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Life cycle assessment of a willow bioenergy cropping system

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Abstract

The environmental performance of willow biomass crop production systems in New York (NY) is analyzed using life cycle assessment (LCA) methodology. The base-case, which represents current practices in NY, produces 55 units of biomass energy per unit of fossil energy consumed over the biomass crop's 23-year lifetime. Inorganic nitrogen fertilizer inputs have a strong influence on overall system performance, accounting for 37% of the non-renewable fossil energy input into the system. Net energy ratio varies from 58 to below 40 as a function of fertilizer application rate, but application rate also has implications on the system nutrient balance. Substituting inorganic N fertilizer with sewage sludge biosolids increases the net energy ratio of the willow biomass crop production system by more than 40%. While CO_2 emitted in combusting dedicated biomass is balanced by CO_2 adsorbed in the growing biomass, production processes contribute to the system's net global warming potential. Taking into account direct and indirect fuel use, N_2O emissions from applied fertilizer and leaf litter, and carbon sequestration in below ground biomass and soil carbon, the net greenhouse gas emissions total 0.68 g CO_2 eq. $MJ^{-1}_{biomass\ produced}$. Site specific parameters such as soil carbon sequestration could easily offset these emissions resulting in a net reduction of greenhouse gases. Assuming reasonable biomass transportation distance and energy conversion efficiencies, this study implies that generating electricity from willow biomass crops could produce 11 units of electricity per unit of fossil energy consumed. Results from the LCA support the assertion that willow biomass crops are sustainable from an energy balance perspective and contribute additional environmental benefits.

Keywords: Willow biomass production; Life cycle assessment; Energy analysis; Greenhouse gas emissions; Fertilizer inputs; Biosolids

1. Introduction

About 7% of the 104 EJ (98 quadrillion BTU) of energy consumed annually in the US currently comes from renewable sources [1]. Biomass in all of its forms composes nearly half of these renewable sources, making it the second most utilized renewable after hydroelectric. Concern over national energy security and the environmental burdens associated with fossil energy sources has prompted interest in expanding domestic renewable energy markets. Biomass, and in particular dedicated energy crops, has received recent attention as a promising means to develop local, sustainable energy sources.

Short rotation woody crops (SRWC) (typically of *Salix* or *Populus* species) are a demonstrated biomass cropping system that is managed more intensively

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than usual forestry practices and harvested on a 3–4 year cycle [2,3]. SRWC systems provide significant opportunities for environmental and other benefits, including reduced net greenhouse gas and SO_x emissions (relative to fossil energy sources), improved soil and water quality, expanded wildlife habitat, increased land use diversity, and revitalized rural economies [4,5].

The Salix Consortium is an alliance of over 20 organizations with a goal of facilitating the commercialization of willow biomass SRWC in the Northeastern and Midwestern regions of the US. In 1995, a development grant was awarded under the Biomass Power for Rural Development Program supported by the US Department of Energy and the Department of Agriculture to develop willow as a dedicated energy feedstock crop. Over 200 ha of willow have been established to date in western and central New York (NY). In the near-term, the harvested willow biomass will be used to supplement new co-firing operations at an electricity generating facility in western NY.

Widespread development of bioenergy in general, and willow biomass-for-bioenergy in particular, is contingent on the environmental sustainability of the system, along with its socio-economic sustainability [4]. Life cycle assessment (LCA) methodology provides a comprehensive systems-based analysis of the energy and environmental performance of a product system [6]. In LCA, the material and energy inputs and outputs are quantified throughout a product's life, from raw material acquisition through production, use and disposal. Potential environmental impacts of the product system are then assessed based on this life cycle inventory.

A LCA model was developed for the full willow agriculture to electricity production system. In this paper, we focus on the willow biomass production system as it is being developed in New York state. The primary aim of the study was to evaluate the energy performance and net greenhouse gas emissions of the biomass feedstock production system. Previous life cycle or energy analysis studies of SRWC systems have considered prospective popular plantations in the US [7] and both willow and poplar biomass production systems under European conditions [8–13]. The current paper provides detailed accounting of willow biomass crop production, supported by demonstration-scale field experience from NY. Both carbon and nitrogen (N_2O) flows are considered in the global warming potential assessment. In addition to the base-case scenario that represents management practices currently in place in NY, we estimate system performance of alternative practices, including the use of sewage sludge biosolids as an alternative for inorganic N fertilizer. Utilization of biosolids in biomass energy production offers a reduced-risk (relative to edible food crops) opportunity to convert a waste stream into a resource. Finally, we consider the implications on system performance of using willow biomass to generate electricity.

2. Methods

Life cycle assessment methodology follows the ISO 14040 guidelines [6]. The model was developed using the software program, Tools for Environmental Analysis and Management (TEAM), by Ecobalance, Inc. Modules for generalized practices such as raw material extraction, large market chemical production (including ammonium sulfate), average grid electricity generation, transportation fuel production, and transport emissions were taken from Ecobalance's Database for Environmental Analysis and Management (DEAM).

The net greenhouse effect was calculated using global warming potentials from the Intergovernmental Panel on Climate Change (IPCC) (direct effect, 100 year time horizon) [14]. Air acidification and eutrophication impact assessment methods followed those presented by Leiden University, Centre for Environmental Science [15]. These impact potential methods compile the contributions of releases throughout the system life cycle, quantified relative to a standard. The air acidification potential calculation, expressed in kg SO_2 eq. ha^{-1}, includes air emissions of ammonia, sulfur oxides, and nitrogen oxides. Eutrophication potential, expressed in kg PO_4 eq. ha^{-1}, includes contributions from air and water emissions of ammonia and phosphorous, air emissions of nitrogen oxides, and water emissions of nitrates and phosphates. Data of nutrient run-off or leaching from willow biomass crops are unavailable and therefore not included in this assessment. Studies in the literature have shown that N leaching is very low in

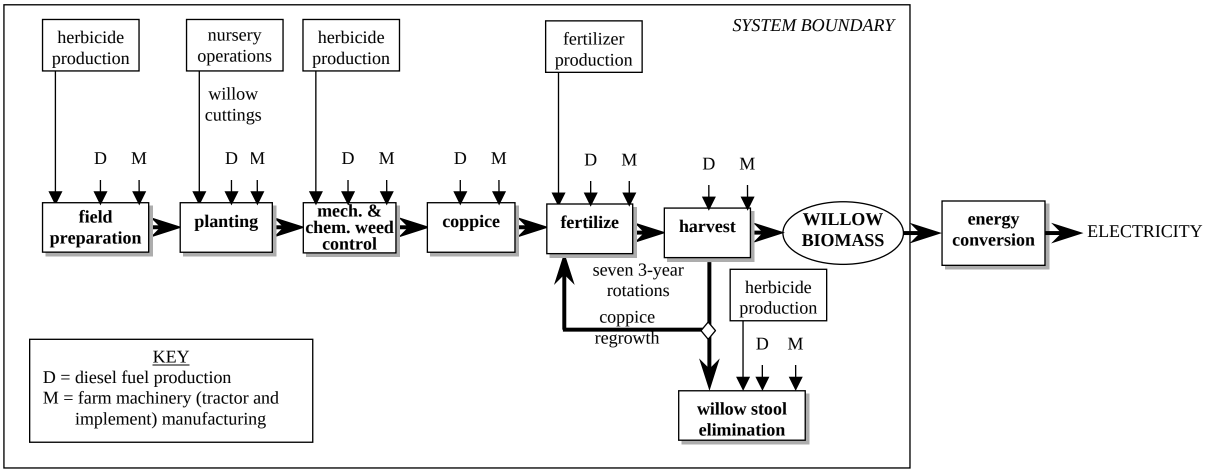

Fig. 1. Schematic of willow biomass cropping system boundary.

Table 1
Willow field operation timeline

Year	Season	Activity
0	Fall	Mow, contact herbicide, plow, disk, seed covercrop, cultipack
1	Spring	Disk, cultipack, plant, pre-emergent herbicide, mechanical and/or herbicide weed control
1	Winter	1st year coppice
2	Spring	Fertilize
3		
4	Winter	1st harvest
5	Spring	Fertilize
6		
7	Winter	2nd harvest
{8–22}		{Repeat 3 year cycle for 3rd–7th harvest}
23	Spring/ Summer	Elimination of willow stools

willow crops [46,47] and so it is expected that this assumption will have little effect on the eutrophication potential in perennial willow crops.

2.1. System description

The willow cropping system boundary is shown schematically in Fig. 1. The willow agricultural production model uses field data collected during the establishment of 65 ha in Western NY in 2000. Table 1 gives a timeline for the major operations undertaken in willow field management. Willow biomass crops are grown as a perennial with multiple harvest cycles (or rotations) occurring between successive plantings. The Salix Consortium anticipates harvesting on 3–4 year cycles, and expects to re-plant after 6–7 rotations [16]. The model base-case scenario assumes seven 3-year rotations and includes 1 year of site preparation, coppicing after the first year of growth, and the removal of the willow stools at the end of the rotation. The life cycle model allocates resource demands and associated emissions for all operations shown in Table 1 evenly across the total biomass harvested over a 23-year timeline. In other words, even though there is more field activity during the first rotation due to field preparation and planting, these burdens are shared equally with biomass harvested in all seven rotations.

Energy is consumed and emissions are released in tractor operations in each field activity. Field operation input data are summarized in Table 2. Tractor size (maximum power-take-off) and weight were derived from tractor models indicated in 2000 field activity records. Some operations (for example, cover crop seeding and 1st year weed control) are conducted based on field management decisions and do not occur on all acreage. Estimates of acreage requiring such operations are again based on experience with the 65 ha planted in 2000.

Table 2
Field operations data for base case

Operation	Implement used	Implement weight (kg)	Tractor power[a] and weight	Operating rate (h ha^{-1})	Input rates and comments
Mow existing vegetation	1.8 m brushhog	470	54 kW 3240 kg	1.5	(55% of acreage)
Apply contact herbicide	7.6 m boom sprayer	670	37 kW 2572 kg	0.5	Glyphosate: 2.5 kg AI ha^{-1}
Plow	1.45 m Moldboard plow[b]	1226	60 kW 3683 kg	1.7	
Disk	3.4 m tandem harrow disk	1053	54 kW 3240 kg	1.4	(2 × coverage)
Cultipack	3.0 m cultipacker	635	54 kW 3240 kg	0.71	(2 × coverage)
Seed covercrop	12.2 m broadcaster	100	37 kW 2572 kg	0.10	2.5 bu. winter rye ha^{-1} (50% of acreage)
Planting	4 row Salix Maskiner Step	1400	78 kW 5670 kg	2.5	15,300 cutting units ha^{-1}
Apply pre-emergent herbicide	7.6 m boom sprayer	670	37 kW 2572 kg	0.46	Simazine: 2.24 kg AI ha^{-1} Oxyfluorfen: 1.12 kg AI ha^{-1}
1st year coppice	2.1 m sicklebar mower	270	54 kW 3240 kg	1.5	
Mechanical weed control	Modified row cultivator	500	37 kW 2572 kg	0.61	(54% of acreage)
Mechanical weed control	Badalini rototiller	400	54 kW 3240 kg	1.6	(29% of acreage)
Chemical weed control	7.6 m boom sprayer	670	37 kW 2572 kg	0.46	Simazine: 2.24 kg AI ha^{-1} (5% of acreage)
Fertilize	7.6 m spreader	180	75 kW 4192 kg	0.21	100 kg N ha^{-1} ammonium sulfate
Harvest	Salix Maskiner Bender	1250	78 kW 5670 kg	3.0[c]	

[a]Maximum power take off (PTO) power.
[b]Plow width is average of two used: 4 × 36 cm (137 cm width) and 4 × 41 cm (152 cm width).
[c]Extensive harvesting with the Maskiner Bender has not yet occurred in New York. Harvesting rates are based on data from European studies using earlier models of this machine.

2.2. Tractor and implement manufacture and operation

Material and energy required in manufacturing agricultural implements and tractors were included in the life cycle inventory. Manufacturing requirements were based on weight, according to data shown in Appendix A (Tables 9 and 10). Manufacturing burdens were allocated to the system on a field-hour basis, distributed over the estimated life of the tractor or

Table 3
Data used in fuel consumption equations

Operation	A	B	C	E_t	S (km h^{-1})	W (m)	T (cm)	F_2
Moldboard plow	113	0	2.3	0.72	5.6	1.45	20.3	0.7
Fall disk	53	4.6	0	0.67	6.4	3.4	10.2	0.88
Spring disk	37	3.2	0	0.72	6.4	3.4	10.2	0.88
Cultipack	180	0	0	0.67	4.8	3.0	6.4	1

Table 4
Assumed power requirements for certain operations

Operation	Maximum PTO power from modeled tractor (kW)	Assumed total power required for operation (kW)
Brushhog	54	37
Herbicide application	37	18.5
Fertilizer application	75	45
Coppicing w/ sicklebar mower	54	37
Rototilling	54	48
Planting with Step planter	78	52
Harvesting with Bender	78	78
Biosolids application	75	60

implement (1200–1500 h for implements, 12,000 h for tractors [17]). Operation burdens are broken down into fuel consumption and oil consumption.

2.2.1. Fuel consumption

Since fuel consumption was not well documented in field records, the life cycle model relies on engineering estimates from the American Society of Agricultural Engineers [18,19]. For operations with significant draft force (plow, disk, cultipack), diesel consumption is estimated by the following:

$$Q_{\text{diesel}} = P_T \left(2.64 \frac{P_T}{P_{\max}} + 3.91 - 0.203 \sqrt{738 \frac{P_T}{P_{\max}} + 173} \right). \quad (1)$$

Assuming that power take-off (PTO), hydraulic, and electric power requirements are negligible relative to drawbar (draft) power with these operations, and combining appropriate equations from [18,19]:

$$P_T = \frac{F_2 WTS}{3.6 E_m E_t} [A + B(S) + C(S)^2], \quad (2)$$

where Q_{diesel} is the diesel fuel consumption (l h^{-1}); P_T the total power required for an operation (kW); $P_{\max}$ the maximum available PTO power (kW); F_2 the dimensionless soil texture parameter for medium textured soils; W the machine width (m); T the tillage depth (cm); S the field speed (km h^{-1}); E_m the mechanical efficiency of transmission and power train = 0.96 for tractors with gear transmissions; E_t the traction efficiency; A, B, and C are the machine-specific parameters.

The parameter values used, also taken from ASAE [19], are summarized in Table 3. Table 4 lists assumed power requirements for field operations lacking appropriate engineering data. Fuel consumption was then calculated by substituting these assumed power requirements for P_T in Eq. (1).

2.2.2. Oil consumption

Oil consumption was estimated with the relation given as follows [19]:

$$Q_{\text{oil}}(\text{l h}^{-1}) = 0.00059 P_{\max} + 0.02169. \quad (3)$$

2.3. Manufacture and transport of field inputs

The manufacture of fertilizer and pesticides was included in the life cycle inventory. Modeling details for these manufacturing processes are shown in Appendix A (Tables 11 and 12). Ammonium sulfate (the base-case fertilizer) is produced in the US as a byproduct as well as through elective manufacturing [20]. A marginal allocation approach was adopted in this study: additional demand for ammonium sulfate would have to be met through elective manufacturing [21]. Thus, production by the direct neutralization of ammonia with sulfuric acid is used (data for production from DEAM). Transport to the farm was taken into account for fertilizer and herbicide supplies. An average distance of 640 km was used, 60% by rail and 40% by truck [22]. The willow cuttings used for planting are produced in a nursery: demands of this nursery production are shown in Appendix A (Table 13).

2.4. Biosolids application

There is considerable interest in using treated wastewater sewage sludge (biosolids) as a nutrient source in SRWC [23,24]. About half of the biosolids produced in the US are recycled for beneficial use through land application [25]. Biomass energy crops are particularly attractive means for treating and utilizing biosolids: a non-food crop further reduces the risk of causing human disease, extensive perennial roots effectively filter mineral nutrients, and, with proper consideration, it is possible to control the flow of heavy metals in the system [26]. In addition, the organically bound fraction of nutrients in biosolids are released slowly, making them available longer into the SRWC rotation-cycle when additional amendment application is prohibitive.

In this report we consider hypothetical scenarios using biosolids as an alternative fertilizer source for willow plantations. Representative biosolids data from a small, rural municipality (Little Valley, NY) and a more industrial municipality (Syracuse, NY) were used. Application rates were 100 kg plant-available N, based on calculation methods in the NY State regulatory guidelines [27]. The analysis does not include production or treatment of the biosolids: biosolids are a waste stream and typically a disposal burden for the wastewater treatment industry. Transportation (by diesel truck) and surface application of biosolids (assumed operating rate = 0.53 h ha^{-1}; tractor requirements shown in Table 4) are included, however. Transportation distances for the Little Valley and Syracuse scenario are assumed to be 25 and 80 km, respectively.

Table 5
Willow biomass characteristics

	Willow biomass[a] (dry weight %)
Carbon	49.4
Sulfur	0.05
Oxygen	42.9
Hydrogen	6.01
Nitrogen	0.45
Chlorine	265 ppm
Ash	1.24
Moisture (at harvest)	~50%
Heating value	19.8 MJ odkg^{-1}

[a]Average of samples of 3-year old SV-1 and S-365 (willow clones still in use) from [28].

2.5. Willow biomass

2.5.1. Harvested yield

Based on experience at SUNY-ESF, the assumed willow biomass yield for the 1st rotation is 10 oven dry tonnes (odt) ha^{-1} yr^{-1}. Thus, the 1st harvest (after 3 years of growth) is expected to produce 30 odt ha^{-1}. Successive rotations have an additional growth advantage because the willow's root system is already established. It is expected that this will increase yields in later rotations by 30–40%. For successive rotations, the assumed yield is 13.6 odt ha^{-1} yr^{-1}. The assumed composition and energy content of harvested willow is presented in Table 5.

Adegbidi [29] conducted experiments with willow clone SV1 consisting of triplicate test blocks at 4 different fertilizer application rates (0, 100, 200, 300 kg N ha^{-1}). One, two, and three-year harvest yields were measured for each test block. In order to estimate the response of biomass yield to N fertilizer application rates, data from Adegbidi were fit by nonlinear regression to an exponential saturation function of the following form (suggested by Ballard et al. [30]):

$$\text{yield} = I + A(1 - e^{v*\text{fert.rate}}). \quad (4)$$

Regression resulted in the following parameter values: $I = 5.876$ odt yr^{-1}; $A = 6.856$ odt yr^{-1}; $v = -0.00916$; $r^2 = 0.63$. Given the limited data available to date, this function is provisional and is used here only in estimating system performance sensitivity to fertilizer application rate.

2.5.2. Below ground biomass

Unutilized biomass in the form of coarse roots and stools represents a potential pool for short-term carbon storage. Data on below ground biomass in SRWC willow systems are limited. It is expected that coarse, woody roots and stumps will reach a nearly stable mass in mature willow biomass systems that will remain for the lifetime of the system (circa 20 years). To estimate this mature below-ground biomass, willow data from Matthews [10], Zan [31] and Volk (unpublished data) were aggregated and a shoot:root ratio was plotted as a function of stool age (data not shown). From this graph, an asymtotic shoot:root ratio of 1.75 was estimated. Using this ratio and assumed shoot harvest yields from mature (3rd rotation) plantations, the maximum accumulated below ground biomass was calculated, and carbon stored was estimated assuming a root carbon content equivalent to that of stem biomass (Table 5). This estimate must be considered preliminary. It is intended to demonstrate the order of magnitude of potential carbon storage in SRWC root biomass.

2.6. Soil carbon

It has been shown in the agricultural and soil science literature that switching from conventional tillage to no-till practices can accumulate soil organic carbon levels on a decade time scale [32–34]. Given the relative infancy of SRWC plantations, the effect of SRWC on soil organic carbon is not well known, although it is suspected that there is potential to sequester soil carbon in long-term (20 year) plantations on historically tilled soils [35,36]. No significant change in soil carbon was seen in a chronosequence study of willow crops that were 2–12 years old [37]. The base-case in this study thus assumes zero net soil carbon sequestration or loss.

2.7. Soil emissions

2.7.1. Ammonia volatilization

Ammonia (NH_3) volatilization from fertilized soils is essentially a physicochemical process and is dependent on fertilizer type, and in some cases soil pH, soil type and weather conditions [38]. Emissions from urea fertilizer are typically the highest and most variable, ranging from 6% to 47% of applied N. Other fertilizer types (ammonium nitrate, compound fertilizers) demonstrate emissions on the order of 1–2% of applied N. NH_3 emissions from application of ammonium sulfate, the base-case fertilizer used here, have proven to be highly pH dependent, with suggested emission factors of 2% for $pH < 7$ and 18% for $pH > 7$ [38]. Currently established willow crops in western NY have soil pHs in the 5–6 range. In this study, an ammonia volatilization factor of 2% was assumed.

For the application of biosolids, ammonia volatilization is estimated according to EPA land application process design guidelines [39]. A volatilization factor of 50% of applied NH_4-N is recommended for surface applied biosolids.

2.7.2. Nitrous oxide (N_2O)

N_2O is a persistent greenhouse gas produced naturally in soils through the processes of nitrification and denitrification. Agricultural soils are estimated to contribute nearly 70% of the anthropogenic N_2O emissions in the US [40]. Evolution of N_2O is governed by a complex array of agriculture practices, biogenic processes, soil properties, and climatic conditions [41]. The addition of nitrogen to agricultural systems in the form of synthetic fertilizer, biosolids and increased biological N-fixation enhances N_2O formation, although formation is also regulated by such factors as temperature, pH and soil moisture content. Due to limited available data for inclusion of crop, soil, and climatic factors, the IPCC Guidelines recommend estimating direct N_2O emissions from the addition of synthetic fertilizer as a simple function of the amount of fertilizer added (N_2O-N emitted $= 1.25 \pm 1\%$ of N addition) [42]. This relation provides an order of magnitude estimate of N_2O emissions and will be used in this study. Note that estimated N loss due to ammonia volatilization is subtracted from the N addition before estimating N_2O emissions with this relation.

The revised 1996 IPCC guidelines recommend including N_2O emissions from the decomposition of crop residues recycled to agricultural soils. The recommended method of calculation is to estimate the nitrogen returned to soils in crop residues and apply the same N_2O emission factor used for synthetic fertilizer application [42]. Annual leaf senescence in willow crops constitutes a significant addition of "crop residue" with relatively high nitrogen content to the soil. Since leaf litter is not incorporated into the soil through tillage and thus accumulates on the soil surface, it is expected that decomposition under most circumstances will be primarily aerobic, thus minimizing the N_2O created by denitrification (an anaerobic process). Still, leaf litter as a source of N_2O emissions is included in this study (calculated according to the IPCC Guidelines) to indicate its potential significance. An annual leaf senescence of 3800 kg ha^{-1} yr^{-1} [43] and a leaf N content of 1.5% [43,44] was assumed.

2.8. Nitrogen balance

In addition to fertilizer inputs, the model also accounts for atmospheric N deposition at a rate of 16 kg N ha^{-1}yr^{-1} [45]. Nitrogen removal, or outputs, include NH_3 and N_2O emissions and harvested biomass (N content according to Table 5). N_2O losses from leaf litter are not accounted for in this balance. Nitrate leaching field data are not yet available from large-scale SRWC in NY. Since fertilizer is not applied during the establishment year, which is when SRWC systems are most susceptible to nitrate leaching [46–48], it is assumed in this assessment that significant nitrate leaching does not occur. Nitrogen content of the soil prior to planting is also not accounted for in the elementary N balance conducted here.

3. Results and discussion

3.1. Energy analysis

Fertilization and harvesting account for the majority of the 98.3 GJ ha^{-1} of primary energy consumed over seven harvest rotations of willow biomass crops (Fig. 2). Fertilizer manufacturing itself makes up 91% of the energy consumed in the fertilization step, while the nursery production of willow cuttings constitute 76% of the planting step. Overall establishment of the crop and management through to the end of the first rotation accounts for 36% of the total primary energy use. Direct energy inputs of diesel fuel represent 46% of the total energy use, while indirect inputs (agricultural chemicals, machinery, nursery operation) compose the balance (Fig. 3).

The net energy ratio (harvested biomass energy at the farm gate divided by fossil energy consumed in production) for agricultural production of willow biomass after the first rotation is 16.6. This ratio increases to 55.3 when considering output and consumption over the full seven rotations (Table 6). In other words, according to our model, 55 units of energy stored in biomass are produced with one unit of fossil energy. The net energy ratio for the system is directly proportional to total yield as the reasonable yield range based on experience in NY, and presented in Table 6, demonstrates. Biomass yield is dependent on a wide array of factors including crop genetics, soil fertility, weather, site preparation, weed competition, insect and disease damage, and animal browse.

The net energy ratio presented here is on the high end of values reported in the literature for the production of woody biomass (see Table 4 in [10]). Much of the range seen in earlier reportings and the discrepancy with our estimates can be attributed to major differences in growing and processing methods (for example, the inclusion of irrigation or active drying), fertilizer application rates (see Section 3.3 below) and biomass yield assumptions. When the contributions from storage and drying, fence erection and maintenance, and transportation are not included in Matthews' energy budget of a SRWC production system in the UK, the resulting net energy ratio is 65 [10]. Mann and Spath conducted a LCA study of a biomass gasification combined-cycle system fed with biomass feedstock from a hybrid poplar cropping system grown on 7-year rotations [7]. They report a net energy ratio of 55 (recalculated to represent energy in biomass divided by energy consumed in feedstock production).

3.2. Greenhouse gas emissions

A predominant environmental benefit of biomass energy is its apparent carbon neutrality with respect to the atmosphere: that is, the CO_2 emitted in utilizing the biomass energy is balanced by the CO_2 absorbed in growing the biomass crop, resulting in

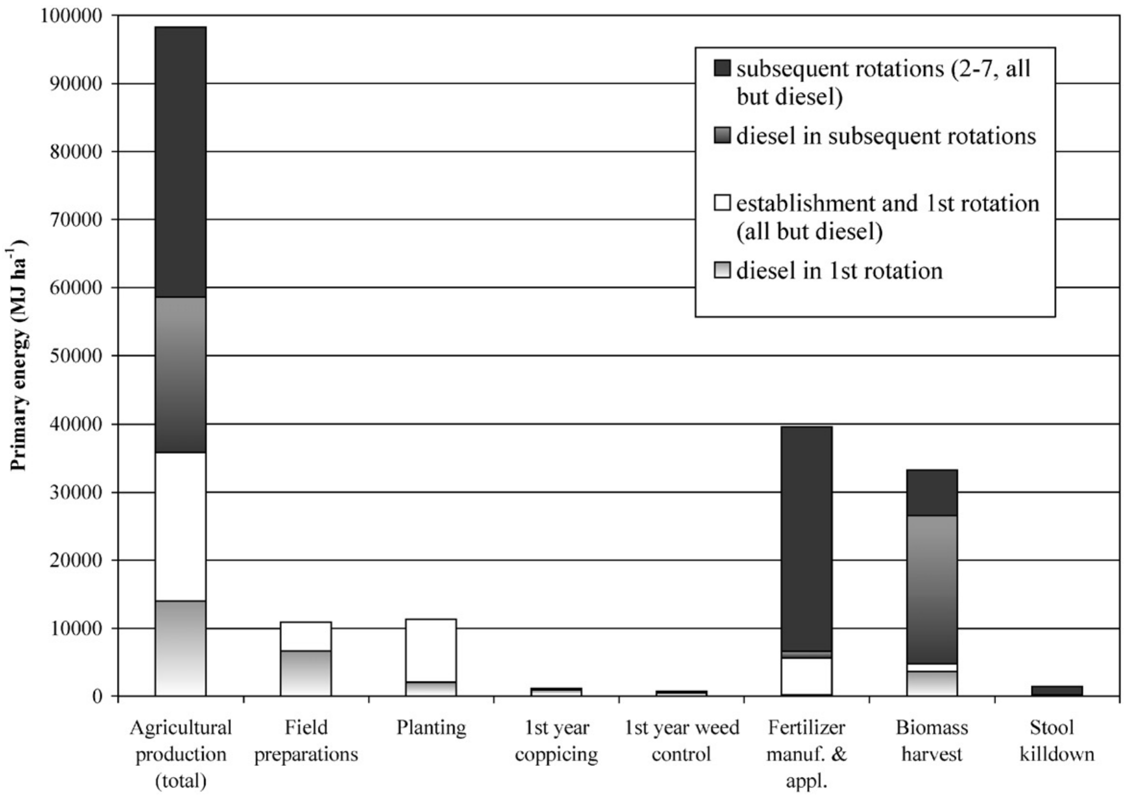

Fig. 2. Primary energy use for major cropping events during the 23 year lifespan of willow biomass crops in New York. “Field preparations” encompasses all of the tilling and weed control activities leading up to planting, including the manufacture of herbicidal inputs. “Planting” includes the nursery production of willow cuttings and the planting operation itself. “Fertilizer manufacturing and application” includes the manufacture and transportation of ammonium sulfate as well as field application of the fertilizer.

no net increase in atmospheric CO_2. However, other sources of CO_2 emissions that exist in the system (tractor operation, fertilizer manufacturing, etc.) must be considered. In addition, emissions of other greenhouse gases, such as N_2O, will also contribute to the net global warming potential of the system. On the other hand, there are potential carbon storage pools in the willow coppice system that may deserve attention. Here we demonstrate the relative magnitudes of the various contributors to the system net global warming potential in an attempt to highlight their respective importance. Table 7 presents estimates for these greenhouse gas flows per hectare of willow plantation, accumulated over 7 rotations (23 years).

Greenhouse gas emissions resulting from diesel fuel combustion and the manufacture of agricultural inputs are predominantly CO_2; together these emissions are equivalent to 1.3% of the carbon that is harvested as biomass. Considering only the CO_2 emissions from diesel combustion and agricultural inputs, 0.31 g C is emitted per MJ of biomass produced. Matthews reports a carbon emissions coefficient of 1.4 g C MJ^{-1} [10]. However, if Matthews' value is adjusted by excluding the contributions of major system differences (fence, storage/drying, transportation) the result is comparable (0.37 g C MJ^{-1}). Fertilizer manufacturing constitutes 75% of the greenhouse gas emissions included under the heading “agricultural inputs” in Table 7.

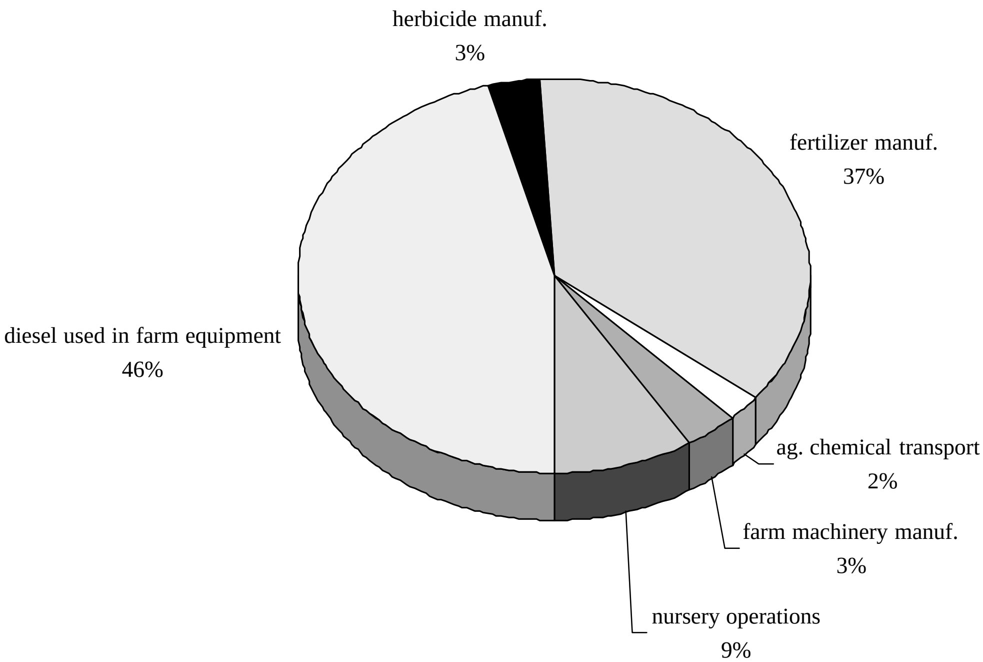

Fig. 3. Breakdown by activity type of primary energy used in producing willow biomass crops.

As indicated, estimates of N_2O emissions are based on IPCC guidelines and do not account for differences that may exist due to fertilizer type, soil type and/or drainage, or other site specific parameters. Efforts have been made to determine the effect of fertilizer type on N_2O emissions (for example, see the review by Harrison and Webb [38]) and in general, empirical emission measurements from anhydrous ammonia (2–5% applied N) are higher than the IPCC estimate while emissions from ammonium, urea, and nitrate based fertilizers tend to be on the low end of the IPCC estimate range. However, weather, timing of fertilizer application, and possibly soil type (drainage) are large factors. N_2O emissions are generally higher under wet conditions (spring application, poorly drained soil) as denitrification is an anaerobic process. Review of empirical studies suggest that emissions from nitrate based fertilizers can be significantly greater than ammonium based fertilizers (e.g. ammonium sulfate) under wet conditions. Specific reports of emissions from ammonium sulfate would suggest that spring application of ammonium sulfate would result in emissions at or below the low end of the IPCC range (i.e., $< 0.25\%$ of applied N) [38]. Thus the N_2O emission estimates presented in Table 7 would seem to be an upper bounds.

Annual leaf senescence in willow biomass crops is significant (3.8 ± 0.2 Mg ha^{-1} yr^{-1}) [43]. Typically, the nutrients contained in leaf litter are considered to remain within the system, becoming available for successive tree growth as the leaves decompose. However, the microbial processes that cause decomposition can also result in atmospheric losses as N_2O. While losses are small (again, likely overestimated by the IPCC correlation), the quantity of leaf litter in SRWC as well as the high global warming potential of N_2O (296 times that of CO_2) amplify the effect. Still, our upper-bound estimates of N_2O emissions from leaf litter amount to only 1.5% (uncertainty range: 0.3–2.6%) of the harvested biomass on a CO_2-equivalents basis.

Below-ground biomass in the form of coarse roots and stools presents a short-term (1–2 decade), reversible carbon storage pool. Coarse root biomass

Table 6
Effects of yield assumptions on the net energy ratio at the farm gate for willow biomass crops grown in NY

Yield parameters				Model results		
Starting yield	Yield increase	Total yield		Energy input	Energy ratio	
(odt ha^{-1})	(%)	(MJ ha^{-1})	(odt ha^{-1})	(MJ odt$^{-1}_{biomass}$)	(MJ$_{out}$ MJ$^{-1}_{in}$)	% of base case
10 (base case)	36	5,434,950	274.4	358.1	55.3	
6	36	3,264,620	164.8	596.1	33.2	60.4
15	36	8,161,560	412.1	238.5	83.0	151
10	5	4,331,340	218.8	449.2	44.1	79.7
10	100	7,713,350	389.6	252.3	78.5	142.0

increases as the willow stand matures, but is expected to reach a relatively stable level in mature plantations with minor variation due to above-ground harvest cycles. Thus, unlike above-ground biomass that accumulates with successive harvests, below-ground biomass maintains a steady state for much of the crop's lifetime. At the end of the crop's life, roots and stumps will likely be left in the soil to decompose, releasing much of the accumulated carbon as CO_2. If the site is re-planted to willow, growth of a new root system will offset CO_2 emissions from decomposing old roots and stools, but no additional net accumulation will be realized. Sequestration on this time scale may be relevant under future carbon emission trading scenarios. The values presented in Table 7 are based on the limited data available, but are intended to provide an order-of-magnitude estimate of below-ground sequestration potential.

Our inventory assumes no net change in soil carbon in the willow system. The potential to sequester carbon in soil under SRWC systems is very site-specific and is dependent on factors such as former and current management practices, climate, and soil characteristics. Heavy tillage can result in decreases in soil organic matter. A site history of conventional tillage without sufficient reintroduction of organic matter through crop residues, cover cropping or manure can lead to a significant depletion of soil organic matter [32]. Introduction of SRWC on such a site would likely result in increases in soil organic matter due to reduced tillage and inputs of leaf litter and fine root mass. On the other hand, converting grasslands or, in the extreme, peat bogs which are high in organic matter, to SRWC may result in decreases in soil organic carbon [10,36]. Furthermore, it is expected that soils will reach a steady state of carbon content slowly, on a decade time scale, making measurement of change difficult. Short-term changes in soil carbon under perennial bioenergy crops have been reported [49,50] but the long-term significance of these changes remain uncertain. West and Marland [33] report a carbon sequestration rate upon switching from a history of conventional tillage to no-till, averaged across a variety of crops and over

Table 7
Greenhouse gas flows[a] per hectare over 7 rotations for the base case (ammonium sulfate fertilizer)

	CO_2	Other GHG Mg CO_2 eq. ha^{-1}	Total
Emissions			
Diesel fuel	+3.12	+0.06	+3.18
Ag. inputs[b]	+2.97	+0.40	+3.37
N_2O from applied N		+3.97(±3.17)[c]	+3.97
N_2O from leaf litter		+7.28(±5.83)[c]	+7.28
C sequestration			
Below ground biomass	−14.10		−14.10
Soil carbon	0		0
Net total	−8.01	+11.7(±9.0)[c]	+3.7
Harvested biomass	−499.2		−499.2

[a]Positive values indicate additions (releases) to the atmosphere.
[b]Includes fertilizer and herbicide manufacturing and transport, machinery manufacturing, and nursery operations.
[c]Bracketed numbers represent the N_2O emission range presented by the IPCC estimate [42].

an average experiment duration of 17 years. Their reported value (337 ± 108 kg C ha^{-1}yr^{-1}) amounts to 24.7 ± 7.9 Mg CO_2 ha^{-1} over 20 years. Achieving such a level of sequestration in SRWC would dominate the other GHG flows in the system, resulting in a net decrease in global warming potential. It is important to note, however, that sequestration of carbon in the soil is neither permanent nor constant.

3.3. Fertilizer application rates and N balance

Fertilizer inputs are energy intensive and strongly influence the energy performance of the overall biomass production system. Fig. 4 shows the overall system energy efficiency (net energy ratio) plotted as a function of fertilizer application rate. The net energy ratio peaks at 58 with the application of 48 kg N ha^{-1} rotation^{-1} and then decreases to below 40 with 300 kg N ha^{-1} rotation^{-1}. However, a simple input–output nitrogen balance suggests that there is a net reduction in system nitrogen over the 23-year crop lifetime at fertilizer application rates below 150 kg N ha^{-1} rotation^{-1} (Fig. 4). While there appears to be an optimal energy efficiency at a fertilization rate below the base-case 100 kg ha^{-1} rotation^{-1}, this energy optima may not correspond with the optimal economic fertilizer application rate. Further, it may be preferable to maximize yield per hectare (land use optimization) at the expense of a slight decrease in energy efficiency. At higher N application rates, however, a surplus accumulates, i.e., more N is being applied than is removed in harvested biomass. Surplus N is sometimes used as an indicator of leaching potential [11], but studies show that N leaching is very low in willow crops even at high N application rates [46,47]. Note that the curves in Fig. 4 are based on Eq. (3) and must be validated with additional data.

3.4. Management scenarios

Table 8 summarizes environmental impact indicators for a select group of potential fertilization and weed control scenarios. Note that due to unavailable data, willow biomass yields are assumed to remain unchanged in these scenarios. Thus, the comparisons presented in Table 8 primarily reflect the influence of ancillary inputs (e.g., fertilizer manufacturing, changes in diesel consumption).

Sulfur-coated urea is a slow-release fertilizer that has been used on some willow biomass crops in NY. Since fertilization is only practical early in the year following harvest, a controlled-release product has been considered in order to make N available over a longer period and reduce the potential for N losses from the system. Data available suggest that slow-release fertilization has no impact on biomass yield [29,30], but the fact alone that urea requires more energy to manufacture than ammonia (76 MJ kg_N^{-1} vs. 55 MJ kg_N^{-1} [51]) significantly affects the system energy ratio. There is empirical evidence suggesting that controlled-release fertilizers have reduced NH_3 and N_2O emission rates [38,52] but these effects are not included here.

Biosolids as a nutrient source are an attractive option for SRWC from the perspective of both biosolids utilization/disposal as well as biomass production economics. Fertilization with biosolids have a favorable affect on system energy efficiency, due to avoidance of the large energy cost of producing inorganic N fertilizer (Table 8). Biosolids likely have an added benefit that is not captured in this analysis: additional N will mineralize and become available to the trees after the application year. Biosolids application rates were modeled so that 100 kg N would be available to the plants in the application year (based on the NH_4-N and NO_3-N of the biosolids, and an estimated mineralization of organic N [39]). But the remaining organic N will continue to mineralize throughout the rotation. For example, EPA's recommended mineralization rate estimates indicate an additional 28 and 13 kg N ha^{-1} would be available in the second and third year, respectively, following application of Syracuse biosolids. Biosolids also contain appreciable quantities of P and K that could be utilized by the growing willows. Available data are not sufficient to predict the extent to which additional nutrient availability would increase biomass yield, but any yield increase would further improve the system energy ratio. Biosolids also introduce organic matter to the soil, resulting in increased soil carbon sequestration [29]. On the other hand, adding readily available carbon along with a nitrogen source can increase N_2O production [53] (not accounted for here). Higher ammonia volatilization is also expected with biosolids

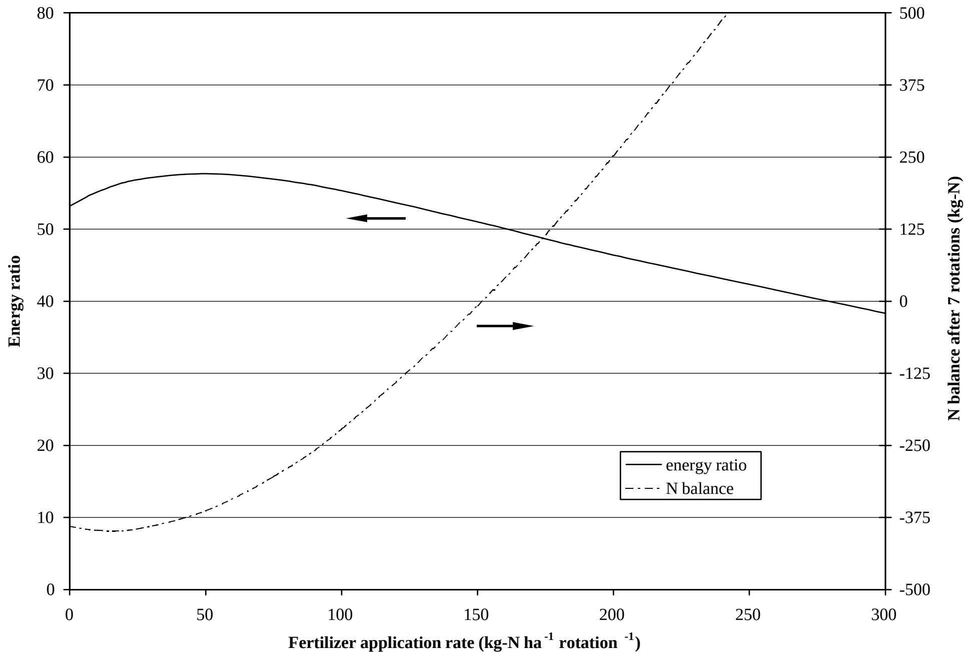

Fig. 4. Net energy ratio (biomass energy at farm gate/ fossil energy consumed) and system nitrogen balance as a function of fertilizer application rate for willow biomass crops grown in New York. Note that the curves are based on limited empirical yield data (see Eq. (3)) and must be considered provisional.

Table 8
Willow production alternative management scenarios

Scenario	Energy ratio (MJ_{out} MJ_{in}^{-1})	Global warming potential[a] (Mg CO_2 eq. ha^{-1})	Air acidification potential (kg SO_2 eq. ha^{-1})	Eutrophication potential[b] (kg PO_4 eq. ha^{-1})
Fertilizer				
Ammonium sulfate (base case)	55	10.5	127.6	13.0
Sulfur-coated urea	45	11.1	77.7	13.7
Biosolids (Syracuse)	73	9.0	306.1	65.6
Biosolids (Little Valley)	80	8.5	115.2	23.7
Herbicide-free	54	10.8	130.2	13.6

[a]Does not include biomass carbon flows (harvested or belowground) or N_2O from leaf litter.
[b]Does not include nutrient run-off or leaching from fertilizer additions.

application, which is the primary contributor to the increased acidification and eutrophication potential seen in Table 8. An additional concern with the use of sewage sludge biosolids is the introduction of trace heavy metals into the soil (see Appendix A (Table 14) for representative data of biosolid heavy metal concentrations). Numerous studies from Sweden [5] and Canada [54] demonstrate that heavy metal leaching and/or accumulation are insignificant in SRWC willows fertilized with biosolids. Salix clones show marked specificity in taking up some heavy metals, and some clones have demonstrated a high capacity to accumulate heavy metals such as cadmium and zinc [55]. If accumulated concentrations in the biomass are high, heavy metals could be removed from the ash through flue gas cleaning when the biomass is combusted [56], thus providing a means for concentrating and removing the metals as an environmental pollutant.

The herbicide free scenario presented in Table 8 involves increased mechanical weed control in place of chemical herbicides. Two additional cultivation passes prior to planting and 4 total ‘first year weed control’ cultivation passes were substituted for post-emergent and pre-emergent herbicide applications. While field trials would need to be conducted to demonstrate the effectiveness of weed control under this scenario (it is assumed that yield is unaffected), the results suggest that such a scenario has minimal affect on system energy consumption and tracked emissions (Table 8).

3.5. Implications for willow biomass electricity generation

While willow biomass could serve as lignocellulosic feedstock for a variety of bioproduct and bioenergy applications, the near-term commercial potential is to utilize the biomass to produce electricity. Biomass energy conversion technologies currently in the commercial or commercial-prototype stage include co-firing with coal in existing boilers, direct-fired boiler/steam turbine generation, and gasification. Efficiencies for these electricity-only energy conversion processes range from 20% for antiquated, direct-fired boiler systems to efficiencies in the high 30s for gasification combined cycle systems [1]. The full biomass-to-electricity system will be the focus of future communications; here we give preliminary consideration to the system performance implications of generating electricity from willow biomass.

Additional fossil energy is required to transport biomass to a central power generating facility. Assuming that willow crops are contained within an 80 km radius around a central facility and a road tortuosity factor of 1.8, the average transport distance is 96 km. Preliminary modeling of biomass transport by 40 tonne diesel trucks over this distance indicates that 188.9 MJ are consumed per odt of biomass ($\sim$0.1 kJ $MJ^{-1}_{\text{biomass delivered}}$ km^{-1}). Moving the biomass produced over 7 harvest rotations from 1 h releases an additional 3.7 Mg CO_2 eq. ha^{-1} (compare with values in Table 7), and reduces the system energy ratio to 36. Assuming an energy conversion efficiency of 30% and accounting for transportation, the base-case willow production scenario could produce electricity with a net system energy ratio of 10.9. This estimate does not include the energy consumed in power plant construction, although previous studies suggest that contributions from construction are small to insignificant [7]. Supplying all of the feedstock to a 100 MW plant operating at a 30% conversion efficiency and 80% operating capacity would require willow crops to be planted on approximately 5% of the area within an 80 km transport radius surrounding the generating facility.

4. Conclusions

The system performance results presented here provide further evidence for the environmental benefits of dedicated biomass energy. By our estimates, willow biomass crop production in NY requires the consumption 0.018 MJ of non-renewable energy to produce 1 MJ of renewable energy in the form of wood fuel. After transportation and energy conversion efficiency estimates are included, the generation of electricity from dedicated willow biomass energy crops would consume 0.092 MJ of non-renewable energy per MJ of electricity generated (0.33 MJ kWh^{-1}). By comparison, the generation of a composite kilowatt-hour of electricity under the current US fuel mix consumes 11.2 MJ kWh^{-1} [57]. The manufacture of inorganic fertilizer accounts for nearly 40% of the energy cost of producing willow biomass. Great opportunity exists to improve the system energy performance through the use of organic waste streams such as sewage sludge biosolids as a nutrient source. Utilization of biosolids in biomass energy production can increase the net energy ratio by more than 40% and also provides a productive use for what was previously treated as a waste stream. Further efficiencies can be gained through continued research into the influence of fertilizer type and application rates on biomass productivity.

System greenhouse gas flows, including emissions from direct and indirect fuel use, N_2O emissions from applied fertilizer and leaf litter, and carbon sequestration in below ground biomass and soil carbon, total to 3.7 Mg CO_2 eq. ha^{-1} over 23 years of willow energy crops, or 0.68 g CO_2 eq. MJ^{-1} of biomass energy produced. If the more uncertain of these contributions, N_2O from leaf litter and below ground carbon sequestration, are not included, the net greenhouse gas emissions are 1.9 g CO_2 eq. MJ^{-1} of biomass energy produced. Estimated transportation of biomass to a central power generating facility would contribute an additional 0.68 g CO_2 eq. MJ^{-1} delivered. Unlike fossil-based energy systems, however, these pre-combustion emissions comprise the net system emissions since combustion of biomass is CO_2 neutral. The global warming potential of nitrous oxide emissions resulting from the addition of N-fertilizer is roughly equivalent to the emissions from tractor operation. Preliminary estimates of the N_2O released from the decomposition of leaf litter suggest that the contribution may be significant, but additional investigation is necessary to better quantify these releases. While the current assessment assumes no change in soil carbon under willow biomass crops, the potential carbon sequestration could easily offset system greenhouse gas emissions.

System evaluation is ultimately limited by data availability. In addition to estimating system environmental performance and demonstrating the relative contribution of individual stages, life cycle assessment can also aid in identifying the significance of major data gaps and uncertainties. More accurate data are needed for important aspects including soil carbon behavior under willow SRWC, below-ground biomass accumulation, N_2O emissions from fertilized soils, and overall system nutrient balances. A more comprehensive assessment would consider additional impacts such as human toxicity, ecological toxicity, and land use. It would also be desirable to incorporate the spatial and temporal distributions of emissions since many impacts are experienced locally or regionally. These additions to the assessment would provide further metrics for evaluating and improving the system, but they are not expected to change the energy performance conclusions. The present analysis clearly demonstrates the sustainability of the willow biomass system from an energy perspective.

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Appendix A.

Manufacturing requirements for ancillary inputs to willow cropping system and characteristics of sewage sludge biosolids are presented in Tables 9–14.

Table 9
Tractor manufacturing (per kg of typical field ready agricultural tractor)

Materials[a]	kg kg^{-1} tractor
Aluminum	0.0033
Copper	0.00083
Fuel and oil[b]	0.042
Glass	0.0020
Cast iron	0.67
Plastic[c]	0.0085
Steel	0.11
Tire rubber	0.16
Manufacturing and assembly energy[d]	MJ kg^{-1} tractor
Process energy	24.42
Transportation energy	1.00
Feedstock energy	0.63
Total primary energy	26.04
Non-renewable energy	25.51
Renewable energy	0.53

[a]Material demand estimated from personal communication with David Newcom, product engineer, John Deere Waterloo Plant, Waterloo, IA.

[b]"Fuel and oil" breakdown estimated as follows: diesel fuel, 84%; engine oil, 5%; transaxle oil, 11%.

[c]"Plastic" breakdown estimated as follows: polyurethane, 25%; polypropylene, 37.5%; acrylonitrile butadiene styrene, 37.5%.

[d]Manufacturing and Assembly energy requirements estimated by scaling on a weight basis the energy requirements in "Life Cycle Inventory of a Generic Vehicle" [58].

Table 10
Inputs for manufacturing of farm implements (per kg implement weight) [59]

Iron ore	1.44 kg
Limestone	0.32 kg
Electricity	3.3 kWh
Mineral oil[a]	0.77 l
Diesel oil	0.29 l
Natural gas	0.19 m^3

[a]Mineral oil input was modeled with "lubricant (unspecified)".

Table 11
Inputs for sulfur-coated urea manufacture (per kg sulfur-coated urea) [51]

Granular urea	0.835 kg
Sulfur	0.12 kg
Sealant (wax and oil)[a]	0.021 kg
Process energy	0.50 MJ

[a]Lubricant (unspecified) substituted for sealant input flow.

Table 13
Nursery production of willow planting stock[a]

Inputs	
Diesel oil (used as fuel)	227 l
Liquified petroleum gas (1pg, used as fuel)	30.2 kg
Gasoline (used as fuel)	757 l
Electricity	9000 kW h
Heavy fuel oil (used for heat)	2271 l
Wood (for heat)	1296 kg
Carbaryl (insecticide)	6.53 kg AI
Glyphosate (herbicide)	3.63 kg AI
Granular mixed fertilizer (15–15–15)	3289 kg
Ammonium sulfate fertilizer	249 kg
Urea fertilizer	249 kg
Surface water (for irrigation)	10,902,000 l
Output	
Planting stock	456,437 units

[a]Data from Saratoga Tree Nursery, Saratoga Springs, NY.

Table 12
Inputs modeled for pesticide production as reported by Green [60]

	Glyphosate		Simazine[a]		Oxyfluorfen[b]	Carbaryl[c]		Inputs modeled as
	MJ	kg	MJ	kg	MJ	MJ	kg	
	(per kg active ingredient)							
Naphtha	33.0	0.752	43.2	0.98		11.0	0.25	Petrochemical feedstocks
Natural gas	93.0	1.76	68.8	1.30		48.0	0.91	Nat. gas
Coke						26.0	0.61	Petroleum coke
Fuel oil	1.0	0.023	14.4	0.34		1.0	0.023	Heavy fuel oil
Electricity	227		37.2			54.0		US average production
Steam	100		24.7			13.0		Heavy fuel oil burned in industrial boiler
Total manuf. of AI	454		190		215	153		
Formulation	20		20		20	30		
Packaging	2		2		2	2		

[a]Simazine manufacturing approximated with data for chemically similar atrazine.
[b]Manufacturing data unavailable of oxyfluorfen; manufacturing energy requirements estimated by average herbicide energy reported by [61].
[c]Insecticide used in nursery production.

Table 14
Characteristics of representative sewage sludge biosolids from two NY municipalities

	Syracuse, NY	Little Valley, NY
Calculated application rate[a] (tonnes ha^{-1})	6.9	5.6
Nutrients (g kg^{-1})		
NH_4-N	5.6	2
NO_3-N	0	0.05
Organic N	38.7	56.0
K	0.9	3.3
P	23.1	21
Trace metals (mg kg^{-1})		
Mercury	Na	4
Arsenic	Na	2
Cadmium	16	3.4
Chromium	63.8	22
Molybdenum	18.6	2.1
Lead	74.9	64
Nickel	20.9	22
Zinc	432	800
Copper	647	540
Magnesium	5.5	Na
Calcium	33.4	Na

Data from [62] and personal communication with New York State Department of Environmental Conservation Region 9 office.
[a]Calculated to provide 100 kg plant-available-N ha^{-1}.

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