produce this amount of purpose-grown biomass. However, currently, only 400–500 ha of willow biomass crops are grown in NY, and there are no biorefineries for producing renewable biofuels from purpose-grown willow biomass in NYS. Consequently, a substantial increase in land use would be required to cultivate enough purpose-grown biomass to meet the demand for renewable fuels [25,26]. The projections in the scoping plan raise questions about whether NYS possesses sufficient available land and the potential to produce the required quantity of purpose-grown biomass to achieve the renewable fuels production target.

Existing assessments of land cover data are often referenced when discussing potential biomass production in NYS. According to the NYS Department of Environmental Conservation [27], approximately 2.9 million ha (20% of NYS land area) are classified as cropland, while forests cover 7.6 million ha (62%). According to the 2021 USGS National Land Cover Database (NLCD) [28], NYS has 6.5% (0.81 million ha) of agricultural cropland and 57% (7.1 million ha) of forest land (Table S2). Furthermore, the Renewable Fuels Roadmap [29] evaluated three scenarios for expanding renewable fuel production in NYS to ensure the industry's social, economic, and environmental sustainability. The Big Step Forward (scenario 1) pathway excluded all agricultural, feed, and forested lands, relying on 0.4 million ha of suitable rural lands to produce 4.3 million dry Mg of feedstocks annually, equivalent to replacing 1.92 billion liters (508 million gallons (MGY)) of biofuel. The Giant Leap Forward (scenario 2) and Distributed Production (scenario 3) included agricultural land, identifying 0.7 million ha for renewable fuels feedstock production to generate 7.9 million dry Mg of feedstock, capable of yielding 5.48 billion liters (1449 MGY) annually (Table 1, Figure S2). However, these estimates raise concerns regarding the criteria used, such as excluding certain land types and practices. In addition, this resolution of estimates is limited as only county-scale estimates were presented.

Table 1. Projected purpose-grown biomass production in NYS from various studies and the potential biofuel production and land *demand* (Table S3 for more details).

Feedstocks	Projected Purpose-Grown Biomass Supply (Million Dry Ton)	Potential Energy Production, GJ (TBtu)	Potential Land Demand (Million ha)
Purpose-grown biomass [9,30]	1.59 (Mature-market low pathway)	~2.86 × 10^{07} (27.1) [a]	0.18 [b]
	1.87 (Mature-market medium pathway)	~3.36 × 10^{07} (31.0) [a]	0.21 [b]
	3.32 (Mature-market high pathway)	~5.95 × 10^{07} (56.4) [a]	0.37 [b]
	3.32 (Evolving and emerging resources pathway)	~5.95 × 10^{07} (56.4) [a]	0.37 [b]
Warm-season grasses and willow [29]	4.3 (Big Step Forward Pathway) [29]	~7.44 × 10^{13} (70.5 [b])	0.4
	7.9 (Giant Leap Forward and Distributed Production Pathways)	~2.12 × 10^{14} (201 [b])	0.7

Conversion factors: [a] Miscanthus, 19.38 MJ/kg; Poplar, 19.66 MJ/kg; Switchgrass 19.10, MJ/kg; Willow, 20.12 MJ/kg [9]; [b] 38.47 MJ/liter of renewable diesel and yield 9.1 dry Mg/ha.yr [24].

The 2023 Billion-Ton Report [9,30] estimated potential agricultural biomass production in NYS from residues, intermediate oilseeds, and purpose-grown crops across different market scenarios (Figure S3). This analysis used the POLYSYS model to decide which crop will be produced on certain types of land based on current production costs and values, so it has restrictions beyond just land availability. In the near-term scenario, biomass was projected at 1.53 million dry tons, with all of it coming from crop residues, increasing to 3.52 million dry tons in the low maturity scenario, 4.02 million dry tons in the medium maturity scenario, and 5.43 million dry tons in high maturity and emerging scenarios (Table S3). These increases in biomass supply are driven by the contributions from intermediate oilseeds and energy crops, which have become significant in more mature markets, particularly the high-maturity market and emerging scenarios for energy crops. In the mature market, high, emerging, and evolving scenarios, willow will provide 1.5 million dry tons of biomass per year.

Cook-Patton et al. [31] conducted a national assessment using spatial layers with a 30-m resolution to identify potential land for reforestation. They identified approximately 2.16 million ha of land in NYS suitable for reforestation across eight opportunity classes. The largest category was pasture, comprising 1.48 million ha, followed by shrubland (0.07 million ha), grassy areas (0.06 million ha), and marginal cropland (0.06 million ha). However, several categories identified in this study, including urban open spaces (0.51 million ha), corridors (0.22 million ha), frequently flooded areas (0.12 million ha), and stream buffers (0.03 million ha), would not be suitable for willow crops. Richardson et al. [32] focused on current agricultural land that is currently in or was recently in agricultural production to come up with an estimate of areas that could be reforested. They identified 0.68 million ha (1.67 million acres) of land suitable for reforestation in NYS. Similarly, NYSERDA [33] found approximately 0.71 million ha of land suitable for reforestation, adjusting for landowner willingness. Despite the careful exclusion processes and integration of multiple datasets in these studies, their analyses were constrained to areas where forests with more than 25% tree cover historically existed, and the classes of identified suitable land overlapped [31]. The areas deemed suitable for reforestation were defined as post-agricultural lands not actively managed for economic value, excluding active agricultural production. Specifically, lands used for hay and pasture production or cultivated cropland (whether idle, summer fallow, or managed for soil improvement) were excluded from the assessment [32,33]. Moreover, these studies did not consider critical limiting factors, such as soil properties or restricting variables like slope, which are essential for evaluating land suitability for specific energy crops. As a result, while the focus was on reforestation efforts, these analyses do not clearly evaluate land potential for purpose-grown crops like willow, which have unique environmental and soil requirements.

Identifying suitable land for purpose-grown crop cultivation and comparing it to the different scenarios presented in the scoping plan will be essential for planning NYS's goal of producing sustainable fuels to reach the CLCPA's economy-wide GHG reduction targets. Identifying the potentially available land is the first step in assessing overall biomass potential. Other restricting factors, such as technical, socio-economic, or sustainability metrics, can be implemented to present future biomass production potential. In addition to identifying the amount of potential land, it is also beneficial to be able to identify spatially where this land is located across the state.

Cultivating purpose-grown biomass on lower-quality lands is often suggested as one approach to minimize conflicts with agricultural production in a region, but it can also present challenges due to yield uncertainty associated with cop establishment and limited resilience with changing weather patterns [34]. Poor willow establishment can impact yield and returns over multiple rotations and negatively impact growth returns for growers [35]. Understanding potential yields at specific locations is crucial for identifying lower-quality lands' overall biomass production potential [36–41]. Therefore, identifying amounts of available lower-quality land, its spatial distribution, and yields associated with the identified areas are essential for sustainable and cost-effective purpose-grown biomass cultivation [24,42–45].

Geographic Information Systems (GIS) play a vital role in land availability analysis, enabling the identification of lower-quality lands for energy crops based on various criteria and restrictions [37,46–50]. The objective of this study is to employ a fuzzy logic land suitability analysis (LSA) model combined with a GIS-based multi-criteria approach to spatially identify, quantify, and characterize lands in NYS where shrub willow could be grown and predict their annual production potential from those lands using an established yield model.

2. Methodology

We applied the fuzzy logic land suitability analysis (LSA) model to identify suitable areas for shrub willow cultivation. This model, integrated with a Geographic Information System (GIS)-based multi-criteria, decision-making (MCDM) approach, functioned as a logical decision support tool [51,52]. Our aim was to quantify the area's potential for shrub willow cultivation while constraining its spatial expansion.

The model assessed various production-limiting factors and competition risks specific to NYS by evaluating the potentiality of each 30 m × 30 m grid cell for willow cultivation. Criteria relevant to willow cultivation, including land cover and use, soil erodibility (whole soil, Kw-factor), distance to surface water (DTW), soil nitrate leaching index (LI), national commodity crop productivity index (NCCPI), soil organic carbon (SOC), slope, average soil water-holding capacity at root depth (AWSC), and field efficiency (FE), were incorporated into the analysis. These criteria allow for the systematic exclusion of unsuitable lands, such as parcels smaller than 2 hectares, which are deemed inadequate for harvesting, and characterization of attributes of land that are identified as suitable (Table 2).

Spatial analysis was conducted using ArcGIS Pro 10.1, and we estimated potential annual shrub willow production using an established model [53] to understand production potential. Validation of the identified suitable lands from the no croplands scenario (NCL, see Table 2) was performed to ensure the accuracy and reliability of the findings.

Table 2. Variables, data sources, resolution, and constraints logic utilized for identifying and characterizing land that is suitable for willow cultivation in New York State.

Variable/Factor	Data Sources	Resolution	Land Use Scenarios and Layer Constraints
Land use and land cover	USDA-NASS Cropland Data Layers (CDL) [54]	30 m × 30 m	***Cropland scenario (CL):*** Includes all cultivated croplands, barren land, herbaceous areas, and shrublands. Excludes forests, open water, developed areas, and wetlands. ***No conventional croplands scenario (NCC):*** Croplands excluding conventional agricultural crops (soybeans, corn, and wheat), barren land, herbaceous lands, and shrublands. Excludes forests, open water, developed areas, and wetlands. ***No croplands scenario (NCL):*** Includes barren land, herbaceous lands, and shrublands. Excludes all croplands, forests, open water, developed areas, and wetlands.
Soil erodibility factor, whole soil (K-factor)	SSURGO data [55]	30 m × 30 m	Land with Kw-factor values 0 and 0.55 µm/s were excluded.
Distance to water bodies (DTW)	USGS National Hydrography Dataset (NHD) [56]	30 m × 30 m	DTW ≥ 3000 m were excluded.
Soil nitrate leaching index (LI)	NY Leaching Index [57–61]	30 m × 30 m	LI values ≥ 2 were excluded.
Soil organic carbon (SOC) content at 0–30 cm	SSURGO data [55]	30 m × 30 m	Soils with SOC content of 0 kg C/m^2 were excluded.
National Commodity Crop Productivity Index (NCCPI)	NASS soil survey database [60,62]	30 m × 30 m	Soils with an NCCPI value of 0 were excluded
Soil available water storage capacity (AWSC) within 30 cm rootzone	Soil Survey Geographic Database (SSURGO) [55]	10 m × 10 m	Soils with ≤20% of AWSC at the depth of 0 to 30 cm were excluded.
Topography (slope)	USGS National Elevation Data (NED) [63]	10 m × 10 m	Lands with a slope ≥ 15% (8.53 degree) were excluded.
Field efficiency (FE)	USDA land cover [54]	30 m × 30 m	Lands with ≤95% harvesting efficiency were excluded.
Parcel size ≤ 2 ha	Raster to polygon conversion	30 m × 30 m	Parcel size ≤ 2 ha was excluded.

2.1. Estimation of Potential Land

The production of biomass from energy crops depends significantly on the availability of productive land and the annual yield per unit of land [64]. The USGS-NLCD land classification [28] is commonly used across the USA to assess the spatial distribution of cropland, natural vegetation, and other land types, and it is more effective at distinguishing broad land cover categories. However, it is less effective in differentiating agricultural uses, such as cultivated crops, versus hay and pasture. In contrast, the USDA-NASS Cropland Data Layers (CDL) is fine-tuned to distinguish individual crop types within the agricultural land cover [32]. This study used the 2022 USDA Cropland Data Layers (CDL) [54] to determine statewide land cover at a 30-m resolution.

Based on 2022 USDA-CDL [54], land cover in NYS consists of 6.5% (0.81 million ha) agricultural crops, 57% (7.1 million ha) forest land, 11% (1.39 million ha) developed areas, 6.1% (0.77 million ha) herbaceous land, 8.9% (1.12 million ha) grassland/pasture, 7.2% (0.90 million ha) wetlands, 3.1% (0.39 million ha) open water, and 0.2% are barren land (21,735 ha) and shrubland (20,404 ha) (Table S2). Our analysis identified potential areas for shrub willow cultivation under three scenarios, all of which excluded forest land, open water bodies, developed areas, and woody wetlands due to conservation regulations, physical limitations, space constraints, and zoning requirements (Table 2). The scenarios (1) Croplands (CL), (2) No Conventional Croplands (NCC), and (3) No Croplands scenario (NCL) aimed to evaluate land availability based on USDA-NASS land use classifications in NYS. In the croplands scenario (CL), all cultivated croplands, barren land, herbaceous, and shrubland were included in the analysis for shrub willow cultivation (Table S2). This scenario encompasses 2.71 million ha of land that has the potential to grow willow prior to applying any constraints. In the No Conventional Croplands (NCC) scenario, 0.73 million ha of conventional crops comprising corn (70%), soybeans (22%), and wheat (8%) were excluded; therefore, 1.98 million ha were included in this scenario. In the No Croplands scenario (NCL), an additional 0.05 million ha of agricultural land used for fruit and vegetable production was also excluded from the analysis, eventually leaving 1.92 million ha of land taken into consideration for assessing potential land for shrub willow cultivation.

2.2. Land Suitability for Constraint Variables

2.2.1. Soil Erodibility (Kw-Factor)

Soil erodibility, whole soil (Kw), is used to quantify how susceptible a soil is to particle detachment caused by water [65], and highly erodible soils are more prone to erosion and nutrient loss, which would eventually reduce the yield of energy crops production [66] and create challenges for long term soil and crop management [67]. The USDA NRCS [60] classified soil erodibility (whole soil, Kw) in NYS into 14 categories, ranging from 0 µm/s (open water bodies) to 0.55 µm/s (Figure S4). We extracted these soil Kw-factors at a 30-m spatial resolution from SSURGO data [55] and excluded both 0 µm/s (0.96 million ha) and the maximum 0.55 µm/s (0.012 million ha) categories from our analysis.

2.2.2. Distance to Surface Water Sources (DTW)

The distance of waterbodies can significantly impact the growth and productivity of shrub willow. Close proximity to waterbodies offers several benefits, including soil saturation, temperature regulation, reduced water stress, and enhanced growth [68,69]. In our analysis, we obtained surface water body polygons (stream data) for NYS from the National Hydrography Dataset (NHD) provided by the United States Geological Survey [56]. We then calculated the distance of water bodies from other land areas using the Euclidean Distance tool in ArcGIS Pro 3.2 and excluded areas that exceeded 3000 m from water bodies.

2.2.3. Nitrate Leaching Index (LI)

The Nitrate Leaching Index (LI) is a measure of how susceptible soil is to the leaching of nitrate and other substances. Higher LI values indicate greater susceptibility to nitrate leaching and nutrient loss, while lower values suggest greater resistance to leaching [70]. An LI value below 2 signifies a low risk of nitrate leaching below the root zone, values between 2 and 10 indicate moderate risk, and values above 10 suggest a high risk of nitrate leaching [58]. The LI is calculated using the Percolation Index (PI) and Seasonal Index (SI), where PI is based on the hydrologic soil groups (HSGs) and annual average precipitation (Pa, in inches), while SI is determined by annual average precipitation (Pa) and total autumn and winter precipitation (Pw, from October through March, in inches) [59]. The USDA-NRCS [60] classifies all soils in the U.S. into four HSGs (A, B, C, D) based on runoff and percolation potential, determined by their water infiltration rate. HSGs data were sourced from the USDA's NRCS database [60], and average precipitation data from the PRISM Climate Group covered a 30-year period (1991–2020) [71], and calculated *PI* (Figure S5), *SI* (Figure S6), and *LI* (Figure S7) using Equations (1)–(3) [57,58]. Equation (1) calculates PI according to each soil type's HSG classification. For soils with dual *HSGs* (e.g., A/D, B/D, C/D), we used the first letter which represents adequately drained conditions [58]. We included areas with LI values greater than 2 (12.06 million ha), as willow cultivation helps reduce nitrate leaching risk [72].

$$\begin{aligned} HSG\ A:\ PI &= \frac{(P_a - 10.28)^2}{(P_a + 15.43)} \\ HSG\ B:\ PI &= \frac{(P_a - 15.05)^2}{(P_a + 22.57)} \\ HSG\ C:\ PI &= \frac{(P_a - 19.53)^2}{(P_a + 29.29)} \\ HSG\ D:\ PI &= \frac{(P_a - 22.67)^2}{(P_a + 34.00)} \end{aligned} \quad (1)$$

$$SI = \frac{2 * P_w}{(P_a)^{\frac{1}{3}}} \quad (2)$$

$$LI = PI * SI \quad (3)$$

2.2.4. Soil Organic Carbon (SOC) Content

Soil organic carbon (SOC) within the top 0–30 cm layer plays a crucial role in crop production, including shrub willow [73,74]. Higher SOC concentrations generally boost crop yields, with gains leveling off at around 2% SOC, while also reducing nitrogen fertilizer dependency [75]. In NYS, SOC levels in this depth range from 0 kg C/m^2 to 96.6 kg C/m^2 [55]. To evaluate SOC suitability for shrub willow cultivation, we obtained SOC values for the 0–30 cm layer from SSURGO data [55] at a 30-m resolution (Figure S8). Our study included the areas with SOC above 0 kg C/m^2 (12.06 million ha) at 0–30 cm soil depth.

2.2.5. National Commodity Crop Productivity Index (NCCPI)

The National Commodity Crop Productivity Index (NCCPI), established by the USDA Natural Resources Conservation Service (NRCS), functions as a measure of soil quality and productivity, with values ranging from 0 to 0.96 (Figure S9). We extracted NCCPI data from the NRCS soil survey database and converted it into a raster format with a 30-m spatial resolution [60]. We included 12.06 million ha of land with an NCCPI value greater than 0, as soils with low NCCPI values indicate lower suitability for energy crop production and yield [41,76–78].

2.2.6. Soil Average Water Storage (AWS) at Root Zone

The soil's AWS at the 30 cm root zone plays a vital role in facilitating shrub willow growth [79]. Due to the shrub willow's susceptibility to drought, soils with low water holding capacity and excessively well-drained are not conducive to willow cultivation [80,81]. Thus, we identified soils with a water holding capacity exceeding 20% as suitable for willow growth. In New York State, soil capability for water storage in the root zone (commodity crop) ranges from 0 to 532 mm [62], with currently available water storage in standard zone 3 (0–30 cm depth) ranging from 0 to 153 mm [55]. This data, derived from the SSURGO database at a 10-m spatial resolution, was used to calculate the water content percentage for each pixel by dividing the existing AWS by the maximum storage capacity. We included soils with greater than 20% water content (covering 11.15 million ha) (Figure S10) as soils with low AWS percentages are associated with reduced productivity for energy crops [41].

2.2.7. Soil Topography (Slope)

Utilizing standard harvesting equipment for willow, such as forage harvesters and wagons, on steep slopes poses significant challenges and can result in increased costs [82,83]. Additionally, steep slopes affect water retention, nutrient availability, and susceptibility to erosion, which can hinder willow growth and productivity [84,85]. Previous studies recommended excluding slopes greater than 6% (3.43 degrees), 8% (4.58 degrees), and 15% (8.53 degrees) due to limitations in forage harvesting equipment [77,78,86]. In this study, slope data were generated from the USGS National Elevation Data (NED) [63] at a 10-m resolution, and areas with slopes greater than 15% were excluded to optimize conditions for willow cultivation (Figure S11).

2.2.8. Field Efficiency (FE)

Field efficiency, representing the percentage of a field effectively utilized for crop production, directly impacts the cost-effectiveness and profitability of energy crop production systems [87,88]. This metric influences crop yields, resource utilization, and production costs. In our study, we extracted cultivated field layers from USDA-NASS [54] at a 30-m spatial resolution and converted them into polygons. To quantify field efficiency for willow, we applied a regression model developed by Griffel et al. [89], which establishes a relationship between field size, shape, and harvesting efficiency (Equation (4)). Fields with an efficiency greater than 95% were included in this analysis (Figure S12).

$$FE_i = \beta_0 + \beta_1 . \ln\left(\frac{P_i}{A_i}\right) \quad (4)$$

where i denotes the field, β_0 is 0.179, β_1 is -0.145, and $\ln\left(\frac{P_i}{A_i}\right)$ represents the natural log transformation of the field i boundary perimeter-to-area ratio.

2.3. Estimation of Potential Willow Production

We employed data on shrub willow yields, measured in dry Mg/ha-yr, as reported by Volk et al. [24]. These yields were derived from a combination of field trials and used to develop the spatial PRISM-ELM model [53,90], enabling us to estimate potential willow production (dry Mg/yr) from potential lands at a 30-m spatial scale (Figure S13). To estimate the potential production for NYS, we multiplied the spatial willow yield data by potential lands. Additionally, we analyzed the distribution of potential land (in ha) based on USGS NLCD land use classification to determine the percentage of land cover types that could be planted with willow and their potential contribution to willow production.

2.4. Accuracy Assessment

We conducted a validity assessment in ArcGIS Pro 3.2 for no croplands scenario (NCL) by creating 100,000 random points on the estimated suitable land. Subsequently, we extracted 4702 points representing 64 known willow fields totaling 485.1 hectares (1198.9 acres) across the following counties: Oneida (9 fields, 34.43 ha), Lewis (3 fields, 9.7 ha), Jefferson (42 fields, 244.8 ha), Chautauqua (8 fields, 123 ha), and Cattaraugus (2 fields, 73.1 ha) (Figure S14). We then constructed a confusion matrix to assess the classification accuracy, utilizing metrics such as the kappa coefficient, precision, and overall accuracy.

3. Results

In the Croplands scenario (CL), our analysis revealed a total of 1.59 million ha of suitable land for shrub willow cultivation. The largest portion of this land, approximately 35% (557,893 ha), is currently categorized as cultivated cropland, followed by herbaceous (32.3%, 515,839 ha) and grassland or pastureland 32.2%, 513,314 ha), respectively. Smaller areas include shrubland (4160 ha) and barren land (3583 ha) (Figure 1). Within the cultivated crops category, 367,314 ha is currently in corn production, 110,840 ha in soybeans, 42,929 ha in wheat, and 36,809 ha in other crops. In the herbaceous land category, 289,060 ha are from other hay or non-alfalfa, 216,792 ha from alfalfa, 5846 ha from fallow or idle cropland, and 4140 ha from other herbaceous land classes such as clover, sod, and herbs.

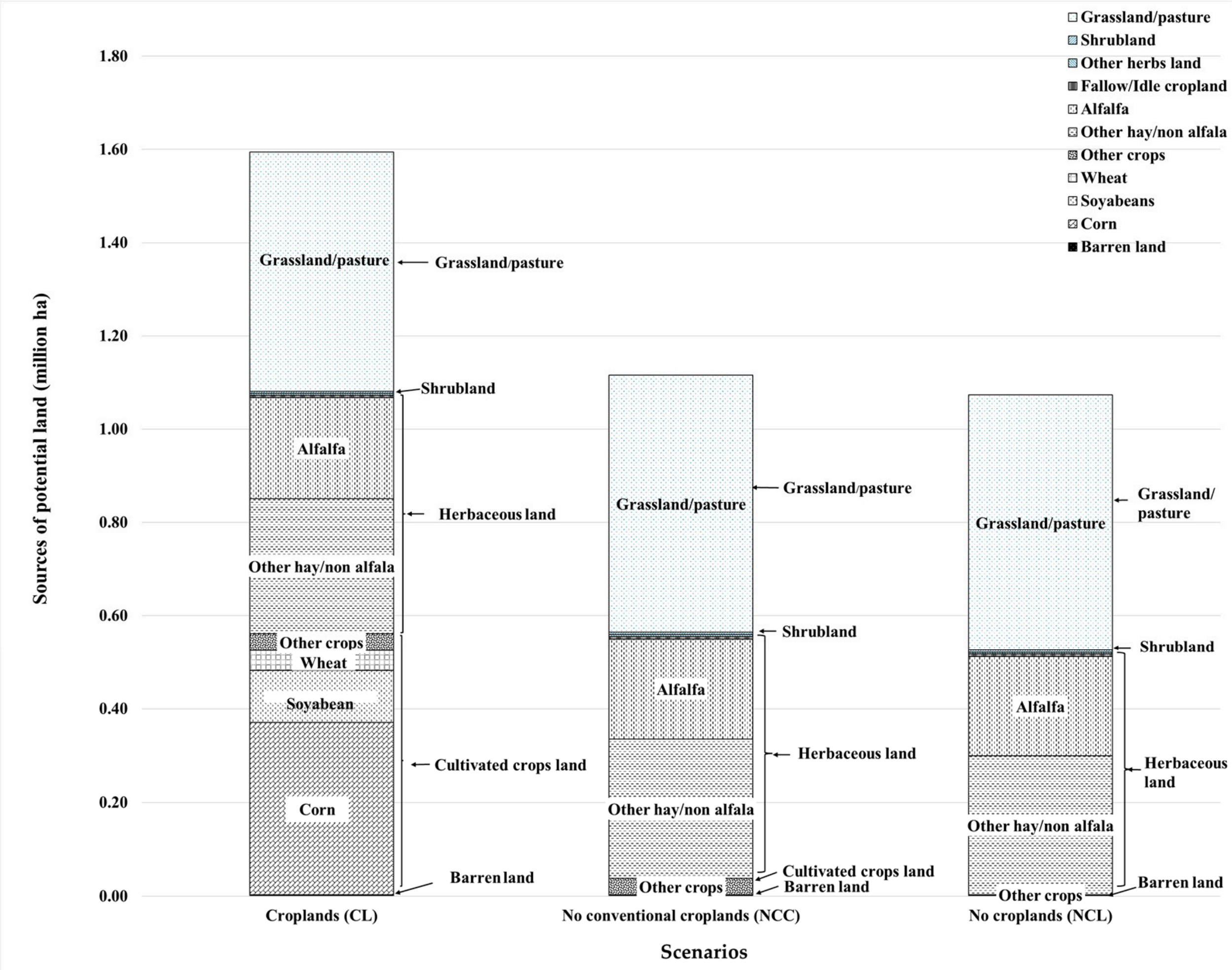

Figure 1. Distribution of current land use classes where shrub willow crops could be grown in NY State for the three scenarios.

Notably, variables such as erodibility and NCCPI had negligible impacts on the total amount of land identified as potential for willow cultivation in the CL scenario. However, soil factors resulted in exclusions, particularly for distance to water bodies (35,520 ha), nitrate leaching (22,117 ha removed), and soil organic carbon (35,613 ha). The largest reduction in potential land area occurred due to low soil water holding capacity, which excluded 338,511 ha, followed by slope (194,751 ha) and field efficiency (169,712 ha) (Figure 2). After removing parcels smaller than 2 ha (316,311 ha), the final land area potential for willow cultivation in NYS was 1.59 million ha in the CL scenario (Figure 2).

Of the 1.11 million ha excluded due to these various factors, grassland or pasture accounted for the largest reduction (603,184 ha) from the initial inclusions, followed by herbaceous land (250,087 ha), cultivated croplands (225,000 ha), barren land (18,152 ha), and shrubland (16,244 ha). The potential 1.59 million ha identified in the CL scenario were spread across 101,766 parcels, with over 82% of parcels being smaller than 20 ha and 15.2% between 20 and 100 ha. 33%% (523,595 ha) of the 1.59 million ha is located in parcels that are 2–20 ha in size and 67% (1,071,195 ha) in parcels greater than 100 ha. The largest parcel identified was 4934 ha, with 31 parcels exceeding 1000 ha each (Figure 3). Most of the larger parcels are in the Finger Lakes, Central New York, and North Country regions (Figure S15).

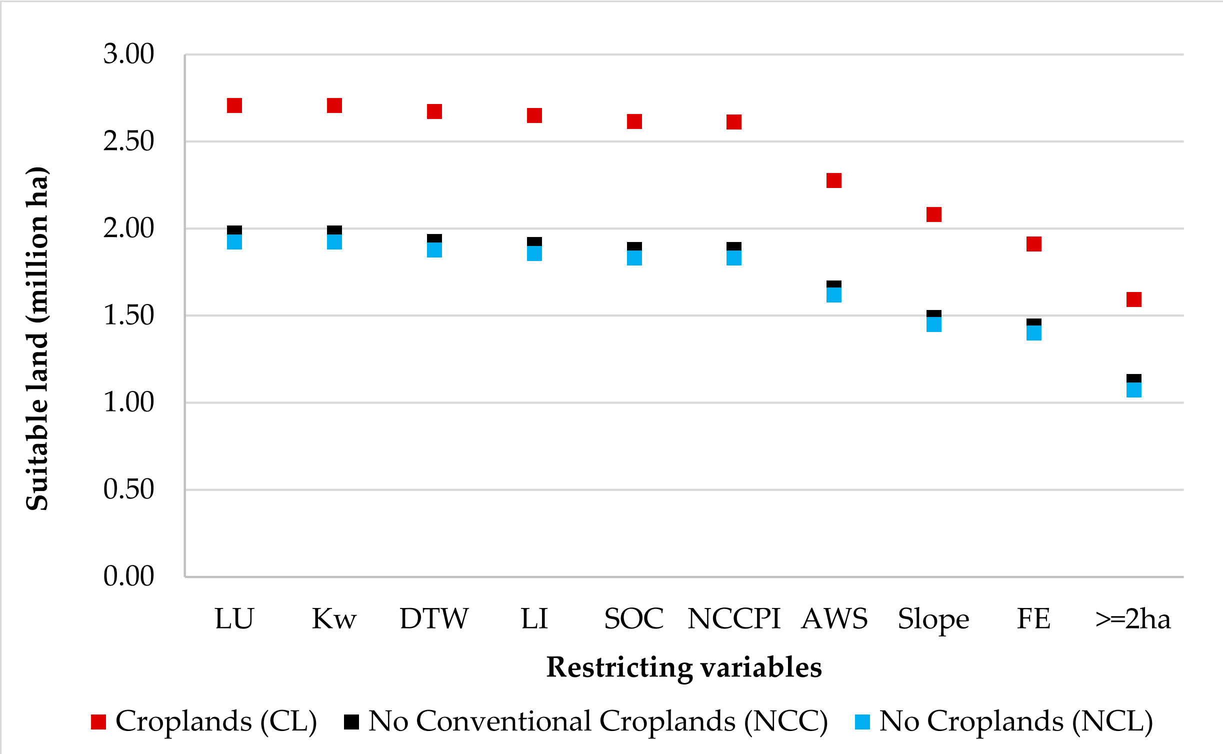

Figure 2. Change in the amount of suitable land with intersecting growth restricting variables for each of the three scenarios (Cropland, No Conventional Croplands, and No Croplands). (Note: LU = current land use, Kw = soil erodibility K-factor, DTW = distance to surface waterbody, LI = soil nitrate leaching index, NCCPI = national commodity crop productivity index, SOC = soil organic carbon storage within 30 cm, Slope = soil topography, AWSC = soil available water storage capacity within 30 cm rootzone, FE = field efficiency, and ≥2 ha = land parcel size greater than 2 ha).

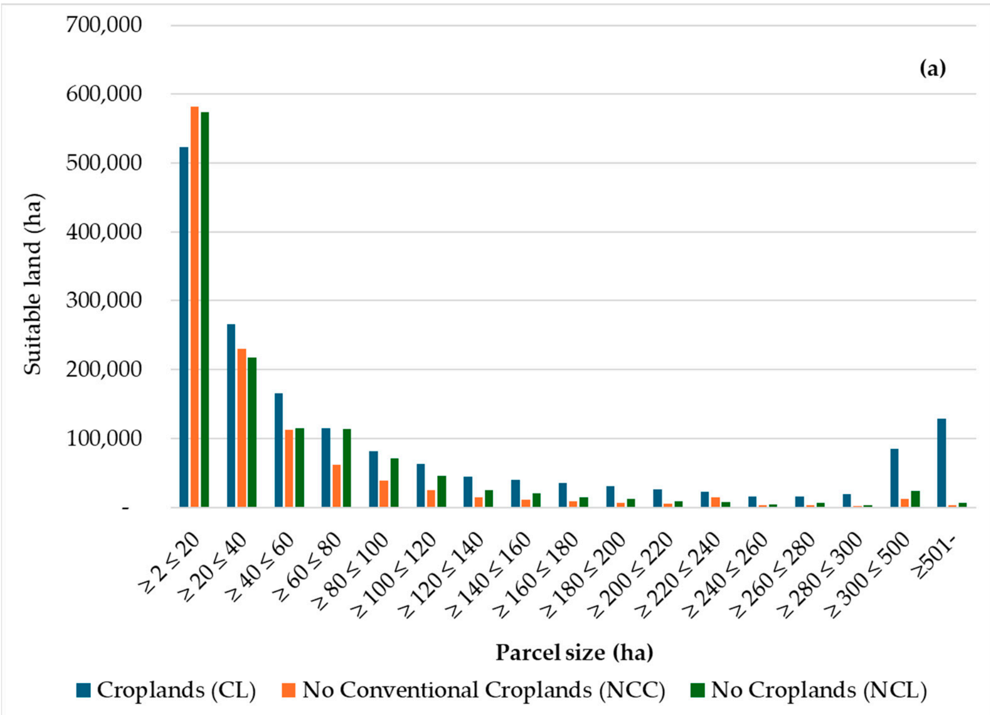

Figure 3. *Cont.*

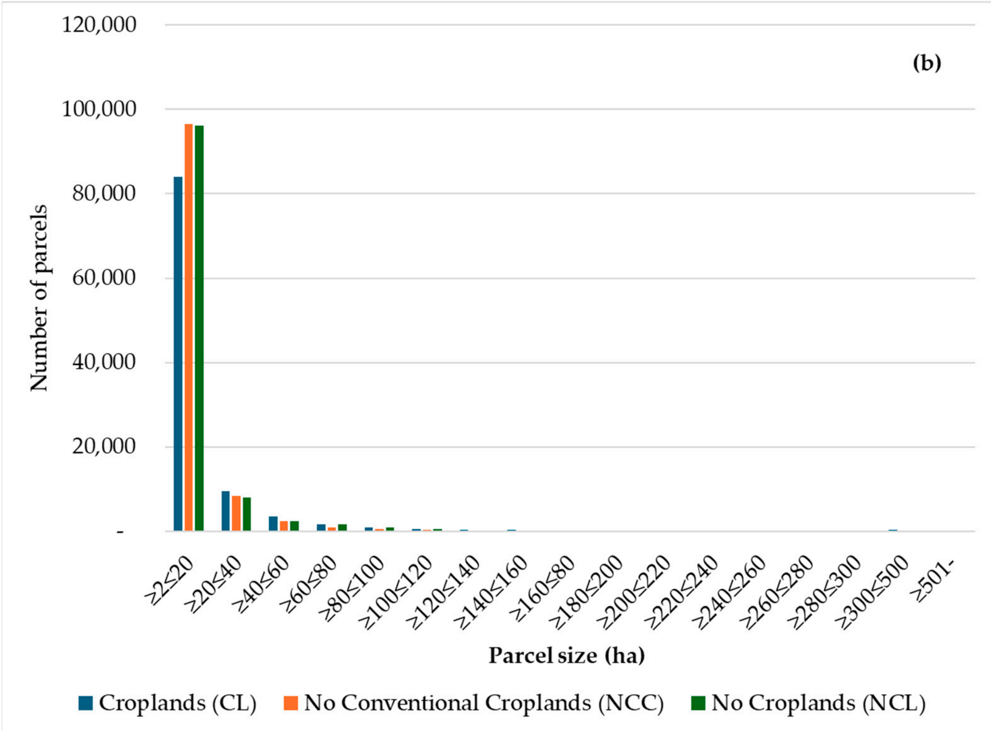

Figure 3. Distribution of (**a**) hectares of suitable land and (**b**) number of parcels in different scenarios by parcel size.

Using the PRISM-ELM geospatial willow production map, the CL scenario is estimated to produce 20.7 million dry Mg of willow biomass annually, with 34.6% from cultivated croplands and grassland or pastureland and herbaceous land, each contributing 32.4%. Barren land and shrubland combined contribute less than 1% (Figures 1 and 4).

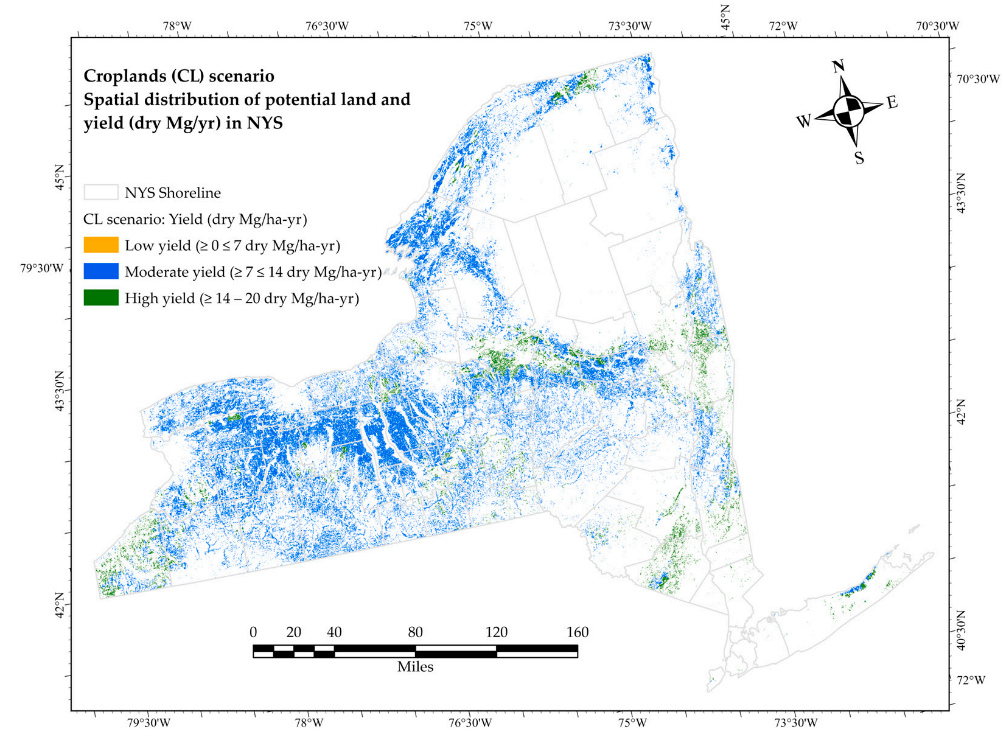

Figure 4. Spatial distribution of potential land and potential yield of willow biomass crops in the Croplands scenario (CL) in NYS.

In the No Conventional Croplands (NCC) scenario, our analysis identified a total of 1.12 million ha of land suitable for shrub willow cultivation. The majority of this land, approximately 49.4% (551,813 ha), is classified as grassland/pasture. In comparison, herbaceous land contributes 46.8% (521,410 ha), cultivated croplands make up 3% (34,165 ha), and shrubland (5080 ha) and barren land (3670 ha) each contributes less than 1%. Within the herbaceous land category, other hay lands account for 297,498 ha (26.7% of the total land), alfalfa covers 214,103 ha (19.1%), idle cropland totals 5714 ha, and other herbaceous land, such as clover and sod, adds 4095 ha (Figure 1).

After applying production limiting factors, a total of 859,852 ha of land was excluded. The largest reduction occurred in the grassland or pasture category, with 65.7% of the total reduction, decreasing from 1,116,498 ha to 564,685 ha. Herbaceous land faced a 28.4% reduction (244,517 ha), with other hay lands losing 136,066 ha and alfalfa losing 100,820 ha. Reductions in cultivated crops (17,261 ha), shrubland (5164 ha), and barren land (18,066 ha) were minor, each accounting for less than 2% of the initial inclusions. Key exclusions were due to the soil's low water storage capacity at the root zone (221,421 ha), slopes steeper than 15% (168,852 ha), and parcels smaller than 2 ha (319,591 ha). Additional exclusions were due to proximity to water bodies (48,709 ha), nitrate leaching index (19,046 ha), and soil organic carbon (27,395 ha) (Figure 2).

The final estimated potential land area for willow cultivation in the NCC scenario is 1.12 million ha, with the potential to produce approximately 14.5 million dry Mg of willow biomass annually (Figure 5). Of this, 49.6% will be sourced from grassland/pasture, 46.7% from herbaceous land, 2.99% from cultivated crops, and shrubland and barren land contribute about 1% together.

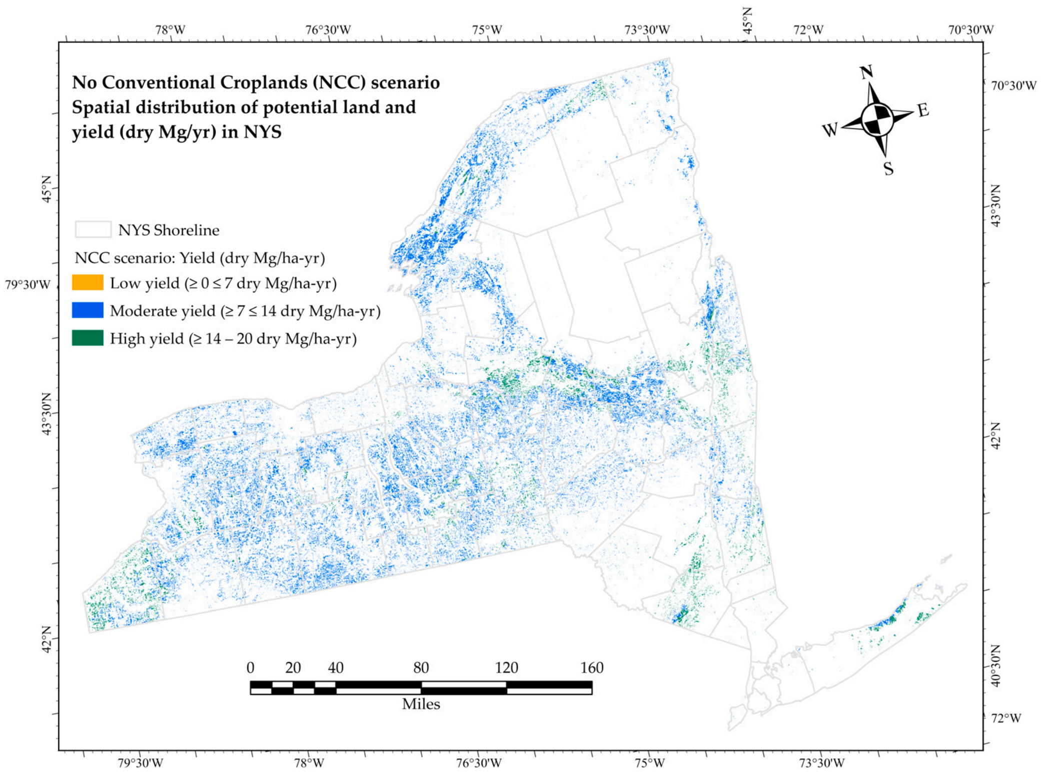

Figure 5. Spatial distribution of suitable land and potential yield of willow biomass crops in the No Conventional Crops scenario (NCC) scenario in NYS.

In total, 109,336 parcels were identified in the NCC scenario, with 88.5% being smaller than 20 hectares and 11% ranging from 20 to 100 hectares. The largest identified parcel was 866 ha, and only five parcels exceeded 500 ha (Figure 3). Most of the larger parcels are in Jefferson and Saint Lawrence counties in the North Country region, which also holds the largest parcel (Figure S16). Of the 1.12 million ha identified, 52%% (523,595 ha) of the area is located in parcels that are 2–20 ha in size, and only 48% of the area (539,453 ha) in parcels greater than 100 ha.

In the No Croplands (NCL) scenario, our analysis identified a total of 1.07 million hectares of land suitable for shrub willow cultivation. Grassland or pastureland accounts for 547,377 ha (51% of the total potential land), while herbaceous land makes up 517,443 ha (48.2%). Smaller contributions come from shrubland (5033 ha) and barren land (3427 ha), which together account for about 1%. Within the herbaceous category, other hay land contributes 296,100 ha (27.7% of the total potential land), alfalfa accounts for 211,928 ha (20%), while idle cropland (5478 ha) and other herbaceous land (3936 ha) together make up about 1% (Figure 1).

After applying production-limiting factors, a total of 851,284 ha was removed from the initial inclusion. The largest reductions occurred in grassland/pasture, decreasing from 1,116,498 ha to 547,377 ha (a reduction of 569,122 ha, about 97%). Herbaceous land decreased from 765,927 ha to 517,443 ha (a reduction of 248,484 ha), shrubland from 20,404 ha to 5033 ha (15,370 ha reduction), and barren land from 21,735 ha to 3427 ha (18,309 ha reduction). The factors causing the largest reduction in land suitability were low soil water storage capacity (214,018 ha), followed by slopes greater than 15% (167,433 ha). Additional exclusions were due to proximity to water bodies (46,212 ha), the nitrate leaching index (18,605 ha), low soil organic carbon (26,828 ha), and field efficiency (49,357 ha) (Figure 2). After excluding small parcels less than 2 ha in size (a reduction of 327,602 ha), the final estimated potential land area for willow cultivation in this scenario was 1.07 million hectares. This land has the potential to produce approximately 14 million dry Mg of willow biomass annually (Figure 6), with 51.1% sourced from grassland/pasture, 48% from herbaceous land, and the remaining 1% from shrubland and barren land categories.

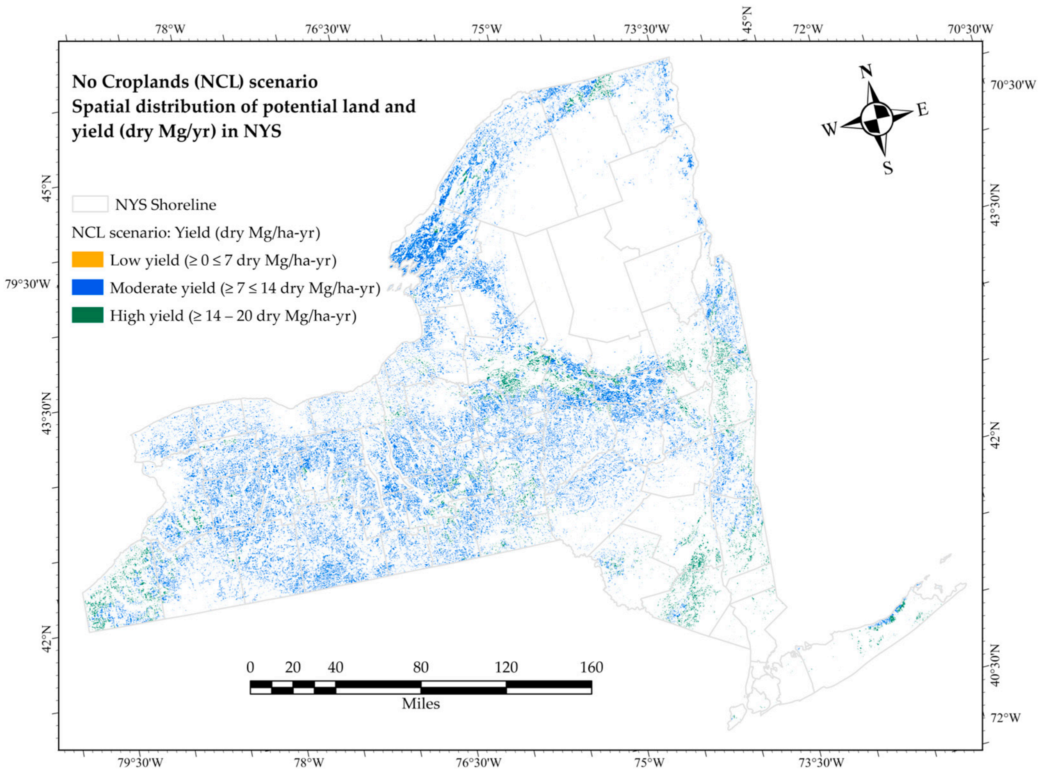

Figure 6. Spatial distribution of suitable land and potential yield of willow biomass crops in the No Cropland Scenario (NCL) in NYS.

In this NCL scenario, a total of 110,037 parcels were identified, with 99% of them being smaller than 20 ha, covering 574,242 ha of potential land. The largest identified parcel was 866 ha, with about 10 parcels exceeding 500 ha each (Figure 3). These larger parcels are primarily located in Jefferson and Saint Lawrence counties in the North Country region, with the single largest parcels exceeding 500 ha (Figure S17). Of the 1.07 million ha identified, 53% of the area (574,242 ha) is located in parcels that are 2–20 ha in size, and only 47% of the area (503,394 ha) is in parcels greater than 100 ha.

4. Accuracy Assessment

Accuracy assessment based on the classification of the NCL scenario indicated that the overall accuracy was 99%, and the kappa coefficient was 75%. Producer accuracy for the "not suitable" class was 62%, while producer accuracy for the "suitable" class was 100%. In addition, user accuracy for the "not suitable" and "suitable" classes was determined to be 96% and 99%, respectively (Table S4).

5. Discussion

Our analysis reveals that there is significant potential for large-scale commercial shrub willow production in NYS, which could play a crucial role in developing a vibrant bioeconomy [91]. A reliable and environmentally sustainable source of feedstock is a key component of developing a bioeconomy, and because willow's composition is similar to hardwoods, it can be blended with forest residues in the state and contribute to a more consistent and reliable supply of material to end users.

Applying multiple production-limiting factors revealed that nearly half of the initially identified land was removed. Key factors influencing the removal of land for willow production include the average water storage capacity in the willow's root zone, slopes greater than 15%, and small parcels less than 2 ha in size. Willow plants are particularly susceptible to water stress [92], requiring 35% to 45% more water than crops grown in comparable agricultural regions [93,94]. Soil moisture holding capacity is crucial for mitigating water stress [95], especially as weather patterns change, such as less frequent rainfall with more intensity, due to climate change. In models to predict the yield of two willow cultivars in the United States, Liu [96] also found that available water capacity had a negative correlation with yield across the range of 0.08–0.23 cm per cm of soil. Approximately 1.53 million hectares of soil in NYS have an average soil water storage capacity of less than 20% (Figure S10), resulting in a notable reduction in suitable land for willow production.

Excluding lands with slopes of greater than 15% reduced a significant amount of land in NYS, as steeper slopes are generally unsafe or impractical for agricultural machinery, particularly the single pass cut and chip harvesting system and associated collection wagons, the most commonly used harvesting system. This system is based on a forage harvester as the prime mover and processor of willow stems, so slopes greater than 15% are not accessible with this equipment. The size of this equipment also means that small fields are difficult to work in because of the space required to turn equipment around at the end of the rows [82]. Smaller fields that are spaced some distance apart have additional costs associated with moving equipment from site to site, which is costly for larger equipment. As a result, we excluded parcels less than 2 hectares in size, which further decreased available land for willow cultivation. These smaller areas could make an important contribution to the supply of biomass while also providing important environmental services when willow is planted as riparian buffers, nutrient filters, living snow fences or for phytoremediation [13]. Previous work has suggested that smaller-scale harvesting systems, such as smaller systems pulled by a tractor, could be effective in smaller areas and work on steeper slopes [83,97]. Future development of these kinds of harvesting systems could make additional land available for growing willow.

Additionally, our analysis has shown that NYS soil exhibits very low erodibility and a moderate tendency for nitrogen leaching, further supporting the suitability of most land for willow cultivation. As a perennial crop, willow benefits from its established root system, canopy cover, and leaf litter after the first year. These factors, along with the slope limitations, contribute to the low erosion potential of willow crops [86] and may result in even lower nitrogen leaching due to the willow's root system, juvenile growth, and regular demand for nitrogen.

Previous trials with shrub willow have demonstrated that good yields can be attained across a wide range of sites with differing NCCPI scores. The trials located in NY that form the basis of the PRISM-ELM yield model [24] had NCCPI values ranging from 0.24 to 0.56. In Constableville, NY, with an NCCPI of 0.24, yields of the top three cultivars in the first rotation being 9.6 dry Mg/ha-yr, while at Big Flats, NY, with an NCCPI of 0.56, the top three cultivars yielded 11.93 dry Mg/ha-yr [98]. Johnson et al. [99] reported that yields of the top three cultivars at the Constable site increased to 11.6 dry Mg/ha-yr in the second three-year rotation and 12.2 dry Mg/ha-yr in the third rotation, indicating that even with the low NCCPI value (0.24), good willow yields are possible. In our NCL scenario, 11% (118,401 ha) of the identified land had NCCPI values below 0.30, 70% of the land ranged between 0.30 and 0.60, and 19% had values above 0.60, indicating that the majority of identified land has favorable NCCPI scores for producing good willow yields (Figure S18). Because shrub willow can perform well across such a wide range of site conditions, we set the cut off threshold low for NCCPI and as a result there was a minimal amount of land removed with this factor.

Most of the NYS's land has favorable SOC levels, with most areas showing more than 0 kg C/m^2, indicating good potential for willow cultivation without significant land exclusion. Cultivating willow could enhance SOC, particularly on sites with lower initial values [100–103]. For example, Rytter [104] found that willow cultivation in Sweden increased SOC by 0.4–0.5 Mg/ha-yr, while Lafleur et al. [102] showed that willow afforestation in Southern Quebec increased SOC in the topsoil by 25%, ranging from 0.4 to 4.5 dry Mg/ha-yr. Knight et al. [101] highlighted that SOC sequestration rates for short-rotation coppice willow vary from 0.23 to 2.8 dry Mg/ha-yr, with sandy soils showing the highest sequestration rates. Our study found that 91% (976,608 ha) of potential land in NYS has less than 10 kg C/m^2, suggesting significant potential to increase SOC at a 0–30 cm depth (Table S5 and Figures S19 and S20). However, discrepancies between SOC sequestration rates from soil sampling and carbon budget calculations highlight the importance of soil texture, land cover change, nutrient availability, and climate [105–107]. Additionally, willow root and leaf litter play a key role in SOC accumulation, though land use history and management practices heavily influence these outcomes. Most of the data is based on research in Europe; further research is needed to verify these findings in North America. Additionally, our analysis identified regions with the highest yield potential as having soil characterized by hydrological soil "group A", featuring 25% air-filled and 25% water-filled pores, along with 45% coarse sand as the dominant mineral and minor amounts of loam, silt, and up to 20% organic matter [55,108]. These are features that align with other parameters that identify areas where good willow growth is possible.

Our analysis of projected low-carbon fuel use in NYS under various Scoping Plan scenarios reveals significant biomass requirements if produced within the state. For example, the Strategic Use of Low Carbon Fuels (SULCF) scenario demands 32.9 million dry Mg of biomass annually by 2030, rising to 41.9 million dry Mg by 2050, requiring approximately 3.61 million ha by 2030 and 4.60 million ha by 2050 if willow is the sole feedstock. Similarly, the Accelerated Transition Away from Combustion and Beyond 85% Reduction scenarios require 5.42 million dry Mg and 11.7 million dry Mg by 2030, with land requirements of 0.60 million and 1.29 million ha, respectively, if willow is the only source of feedstock. The No Cropland scenario in our study demonstrates that considerable land exists for willow production to meet these demands outlined in the Scoping Plan scenarios. Specifically, our estimates suggest that producing 7.76 million dry Mg of purpose-grown biomass to meet the 5.91×10^{13} GJ (56 TBtu) target in the SULCF scenario by 2030 could be achieved using approximately 0.74 million ha of land (Figure S1). While comparing our results with the Scoping Plan's projected low-carbon fuel demand provides useful context and scale for land area and biomass needs, it is important to note that willow is not the only available feedstock. Other feedstock sources include forest residues, projected to be as high as 11.2 million dry Mg [109], and organic waste streams from agriculture (1.53 to 1.89 million dry Mg) and municipal solid waste (8.2 to 10.1 million dry Mg), according to various scenarios in the BT2023 report [9].

Our estimated potential land and willow production across all scenarios are higher than those in the Renewable Fuel Roadmap [29] and the various scenarios in the BT2023 report [9] (Table 1). The RFR estimated that 0.4 to 0.7 million hectares of non-forest land could be available for bioenergy, assuming only half of the landowners would engage in biomass production. It also limited pasture and cropland based on future projections of milk production, the state's primary agricultural activity, and efficiency improvements in the dairy industry. These restrictions, and particularly the assumption on landowner participation, which were not included in our study, made a difference in the results. Removing the landowner assumption in the RFR would result in 0.8 to 1.4 million ha of potential land for willow, which is closer to the estimates from this study. The BT2023 report, using the POLYSYS model, only included land where willow production would generate equal or greater revenue for landowners, while our study did not include economic screening factors. Both studies placed different kinds of restrictions on the land available for willow production. Additionally, our identified land is also comparatively higher than the 0.68 million ha (1.67 million acres) identified by Richardson et al. [32] and the 0.71 million ha identified by NYSERDA [33]. However, our estimated potential land is lower than the 2.16 million ha identified by Cook-Patton et al. [31], which accounted for private landowners' willingness to reforest their land (Figure 7). In addition to the absolute values, this study provides spatial resolution at a fine scale (30 × 30 m) on where willow can be grown in NY and the characteristics of this land.

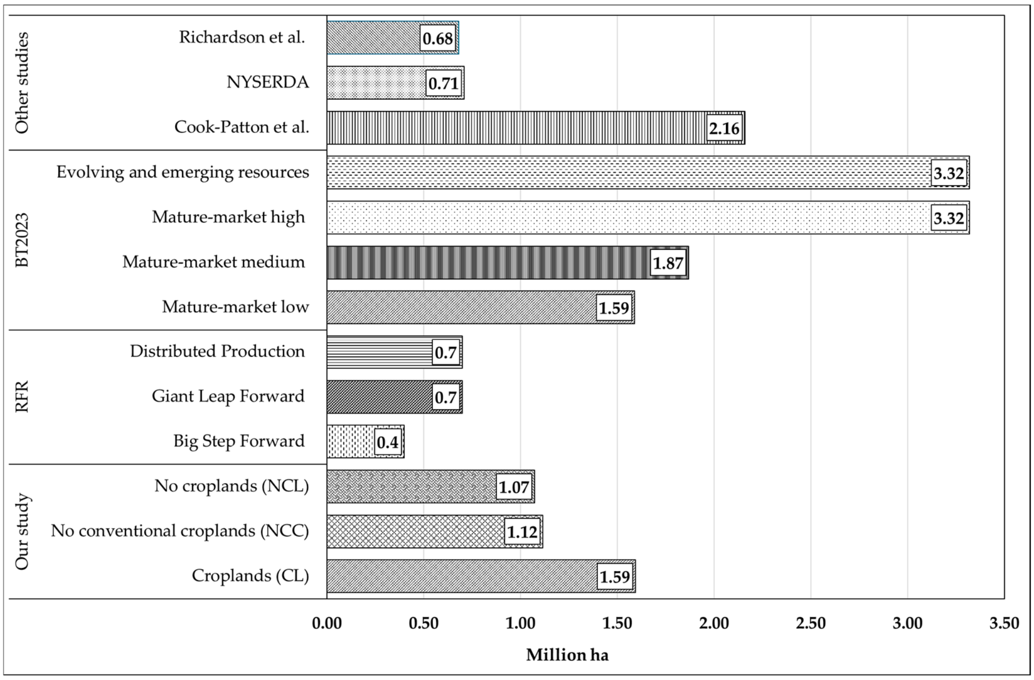

Figure 7. Comparison of potential land where purpose-grown crops or trees can be grown in New York State with the findings of this study. (Note: RFR = Renewable Fuel Roadmap [29], BT2023 = 2023 Billion-Ton Report [9], Richardson et al. [32], NYSERDA [32], Cook-Patton et al. [31]).

Our estimated potential shrublands are comparatively lower than Beier's [110] estimate of 0.57 million ha (1.4 million acres). The difference arises because Beier's study included marginal and transitional lands with a mix of woody plants, grasses, old pastures, croplands, and industrial sites for carbon benefits in NYS, while we categorized them according to NLCD classification. Furthermore, our potential grassland/pasture estimates, ranging from 0.51 to 0.56 million ha, are lower than Cook-Patton's [31] estimate of

1.48 million ha. This difference stems from our inclusion of production-restricting factors, which led to the exclusion of land. However, unlike Cook-Patton's [31] study, we did not account for landowners' willingness to engage in planting. Our evaluation aligns with U.S. national classification standards [111,112], indicating that expanding willow production in these locations is feasible without compromising cropland.

The identification of 1.07 to 1.59 million ha of land in NY that can be used to grow purpose-grown crops, like willow, indicates the potential for this source of biomass to be an important part of a growing bioeconomy. The expansion of purpose-grown crops on even a fraction of the potential area would modify the landscape and have the potential to provide both benefits and impacts, which should be monitored and assessed as crop expansion occurs. For example, studies have noted that willow biomass crops support a wide variety of species, such as birds [18,113], pollinators [114], and ground beetles [115], and could support landscape biodiversity when integrated with other land uses [116]. Suppose willow became the predominant land use in a given area. In that case, there is potential that impacts on biodiversity could be negative, especially if the willow replaces highly-sensitive ecosystems that support a large amount of biodiversity.

6. Conclusions

The cultivation of willow for biomass production presents a promising and sustainable pathway to meet NYS's growing energy demands while minimizing environmental impacts. This study assessed the potential for expanding willow cultivation across New York State, a key component of meeting the state's decarbonization and renewable energy goals as outlined in the Climate Leadership and Community Protection Act (CLCPA). Our findings indicate that NYS has between 1.07 and 1.59 million hectares of potential land for willow production across different land use scenarios, which could yield between 14.0 to 20.6 million dry Mg of biomass annually. This biomass potential aligns closely with the Scoping Plan's projected need for purpose-grown crops, like willow, to meet biofuel demand. The results show that grassland, shrubland, and herbaceous land types are predominant areas for willow cultivation, making up 64% to 99% of potential land across all scenarios. Importantly, our findings demonstrate that large-scale willow production can be achieved without encroaching on land currently classified as cropland, thereby mitigating concerns about food vs. fuel competition and supporting biodiversity conservation.

These insights are critical for policymakers and land managers as they strategize to meet NYS's biofuel production targets. However, further research is needed to identify optimal locations for biorefineries, assess net emissions across a broader range of factors such as biomass density and proximity, and analyze the full lifecycle of low-carbon fuel production from willow, including aboveground, below ground, and change in soil organic carbon. This will also involve comprehensive cost assessments of CO_2 avoidance and the economic feasibility of these systems. Such future studies will refine our understanding of willow-based bioenergy and enhance the role of biomass in helping NYS achieve its decarbonization goals while preserving ecological and agricultural integrity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13111831/s1, Figure S1: Low carbon fuel production targets by source of biomass in NYS scoping plan's Strategic Use of Low Carbon Fuels (SULCF) scenario for 2030 (Conversion Factor: 38.47 MJ/Liter of renewable diesel, 212 L of renewable diesel production per dry Mg and purpose grown biomass yield 9.1 Mg per hectare per year; Figure S2: Estimated feedstocks supply for biofuels production for NYS in Renewable Fuels Roadmap; Figure S3: Potential Biomass Production from the Agricultural Sector in NYS According to BT2023; Figure S4: Distribution of soil erodibility factor, whole soil (Kw) in μm/s in NYS; Figure S5: Percolation index in NYS; Figure S6: Seasonality index in NYS; Figure S7: Nitrate leaching index in NYS; Figure S8: Distribution of SOC at 0–30 cm depth of soil in NYS; Figure S9: Distribution of National Commodity Crop Productivity Index (NCCPI) in the soil of NYS; Figure S10: Soils with greater than 20% of Average Water Storage Capacity (AWSC) at plants' root zone (30 cm); Figure S11: Land with slope less than 15% in NYS; Figure S12: Fields with more than 95% harvesting efficiency; Figure S13: Potential willow production map (dry Mg/ha-yr) in PRISM-ELM model in NYS; Figure S14: Geographical locations and name of willow field trails; Figure S15: Distribution of parcel size identified in Croplands (CL) scenario in NYS; Figure S16: Distribution of parcel size identified in No Conventional Croplands (NCC) scenario in NYS; Figure S17: Distribution of parcel size identified in No Croplands (NCL) scenario in NYS; Figure S18: Distribution of NCCPI values in the identified potential land under the "No Cropland (NCL)" scenarios; Figure S19: Distribution of SOC (kg/m^2) at 0–30 cm depth in the potential land identified in No Croplands (NCL) scenario in NYS; Figure S20: Distribution of SOC values in the identified potential land under the "No Cropland (NCL)" scenarios. Table S1: Low carbon fuels production target in NYS's Scoping Plan; Table S2: Land use classes in New York State in 2022 and restricted classes from USDA-NASS land use data for suitable land assessment (1 is included, while 0 is restricted for willow cultivation); Table S3: Potential biomass production (dry Mg) from the agricultural sector in NYS according to BT2023; Table S4: Accuracy assessment of land characterization; Table S5: SOC content at 0–30 cm depth of soil in the identified potential in No Cropland (NCL) scenario in NYS.

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