GEORGIA DOT RESEARCH PROJECT 16-06

FINAL REPORT

WASTE MANAGEMENT OF HIGHWAY RIGHT OF WAY AREAS IN SOUTHEAST GEORGIA

Georgia Department of Transportation

OFFICE OF PERFORMANCE-BASED MANAGEMENT AND RESEARCH

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16. Abstract
Maintenance of highway right of way (ROW) areas has become challenging during the last years due to the high cost, and little to no economic return associated with disposing vegetation waste generated on highways across Georgia. In response, a study was done to examine the feasibility of using ROW areas to generate biomass for energy production. Particularly, this study included an analysis of the ROW current vegetation potential for energy production, the development of a site selection process for the establishment of bioenergy crops, a pilot study that quantified biomass and energy production from three feedstocks, and an economic assessment. Results revealed that replacing existing ROW vegetation with bioenergy crops is a feasible alternative because most of the existing vegetation has no potential for energy production. Specifically, results showed that switchgrass, big bluestem, and woodland sunflower adapted well to the ROW conditions, which included a high soil density due to compaction, acidic sandy soils, low nutrient conditions, and variable weather patterns. Switchgrass and big bluestem produced biomass and energy values comparable to similar feedstock produced in better environments. From an economic standpoint, results revealed that growing switchgrass and big bluestem from seeds was the most cost-effective option over a longer period. Overall, results demonstrated that ROW areas can be used for green energy production. However, each option considered (e.g., crop type, planting method, recovery period, etc.) will present advantages and limitations based on GDOT immediate needs and requirements.

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Right-of-way, vegetation, sustainability, green energy, biomass, bioenergy, switchgrass, big bluestem, woodland sunflower

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Final Report

WASTE MANAGEMENT OF HIGHWAY RIGHT OF WAY AREAS IN SOUTHEAST GEORGIA

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Contract with
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In cooperation with
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Federal Highway Administration

September 2020

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

Maintenance of highway right of way (ROW) areas has become problematic during the last several years due to the high cost and little to no economic return associated with disposing vegetation waste that is continuously generated along all highways and interstates across the state of Georgia. The Georgia Department of Transportation (GDOT) in collaboration with Georgia Southern University, in an effort to adopt and implement a sustainable ROW maintenance practice, studied and evaluated the feasibility of replacing ROW vegetation of highways with high-value alternatives such as switchgrass (*Panicum virgatum L.* 'Alamo'), big bluestem (*Andropogon gerardii*), and woodland sunflower (*Helianthus divaricatus*). Experiments were conducted to assess biomass productivity, and environmental and economic impacts associated with producing these feedstocks along a section of Interstate 16 (I-16) ROW spanning Districts 2 and 5. A study area of I-16 located between mile 85 south of Statesboro, Georgia, and mile 155 at Pooler, Georgia, (west of I-95) was used for preliminary data collection. Preliminary research conducted prior to the pilot study showed that there are many ROW acres along I-16 that could be used to grow bioenergy crops. Continuous bioenergy crop production along this section of I-16 ROW will be challenging due to some areas having limited parcel size and poor soils. The majority of soils present along the ROWs may be characterized as slightly acidic sandy soils. As a result, the ROW soils analyzed in this study had low water-holding capacity, poor soil structure, and low nutrient content (fertility). However, most of these limitations can be reduced with proper management. A taxonomy study showed that the majority of the identified vegetation along the I-16 ROW contains no biomass production potential, as most specimens collected were comprised of weedy vegetation. There were some few, but notable specimens identified in the ROW taxonomy that presented value to the ROW if properly managed.

Field and laboratory research conducted over a two-year period determined that switchgrass, big bluestem, and woodland sunflower adapted well to the poorly drained sandy soils present throughout the highway ROW. However, it was shown that a limiting factor of the biomass plots was compaction, as feedstock productivity decreased with bulk density increases. As a result, the depth of seed placement and the level of soil compaction will be important to feedstock

establishment and growth in ROW areas. Fertilizer inputs did not result in significant feedstock productivity for big bluestem and woodland sunflower; however, switchgrass exhibited a yield increase of 49 percent in the second year using excessive levels of fertilizer input. Biomass feedstock productivity increased throughout the first two years in field plots that saw no fertilizer application. It was determined that these feedstocks can adapt to highway ROW conditions without the use of excessive fertilizers. In addition, biomass quality and energy levels were not significantly influenced with the use of fertilizers. Results showed that woodland sunflower energy yields increased with all fertilizer levels with a minimum and maximum energy content of 18.6 and 20.1 kj/g respectively. Big bluestem energy yields increased with fertilizer levels up to 54 lb N/ac with a minimum and maximum energy content of 25.1 and 27.4 kj/g. Alternatively, switchgrass energy yields slightly decreased with fertilizer levels providing a minimum and maximum energy content of 22.1 and 22.9 kj/g respectively. These results indicated that higher rates of fertilizer will not result in significant energy gains per mass of feedstock suggesting that the observed energy content may be related to other factors such as feedstock chemical composition. Overall, results suggested that big bluestem would be the best feedstock to implement in ROW areas from an energy production standpoint.

ROW production of the biomass feedstocks had no considerable impact on the amount of organic matter and nutrients being transported downstream as a result of site preparation and management activities to prepare the ROW for biomass production. Total suspended solids (TSS) concentrations in water samples collected beneath these alternative crops were lower than TSS concentrations from water samples collected outside the cropping system used for this study. In addition, soil organic carbon (SOC) concentrations in soils beneath these alternative crops increased over the two-year growing period, indicating that these feedstocks can have a positive effect on soil quality (i.e., soil organic carbon) while also contributing to reduction of greenhouse gases (GHG) associated with highway corridors. Soil analysis indicated long-term (>5 years) production of these feedstocks will require eventual soil amendments as the feedstocks absorbed some essential elements through their root system over the two-year period. Producers entering a long-term contract (≈10 years) with an end user may want to consider incorporating soil amendments (i.e., fertilizers, legumes, etc.) in between contract periods to improve depleted soils that have been used for ROW feedstock production.

After evaluating the costs associated with long-term production of biomass feedstocks in the ROW, it was determined that feedstock establishment with seeds would be most cost-effective for GDOT. When establishing feedstocks with seed, GDOT administrators interested in the feasibility of producing these feedstocks under an assumed 10-year contract can expect to break even with the initial investments after 2.5 to 3 years of feedstock production. This study shows that implementing biomass feedstocks in the ROW can develop into a sustainable alternative for GDOT maintenance since it would decrease the carbon footprint of maintenance activities, increase sustainability by producing a lower emission, develop renewable energy, require less mowing/harvesting cycles throughout the year, and reduce the use of herbicide for weed control on the ROWs.

CHAPTER 1. INTRODUCTION

BACKGROUND

The transportation network across the United States includes a series of highways and interstate routes that contain a designated right of way (ROW). A typical ROW encompasses public facilities such as the driving surface, roadside areas, road and county drainage systems, aerial and underground public utilities, sidewalks or non-motorized paths, and traffic signals. The roadside includes the sides of the road corridor beyond the paved road (i.e., shoulders and verges), including impacted or maintained areas within the ROW (Steinfeld et al. 2007). ROWs serve many purposes, including road delimitation, maintenance or expansion of existing services, safety, and pollution control. Generally, these ROW areas are 95 percent state-owned and are maintained by state authorities, while their construction, in most cases, is entirely funded by the federal government. Over the years, the United States Department of Transportation (USDOT) has come to oversee approximately 160,000 lane miles of highways under state DOT supervision (FHWA 2016), which also represents a significant amount of associated unpaved roadside to maintain. ROW areas, including median and roadside recovery zones, normally contain native vegetation (e.g., grass, small trees, bushes, etc.) that requires regular maintenance to avoid any hazard resulting from excessive vegetation growth. As a result, an ever-increasing National Highway System (NHS) has contributed to the rising cost associated with mowing operations and weed suppression along highways.

Given the substantial amount of roadside under DOT supervision, ROW areas are being examined by federal and state transportation departments as potential zones for renewable energy production (e.g., solar, wind, biomass, etc.). This growing interest stems from advances in energy-generation technologies that have improved the capacity for energy production from various renewable sources in recent years. These advancements have also increased the potential for generating revenue from energy-production activities, which may counterbalance a fraction of the ROW maintenance costs. Generating renewable energy within the highway ROW is an emerging concept in the U.S., due to current interest in installing decentralized energy-producing technologies on land areas not traditionally considered for energy generation, such as ROW areas. By comparison, traditional renewable energy-production infrastructure, such as windmills, solar farms, or bio-crops fields, are located in centralized areas that are far from the majority of energy consumers. Therefore, attention has turned to localized, smaller-scale applications, which can be placed and used near their corresponding end users (Poe et al. 2012).

Currently, solar, wind, and bioenergy crop growth/harvesting technologies offer the most immediate alternatives for generating renewable energy in the ROW. However, social, political, ecological, and economic uncertainties of utilizing such technologies are still prevalent, limiting their application in many highways across the states. Among these available alternatives, bioenergy production from organic materials found in vegetation residues from ROWs is one of the most promising options for energy production, while providing economic return and public acceptance from a transportation management perspective (Poe et al. 2012). Bioenergy crop or feedstocks are defined as any plant material used to produce renewable bioenergy. Biorenewables are chemicals created by biological organisms to produce heat, power, transport fuel, and other products of recent origin distinct from fossil fuels (Halford and Karp 2011). Bioenergy crops have the capacity to produce a large volume of biomass, high energy potential, and can be grown in marginal soils (Pennington et al. 2012). Bioenergy production in ROWs includes utilizing areas that are not designated for agricultural purposes to grow and harvest vegetation for the production of biomass, bioenergy, or any other waste-to-energy conversion product. Converting biomass residues into a value-added product and/or generating biofuel/bioenergy from excess vegetative wastes may offset the cost of clearing and maintaining highway ROWs, while providing an alternative source of renewable energy. Additional benefits of growing crops for energy production in ROW areas include: creation of environmental buffer zones; pollution mitigation; visual quality enhancement; reduction or elimination of weed species; and other economic benefits, such as potential revenue establishment for the DOT and economy growth stimulus for local and domestic industries.

To assure the development and successful application of a sustainable alternative for ROW management (i.e., bioenergy production in ROWs), a series of factors should be considered initially. For instance, the energy production potential, which will depend on the type of vegetation, the homogeneity of the crop, and the total biomass that can be extracted from each crop. In addition, vegetation type and quality depend on factors such as soil type, water availability, weather, and plant maintenance. Further, maintenance costs should be kept to a minimum to assure an economically feasible and sustainable solution.

This study was designed to evaluate the potential for bioenergy production in ROW areas and to assess the environmental and economic feasibility of replacing existing ROW vegetation with common crops used for bioenergy generation, considering all the limitations and constraints existing in ROWs. Three crops were selected for this study based on a thorough literature review that focused on ease of plant establishment, low crop maintenance requirements, high mass and energy yields, low environmental impacts, and native vegetation preservation, among others (see chapter 3). Crops selected include switchgrass (*Panicum virgatum L.* 'Alamo'), big bluestem (*Andropogon gerardii*), and woodland sunflower (*Helianthus divaricatus*). A pilot study was performed to investigate mass and energy yields from these crops through field experiments on the Interstate16 (I-16) ROWs. The concept of harvesting high-value biomass in tandem with the Georgia Department of Transportation's (GDOT) annual mowing cycles was the economical foundation for this study. The outcome of this study is a thorough evaluation of the feasibility for GDOT to establish, produce, maintain, and harvest dedicated biomass feedstocks in highway ROW to help minimize current maintenance costs.

PROBLEM STATEMENT

GDOT maintains more than 750,000 acres of highway ROW by continuously mowing grass, clearing dead vegetation and plant debris, applying weed control, collecting litter, etc. Maintenance of these highway ROW areas has become problematic during the last several years due to the high operational costs associated with it. Recent reports show that GDOT spends approximately $44 million annually on mowing and litter pickup, which amounts to an equivalent highway ROW management cost of approximately $59/ac/year. In most cases, there is no economic return associated with disposal of the vegetation waste that is continuously generated on ROWs. Furthermore, it is environmentally impractical to eliminate the ROW vegetation for the sole purpose of decreasing maintenance and disposal costs. For instance, vegetation in ROW areas plays an important role in abating pollution generated in highways resulting from transportation activities. As residue from hydrocarbons, rubber, metals, and other chemicals leach from automotive vehicles, vegetation in the ROW provides a necessary buffer to decrease the amount of pollutants that may reach ecosystems, the atmosphere, and water bodies surrounding highways (Finley and Young 1993, Novotny 2002). In addition, ROW vegetation may provide an adequate ecosystem for certain plants and animal species (e.g., bees) and provide an additional aesthetic value, which affects the public perception.

Opportunely, in recent years, many transportation agencies in the U.S. are investigating the viability of utilizing highway ROWs for decentralized renewable energy production given the ample amount of land they occupy (Poe et al. 2012). Converting biomass residues into a value-added product and/or generating biofuel from excess vegetative wastes may offset the cost of clearing and maintaining highway ROWs while providing an alternative source of renewable energy. However, not all the vegetation found in ROWs is suitable for biofuel production. In some cases, vegetation waste may be more appropriate for other activities (e.g., compost production), while in other circumstances where it is impractical to use existing vegetation for any revenue-generating operation, it may be more cost-efficient to replace the current vegetation with a particular plant species containing a higher potential for biofuel production (Bomford et al. 2014). To determine if utilizing ROW areas for bioenergy crop production is a sustainable solution for the vegetation waste disposal issue, it is crucial to assess the biomass production potential for the ROW vegetation in specific areas along the state highways, examine the feasibility and measure the consequences of replacing existing vegetation with energy-generating feedstock, and investigate the cost of implementing such solutions. While GDOT is not interested in competing with local business in the areas of power, wood, or any other type of commodity production, GDOT is in a unique position to evaluate whether the economical return obtained through the production of bioenergy crops in ROWs will offset the cost of routine vegetation-management activities.

OBJECTIVE

The overall goal of this research project was to assess the feasibility of establishing and growing bioenergy crops in ROW areas to produce a bioenergy-generating feedstock that, when harvested, can be used to offset the operational costs associated with ROW maintenance in the state of Georgia. Within this goal, the aim was to develop a comprehensive study that assessed a viable option of managing ROW areas by considering the possibility of utilizing ROW waste for bioenergy production as a cost-effective alternative to decrease ROW maintenance costs.

Specifically, the main objective of this research project was to study the feasibility of replacing existing ROW vegetation with three crops (i.e., switchgrass, big bluestem, and woodland sunflower) to study the bioenergy production potential of these crops under normal environmental conditions in ROWs in Georgia. From an economic perspective, the objective was to perform an economic assessment to identify the breakeven point where the generated biomass production would offset a fraction of the ROW maintenance costs. Specific objectives included:

- Identify bioenergy plants to be incorporated into a biomass feedstock production system under a highway ROW environment.
- Develop a geospatially-enabled protocol to identify and delineate suitable feedstock-specific production areas that can be used to establish and manage bioenergy crops across the state of Georgia.
- Determine the optimum growing conditions at selected ROW areas for bioenergy crop establishment using soil quality indicators and testing for different agronomic treatments, such as fertilizer application rates and other environmental factors.
- Assess the biomass feedstock production and bioenergy production potential of selected bioenergy crops through a pilot study done along I-16.
- Perform an economic assessment on the feasibility of producing biomass feedstocks to offset GDOT's ROW maintenance costs.
- Determine the environmental impact associated with the use of bioenergy crops in ROW areas.

RESEARCH SIGNIFICANCE

This research will provide to GDOT valuable information on the feasibility of implementing biomass feedstocks in ROW areas from an energy production, economic, and environmental perspective. Collected data were analyzed to create an accessible geographic information system (GIS), summarizing geographical statistics about the areas with higher potential for biomass production. A quantitative analysis of the biomass that can be used for biofuel from certain plant species found in the study area provided information to determine which option offered a more sustainable solution to the vegetation waste generation issue. Additionally, the study determined the feasibility of replacing the ROW vegetation of specific areas to high potential biofuel crops, such as switchgrass (*Panicum virgatum*), which can be grown in marginal land areas obtaining moderate to high yields. The goal of the project was to provide to GDOT viable alternatives to decrease the costs associated with vegetation waste disposal while providing a valuable source for energy. The extensive cost–benefit analysis was used to identify the breakeven point of potential investments into various waste-to-energy activities. Finally, it is expected that the procedures implemented, and the results obtained through the proposed project may be extrapolated to assess different highway systems across the state of Georgia.

METHODOLOGY

This research project was originally designed and planned to follow a series of recommendations made by GDOT personnel in a sequence of meetings that began during the proposal preparation period and continued through the initial phase of the project execution stage. These planning meetings were held with staff from GDOT's Office of Performance-Based Management and Research, and managers and staff from GDOT Districts 2 and 5. Mr. Binh Bui from GDOT, Mr. Jimmy Smith from District 2, and Mr. Bradford Saxon from District 5 facilitated discussions between GDOT operation and maintenance personnel and the Georgia Southern University (GSU) research team. Topics addressed during the meetings included: immediate ROW maintenance issues to be addressed, safety on ROW areas, environmental and economic impacts of using the ROW's existing vegetation to be a high yield bioenergy crop, site location, extent of the project, economic limitations and constraints, similar projects done or being implemented, and other topics deemed necessary to address. Recommendations taken from all these meetings were incorporated in the design and early execution of the project. Follow-up meetings were also held during the execution of the project to communicate progress and milestones achieved during each stage of the project. In the planning stage, the following methodology (designed tasks) was developed to assure that all objectives were accomplished by the end of the project:

Preliminary Planning for the Proposed Pilot Study

To define the initial conditions and requirements for this project, a total of three meetings were conducted with personnel from GDOT. These meetings were held with personnel from the

GDOT research team, engineers and maintenance operators from Districts 2 and 5, and the research team from GSU. Important initial parameters and conditions that were defined in these meetings included: access to preliminary information from GDOT, vegetation type to be planted in ROW areas, safety priorities in ROW areas along highways, possible locations in Districts 2 and 5 to install the pilot study, GDOT personnel involvement during the project execution, and definition of profit margins, among other topics.

Study Area

For this study, a section of I-16 located between mile marker 90 southwest of Statesboro, Georgia, and mile marker 155 at Pooler, Georgia, (west of I-95) was used for the implementation of the pilot study. Bulloch, Candler, and Emanuel Counties were included as part of the study area. Candler and Emanuel Counties fall under the jurisdiction of GDOT District 2, while Bulloch County falls under the jurisdiction of District 5.

Literature Review

Initial discussions with GDOT personnel representing the GDOT Office of Research revolved around establishing value-added vegetation to the ROW. In addition, there was an emphasis to incorporate a feedstock that could enhance the aesthetics and biodiversity in the ROW. Based on these discussions, the research team conducted a thorough literature review to determine ideal feedstock characteristics for bioenergy production on the highway ROW. When assessing energy crop candidates for the study, the researchers referenced literature focusing on a wide range of topics covering distribution and adaptation of feedstocks, capacity to produce with minimal inputs, noninvasive characteristics, capacity to thrive on marginal (unproductive) lands, energy content for different types of crops, ability to absorb and store atmospheric carbon, drought tolerance, and cost of production.

Selecting Bioenergy Plants for Study on the ROW

Switchgrass, big bluestem, and woodland sunflower were selected as the bioenergy feedstocks for the pilot study. Switchgrass is a native warm-season perennial grass with high production yield and a wide geographical adaption in Central and North America (Mclaughlin and Kszos 2005). Big bluestem, another a native warm-season perennial grass, has a robust root system and stores carbon belowground due to a large underground root system extending 7–8 ft in mature stands. Big bluestem has been characterized as a plant with high nutrient use efficiency (NUE). Woodland sunflower is a noninvasive plant that can produce thermal energy by combustion. Furthermore, woodland sunflower is found in open fields with partial shade or full sun, which is reminiscent of many highway ROW areas. The two perennial grasses were incorporated to generate more biomass on the ROW, while the sunflower was used to enhance aesthetics and biodiversity in the ROW.

Developing Geospatially Enabled Highway ROW Property Maps

As a first step in identifying suitable areas for feedstock establishment along the ROW, property maps that could be available electronically with a geospatially enabled format were developed. An electronic property map contains information pertaining to ROW configurations, clearance, and parcel area related to the highway. Having electronically available ROW property maps would likely facilitate analyses of potential sites for biomass production within the ROW. Electronically accessible ROW property maps that could be incorporated into a GIS system would facilitate the development of a site suitability model for feedstock establishment as was observed in this study. High resolution imagery was used in this study to facilitate the development of a geospatially enabled ROW property map for I-16 (see chapter 3).

Selecting Suitable Sites for ROW Energy Crops

One of the main objectives of the project was to evaluate the effects of establishing biomass feedstocks within different ROW setups. However, before establishing bioenergy crops in the ROW, there was a need to develop a tool or method that can be used to select optimum sites within the ROW area for crop establishment. In addition, it was necessary to collect soil information from different ROW areas and incorporate that information into the proposed tool to be developed. To account for the heterogeneous nature of soils distributed across the highway ROWs, a GIS model was developed to facilitate site evaluations for feedstock establishment. Using ArcGIS model builder, the parameters described in chapter 3 (Developing Geospatially Enabled Highway ROW Property Maps) were incorporated into a series of geoprocessing (i.e., GIS operation used to manipulate data) steps to develop a site selection model for each feedstock used in this study. The resulting model was used to select the sites where the pilot study was performed. For this study, the results of the model represented a spatial delineation of suitable ROW along I-16 to establish the biomass feedstocks selected for the pilot study. The selected sites for the biomass feedstock study were located at mile markers 90, 102, 108, 121, and 130.

Conducting a Baseline Survey of the ROW Sites

To properly evaluate the success of the bioenergy feedstock study, measurement of soil quality parameters of ROW land previously affected by earthwork done during construction or any other maintenance activity was necessary. As the sites for the pilot study are located on such lands, there was an interest in establishing a baseline survey of the soil quality for the selected ROW areas. The baseline survey was done using soil core analyses to evaluate the initial soil quality of the ROW sampling sites. Results from the baseline survey were also used to develop the GIS model used for the selection of suitable sites for feedstock establishment in ROWs.

Establishing ROW Sites for Biomass Feedstock Assessment

At this stage of the study, a second meeting was scheduled with GDOT to review the updated pilot study and define the preliminary tasks to be completed before starting the second phase of the project. GDOT engineers and maintenance operators from Districts 2 and 5 met with GDOT and the GSU research team in GDOT's District 5 main office in Jesup, Georgia, in May 2017. Topics addressed during the meeting included: selected feedstocks to be planted in ROW areas (final revision), safety priorities in ROW areas, pilot study site location approval along I-16 in Districts 2 and 5, GDOT assistance during the site preparation, and other traffic-related aspects. A final meeting was held in the Statesboro GDOT office to schedule the site preparation activities and to perform a visual inspection of the sites chosen prior to implementing the pilot study. This meeting culminated with GDOT preparing in June 2017 the selected sites, at which the feedstock crops would be planted as part of the pilot study.

Performing a Study on Biomass Production in the ROW

One of the main objectives of the project was to evaluate, through an in-situ pilot study, the viability of replacing ROW vegetation of highways with multipurpose feedstocks such as switchgrass and big bluestem. Field experiments were conducted over a two-year period, as part of the pilot study, to assess biomass productivity and the cost associated with ROW management of such alternative crops, given a scenario where GDOT implements a statewide biomass feedstock system within highway ROWs. The objective was to determine if selected feedstocks would grow at rates sufficient to provide enough biomass for energy production without adding any significant maintenance cost. The pilot study was undertaken to measure growth yields, plant growth requirements, plant health, and energy yields during two different planting seasons (see chapter 6).

Developing a Cost Analysis Method for Evaluating Feasibility for Biomass Production in the ROW

The final goal of the project was to provide GDOT with information pertaining to expected costs and the breakeven payback period associated with establishing, maintaining, and delivering high-value biomass to end users who would be able to process the ROW products as sources of energy. An economic assessment describing the cost and returns associated with the establishment and production of renewable bioenergy products in ROWs was done using a developed economic model. This model identified the breakeven point of this potential investment by considering different bioenergy crops, different establishment requirements (e.g., fertilizer application), and different market scenarios.

Assessing Impacts of the ROW Pilot Study

This study also assessed the environmental impacts of using the ROWs for biomass feedstock production. The environmental assessment was done to determine if excessive amounts of nutrients and sediments were transported downstream as a result of the tilling and fertilizing activities initially performed to prepare the ROW sites for bioenergy feedstock establishment. Additional environmental effects such as carbon cycling were also analyzed as part of the study.

CHAPTER 2. A FRAMEWORK FOR SUSTAINABILITY IN THE ROW

ENERGY CROPS

Growing worldwide pressure for the adoption of renewable energy resources, combined with the desire of some nations to reduce their reliance on fuel supplies from major producers has intensified the interest in increasing the production of liquid fuels from dedicated energy crops. From an environmental perspective, the continuous consumption of traditional fossil fuels has contributed to an increase in greenhouse gases (GHGs), becoming a major contributor to climate change. Within this area, the transportation industry is one of the main producers of GHGs because most of the transportation energy demand is satisfied through the burning of fossil fuels. From an economic standpoint, the demand for fossil fuels is increasing at such a rate that current mining, exploration, and production technologies will soon not be able to meet the demand. This strong demand for liquid fuels comes from both the already established first-world economies and the emerging new economies. As a consequence of these environmental and political drivers, the need for alternative sources of renewable energy—which decreases carbon emissions and can be harvested in a sustainable way—has respawned the interest of using biofuels to satisfy part of the total energy demand. Therefore, the potential for biofuels to meet at least some of this future demand is manifest.

There are many possible alternatives to fossil fuels, particularly for heat and power generation, including wind, hydro, solar, and plant biomass, all of which are expected to play a role in satisfying the energy demand while decreasing GHG emissions. However, there are few alternatives to replace transport fuels (e.g., electric, hydrogen, and biofuels). As the number of vehicles on the roads is continually rising, emissions from the transport sector must clearly be curbed, or they will counter any reductions achieved by other sectors. Energy crops have the potential to provide a source of renewable energy that can reduce GHG emissions and help combat climate change. Life-cycle analyses of biomass to heat and power produced in this way show high carbon savings and GHG reductions. However, producing energy crops requires resources (e.g., land, water, and energy), and using these resources for energy means that they are not available for food. Whilst energy crops certainly hold solutions to these challenges, they may also be part of the problem when competing directly with agriculture. As the global population continues to increase, so too does the demand for easily accessible arable land. This idea of leveraging less productive land for alternative uses stems from the “food vs. fuel” debate (Ribeiro 2013). With the current trend of nations across the globe producing stronger economies and competitive markets, there is a need to ensure arable land designated for food crops is not diminished for alternative uses (i.e., bioenergy crop farming and biofuel and energy generation). A potential pathway to mitigating food and fuel production concerns exists in the utilization of less productive land in the U.S., such as the vast area of land present in the ROW systems across the country. ROWs in the U.S. National Highway System offer an estimated 3.4 million hectares of unpaved land (FHWA 2010). Thus, a significant amount of easily accessible ROW land is currently available to investigate its potential for producing biomass feedstocks.

In the state of Georgia, at a more local scale, implementing biomass feedstocks in the ROW may develop into a sustainable alternative for generating decentralized renewable energy while contributing to a decrease in carbon emissions, which will compensate for the emissions produced in the transportation sector. Utilizing bioenergy crops in ROW areas may help offset costs associated with maintenance of the ROWs, thereby increasing the sustainability of GDOT’s maintenance practices, which include mowing and harvesting of existing vegetation and weed control, while producing lower emissions and generating renewable energy feedstocks. Furthermore, utilizing perennial feedstocks such as switchgrass, big bluestem, and woodland sunflower for energy production can be carbon–neutral because carbon dioxide released from combustion may be absorbed by these feedstocks (Greenwell and Keene 2013). Therefore, the ability for generating green renewable energy combined with the potential of capturing carbon dioxide from vehicle emissions certainly makes the use of ROWs for biomass and bioenergy generation a sustainable solution for ROW waste management.

TECHNOLOGY FOR CONVERTING BIOMASS TO HEAT, POWER, AND TRANSPORTATION FUEL

Conversion of biomass to energy products is done using two main process technologies: thermochemical and biochemical/biological. The most commonly used conversion process under thermochemical technology is the direct combustion of wood (i.e., cellulose) resulting in wood-derived fuels that may be used for heat and/or power (i.e., electricity), while the most commonly used conversion process under biochemical/biological technology is the fermentation of sugar and starch crops, such as corn, to produce ethanol for transportation fuel (Bayraktar et al. 2013). Over the years, considerable efforts have been made to develop and commercialize new processes for the thermochemical conversion of biomass: combustion, pyrolysis, gasification, and liquefaction. These new conversion processes have the potential of converting lignocellulosic feedstocks (e.g., switchgrass and big bluestem) into solid, liquid, or gaseous fuels. Combustion involves the heating or burning of a unit of dry matter (DM) in the presence of pressured air, which results in power/heat generation (McKendry 2002a). The resulting power/heat generated is expressed as the caloric value and is a viable metric of the amount of heat obtained by burning a mass unit of biomass. Studies have shown that calorific value of a material can be obtained by cellulosic and woody material (McKendry 2002b, Lunguleasa 2009). At this time, these up and coming technologies are not generally considered commercially viable, and what conversion facilities will pay for perennial biomass feedstocks remains unknown, as markets for cellulosic feedstocks do not currently exist (Epplin et al. 2007).

SIMILAR ROW RENEWABLE ENERGY STUDIES BY DOTS ACROSS THE U.S.

Over the years, DOTs have expressed interest in pursuing energy crop growth/harvesting, or bioenergy technologies for generating renewable energy in ROWs. At least five states have investigated the possibility of intentionally cultivating dedicated energy crops in the ROW or harvesting existing ROW biomass to supply existing or prospective bioenergy conversion facilities (table 1).

Table 1. Renewable energy studies relevant to the highway right of way.

Initiative	*Pilot Projects*
Bioenergy	Kentucky State University, Switchgrass Pilot Project
	Michigan State University, Pilot Project
	North Carolina DOT, Bioenergy Pilot Project
	Tennessee DOT, Switchgrass Pilot Project
	Utah DOT and Utah State University, Freeways to Fuel Pilot Project

Kentucky

Bomford et al. evaluated the potential of producing switchgrass for bioenergy feedstock using Kentucky highway rights of way. It was determined that Kentucky's freeways could generate 64,000 tons per year of switchgrass and ultimately 5.54 million gallons of cellulosic ethanol, or 74 GWh of electricity annually. Nearly 2 percent of freeway fossil fuel use in Kentucky could be offset by ROW-grown switchgrass converted to ethanol (Bomford et al. 2014).

Michigan

The second phase of a Michigan State University (MSU) project started in 2011 and included the production of a variety of bioenergy crops on six ROW demonstration sites, two airport sites, two urban area sites, and two agricultural sites in state game areas. The small test plot areas were hand harvested to measure yield. The 1-ac plot areas were mowed after hand harvest. Results from the project showed canola yields from the ROW test plots ranging from 500 to 600 lb/ac, compared to test trials in farm fields that resulted in 1200 to 1300 lb/ac (Pennington et al. 2012).

North Carolina

Poe et al. (2012) reported that North Carolina State University (NC State) partnered with the North Carolina DOT (NCDOT) to participate in the national FreeWays to Fuel initiative, growing biomass crops off highway rights of way and converting them to biodiesal to fuel DOT vehicles. The goal of the pilot project was to evaluate the yield potential and management strategies required to grow oilseeds in the compacted and highly disturbed soils found in the ROW. NC State established canola and sunflowers along state highways. After processing the bioenergy crops, a total of 108 gallons of oil were extracted from 2,900 pounts of plot-grown canola (Poe et al. 2012).

Tennessee

In the spring of 2010, the Tennessee Department of Transportation (TDOT) with the support of Genera Energy LLC established four test plots of switchgrass on interstate ROW. Genera Energy, a for-profit bioenergy firm wholly owned by the University of Tennessee Research Foundation, partnered with DuPont Cellulosic Ethanol to develop the first and only commercial switchgrass-to-cellulosic ethanol plant operating in the U.S. The purpose of the pilot was to determine if switchgrass growing in the ROW could reduce mowing needs and provide increased erosion control, and to explore the future possibility of producing biomass for energy. None of the test plots were harvested in the growing season, so no yield information is available (Bayraktar et al. 2013).

Utah

The Utah Freeways to Fuel project was the first effort in the nation to explore the opportunity to grow bioenergy feedstocks on highway ROWs. Researchers from Utah State University established five test plots along the roadside in four Utah regions on the I-15 corridor (Whitesides and Hanks 2011). The test plots of canola and safflower did not generate sufficient yields for economic viability. Some sites were deemed unsuitable due to elevation or soil conditions. Annual precipitation throughout the duration of the study was low, which also diminished yields.

CHAPTER 3. PRELIMINARY STUDY – SITE SELECTION PROCEDURE AND RESULTS

This chapter explains in detail the methodology used in the design and execution of the preliminary part of the study, which anteceded the implementation of the pilot study. The procedure as provided in this chapter can be used to replicate the study in other locations across or outside the state of Georgia, regardless of characteristics in the new site locations that differ from the ones described in this study. This chapter also follows the chronological order in which each step was performed in the preliminary study.

PRELIMINARY PLANNING FOR THE PROPOSED PILOT STUDY

The first part of the project dealt with all the preliminary planning that was needed to define the required parameters and initial conditions to design and build the proposed pilot study. To define the initial conditions and requirements for this project, a total of three meetings were conducted with personnel from GDOT. Meetings included the GDOT research team, engineers and maintenance operators from Districts 2 and 5, and the research team from Georgia Southern University. Important initial parameters and conditions that were defined in these meetings included: access to preliminary information from GDOT, vegetation type to be planted in ROW areas, safety priorities in ROW areas along highways, possible locations in Districts 2 and 5 to install the pilot study, GDOT personnel involvement during the project execution, and definition of profit margins, among other topics. All the information gathered in the first meeting was used to update and reform the proposed pilot study.

BIOENERGY PLANTS SELECTION

Initial discussions with GDOT personnel revolved around establishing value-added vegetation to the ROW. In addition, there was an emphasis to incorporate a feedstock that could enhance the aesthetics and biodiversity in the ROW. Based on these discussions, a literature review was conducted to determine ideal feedstock characteristics for bioenergy production on the highway ROW. When assessing energy crop candidates for the study, the research team referenced literature focusing on a wide range of topics related to bioenergy generation, feedstock establishment, and biomass product markets, among others. Specific topics researched in the literature review included: covered distribution and adaptation of feedstocks, capacity to produce with minimal inputs, noninvasive characteristics, capacity to thrive on marginal (unproductive) lands, energy content, ability to absorb and store atmospheric carbon, drought tolerance, and cost of production. Based on this literature review, an initial list of native, low-risk feedstock for Georgia was developed as listed below:

- Big bluestem (*Andropogon gerardii*)
- Indiangrass (*Sorghastrum nutans*)
- Prairie cordgrass (*Spartina pectinate*)
- Sweet sorghum (*Sorghum bicolor* “Sweet”)
- Switchgrass (*Panicum virgatum*)
- Vetiver grass (*Chrysopogon zinzanioides* var. “Sunshine”)

These feedstocks can be grown in Georgia and all have biodiesel, ethanol, and heat of combustion applications. Switchgrass and big bluestem were selected out of the feedstock options for the pilot study due to the following characteristics:

- Widespread distribution and adaptation
- Robust root system capable of storing carbon below ground
- High productivity with minimal inputs
- Capacity to thrive on marginal (unproductive) lands
- Drought tolerant
- Low ash and nitrogen content
- Thermal energy
- High ethanol yield
- Phytoremediation
- Noninvasive

In addition, woodland sunflower was selected for this study due to the following characteristics:

- Diversity and wildlife
- Pollinator

- Thermal energy
- Noninvasive
- Ornamental use
- Deer-resistant
- Easy to cultivate

Switchgrass

Switchgrass (*Panicum virgatum L.* 'Alamo') is a native warm-season perennial grass with high production yield and a wide geographical adaption in Central and North America (McLaughlin and Kszos 2005). In addition to the high yield and adaptability of this feedstock, researchers have characterized the plant as an exceptional biomass producer, capable of growing 10 ft or more (Rinehart 2006). Switchgrass is considered a renewable energy resource due to its low moisture content, which has been associated with higher quality biofuel and combustion (Rinehart 2006, Sanderson et al. 2006). Its high cellulosic content makes switchgrass an adequate candidate for ethanol production and a good combustion fuel source for power production. Studies have reported switchgrass is capable of ethanol productivity up to 30 gal/ac (Stork et al. 2009). Switchgrass 'Alamo' is considered a low-risk, native taxa for feedstock development in Georgia (Quinn et al. 2015). Additional switchgrass information is provided in table 2.

Table 2. Switchgrass description.

Switchgrass 'Alamo'	**Family**: Poaceae **Distribution**: Throughout U.S., including Georgia **Habitat**: Open woodlands, edge of marshes, roadsides, and ditches **Higher Heating Value**: 17.26 MJ/kg **Ethanol Recovery**: 117 L/ac **SOC Storage**: 1.1 to 2.9 Mg C/ha/yr (0–30 cm)

Big Bluestem

Big bluestem is a widespread and highly productive tall grass. The native perennial warm-season C4 tall grass produces as much as three times the biomass as switchgrass in native unmanaged grasslands. Big bluestem has a robust root system and stores carbon belowground due to a large underground root system, extending 7–8 ft in mature stands. Big bluestem has been characterized as a plant with high NUE, which is associated with the ability of the feedstock to utilize nutrients for maximum yields. Studies have shown that big bluestem produces more biomass with fewer resources (e.g., fertilizer and irrigation) compared to switchgrass (Zhang et al. 2015a). Big bluestem maintains diversity and wildlife through different ecosystem services, such as wildlife habitat, and can thrive on marginal lands (i.e., areas that are unsuitable for conventional crops) such as right-of-way areas. This has been demonstrated across the U.S., as millions of acres of marginal lands have been targeted for low input, sustainable feedstocks (i.e., big bluestem, switchgrass, and Indiangrass). Studies have reported switchgrass is capable of ethanol productivity up to 32 gal/ac (Stork et al. 2009). Big bluestem is considered a low-risk, native taxa for feedstock development in Georgia (Quinn et al. 2015). Additional information for big bluestem is provided in table 3.

Table 3. Big bluestem description.

Big Bluestem	**Family**: Poaceae **Distribution**: Throughout U.S., including GA **Habitat**: Found in open woods, prairies, meadows, and roadsides **Higher Heating Value**: 18.14 MJ/kg **Ethanol Recovery**: 122 L/ac **SOC Storage**: 32 Mg C/ha after 6 years of establishment (0–10 cm)

Woodland Sunflower

Woodland sunflower is a noninvasive plant that can produce thermal energy by combustion. Previous studies have suggested that woody residue from plants could be used in a bioenergy market (Gavrilescu 2008, Lunguleasa 2009). Furthermore, woodland sunflower is found in open fields with partial shade or full sun, which is reminiscent of many highway ROW areas. The presence of woodland sunflower on the ROW could be beneficial from a biodiversity perspective, as woodland sunflower tends to attract a range of insects, such as bees, wasps, flies, and butterflies (The Xerxes Society 2016). Additional information for woodland sunflower is provided in table 4.

Table 4. Woodland sunflower description.

Woodland Sunflower	**Family**: Asteraceae **Habitat**: Dry woods and openings **Height**: 2–6 ft **Environmental Notes**: Nectar serves as food for 'silvery checkerspot butterfly' and 'bordered patch butterfly'. Birds and small mammals eat the seeds. **Bioenergy**: Energy generation through combustible wood material

DEVELOPING GEOSPATIALLY ENABLED HIGHWAY ROW PROPERTY MAPS

As a first step in identifying suitable areas for feedstock establishment along the ROW, property maps that could be available electronically and/or in geospatially enabled format were developed for the section of I-16 under consideration using ArcGIS. An electronic property map would display information pertaining to I-16 ROW configurations, clearance, parcel area, and general features related to the highway ROW. In addition, the electronically available ROW property map would facilitate analyses of potential sites for biomass production within the I-16 ROW. The process for developing a ROW map for I-16 involved accessing a series of open-source datasets containing imagery from the National Agriculture Imagery Program (NAIP). The NAIP program is administered by the U.S. Department of Agriculture's (USDA) Farm Service Agency (FSA). NAIP aerial imagery is available for distribution within 60 days of the end of a flying season and is intended to provide current information of agricultural conditions, such as vegetation canopy analysis, hydrology, land-use change, and green space in support of USDA farm programs. For USDA-FSA, the 1-meter (3.28 ft) and ½-meter GSD product provides an ortho image base for Common Land Unit boundaries and other datasets. The 1-meter and ½-meter NAIP imagery is generally acquired in projects covering full states, in cooperation with state government and other federal agencies that use the imagery for a variety of purposes, including land use planning and natural resource assessment.

Mowable ROW Location for Pilot Study

From the preliminary meetings, it was decided that the pilot study should be established in ROW areas of I-16. To facilitate continuous access to the sampling sites, counties close to the main Georgia Southern University campus in Statesboro, Georgia, were chosen for the pilot study establishment. In addition, counties were selected to incorporate at least two GDOT districts into the project execution. Candler and Emmanuel Counties, as well as Bulloch County, were selected for the study area to represent Districts 2 and 5, respectively (see figure 1).

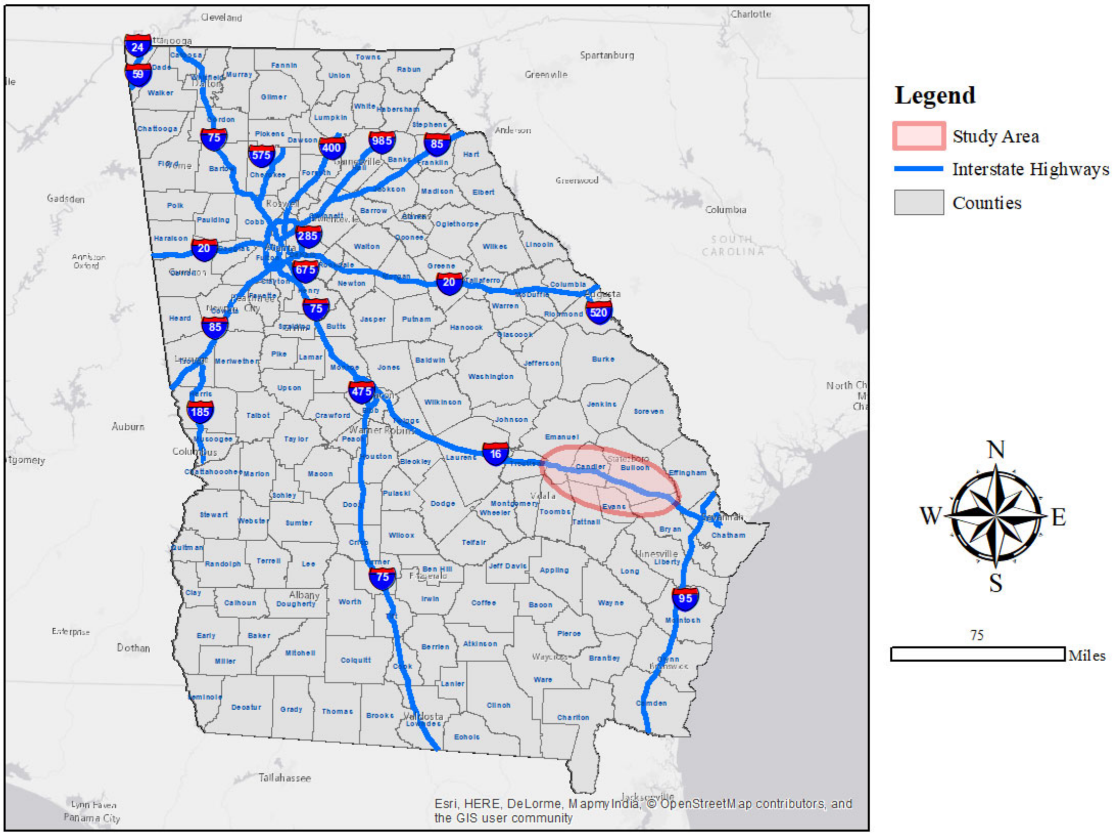


Figure 1. Map. Georgia's interstate highway system with I-16 study area.

High-resolution imagery of fence rows and tree lines separating government from private property was incorporated into ArcGIS to determine I-16 ROW boundaries throughout the study area. The highway imagery was derived from a series of datasets provided by the USDA-FSA's 2015 Orthoimagery. These downloaded images of ROW boundaries were used to digitize the available ROW for I-16 in ArcGIS 10.4 (see figure 2). The ROW parcel size throughout this section of I-16 was derived from the digitized imagery within ArcGIS 10.4. The major steps for obtaining the electronic ROW property map for this section of I-16 were downloading the Orthoimagery datasets, projecting them to North American Datum of 1983 (NAD 83), and digitizing in ArcGIS to produce an electronically available ROW property map for this section of I-16 (see figure 2). The property map would be available to GDOT administrators for future studies on the ROW of this section of I-16.

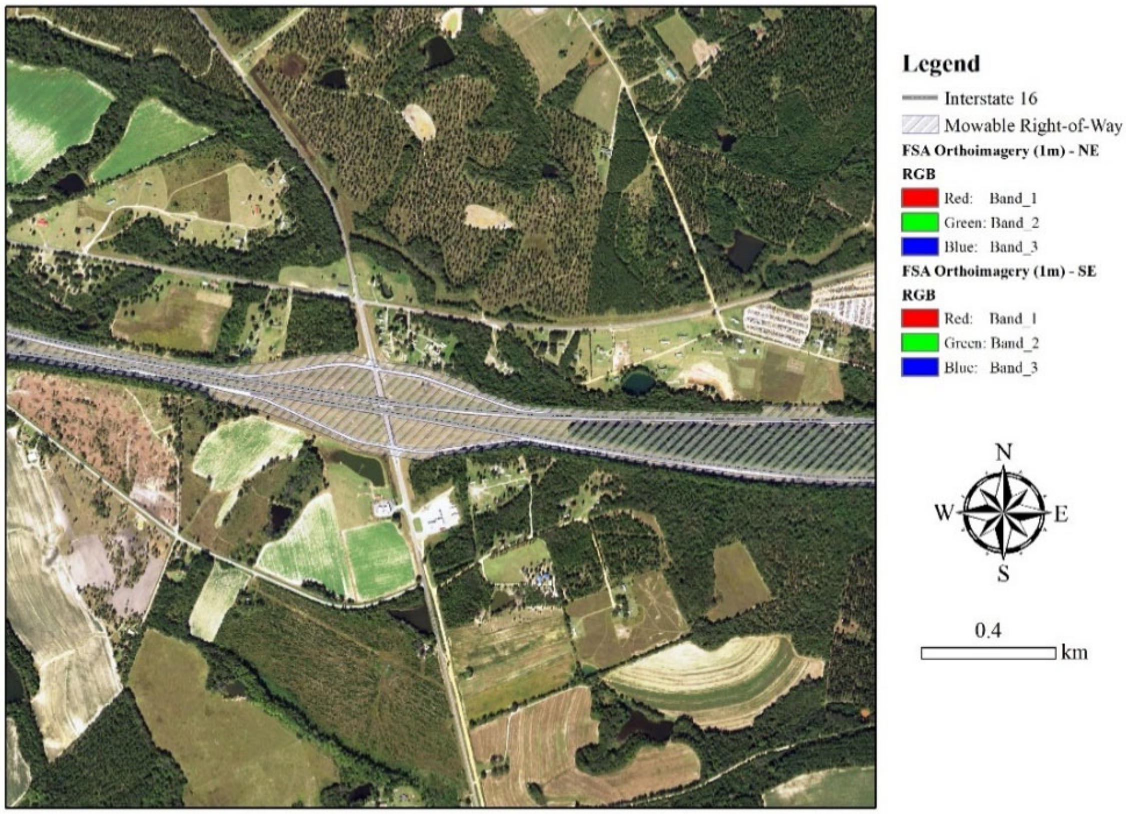


Figure 2. Map. A high-resolution aerial image of the I-16 segment with cross-hatched polygons superimposed on mowable ROW.

Incorporating Soil Properties for Growing Conditions to Identify and Delineate Soils for Bioenergy Crops Establishment in the ROW

Combining the electronic ROW property map for I-16 with the Soil Survey Geographic Database (SSURGO) allowed for delineation of the soil types and topography along the highway ROW areas. The SSURGO is a readily available database designed by the USDA and Natural Resources Conservation Service (NRCS) for natural resource planning and management of farms, ranches, townships, and counties. The SSURGO comprises georeferenced spatial polygon data collected through intensive soil surveys over a given area (soil map unit [SMU]). These SMUs function as the basic geographic unit of the SSURGO and delineate the extent of different soils in the digitized soil map at a scale of 1:24,000 (NRCS 2006), resulting in high-quality descriptions of soil, biological, climate, hydrology, and production properties of soils. Some of these properties that can be found in the SSURGO include plasticity, taxonomy, flooding frequency, organic matter, bulk density, and pH level.

For this study, a series of electronic maps were created to compile and visualize relevant conditions and parameters required for feedstock plant establishment and growth (see figure 3). These maps were developed using ArcGIS features and commands to perform spatial queries on the SSURGO data to determine attributes that corresponded to ideal growing conditions for each crop analyzed. Subsequent steps involved performing a spatial intersection of the digitized I-16 ROW and SSURGO data representing growing conditions (parameters) anticipated in the ROW. This process was used to map areas within the highway ROW based on the following growing parameters: drainage, erosion, hydrologic group, soil taxonomy, earth coverage, and slope. These parameters were selected based on their expected effects on feedstock productivity and were incorporated into a GIS to electronically delineate suitable feedstock-specific areas of production for this section of I-16. The mapped ROW parameters and their associated SSURGO attribute field names are described in the sections below.

ROW Parameter – Drainage Class

Figure 3a is a map of *drainage class* for this section of ROW. This parameter can be categorized by the relative rate and length of periods when soil is absent of water saturation in seven classes ranging from poorly to excessively drained. Drainage class was incorporated into the site selection model because it is generally associated with natural drainage conditions of the soil, and it refers to the frequency and duration of wet periods. Identifying areas with minimal periods of wetness (not prone to flooding) would provide areas that are suitable for the establishment of new feedstocks along the ROW. In addition, ROW areas with wet soils at harvest can reduce field access and cause rutting and damage to plant crowns. The 2019 SSURGO attribute field name for drainage class is drainagecl.

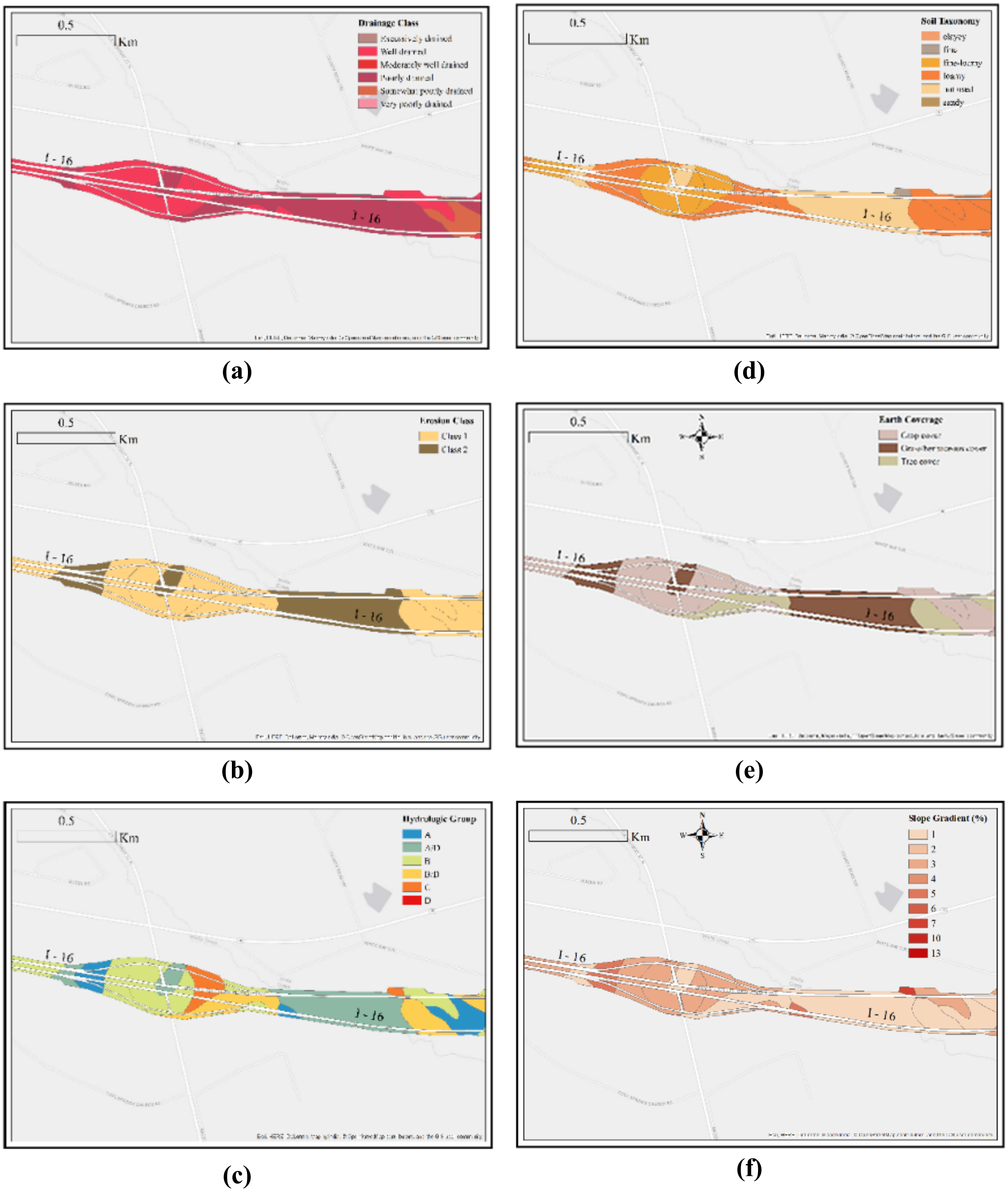


Figure 3. Illustrations. Description of each ROW parameter incorporated for geoprocessing site selection model: (a) drainage class; (b) erosion class; (c) hydrologic group; (d) soil taxonomy; (e) earth coverage; (f) slope gradient (percentage).

ROW Parameter – Erosion Class

Figure 3b is a map of *erosion class* for this section of ROW. Soil erosion is the detachment and movement of soil material. The process may be natural or accelerated by human activity. Erosion class was incorporated into the site selection model due to the ROW being exposed to highway construction activities, which can cause the removal of original soil. Over time, erosion can cause the removal of topsoil containing important nutrient compositions such as organic matter and nutrients. This parameter can be categorized by classes of soil loss in the top soil layers in five classes: None (area of soil deposition); Class 1 (1 to 25 percent of original topsoil has been removed by erosion); Class 2 (26 to 74 percent of the original topsoil has been removed by erosion); Class 3 (75 to 99 percent of the original topsoil has been removed by erosion); and Class 4 (all of the original topsoil has been removed by erosion). The 2019 SSURGO attribute field name for erosion class is erocl.

ROW Parameter – Hydrologic Group

Figure 3c is a map of *hydrologic group* for the soils along this section of ROW. This parameter can be categorized in seven classes that depict the rate that the soil absorbs rainfall: Group A (soils comprising deep, well drained sands or gravelly sands with high filtration and low runoff rates); Group B (soils comprising deep, well drained soils with a moderately fine to moderately coarse texture and a moderate rate of infiltration and runoff); Group C (soils with a layer that impedes the downward movement of water or fine-textured soils and a slow rate of infiltration); Group D (soils with a very slow infiltration rate and high runoff potential); Group A/D (soils naturally have a very slow infiltration rate due to a high water table but will have high infiltration and low runoff rates if drained); Group B/D (soils have a very slow infiltration rate due to a high water table but will have a moderate rate of infiltration and runoff if drained); and Group C/D (soils naturally have a very slow infiltration rate due to a high water table but will have a slow rate of infiltration if drained). Hydrologic groups were incorporated into the site selection model to grade soils in the ROW under wet conditions. Information of water retention is important to plant development because established plants require access to readily available water in soils. However, too much water is not ideal as this can potentially drown out newly establishing plants in the ROW. The 2019 SSURGO attribute field name for hydrologic group is hydgrp.

ROW Parameter – Soil Taxonomy

Figure 3d is a map of *soil taxonomy* for this section of ROW. Knowing soil taxonomy is essential for estimating the available water-holding capacity (AWHC) and cation exchange capacity (CEC) of a soil. CEC may be defined as the measure of how many cations can be retained or exchanged on soil particle surfaces. Negative charges on the surfaces of soil particles bind positively charged atoms or molecules (cations), but allow these to exchange with other positively charged particles in the surrounding soil water. The CEC is directly related to the amount of clay and organic matter present in the soil—the higher the clay or organic matter content, the higher the CEC. A soil with a high CEC holds a much greater number of cations, such as calcium and magnesium, than a soil with low CEC. The 2019 SSURGO attribute field name for Soil Taxonomy is taxpartsize.

ROW Parameter – Earth Coverage

Figure 3e is a map of *earth coverage* for this section of ROW. This parameter can be categorized by different descriptions of groundcover based on a set of vegetal and nonvegetal classes. Descriptions range from herbaceous plants, such as forbs and graminoids, to nonherbaceous plants. Determining which areas along the ROW contain low-lying herbaceous plants helps with identifying ROW soils with higher levels of organic matter. Most herbaceous plants contribute to organic matter concentrations in nearby soils due to decaying plant material decomposing into the soils. The 2019 SSURGO attribute field name for earth coverage is earthcovkind2.

ROW Parameter – Slope Gradient

Figure 3f is a map of *slope gradient* for this section of ROW. This parameter can be categorized by elevation differences between two points, which is expressed as a percentage of the distance between those points. This SSURGO attribute column displays the slope gradient of the dominant component of the map unit based on composition percentage. This parameter was included into the site selection process due to its relevance to accessibility for farm equipment. In addition, ROW areas with steeper slopes may present erosion and excess runoff hazards to new plants. The 2019 SSURGO attribute field name for slope gradient is slopegraddcp.

SELECTING SUITABLE SITES FOR ROW ENERGY CROPS

Using ArcGIS, the selected ROW parameters (previously described) were incorporated into the site selection process to help evaluate the effects of different ROW characteristics and soil conditions on feedstock productivity to select the ideal establishment location for a pre-selected feedstock. In addition, this process would provide information on feedstock adaptability to different ROW conditions. ArcGIS was used to develop a model that would facilitate the ROW site selection process for the pilot study by developing an automated workflow of geoprocessing tools and operations for the site selection. The Geoprocessing tools perform analysis, data management, editing, and other operations on an input dataset to produce a new output dataset. In this study, the resulting geoprocessing model allowed for expediting and documenting the research team's spatial analysis and data management processes.

Using the ArcGIS ModelBuilder, the plant parameters described in chapter 3 (Bioenergy Plants Selection) were incorporated into a series of geoprocessing (i.e., GIS operation used to manipulate data) steps to develop a site selection model for each feedstock used in this study. The geoprocessing operations used for the site selection model are illustrated in chapter 3 (Geoprocessing Site Selection Model – Part 1 and 2). The resulting product was a GIS-based model that can easily be used to generate a spatial representation of areas that are suitable for the establishment of energy crops. In addition, the model is presented as a site selection service that can be easily reused or repurposed with different criteria tailored toward specific applications regarding future projects established along the ROW system. Depending on the inputs provided by the user, the geoprocessing model can also be applied to alternative highway applications of interest to GDOT (e.g., wildflower program) because the site suitability selection process used by the model would be the same.

Preliminary Data Collection for the Geoprocessing Model

Input datasets (e.g., road, hydrology, and county delineation) for this study were collected from a host of publicly accessible open source data. Major road data were obtained from the U.S. Census Bureau, Geography Division. Spatial data for surface water bodies, such as lakes and ponds, were obtained from the National Hydrography Dataset (USDA, NRCS) and were incorporated into ArcGIS to illustrate locations of nearby water surfaces and to facilitate the creation of a safe zone (i.e., buffer) around nearby wetlands to separate them from potential areas of feedstock production. County boundaries used to delineate the study area were obtained through the U.S. Census Bureau, Geography Division. Information pertaining to soil parameters was collected by accessing the SSURGO database and was used to delineate various soil types and characteristics along the highway ROW. Data pertaining to crop characteristics, such as area of adaption and suitable soils, were obtained from the USDA plant fact sheets.

Geoprocessing Site Selection Model – Part 1

Geoprocessing models were employed using a GIS application to identify representative sampling zones within ROWs to study the impacts of replacing roadside vegetation with alternative crops that are used for bioenergy production. GIS tools provide a robust geographic engine that is powerful in performing spatial analysis and modeling. Soil and hydrologic parameters, variable throughout the study area, were incorporated in the GIS ModelBuilder application to select the best areas where bioenergy crops could be established. The site selection model allows for the depiction of different growing conditions set by the user to facilitate decision-making for feedstock establishment along the ROW. The end result of the site selection model is to map areas of ROW land that comply with criteria developed for different feedstocks. For this study, the datasets needed for the site selection model were incorporated into a model using the ModelBuilder application within ArcGIS 10.4. Using ArcGIS ModelBuilder, the datasets and site parameters described in chapter 3 (Developing Geospatially Enabled Highway ROW Property Maps) were incorporated into the site selection model. The resulting GIS model can be briefly described as follows: each input for each geoprocessing operation within the site selection model is highlighted in blue (see figure 4 and figure 5), the geoprocessing operations are shown in yellow, and the generated outputs from each geoprocessing operation are highlighted in green (figure 4 and figure 5). The “Make Feature Layer” operation (yellow) generated a feature layer (green) from the SSURGO database (blue) for each parameter of interest. The generated feature layer from this operation is created through a SSURGO database query for attributes corresponding to the parameters of interest.

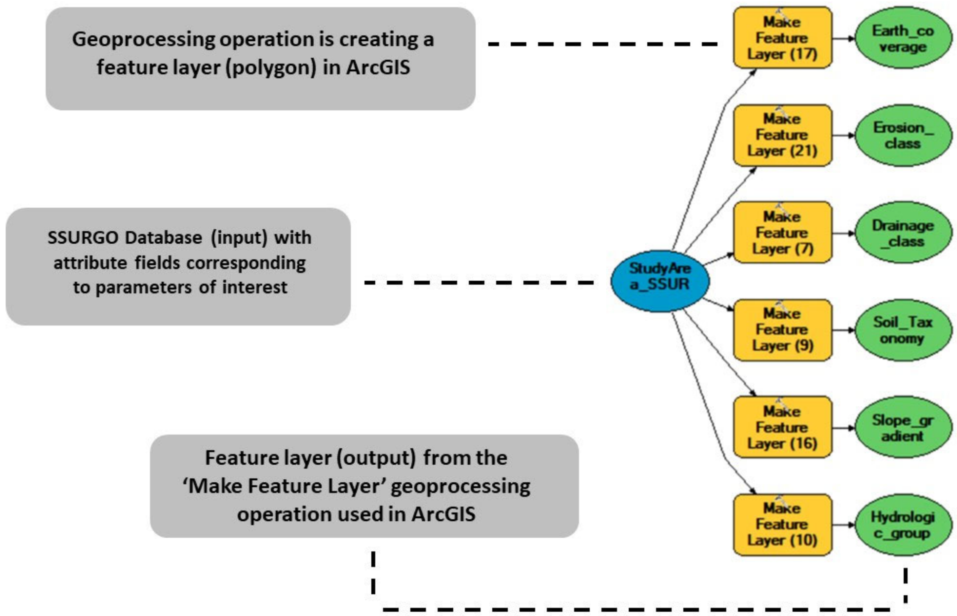
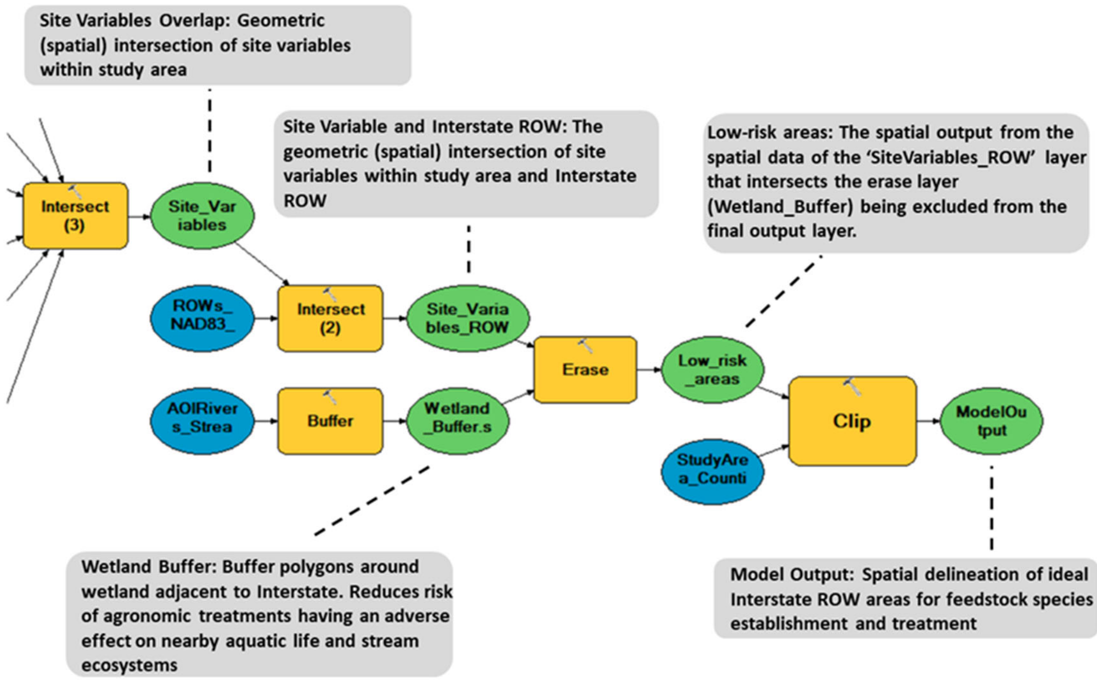


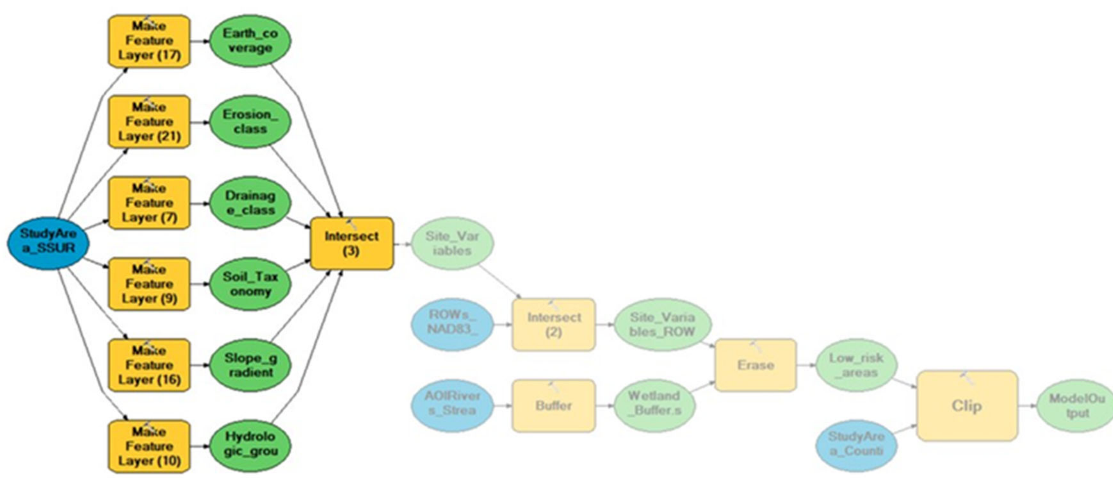
Figure 4. Diagram. Geoprocessing site model performing spatial queries on selected SSURGO attributes (i.e., site variables) within the ModelBuilder application in ArcGIS 10.4.

Geoprocessing Site Selection Model – Part 2

The next geoprocessing operation used in the model was an "Intersect" operation, which computed a geometric intersection of each feature layer generated by the previous operation. The "Buffer" geoprocessing operation was used next to delineate a 500-ft clearance from wetlands near I-16. The polygon representing a clearance of 500 ft around all ponds and lakes generated by the buffer was combined with the digitized ROW areas for the "Erase" operation. This geoprocessing step omitted areas of ROW that were located within the wetland buffer. Finally, a "Clip" operation was utilized to ensure that the delineated suitable sites for the energy crop are within the study area. These geoprocessing inputs, operations, and outputs for this section of the model are illustrated in figure 5a. The completed site selection model is shown in figure 5b.



(a)



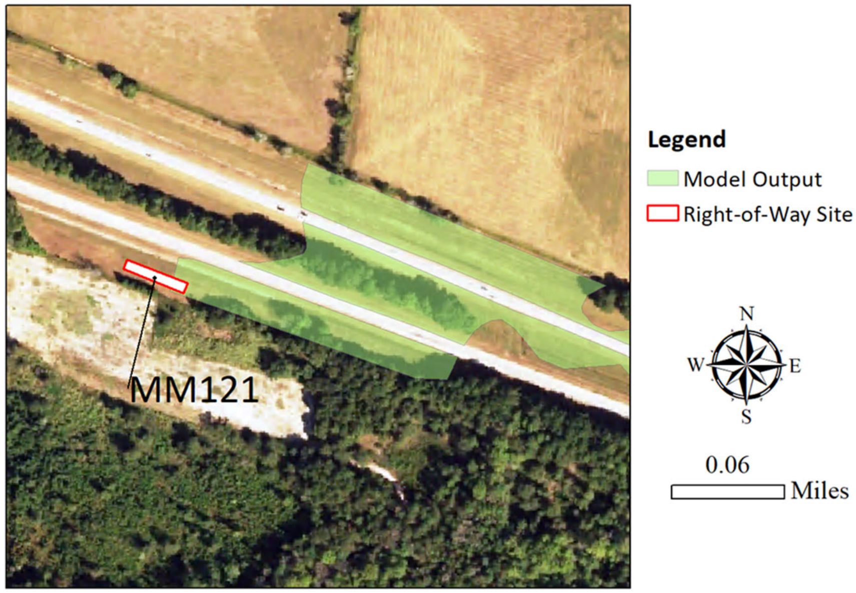
(b)

Figure 5. Diagrams. (a) Geoprocessing operations performing a series of spatial analysis between the site parameters and relevant land and water features (i.e., I-16 and nearby wetlands) within the ModelBuilder application in ArcGIS; (b) completed site selection model as shown in ArcGIS ModelBuilder.

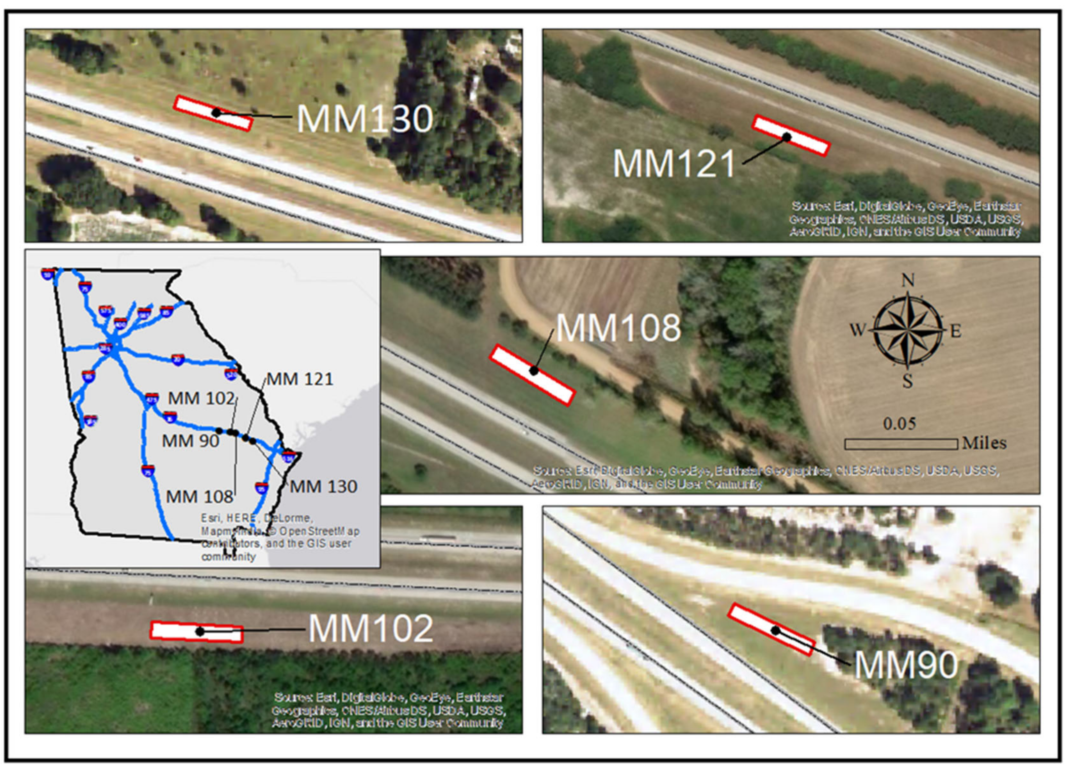
Selecting Sites for ROW Pilot Study

Based on the input datasets incorporated into the site selection model, the generated model output was a map of the highway ROW with highlighted areas that represented suitable sites for bioenergy feedstocks. From this analysis, five ROW sites were selected for the pilot study with each site spaced approximately 10 miles apart along I-16 in Georgia (figure 6a and b). The selected sites would later be prepared as establishment sites for assessing the productivity of switchgrass, big bluestem, and woodland sunflower under highway ROW conditions in southeast Georgia. These sites, which were identified as the best zones to plant the feedstocks for the study, were obtained using the geoprocessing model outputs based on the interest in evaluating the effects of establishing biomass feedstocks within different ROW configurations and by considering the variability in soil properties found along I-16. The objective was to choose sample sites that were representative of different soil conditions that prevail in southeast Georgia.

Sample locations obtained from the model output were further selected based on additional criteria not included in the model to assure a more dispersed and unbiased location selection along I-16. Mile marker 90 (MM90) was chosen due to it being on an interchange. Mile marker 102 (MM102) was chosen due to it being located on a depressed verge on the eastbound side of I-16. Mile marker 108 (MM108) was selected due to being positioned on a depressed verge on the westbound side of I-16. Mile marker 121 (MM121) was selected due to it being on an elevated verge on the westbound side of I-16. In addition, this location exhibited a high concentration of prickly pear (*Opuntia ficus-indica*), a particular species of cactus. Mile marker 130 (MM130) was chosen due to its position on a depressed verge on the eastbound side of I-16. As part of a preliminary site assessment, each site was visited with GDOT personnel to verify that enough space and adequate safety conditions existed to establish the pilot study. Once the sites were delineated in the field, the geographic coordinates for each site were obtained using a geographic positioning system (Leica GS14) to incorporate them in future GIS analyses.



(a)



(b)

Figure 6. Maps. (a) Resulting ROW site polygon output for suitable areas for feedstock establishment; (b) map of sites selected for pilot study.

CONDUCTING BASELINE SURVEY OF ROW SITES

Performing an assessment of the soil quality in the ROW, previously affected by earthwork as a result of road construction, was crucial to determine the precise location where bioenergy feedstocks would be planted. From an agricultural perspective, soil quality can be reduced by changing the topsoil with soil types or aggregates containing low organic matter content; by soil compaction, which diminishes soil volume and increases soil density, directly affecting water and oxygen penetration; and by changing soil slopes when building or repairing highways. Typically, these earth movement activities take place near the natural (original) grounds that are adjacent to constructed cut-and-fill slopes that support the highway. Conversely, the natural grounds within the ROW represent the terrain that existed prior to disturbance and/or road construction. Because the selected sites for the pilot study were positioned between the earthworks soil and the natural grounds, there was an interest in establishing a baseline evaluation of the soil quality for the selected ROW areas. Each site evaluation would be incorporated into a baseline survey conducted prior to the monitoring and evaluation of the bioenergy feedstocks to help determine the impact on soil quality from feedstock production. Results from the baseline survey were used to establish the initial conditions that existed in the soils of each ROW site used in the pilot study. Results from the baseline survey are further discussed in chapter 5 (Baseline Survey of ROW Sites).

Soil Quality Indicators

The site evaluation for the selected ROW sites was established using a series of common soil quality indicators. These indicators were chosen based on the literature review, in which the research team consulted more than 60 publications and references related to the importance of soil quality parameters, such as soil organic carbon (SOC), pH, phosphorus, bulk density, potassium, soil texture, soil nitrogen (soil N), calcium, and magnesium, and their effects on plant establishment and growth.

Soil Organic Carbon

Soil organic carbon provides a viable energy source for healthy soil microbial activity. The presence of SOC in soils stabilizes and helps bind soil particles, which can help minimize adverse effects from erosion (NRCS 1996). Plant health is influenced by the level of SOC in soils, as the water-holding capacity of a soil medium can be improved with increasing levels of SOC. In addition, SOC presence in soils increases storage and nutrient availability (e.g., nitrogen, phosphorus, sulfur, etc.) necessary for plant growth and for developing plant and soil organisms that are beneficial to soil and plant health.

pH

Soil pH directly affects solubility and availability of plant nutrients, as well as organic matter cycling in soils (e.g., production and decomposition). Studies have shown that pH is able to influence nutrient availability to plants due to its influence on a soil's CEC (McCauley, Jones, and Jacobsen 2009).

Nitrogen and Phosphorus

Nitrogen is an important component of proteins and plays an integral role in enzymatic activity. Studies have highlighted that in most terrestrial ecosystems, plant development is N-limited. As a result, for most herbaceous species, N resorption efficiency is used to determine nutrient use efficiency of plants (Aerts and Chapin 1999). Phosphorus is an essential macronutrient for life in general. It plays a role in energy transfer in plant cells and is required for plant growth in relatively large quantities, as its presence helps with flowering and root development.

Bulk Density

Bulk density in soils serves as an indicator of soil porosity and compaction. A higher bulk density can stunt root growth and limit root penetration, which can result in limited water and nutrient uptake. A higher bulk density may also hinder oxygen penetration to plant roots. Bulk density can be altered by crop and land management practices (i.e., cultivation) that affect soil cover, organic matter, soil structure, and porosity (NRCS 2008).

Potassium, Calcium and Magnesium

Studies have shown that potassium is acquired by plants in greater quantity than all other mineral elements, other than nitrogen and phosphorus (Schwartzkopf 1972). Potassium serves several functions ranging from cell division and growth to formation of starch and sugar within the plant.

Calcium has been shown to have a primary role in cell wall and root development, and it has been noted that calcium-deprived plants exhibit shorter roots. Magnesium has a primary role in photosynthesis, being the central atom in the chlorophyll molecule (Schwartzkopf 1972).

Soil Size and Texture

Soils are composed of minerals of varying sizes, ranging from clay (smallest) to stone (largest). The mineral element supports plant health, and its presence minimizes disease susceptibility (Gliessman 2006). Each mineral particle in a soil sample can be grouped into one of six categories depending on its size: clay < silt < sand < gravel < cobble < stone. The fine soil fraction is composed of a combination of sand-, silt-, and clay-sized particles. The proportion of these size groups in a soil is called the soil texture. Soil texture is an important function of soil water storage because the unique arrangement of pores created in each texture class holds differing quantities of moisture (Steinfeld et al. 2007).

Measuring Soil Quality Indicators

Within each ROW field, a series of soil cores (n=15) were collected using a hand auger (2-inch diameter, 20-inch depth) to quantify and compare levels of SOC and soil N. Figure 7 illustrates the approximate general location of the extracted soil cores from each ROW field, with each field having a surface area of 1,012 ft^2.

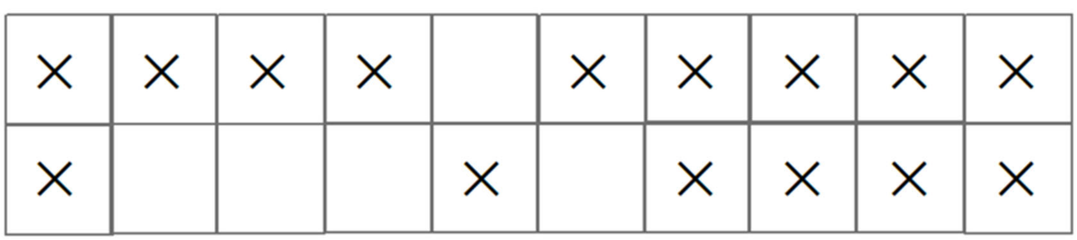


Figure 7. Diagram. Soil sampling layout.

After the sampling cores were extracted and transported to the laboratory, the SOC and soil N concentrations were determined using the following equations:

$$T_C = \Sigma(OC\% * BD * TH) \quad (1)$$

$$T_N = \Sigma(N\% * BD * TH) \quad (2)$$

Where, T_c and T_N are the SOC and soil N content (lb/ft^2) attributed to each soil core, respectively. *OC%* and *N%* represent the measured soil organic carbon and soil nitrogen percentages contained within one of the segregated layers in the soil core (mg-SP per 50 mg soil). *TH,* the thickness (inches) of the attributed soil layer associated with the soil sample, was included, while *BD* is the bulk density of the soil layer attributed to the soil core. *BD* and *TH* for each soil core were measured during site observations while soil cores were being collected, with *BD* being measured from the middle of each sampling site from each soil layer. The samples were subsequently placed in an oven for 72 hours to dry, and ground to pass a 0.025-mm screen prior to determination of soil organic carbon and nitrogen content. Each sample was homogenized using a Mixer/Mill® 8000D (SPEX® SamplePrep, Metuchen, New Jersey) to ensure samples were reduced to analytical fineness. The dry combustion method (Nelson and Sommers 1996) was used to derive soil organic carbon and nitrogen percentage of the soil samples. Each batch contained 32 samples; replicate measurements were made on 33 percent of the samples for determination of any significant calculated errors. Every 10 samples, a reference standard of aspartic acid (10.52% N, 36% C) was introduced to ensure precision and accuracy of measurements. Oven-dry bulk density was determined for each soil depth by calculating mass per unit volume. Finally, SOC and soil N contents of each soil layer were summed to produce a representative total for each extracted soil core. To supplement the SOC and soil N analysis, excess material from each soil core was submitted to the University of Georgia (UGA) Agricultural and Environmental Services Laboratories (AESL) to determine pH levels and concentrations of phosphorus, potassium, magnesium, and calcium.

CHAPTER 4. PROCEDURES FOR PILOT STUDY

ESTABLISHING ROW SITES FOR PILOT STUDY

At this stage of the project, a second meeting was scheduled with GDOT to review the updated pilot study design and define the preliminary tasks to be completed before starting the second phase of the project. GDOT engineers and maintenance operators from Districts 2 and 5 met with GDOT and the GSU research team in GDOT's District 5 main office in Jesup, Georgia, in May 2017. Topics addressed during the meeting included: selected feedstocks to be planted in ROW areas (final revision), safety priorities in ROW areas, pilot study site location along I-16 final approval, GDOT assistance during the site preparation, and other traffic-related aspects. A final meeting was held in the Statesboro GDOT office to schedule the site preparation activities and to perform a visual inspection of the sites chosen prior to implementing the pilot study.

These meetings culminated with GDOT preparing in June 2017 the selected sites where the feedstock crops would be planted. A disc harrow was used to till the soils along the ROW at each of the selected sites. Weather data from each site (i.e., temperature and precipitation) were obtained by matching each site's coordinates with climate data (Monthly Summaries) recorded at weather stations within the Georgia Automated Environmental Monitoring Network. Within ArcGIS, the coordinates associated with the surrounding weather stations were used to generate precipitation and temperature surfaces across the study area (see figure 8). The objective was to relate precipitation and temperature data to obtained growth yields for each feedstock analyzed during the study.

Using the coordinates from the selected sites, mean precipitation and temperature data from the weather (raster) surface were summarized within each site using zonal statistics in ArcGIS. The zonal statistics tool summarizes the values of a raster within a zone (area) of another spatial dataset (raster or polygon). This process was used to obtain monthly weather data throughout the upcoming growing seasons for the duration of the study. Results for the entire period of study are provided in table 13 and table 14 in chapter 6.

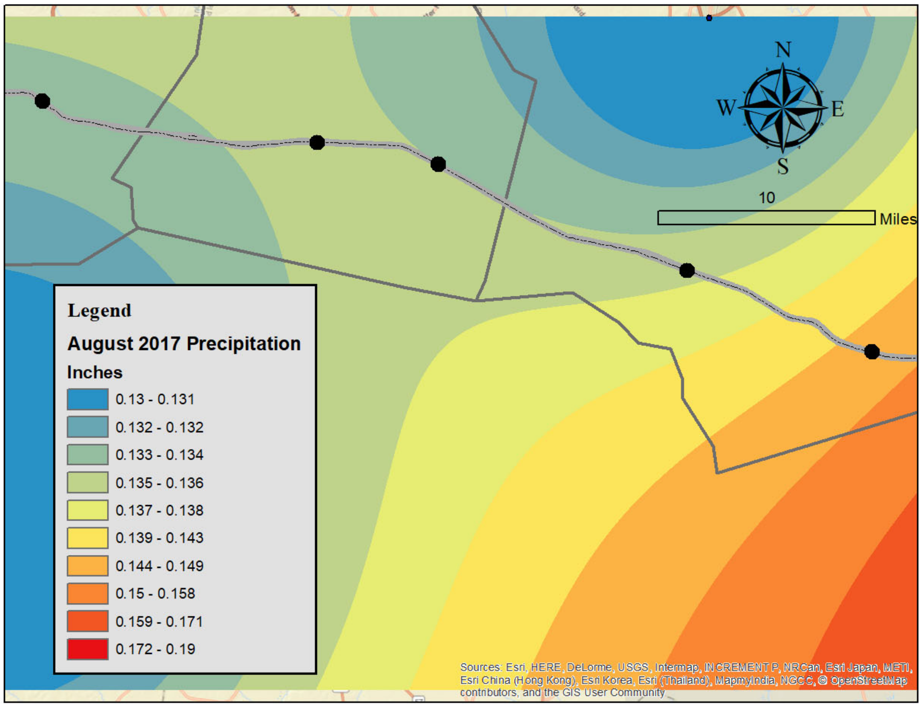


Figure 8. Map. August 2017 precipitation map.

Agronomic Treatment Design

Evaluating the effects of different agronomic growing conditions, such as temperature, light, water, soil type, and mineral nutrients, on ROW feedstock productivity was the basis for the experimental design. In addition, evaluating the year-to-year variability in feedstock productivity under ROW conditions was important to the study, as this information would aid the decision-making process used to assess the feasibility of growing these feedstocks over long-term periods (>5 years). Therefore, field observations were focused around feedstock responses to different levels of fertilizer (FR) and planting methods (PM) over two growing cycles spanning 2017–2018.

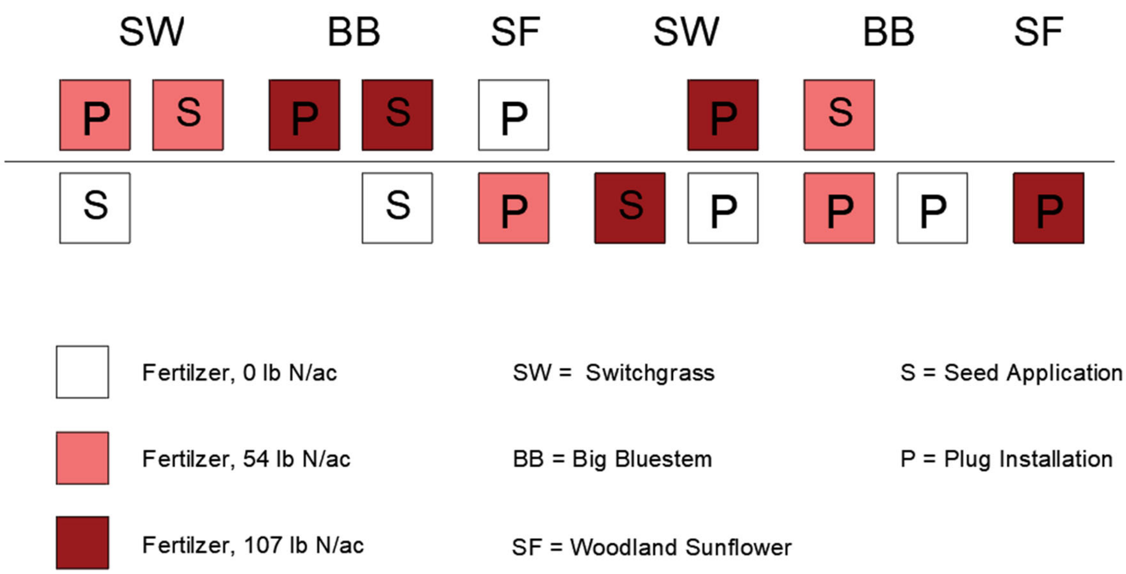
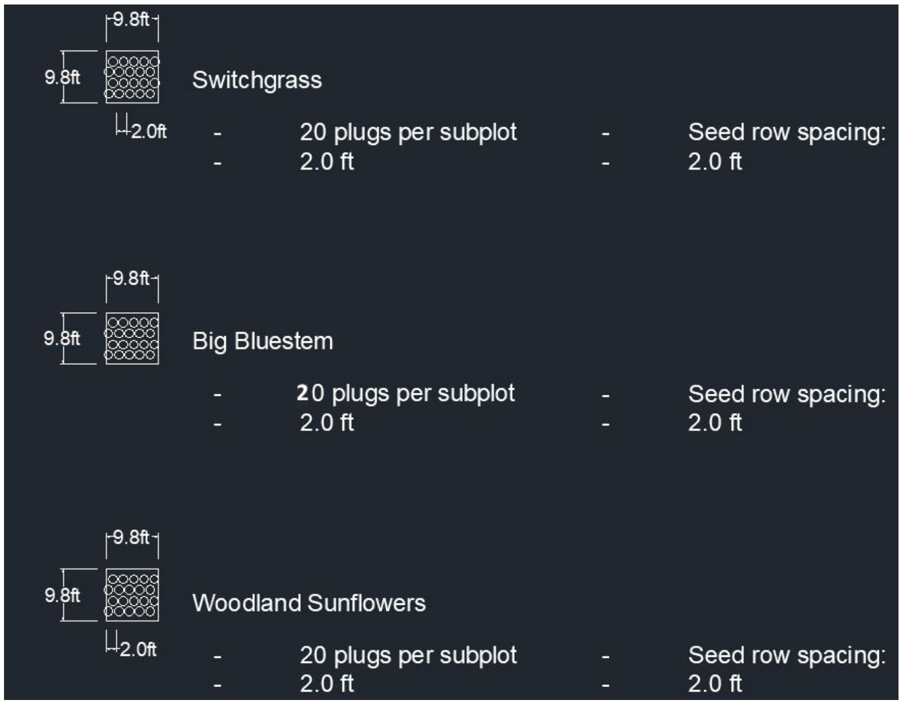


Figure 9. Diagram. Instance of split-plot arrangement at mile marker 90.

In the field, each ROW sampling site was partitioned using a split-plot arrangement, where fields were divided into plots and subplots for the establishment of seed- and plugin-planted crops for data collection (see figure 9). For the pilot study experimental layout, split-plot designs were used because this type of arrangement allowed the application of different treatments, and simultaneously provided a random arrangement across the sampling site. As a result, each ROW field was divided into six main plots, with each main plot comprising three subplots. Feedstocks were assigned to main plots using randomized complete block design (RCBD) (blocked by field), while FR and PM were assigned to the subplots using RCBD (blocked by feedstock). Seeded and plug (seedling) planting methods were used and compared to observe their effect on stand density, cost of production, and expected number of years it will take for a producer to recover the investment of establishing these feedstocks. The FR treatments were applied at the subplot level using rates of 0, 54, and 107 lb/acre of a nitrogen (N) based fertilizer. The fertilizer used was a slow-release Osmocote® (15-9-12) fertilizer (Scotts Miracle-Gro, Inc., USA).

Observations concerning biomass yield, plant analysis development (i.e., health and growth), and energy content were recorded at the subplot level for stands (the group of plants growing within the subplot area) established using the plug planting method (PM). Statistical software JMP 12

(SAS Institute, Inc. 2015) was used to assess treatment-level differences using two-way analysis of variance (ANOVA). The Tukey's HSD test was used to compare treatment means at the $p < 0.05$ level.



SW = Switchgrass; BB = Big Bluestem; SF = Woodland Sunflower

Figure 10. Diagram. Instance of split-plot arrangement at mile marker 90.

Within each subplot (9.8 × 9.8 ft), four planting rows were established in an east–west direction for plugs spaced 1.9 ft apart (see figure 10). Big bluestem (*Andropogon gerardii*) seedlings (Perennial Market, USA), woodland sunflower (*Helianthus divaricatus*) seedlings (Perennial Market, USA), and switchgrass 'Alamo' (*Panicum virgatum L.* 'Alamo') seedlings (Perennial Market, USA) were planted between August 2 – 17, 2017. As recommended by the Georgia Cooperative Extension Service agency at UGA, seeds (Roundstone Native Seed LLC, USA) for switchgrass 'Alamo' and big bluestem treatment plots were sown at rates of 6 and 9 lb/acre, respectively, on August 5, 2017.

Stand Density

Stand density is represented as a quantitative measurement of the conditions that describe the number of plant stems on a per unit area basis in either absolute or relative terms (Bettinger et al.

2017). For this study, stand density was determined at the harvest period by surveying the field and counting grass seedlings with two or more tillers, as this is necessary to survive winter and, thus, be considered a fully established seedling (O'Brien et al. 2008). Sanderson et al. (2012) noted that switchgrass stand density managed for bioenergy of >20 seedlings/m^2 are considered good, 10–20 seedlings/m^2 are considered fair, and <10 seedlings/m^2 are considered poor. Thus, a categorical scale (good, fair, and poor) was implemented for switchgrass and big bluestem seeded plots with the assumption that these feedstocks are being managed for bioenergy purposes. Additionally, the stand density percentage was determined by dividing the stand density (seedlings/m^2) by initial seeded density (seeds/m^2). Status of switchgrass and big bluestem plug treatment plots at harvest were measured using a categorical scale (good, fair, and poor) based on dividing stand density (plugs/m^2) at harvest by initial planting density (plugs/m^2) and subsequently categorizing the plots as good for a stand density percentage >66, fair for stand density percentage of 33–66, and poor for stand density percentage <33. No irrigation systems were utilized for this study as natural precipitation was used to saturate the soils beneath the feedstocks.

NDVI and SPAD Measurements

Normalized difference vegetation index (NDVI) and soil plant analysis development (SPAD) were used to evaluate feedstock canopy health across fertilizer treatments for each species established among plots. Plant health was monitored throughout the study to determine if the ROW soil and environment conditions had an impact on the overall health (i.e., vigor) of the feedstocks. Reflectance measurements from a canopy level were made using a handheld NDVI meter (CM 1000 NDVI, Fieldscout), while leaf-level contents of chlorophyll were obtained using a Minolta SPAD 502 meter (SPAD 502 Plus Chlorophyll Meter, Spectrum Technologies, Inc.). Plant NDVI relates the reflectance in the red (red NDVI) and near infrared (NIR) spectral light bands. The absorption in the red band estimates the chlorophyll content of the plant based on the NIR band, which is also sensitive to canopy cover. Many researchers have reported a good relationship between plant NDVI and photosynthetic efficiency (Liu and Wiatrak 2011, Kakani and Reddy 2010). NDVI was selected because the measurements collected at a canopy level are not affected by leaf thickness, which tends to be influenced by plant stressors, such as water and/or nutrient deficiencies. With the knowledge that fertilizer treatments were being applied for this agronomic study, the impact of N fertilizer on canopy development at each treatment (i.e., subplot) can be adequately expressed in terms of reflectance (i.e., greenness), therefore integrating the effect of leaf thickness on reflectance into the NDVI measurements. In addition, NDVI was incorporated due to its ease of use. This provides the ability to increase the number of plants being monitored and, therefore, potentially reduce variability.

The Minolta SPAD 502 chlorophyll meter quantifies the relative amount of chlorophyll present by measuring the transmittance of the leaf in two wave bands (i.e., 600–700 and 400–500 nm) obtaining readings in arbitrary units, relative to the amount of chlorophyll present (Loh et al. 2002). Healthy vegetation absorbs blue- and red-light energy to fuel photosynthesis and create chlorophyll (Davenport et al. 2005). A plant with more chlorophyll will reflect more NIR energy than an unhealthy plant. Therefore, analyzing a plant's spectrum for absorption and reflection in visible and in infrared wavelengths provides accurate information about the plant's health, vigor, and productivity.

Plant NDVI was measured in samples from three randomly chosen plants within each subplot. A total of three NDVI meter readings were collected at each plant to improve instrument accuracy. SPAD measurements were taken immediately after the NDVI measuremnts from the same plants using the SPAD meter on selected leaves. All chlorophyll measurements (i.e., SPAD) were performed on single, fully expanded leaves from three plants of each species. Triplicate readings were taken from each leaf sample and subsequently aggregated to produce an averaged value. All observations were performed on cloudless days with consistent sampling times (10:00 am – 12:00 pm), as studies have shown these measurements need to be collected with full sunlight and are somewhat sensitive to the time of day the measurement is taken (Davenport et al. 2005).

Harvesting

For this study, two harvesting seasons in two different years were defined. The first harvesting season was completed in 2017, while the second was in 2018. Two harvesting seasons were used to capture the difference that would exist in separate meteorological years. In addition, measuring growth yields on plants that survived the first season was of interest for the project. For both growing seasons, a single harvest was performed during December, as studies have shown that biomass harvested during winter exhibits higher structural carbohydrates and lignin, as well as lower protein and ash compared to earlier-harvested biomass (Mitchell 2013). In addition, harvesting late in the growing season allows nutrients such as nitrogen, phosphorus, and potassium to translocate from the aboveground biomass into the root system following crop senescence, resulting in a reduction of nutrient replacement for subsequent growing seasons (Boyer et al. 2015).

Plants were harvested using a one-cut method. The decision to pursue a one-cut approach, in contrast to a two-cut system, was made primarily due to an emphasis on the potential for high yields of switchgrass and big bluestem. Studies have shown that a two-cut system does not significantly enhance biomass production in the following year when grown for intended use in a biomass feedstock, as the increased harvest cycle inhibits nutrient translocation and storage to belowground biomass (i.e., roots) resulting in less availability for aboveground use in subsequent growing seasons (Guretzky et al. 2011). Furthermore, the two-cut system can also lead to removal of excess nutrients per acre (Sanderson et al. 2012). Harvested biomass from both growing cycles was dried using a tarp in a greenhouse over a period of 90 days at 33°C. This method of drying was selected over a traditional oven due to the excessive amounts of harvested biomass from all species of feedstock. In addition, this method of storage and drying would be expected for a potential large-scale ROW production scenario. Annual yields for future production were projected from 2018 (year 2) based on the assumption that switchgrass and big bluestem stands typically reach maturity in the third year of production (Parrish and Fike 2005). In addition, switchgrass and big bluestem yields for future production years were projected with the assumption that second-year yields are typically 67 percent of third-year yields (Khanna et al. 2008; Sanderson et al. 2006).

Heat of Combustion

Feedstock energy yield was measured using oxygen bomb calorimetry. Based on this method, a bomb calorimeter was used to determine the total caloric content of the pelletized feedstock. The homogenized ground feedstock material was pressed into approximately 100-mg pellets and analyzed for energy content (J) in a Parr Instruments oxygen bomb calorimeter (Parr Instrument Co., Inc, Moline, Illinois). Total caloric content derived from each pellet was measured using equation (3) (Lunguleasa 2009):

$$q_v = \frac{C_{cal} \cdot (t_f - t_i + t_c) - q_s}{m} \tag{3}$$

Where, q_v is caloric power (kj/g), C_{cal} is heat capacity of the calorimeter, t_f is final temperature, t_i is initial temperature, t_c is temperature of combustible biomass, q_s is heat consumed to burn the wire, and m is the mass of the feedstock pellet. The calorific value (CV) of a material is an expression of the energy content, or heat value, released when burnt in air. The CV is usually measured in terms of the energy content per unit mass, or volume (McKendry 2002a).

Plant Elemental Analysis

To assess the elemental composition of the feedstock planted in a ROW environment, a plant elemental analysis was performed. Plant tissue samples collected from harvested biomass were placed in an oven to dry for ~24 h at 65°C. Dried samples were then ground in a Wiley® Mill (Thomas Scientific, New Jersey, USA) and passed through a 20-mm mesh screen. The samples were digested following EPA Method 3052 (USEPA 1995). The digested solutions were transferred quantitatively into volumetric flasks and brought to 100-mL volume with deionized water. Finally, the solutions were analyzed for various elements (P, K, S, Ca, Mg, Fe, Mn, Al, B, Cu, Zn, and Ni) following EPA Method 200.8 (Creed et al. 1994) by inductively coupled plasma optical emission spectroscopy (ICP-OES) using an ARCOS FHS16 spectrometer (Ametek Spectro, Germany). Independent laboratory performance checks were also done with acceptable deviations for recoveries set at 100 ±5%.

Nutrient Use Efficiency

The evaluation of nutrient use efficiency was an integral part of characterizing the feedstock species based on their ability to utilize nutrients for maximum production. Baligar et al., (2001) noted that NUE is established on uptake, incorporation, and utilization efficiency of the whole plant (i.e., root and shoot parameters). Nutrient efficiency ratio (NER), a commonly used efficiency definition, was utilized to help differentiate switchgrass, big bluestem, and woodland sunflower into efficient and inefficient nutrient utilizers using the following equation:

$$NER = \frac{Units\ of\ yield, kg}{Unit\ of\ Elements\ in\ tissue, kg} \tag{4}$$

Total Organic Carbon and Total Nitrogen

In addition to evaluating the agronomic treatments on feedstock productivity, an environmental assessment was performed to determine if an excessive amount of organic matter and nutrients were transported downstream by water runoff as a result of the tilling and fertilizer activities initially used to prepare the ROW sites for bioenergy feedstock establishment. As a result, total organic carbon (TOC) and total nitrogen (TN) concentrations were measured in water samples collected at each site after a series of rainfall events. TOC and TN were analyzed in the Environmental/Water Resources Laboratory at GSU following the latest water quality methods and standards (APHA et al. 2012).

Total Suspended Solids

An assessment was done to determine if excessive suspended solids were transported downstream as a result of the tilling activities initially used to prepare the ROW sites for bioenergy feedstock establishment. Total suspended solids (TSS) was defined as the total amount of solid material, suspended in water, that is retained by a filter of 1.5-µm pore size. Prevention of erosion and suspended solids transport was a critical component of the environmental impact assessment in this study. For this assessment, water samples were collected outside and at the center of each feedstock plot to assess the filtering capacities of switchgrass, big bluestem, and woodland sunflower. TSS was measured using the EPA-approved method 340.2 (USEPA 1993). To determine the best location for water sample collection at each site, elevation data collected in situ were incorporated to ArcGIS to determine expected runoff flow direction and water accumulation at the surface of each ROW site based on topographical data (see figure 11).

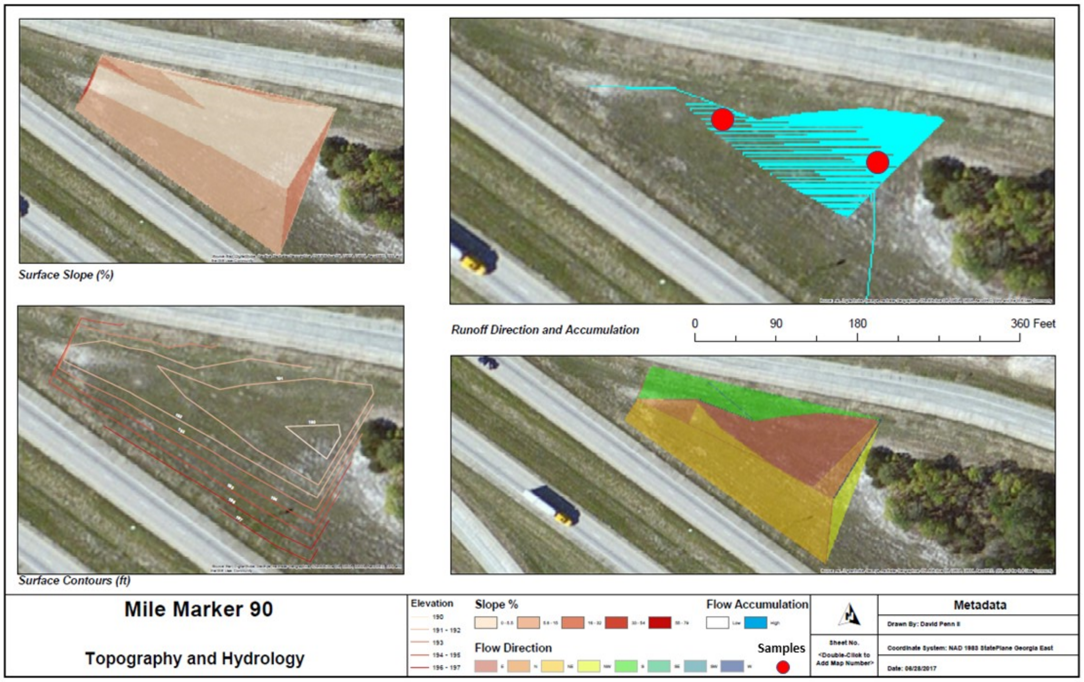


Figure 11. Maps. Mile marker 90 – topography and hydrology map.

During analysis, an aliquot of the sample—usually 0.1 L, but a smaller volume if more than 200 mg of residue may collect on the filter—was withdrawn using a precision pipette. The aliquot was passed through a 1.5-µm filter (Whatman™ Grade 934-AH). After filtering, the filter and contents were removed and dried at 103–105°C and weighed.

Vegetation Taxonomy

Outside of the bioenergy feedstocks implemented in the ROW, GDOT was interested in investigating whether native vegetation along I-16 ROW possess high-value applications in terms of energy production. To evaluate the potential of ROW vegetation, a taxonomy assessment of the plants by genus and family was performed. Six vegetation survey plots (1 m × 1 m) were established along the perimeter of each ROW feedstock site to obtain a representative area of roadside vegetation. Effort was made to collect high-integrity specimens by collecting the full plant, including roots and other underground portions. A unique number was assigned to each collection of species, along with the number of individuals of each species.

Each unique type of vegetation observed within the survey plots was recorded and subsequently transported to an herbarium lab for deposition. Great care was made to include specimens with flowers and/or fruits, along with a portion of the stem, as successful plant classification tends to be based on the morphology of flowers and fruits. Identification of unknown plant material sampled from roadside flora was performed through use of dichotomous keys, along with illustrations and published plant descriptions. Plants that were not readily identifiable to a species were grouped by genus or family. The identified plants were incorporated into Simpson's diversity index to calculate a diversity score for vegetation communities present at each ROW site. The final score was based on both the number of different species in the community and the number of individual plants present for each of those species. The higher the score, the more diverse the community is. Simpson's diversity index was determined with the equation below:

$$\textit{Simpson's Diversity Index (D)} = 1 - \frac{\Sigma n(n-1)}{N(N-1)} \tag{5}$$

Where, Σ = sum of (total), n is the number of individuals of each different species, and N is the total number of individuals of all the species.

ECONOMIC ASSESSMENT ON BIOMASS PRODUCTION IN THE ROW

An economic assessment was conducted to evaluate the financial feasibility of replacing ROW vegetation of highways throughout the state with high-value feedstocks such as switchgrass, big bluestem, and woodland sunflower. Results from the pilot study were used to assess the costs and net revenues associated with ROW production of biomass feedstocks crops given a scenario where GDOT implements a statewide biomass feedstock system within highway ROWs. The goal of the feasibility assessment was to provide GDOT with information pertaining to expected costs and breakeven payback period(s) associated with establishing, maintaining, and delivering high-value biomass to end users who would be able to process the ROW bioproducts as source for energy. In this study, the cost analysis associated with developing renewable products within the ROW was facilitated by developing an economic model capable of identifying the breakeven point of this potential investment.

Production Budget Assumptions

The economic model used for this study is based on unit production budgets associated with the establishment, harvest, and transportation of perennial feedstocks produced for bioenergy purposes. Machinery prices, schedules, and baseline inputs were provided by crop budgets from the UGA Extension (Smith 2019). Machinery related to capital recovery, maintenance, and fuel prices associated with typical farm situations were also referenced by the UGA Extension (Smith 2017). Assumptions common to the establishment and harvest budgets included the use of a 120-hp tractor to power farm implements, a labor rate of \$8.5/hr, and a nominal interest rate of 8 percent. It was assumed that herbicide treatment using Roundup™ would be applied pre-emergence and would not be used in the subsequent years of production. For the storage budget, it was assumed that the harvested biomass would be stored outdoors near the harvested ROW plots. Assumptions used for the transportation budget included the use of a standard semi-tractor trailer with 8 × 9 × 48-ft dimensions capable of transporting stored biomass to a biorefinery plant (USDOT 2004). The distance from the storage unit to the biorefinery plant was assumed to be 50 miles with a travel speed of 50 miles/hour for the semi-tractor trailer. The final production budget is based on a 10-year timeline. The assumptions used for the production budgets can be changed to reflect different production scenarios encountered in feedstock development programs. The resulting model can adjust to these changes keeping accurate results pertaining to the expected costs and profits associated with producing biomass feedstocks under varying conditions. If needed, GDOT can update any of the input values in the model to perform a similar analysis in different locations across the state.

Establishment

The total establishment cost per acre ($E_{\$}$) can be summarized as follows:

$$E_{\$} = PREP + HERB + PLANT_m + FERT_r + LABOR_h \tag{6}$$

Where, the subscript m is the planting method (seed or plug) for feedstock species; the subscript r is the rate of fertilizer (lb/acre); *PREP, HERB, PLANT,* and *FERT* are the labor, variable, and fixed costs of tilling the soil, herbicide application, planting, and fertilizing the feedstock material. $LABOR_h$ is the hourly wages for operating establishment (preharvest) machinery with wages for each operation being \$8.5/hour (Wang et al. 2009). Establishment costs were limited to the first year of production and assumed a 14-ft disk harrow and a 13-ft boom-type sprayer for preemergence herbicide application. Planting costs (\$/acre) or seeded plots were obtained from the seed rate (lb of pure live seed [PLS] per acre, or lb PLS/acre) multiplied by seed price (\$/lb). The planting costs for plots with seedlings (plugs) represented the planting density (plug/acre) multiplied by plug rate (\$/plug). Seed prices as determined by custom rates for switchgrass and big bluestem were \$14.00/lb and \$12.50/lb, respectively. A seeding rate of 6 lb PLS/acre for switchgrass and 9 lb PLS/acre for big bluestem were used for seeded treatment plots. Plug prices as determined by custom rates for switchgrass and big bluestem were \$1.30 and \$1.00/plug, respectively. The planting density for plug treatment plots was 2.22 plugs/m^2 for switchgrass and big bluestem, using four rows comprising plugs spaced 1.9 ft apart. Due to this study being based on a previous agronomic study investigating effects of N fertilizer for switchgrass and big bluestem, N costs (\$/acre) were obtained from the FR treatment level (lb/ac) multiplied by N costs of \$0.47/lb using three rates of fertilizer (0, 54, and 107 lb N/ac). Fertilizer prices (\$/lb) were derived from the 2017 Agricultural Prices publication by the U.S. Department of Agriculture and the National Agricultural Statistics Service (USDA-NASS 2017).

Harvest

The total harvest cost per acre ($H_{\$}$) can be summarized as:

$$H_{\$} = MOW_m(f) + RAKE_m(f) + BALER_m + STAGE_m + LABOR_h \tag{7}$$

Where, the subscript *m* is the baling method (round or rectangular) for *MOW, RAKE, BALER,* and *STAGE,* respectively; *MOW, RAKE, BALER,* and *STAGE* are the labor, variable, and fixed costs of mowing, raking, baling, and staging feedstock material (Duffy and Nanhou 2001). $LABOR_h$ is the hourly wages for operating harvest machinery with wages for each operation being \$8.5/hour. Harvesting of switchgrass and big bluestem was done once per year as recommended by previous agronomic studies of these perennial feedstocks (Rinehart 2006; Kering et al. 2011). Higher rates of removal associated with high-frequency biomass harvest cycles can drive up fertilizer input costs due to supplementing depleted soil nutrients as a result of lost nutrients in the form of harvested biomass (Kering et al. 2011). Research involving production cost of switchgrass feedstock used solid rectangular bales over round bales, due to observing higher throughput (capacity) associated with the baler (Cundiff and Marsh 1996). With the knowledge that using conventional hay technology with the rectangular bale (4 ft × 8 ft) system would be more cost-effective when compared with round bales, a large rectangular baling method was used for this study with an associated baling density of 1 ton/bale. Thus, more harvested biomass could be prepared for storage and transport by using rectangular bales. Despite the machine time for mowing and raking not varying with yield, the baling and staging operations were assumed to operate as a function of yield. Baling was assumed to operate at a rate of 12 tons/hour for large rectangular bales.

Storage

The total storage cost per acre ($S_{\$}$) was calculated using the following equation:

$$S_{\$} = \frac{Unit_t(\%) * [Unit_t(\$) * Unit_t(a)]}{BALE_m(y)} * YIELD \tag{8}$$

Where, the subscript *t* is the type of storage unit (indoor or outdoor); *m* is the method of baling (round or rectangular); *y* is the amount of baled biomass (tons) in storage; *%* is the yearly ownership cost of the unit expressed as a percentage associated with the storage unit; *\$* is the cost/ft^2 of the storage unit; *a* is the area (ft^2) of storage; and $YIELD$ is the amount of harvested biomass per acre. Previous studies have reported that dry matter losses of switchgrass feedstock can be exacerbated depending on the method of storage (Wang et al. 2009, Shinners et al. 2010). Larson et al. 2010 reported that indoor storage of baled biomass significantly improved switchgrass DM integrity in the form of reduced moisture content (Larson et al. 2010) and uniform chemical composition (Shinners et al. 2010) when compared to outdoor storage alternatives.

Transportation

Transportation logistics will vary depending on the scenario; thus, assumptions are made regarding hauling stored biomass to a biorefinery. A standard semi-tractor trailer with 8 × 9 × 48-ft dimensions (USDOT 2004) will transport stored biomass to a biorefinery plant. The distance from the storage unit to the biorefinery plant was assumed to be 50 miles with a travel speed of 50 miles/hour for the semi-tractor trailer. Therefore, it costs two hours per round trip to the biorefinery with the semi-tractor trailer capable of hauling 18 tons of large rectangular bales per hour or 29 tons of large round bales per hour. The transportation cost per acre ($T_{\$}$) was determined with the following equation:

$$T_{\$} = [LABOR_h * \frac{DIST}{SPEED}] * 1.25 \tag{9}$$

Where, $LABOR_h$ is as previously defined; $DIST$ is the travel distance (miles) to the biorefinery; $SPEED$ is the miles per hour of the semi-tractor trailer. Labor time is 1.25 times the corresponding driving time (Wang et al. 2009). It should be noted that additional methods of transporting the harvested biomass can be incorporated into the model to reflect different transportation scenarios.

Unit Production Costs

Breakeven payback periods for a 10-yr span were determined by calculating the annualized unit production cost (\$/acre). An assumed 10-yr stand lifespan for switchgrass and big bluestem was used for this study, following cost-of-production literature (Duffy 2007, Mooney et al. 2009). In addition, this period of time coincides with the recommended production lifespan of these perennial feedstocks from an agronomic perspective because there may be a steady decline in switchgrass production over consecutive growing seasons due to long-term exposure to factors such as soil bacteria, plant pests, and depleted nutrient levels in soils (Haque et al. 2009). As a result, establishment costs ($E_{\$}$) were amortized over 10 years at a rate of 8 percent and were included in the post-establishment year budgets (Mooney et al. 2009). The post-establishment year budgets also included the cost of subsequent N fertilizer application, harvest, and transportation. Thus, the total cost of production ($P_{\$}$) on a land-area basis (\$/acre) can be described as follows:

$$P_{\$} = E_{\$} + H_{\$} + S_{\$} + T_{\$} \tag{10}$$

Where, $E_{\$}$, $H_{\$}$, $S_{\$}$, and $T_{\$}$ were previously defined. As a result, $P_{\$}$ was annualized through discounting the maintenance, harvest, storage, and transportation costs into their establishment year value. The discounted values were amortized over the period (years) of production for switchgrass and big bluestem feedstocks with a discount rate of 5.9 percent, using the present value formula:

$$\sum_{p=0}^{S-1} \frac{P_{\$}}{(1+r)^{p}} \tag{11}$$

Where, *S* is the sum of production time (years), $P_{\$}$ is the current cost of production on a land area basis ($/acre) for period *p* obtained from the production budgets, *r* is the discount rate representing the opportunity costs of capital ($), and establishment is assumed to occur at time *p* = 0. A real discount rate of 5.9 percent was calculated by subtracting the 10-yr average inflation rate of 2.1 percent for the period 2007–2017 (Current US Inflation Rates: 2009–2019, 2008). The net cash flow (NCF) was determined by amortizing the net present value of production over the production time (years) using the capital recovery formula (Mooney et al. 2009):

$$NCF = NPV * \frac{r}{1-(1+r)^{N}} \tag{12}$$

Where, *NPV* is the net present value of total production cost on a land-area basis in 2017 dollars ($/acre), and *r* and *S* are as defined above. Breakeven payback period (BPP) was calculated by determining when revenues (NCF) exceed total expenses ($P_{\$}$).

$$BPP = \frac{NCF}{P_{\$}} \tag{13}$$

Yields for future production years were projected from 2018 yields based on the assumption that switchgrass and big bluestem stands typically reach maturity in the third year of production (Parrish and Fike 2005). In addition, switchgrass and big bluestem yields for future production years were projected with the assumption that second-year yields are typically 67 percent of third-year yields (Khanna, et al. 2008; Sanderson et al. 2006).

Feedstock Market Value

It is uncertain what refineries will pay for switchgrass and big bluestem, as commercial markets for cellulosic feedstocks do not currently exist (Epplin et al. 2007); however, it can be expected that they will have to pay at minimum its value as a livestock feed. Switchgrass and big bluestem have historically been planted as a forage crop and related markets may exist (Mooney et al. 2008). Thus, an alternative to using current market prices was to use the breakeven price that is expected to make switchgrass and big bluestem competitive with alfalfa (Williams et al. 2015), a commonly grown forage crop. As a result, this analysis uses a farm gate price of $84/ton and $103/ton for switchgrass and big bluestem, respectively, as identified in previous research for calculating potential net revenues. Woodland sunflower does not have any published market value as a livestock feed due to its wood composition, thus it was not included in the production budgets. Reseeding and irrigation are not addressed for this establishment budget, as many studies involving biomass feedstock production of switchgrass and big bluestem ignore these factors in production cost (Mooney et al. 2008; Perrin et al. 1972; Griffith et al. 2014).

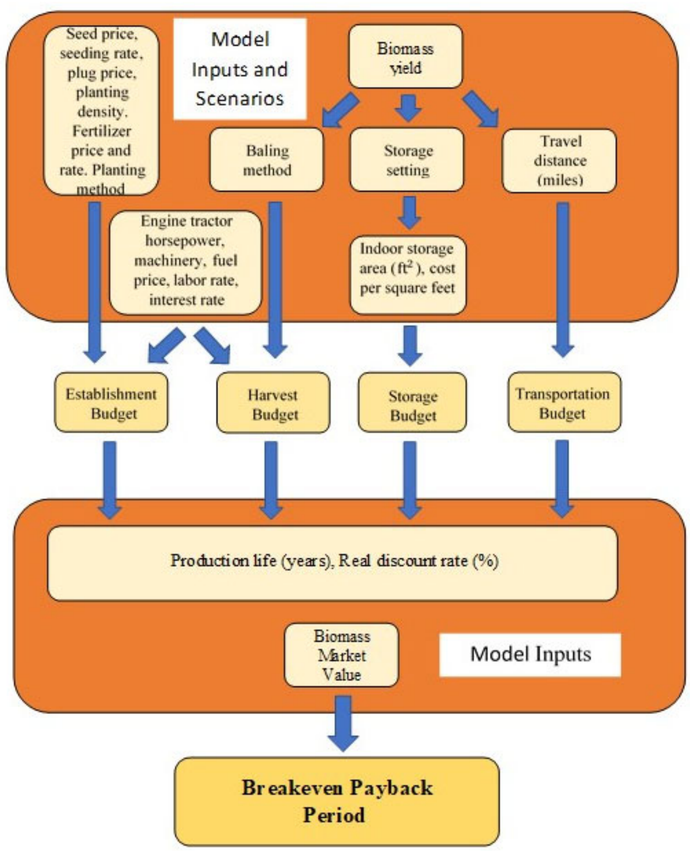


Figure 12. Diagram. Economic model inputs and outputs.

Model Inputs and Definitions

Based on the aforementioned inputs and outside assumptions associated with each unit production budget (e.g., establishment, harvest, storage, and transportation), an economic model was developed from this study (see figure 12). The production scenarios illustrated in the model were developed to show the different costs and revenues involved in growing switchgrass and big bluestem. A spreadsheet using these scenarios of costs and revenues and breakeven payback periods was developed at GSU to fit specific production conditions. Producers can change the quantity of inputs, respective prices, and assumptions, allowing for costs and revenue adaptation for various scenarios.

Calculation Metrics for Model

The additional formulas for the economic feasibility model shown in figure 12 are outlined below. The formulas were developed to illustrate cost/profit per acre and are presented under their respective production budget.

Establishment Budget

Seed Planting Material = Cost of seed ($/lb) × Amount (lb/acre) (14)

Plug (Seedling) Material = Cost of plug ($/plug) × Amount (lb/acre) (15)

Fertilizer Material = Cost of fertilizer ($/lb) × Amount (lb/acre) (16)

Herbicide Material = Cost of herbicide ($/pint) × Amount (pint/acre) (17)

Machinery Fuel = (Fuel gallon/acre) × Price of fuel/gallon (18)

Machinery Repairs and Maintenance = (Repair $/acre) × Acre(s) (19)

Machinery Labor = 1.25 × [Machinery throughput rate (hr/acre)] (20)

Harvest Budget

$$\textit{Fertilizer Material} = \textit{Cost of fertilizer (\$/lb)} \times \textit{Amount (lb/acre)} \qquad (21)$$

$$\textit{Herbicide Material} = \textit{Cost of herbicide (\$/pint)} \times \textit{Amount (pint/acre)} \qquad (22)$$

$$\textit{Machinery Fuel} = \textit{(Fuel gallon/acre)} \times \textit{Price of fuel per gallon} \qquad (23)$$

$$\textit{Machinery Repairs and Maintenance} = \textit{(Repair \$/acre)} \times \textit{Acre(s)} \qquad (24)$$

$$\textit{Machinery Labor} = 1.25 \times [\textit{Machinery Throughput Rate (hr/acre)}] \qquad (25)$$

$$\textit{Staging} = \textit{Yield (tons)} \times 2000 \textit{ (lb)/lb per Baling Method (Rectangular or Round)} \qquad (26)$$

Storage Budget

See equation 8 in chapter 4 (Storage).

Transportation Budget

See equation 9 in chapter 4 (Transportation).

Sensitivity Analysis

A sensitivity analysis was performed on the breakeven payback period for growing switchgrass and big bluestem feedstocks under a 10-yr contract. The breakeven payback associated with using fertilizer inputs of 54 lb N/ac to establish feedstock production would be the baseline for the sensitivity analysis, as this level of input represents a realistic amount for perennial feedstocks being managed for bioenergy purposes should fertilizers be used during the establishment (year 1) (Rinehart 2006).

CHAPTER 5. RESULTS FROM THE ROW SITES BASELINE SURVEY – PRELIMINARY STUDY

GEOSPATIALLY ENABLED HIGHWAY ROW PROPERTY MAPS

The results of digitizing the ROW throughout the study area revealed that the Bulloch, Candler, and Emanuel County sections of the highway span approximately 53 miles. Additional information regarding ROW characteristics for this section of I-16 are presented in table 5.

Table 5. Summary of I-16 ROW characteristics derived from digitized imagery.

County	***Interstate 16 – ROW Characteristics***	
Emanuel	Span	10 mi
	Area	129.7 ac
	Interchanges	2
	Interchange Parcel Area (max)	5.1 ac
	Interchange Parcel Area (min)	2.9 ac
	Clearance from Highway (max)	110.2 ft
	Clearance from Highway (min)	14.8 ft
Candler	Span	17.3 mi
	Area	614.8 ac
	Interchanges	3
	Interchange Parcel Area (max)	5.5 ac
	Interchange Parcel Area (min)	2.6 ac
	Clearance from Highway (max)	146.3 ft
	Clearance from Highway (min)	24.3 ft
Bulloch	Span	26.1 mi
	Area	507.7 ac
	Interchanges	4
	Interchange Parcel Area (max)	11.2 ac
	Interchange Parcel Area (min)	3.0 ac
	Clearance from Highway (max)	150.3 ft
	Clearance from Highway (min)	32 ft

Site properties showed that parcels throughout the section of I-16 are narrow in places, but in other places extends several hundred feet or more beyond the edge of the road surface, depending on the ROW configuration. For example, I-16 ROW parcels configured for an interchange (e.g., on/off ramp) range from 2.6 to 11.2 acres of mowable area. The parcels configured for separating the highway shoulders from the tree lines adjacent to private property range 15 to 150 ft in ROW clearance. When incorporating all digitized ROW configurations (i.e., interchanges and outside shoulder areas) present for this section of highway, there is approximately 1,252 ac of mowable ROW. These results showed that there is a good amount of land available for bioenergy crop production in the ROW for I-16. Despite the ample amount of land for production, the variability of parcel size reported for this section of highway may cause some challenges for continuous bioenergy crop production across the ROW due to potential limitations of farm equipment accessing the ROW. ROW areas placed on interchanges can be a better option due to easy access for farm equipment to these sites.

BASELINE SURVEY OF ROW SITES

The results of the site selection model represented five different ROW sites to be used for the pilot study. Each site was located on parcels with a minimum ROW clearance of 40 ft, as the selected parcels facilitated easy access for site-preparation equipment. The selected sites were evaluated prior to the pilot study to determine the ROW soil's quality prior to feedstock establishment. The results of the site evaluations are described below.

Soil Taxonomy and Classification

The selected sites were predominately characterized with sandy soils such as Albany, Tifton Loamy, and Chipley sand (see table 6).

Table 6. Site characteristics of selected areas of study.

Location	*Site Characteristics*
Mile Marker 90 (Lat: 32.4028032, Long: −82.3096867)	Elevation: 193 ft Landuse: Developed, medium intensity Soil Order: Ultisols Soil Series: Bonifay sand Topography: 1–5% slopes Geomorphic Description: Coastal plains, interfluves
Mile Marker 102 (Lat: 32.3750541, Long: −82.0931752)	Elevation: 167 ft Landuse: Developed, medium intensity Soil Order: Ultisols Soil Series: Bonifay sand Topography: 1–8% slopes Geomorphic Description: Coastal plains, interfluves
Mile Marker 108 (Lat: 32.3606028, Long: −81.9982345)	Elevation: 232 ft Landuse: Developed, low intensity Soil Order: Ultisols Soil Series: Tifton loamy sand Topography: 0–2% slopes Geomorphic Description: Coastal plains, interfluves
Miler Marker 121 (Lat: 32.2891779, Long: −81.802676)	Elevation: 139 ft Landuse: Developed, low intensity Soil Order: Ultisols Soil Series: Albany sand Topography: 0–2 % slopes Geomorphic Description: Coastal plains, interfluves
Miler Marker 130 (Lat: 32.2344898, Long: −81.6573839)	Elevation: 110 ft Landuse: Developed, open space Soil Order: Entisols (fluvents) Soil Series: Chipley sand Topography: 0–2 % slopes Geomorphic Description: Coastal plains, interfluves

Mile markers 90 and 102 have Bonifay sandy soil, which consists of very deep, well-drained, moderately permeable soils. Mile marker 108 comprises Tifton sandy soils, which generally have sand or loamy sand surface horizon textures underlain by sandy loam or sandy clay loam subsoil texture. Mile marker 121 exhibits Albany sandy soils, which are somewhat poorly drained and have loamy sand surface horizon textures with a very dark grayish brown hue. Mile marker 130 has Chipley soil series, which consists of very deep, somewhat poorly drained, and very rapid or rapidly permeable soils, and are formed in thick deposits of sandy marine sediments. Further soil quality assessment at the selected sites showed that the main soil orders are Ultisols and Entisols. Particle size distribution analyses revealed that the average percentage of sands and fines (i.e., silt and clay) present across all right-of-way sites was 91.9 and 7.56 percent, respectively. These results showed that the soil textures for the selected ROW sites were mostly characterized by some variant of sandy soil (see figure 13).

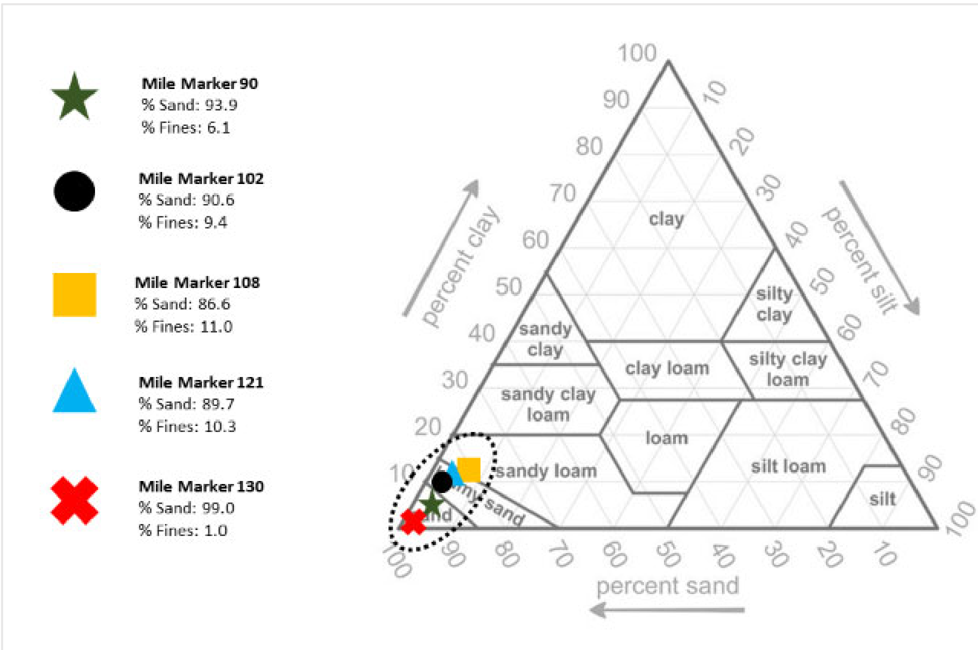


Figure 13. Diagram. Soil texture classifications for right-of-way sites.

Soil texture classification for the five ROW sites showed that the soil at mile markers 90 and 130 were classified as sandy, soil at mile marker 108 and 121 as sandy loam, and the soil at mile marker 102 as a loamy sand. When considering the soil textures dominating these ROW sites (e.g., sandy loam, loamy sand, and sand) these soils are not able to hold much water due to the low surface area and low sorption capacity associated with sand particles (see figure 14). As a result, these soils may perform poorly in storing water, which could lead to water shortage for plants during drought periods and high amounts of stormwater runoff in the ROW (NRCS 2008).

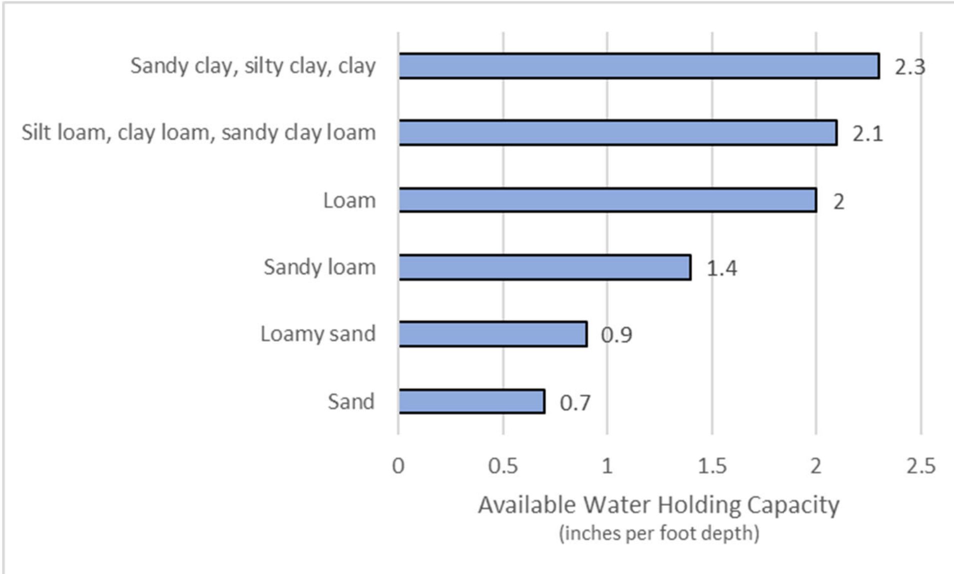


Figure 14. Graph. General relationship between soil texture and available water-holding capacity.

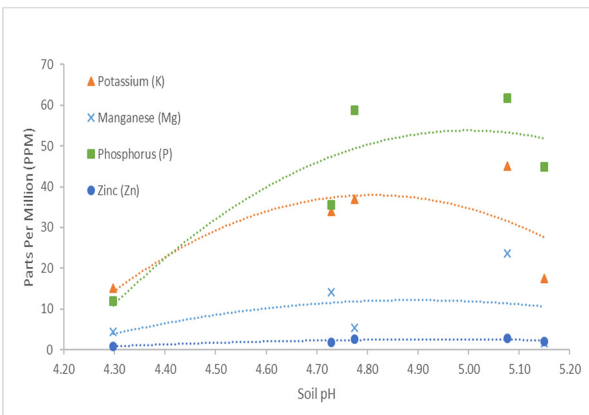
Soil Quality Indicators

The results from the soil quality indicators referenced in chapter 3 (Soil Quality Indicators) are presented in table 7. These indicators were chosen based on the importance of the selected soil quality parameters on plant establishment and their effects on agricultural practices in general. Results from the soil analysis showed that slightly acidic soils prevailed at the selected ROW sites, as the soil pH values were between 4.3 and 5.1. When plotting the results, it was observed that the low pH values may have some influence on nutrient availability for newly established biomass feedstocks (see figure 15).

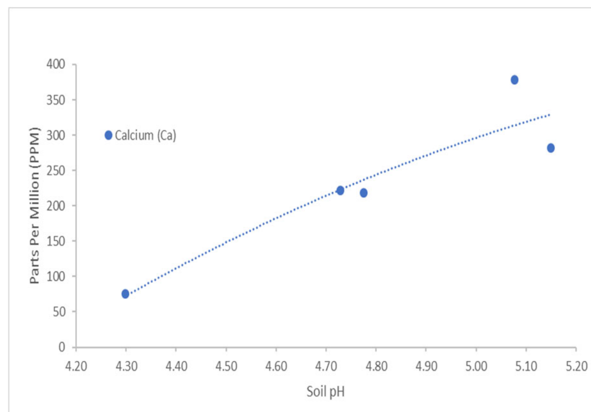
Table 7. Site characterization using summary statistics from year of establishment for all five right-of-way studied sites.

Mile Marker	*Bulk Density (g/cm^3)*	*pH*	*Calcium*	*Potassium*	*Magnesium*	*Manganese*	*Phosphorus*	*Zinc*
90	1.35	5.1	281.9	17.4	58.2	1.7	44.9	1.9
102	1.58	4.3	75.4	15.1	19.2	4.4	11.9	0.9
108	1.58	5.1	378.1	44.9	53.2	23.6	61.8	2.9
121	1.44	4.7	221.6	34.0	47.6	14.1	35.5	1.9
130	1.48	4.8	217.9	36.9	55.2	5.4	58.7	2.7

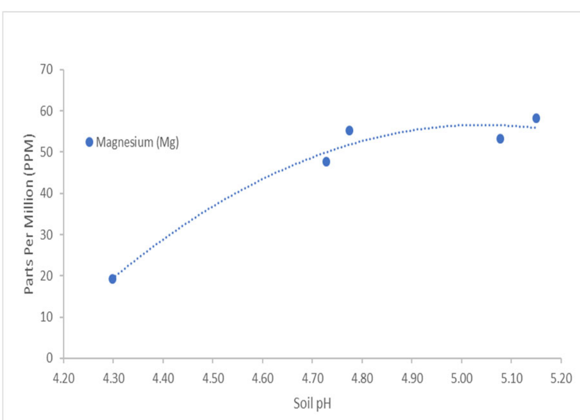
* Elemental analysis results are presented in parts per million (PPM).



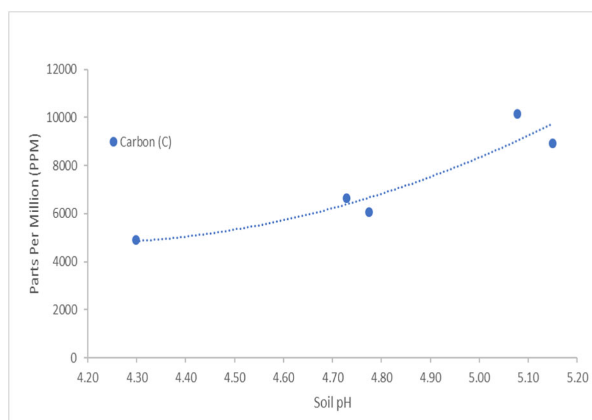
(a)



(b)



(c)



(d)

Figure 15. Graphs. Bivariate scatterplots illustrating the relationship between soil pH values and nutrient availability for a) K, Mn, P, and Zn; b) Ca; c) Mg; and d) C.

Phosphorus and zinc concentrations across all sites appeared to be highest when the pH is 5, while potassium and manganese appear to be readily available when the pH value was 4.8 (see figure 15a). When assessing the scatterplots for calcium, it is apparent that there is a positive relationship between soil pH and the nutrient accessibility of calcium, as calcium increases drastically with pH (see figure 15b). Magnesium and carbon also show a strong relationship with pH, as both increased with rising pH (figure 15c and d). These scatterplot results were validated by performing a correlation coefficient test on the nutrients and pH levels present at the sites. The coefficient results show that a strong relationship exists between calcium concentrations and pH values ($r = 0.9234$; $p = 0.0252$). It was also determined that manganese concentrations and pH values ($r = 0.9029$; $p = 0.0358$) and carbon concentrations and pH values ($r = 0.9091$; $p = 0.0324$) displayed a statistically significant relationship. The acidity associated with these ROW sites tends to influence availability of carbon, manganese, and calcium more than the other elements sampled at the sites. Therefore, results suggest that most soils sampled along the I-16 ROWs can be characterized as slightly acidic sandy soils with low water-holding capacity, a poor soil structure, and having low concentrations of nutrients and minerals required for efficient plant growth (fertility).

Soil organic carbon and soil N contents measured at the top 20 cm of soil were used to determine the carbon to nitrogen (C:N) ratios present at the ROW sites (see table 8). The C:N ratio was used as an indicator of the degree of decomposition and quality of the organic matter held in the soil.

Table 8. Soil organic carbon and soil nitrogen summary for all five ROW studied sites prior to the pilot study.

Mile Marker	*N (kg/m^2)*	*C (kg/m^2)*	*C:N (kg/m^2)*
90	0.64	3.57	5.58
102	0.47	1.69	3.63
108	0.88	4.02	4.55
121	0.67	2.90	4.31
130	0.53	2.16	4.08

When comparing C:N ratios across the ROW sites, mile marker 90 had the highest C:N ratio of 5.6, while mile marker 102 had the lowest C:N ratio of 3.6. The averaged C:N ratios for all sites was 4.75, which suggests that the soil organic matter held under these sites is considerably high in nitrogen, which further suggests that the soils are not nitrogen deficient. High nitrogen concentrations may influence nitrogen uptake by plants, since most microbial activity requires C:N ratios around 24 to function without any type of immobilization or mineralization of available nitrogen occurring in the soils (NRCS 2011). The observed C:N ratios may be attributed to nitrogen leaching from farmlands adjacent to the ROW sampling sites that happen after the construction of these highway areas. Amendment of these ROW soils with fertilizers for biomass feedstock productivity may sometimes be hazardous from an environmental perspective, as inorganic fertilizer usage could result in leaching of plant nutrients due to rain and soil types in the ROW. In addition, depending on the amount of soil being moved, the excavation and placement process may have also imported off-site materials, such as sand and/or gravel, from nearby areas where soils may have been enriched in nitrogen. From an economic perspective, market fluctuations in price may discourage fertilizer application along the ROWs because this practice might not be cost-effective for long-term biomass production. In response to these concerns, the effectiveness of using fertilizers to facilitate successful feedstock production would be evaluated in the pilot study.

CHAPTER 6. PILOT STUDY RESULTS

BIOMASS FEEDSTOCK PRODUCTIVITY ON THE ROW

Evaluating ROW feedstock productivity and the effectiveness of different agronomic treatments on plant establishment and growth was the basis for the experimental design. Therefore, three plant management scenarios controlled by fertilizer application rates were designed to test and compare crop establishment and growth. Fertilizer application was selected as a main variable because this factor, which can be controlled in the field, would have a significant effect on plant establishment and growth.

Table 9. Effects of fertilizer treatment on feedstock properties.

	Fertilizer N Treatment	2017			2018			Energy (kj/g ± SE)
		Yield/acre (tons ± SE)	*Chlorophyll (SPAD ± SE)*	*(NDVI ± SE)*	*Yield/acre (tons ± SE)*	*Chlorophyll (SPAD ± SE)*	*(NDVI ± SE)*	
WS	0 lb N/ac	1.68 ± 0.38	39.75 ± 2.25	0.6 ± 0.02	2.24 ± 0.58	30.04 ± 1.68	0.63 ± 0.01	18.6 ± 0.90
	54 lb N/ac	1.44 ± 0.38	38.24 ± 2.25	0.57 ± 0.02	2.84 ± 0.58	29.82 ± 1.68	0.66 ± 0.01	19.1 ± 0.90
	107 lb N/ac	1.83 ± 0.38	42.13 ± 2.25	0.64 ± 0.02	4 ± 0.58	31.36 ± 1.68	0.65 ± 0.01	20.11 ± 0.90
	df	*p-values*						
	2	0.7745	0.5011	0.1813	0.1532	0.7886	0.1991	0.5069
BB	0 lb N/ac	2.57 ± 1.02	37.57 ± 1.49	0.54 ± 0.02	3.23 ± 1.35	41.79 ± 1.70	0.7 ± 0.01	25.1 ± 1.74
	54 lb N/ac	2.97 ± 1.02	38.51 ± 1.49	0.57 ± 0.02	5.78 ± 1.35	42.29 ± 1.70	0.74 ± 0.01	27.42 ± 1.74
	107 lb N/ac	5.01 ± 1.02	38.16 ± 1.49	0.58 ± 0.02	5.91 ± 1.35	39.43 ± 1.70	0.75 ± 0.01	22.56 ± 1.74
	df	*p-values*						
	2	0.2524	0.904	0.2804	0.3354	0.4769	0.8	0.2052
SW	0 lb N/ac	0.49 ± 0.29	38.03 ± 1.67	0.48 ± 0.03	5.12 ± 0.49	36.71 ± 1.61	0.68 ± 0.01	22.92 ± 1.54
	54 lb N/ac	0.63 ± 0.29	40.21 ± 1.67	0.49 ± 0.03	5.26 ± 0.49	37.16 ± 1.61	0.7 ± 0.01	22.23 ± 1.54
	107 lb N/ac	0.92 ± 0.29	37.98 ± 1.67	0.49 ± 0.03	7.62 ± 0.49	40.65 ± 1.61	0.7 ± 0.01	22.09 ± 1.54
	df	*p-values*						
	2	0.5898	0.5808	0.934	**0.0117**	0.2256	0.1478	0.9528

WS = Woodland Sunflower; BB = Big Bluestem; SW = Switchgrass 'Alamo'; SE = standard error

**Significant differences were observed at the 0.05 probability level (p < 0.05). The significant (p < 0.05) main factor p-values are in bold.*

When evaluating the effect of fertilizer applications on switchgrass productivity in the ROW, results showed that biomass production in the establishment year was not significantly influenced by fertilizers (see table 9). Alternatively, biomass yields from big bluestem had a noticeable increase in year 1 for plots treated with high fertilizer levels and for plots treated with moderate and high fertilizer levels in year 2. Woodland sunflower feedstocks did not have significant responses to N fertilizer treatments in years 1 and 2 (d.f. = 2; p > 0.05), although an increase in biomass was observed for the highest fertilizer level in year 2. When averaging growth yields over all FR treatments for comparison between growing seasons, switchgrass yield recorded in year 1 was 12.6 percent of the second-year yield, harvested yield for big bluestem stands were 70.7 percent of the second-year yield, and woodland sunflower yield recorded in year 1 was 54.5 percent of the second-year yield.

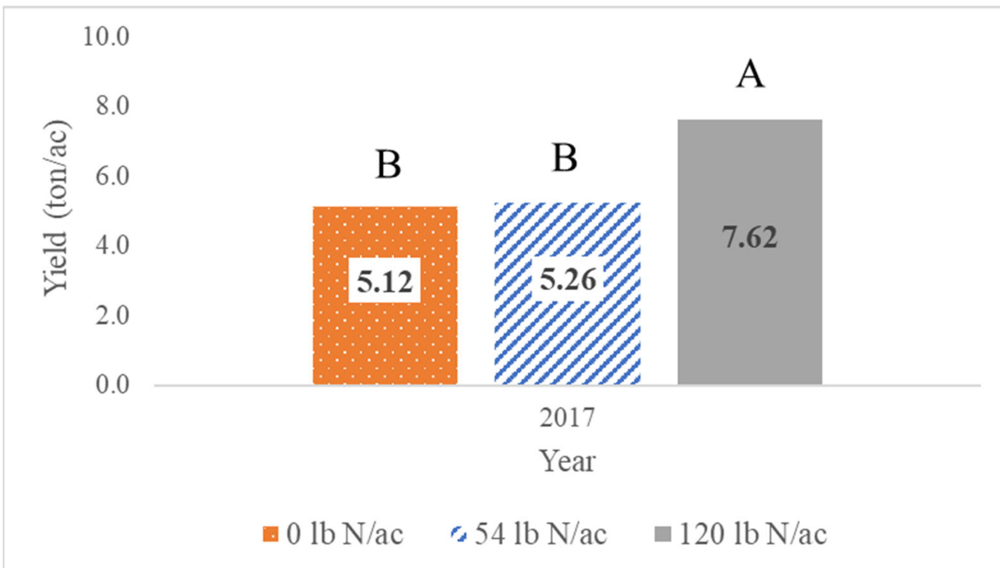
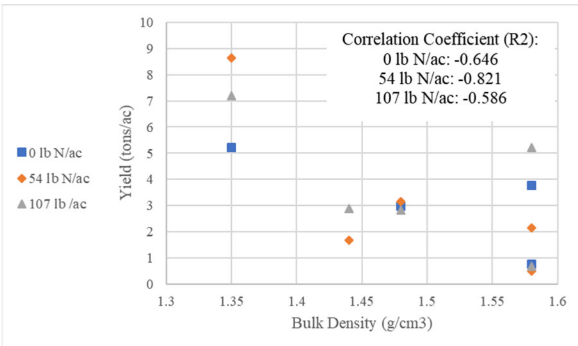


Figure 16. Graph. Switchgrass 'Alamo' mean biomass yield (tons/ac) in response to three fertilizer applications (control [0 lb N/ac], low [54 lb N/ac], and high [107 lb N/ac]). Bars with different letters indicate significant differences at the 0.05 probability level.

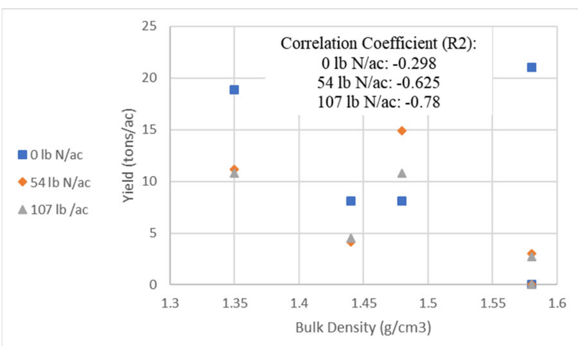
Overall, results showed that the three studied crops were able to establish in the ROW sampling sites, but the biomass yield produced during the establishment year was lower than the biomass yield for the second year. Specifically, these results showed that while all species of feedstock increased in production from the first to the second year, switchgrass biomass gains in year 2 were statistically significant. Using the second year of production, annual yields for switchgrass from year 3 onward are projected to be 8.55, 8.78, and 12.72 tons/acre for each 0, 54, and 107 lb N/ac fertilizer level, respectively. Switchgrass projected yields for un-fertilized plots were slightly higher than reported yields of lowland ecotypes of switchgrass (~ 6 tons/acre annually) in the southern U.S. (Sanderson, 2012). These projected yields were higher than 4.5 tons/acre, which is deemed as sustainable production for switchgrass in the U.S. (McLaughlin et al., 2002). Using the second year of production, annual yields for big bluestem from year 3 onward are projected to be 5.39, 9.66, and 9.87 tons/acre for each 0, 54, and 107 lb N/ac fertilizer treatment, respectively. The projected yields for big bluestem un-fertilized plots were higher than reported yields for the U.S. southern plains, with prior research showing ~ 2 tons/acre of annual production with no fertilizer application (Owsley, 2002).

Bulk density in soils serves as an indicator of soil porosity and compaction. Studies have shown that for sandy soils, a higher bulk density (>1.6 g/cm^3) may stunt root growth and limit root penetration, which can result in limited water and nutrient uptake. Yields from each feedstock grown in the ROW were plotted against soil bulk density values from each site to determine if any relationship existed between soil compaction and biomass productivity for each feedstock (see figure 17). Considering all sample sites, the average bulk density was 1.49 grams/cm^3. During the establishment year, woodland sunflower displayed a low correlation with bulk density, where an increase in bulk density resulted in a moderate decrease in yield ($r = 0.646$). It should be noted that woodland sunflower plots treated with no fertilizers were not affected by bulk density as plots with low and high levels of fertilizer inputs (see figure 17a). Regardless of fertilizer applications, woodland sunflower, big bluestem, and switchgrass stands were not significantly related with bulk density (see figure 17a, b, and c). It is possible that during the establishment year, plants' growth rates were not sufficiently high to be affected by soil density.

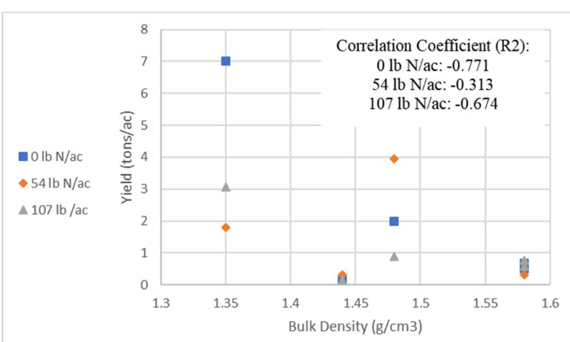
During the second growing season, woodland sunflower stands treated with no fertilizer had a significant negative relationship with bulk density ($r = -0.964$; $p = 0.008$). This phenomenon was also observed for woodland sunflower stands treated with low levels of fertilizer ($r = -0.890$; $p = 0.043$), as illustrated in figure 17d. It should be noted that woodland sunflower plots treated with no fertilizers were influenced more by soil bulk density than plots with low and high levels of fertilizer inputs. For big bluestem plots observed during the second year, stands treated with no fertilizer ($r = -0.881$; $p = 0.049$) and stands treated with high fertilizer ($r = -0.916$; $p = 0.029$) had a significant negative relationship with bulk density (see figure 17e). Switchgrass stands with no fertilizer were influenced by bulk density to the same degree as woodland sunflower and big bluestem stands (see figure 17f). A negative correlation between biomass yield and bulk density means that biomass yield decreased as the compacted soils prevented healthy root development resulting in lower plant growth. Regardless of the level of soil compaction, the three crops were able to establish and grow in the ROW compacted soils.



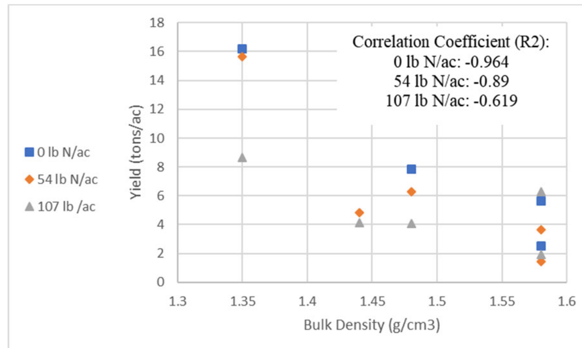
(a)



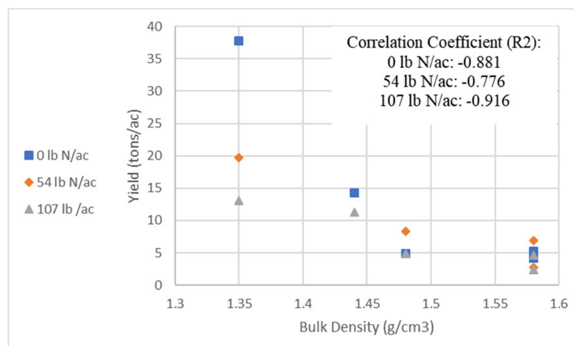
(b)



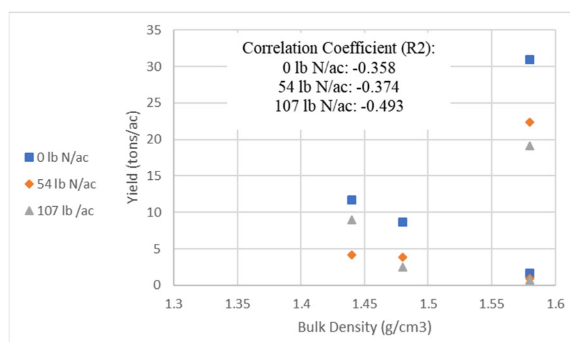
(c)



(d)



(e)



(f)

Figure 17. Graphs. Bivariate correlation plots for 2017 between soil bulk density and: (a) woodland sunflower; (b) big bluestem; (c) switchgrass. Bivariate correlation plots for 2018 between soil bulk density and: (d) woodland sunflower; (e) big bluestem; (f) switchgrass.

EVALUATING STAND DENSITY ON THE ROW

The second objective of the pilot study was to determine the response of stand density (i.e., number of plants grown per subplot) to fertilizer and planting methods. Stand density percentage for plots containing plugs was obtained by dividing the number of observed plants fully developed by the number of intended plants (i.e., 20) in each subplot. For plots with seeds, stand density percentage was obtained by diving the number of developed seedlings by the number of seeds sown in each subplot.

Table 10. Effects of planting method and fertilizer N treatment combinations on stand density percentage.

	Treatments (Planting Method: Fertilizer N)	*2017 Stand Density (% ± S.E)*	*2018 Stand Density (% ± S.E)*
Big Bluestem	Seeded: 0 lb N/ac	0.20 ± 0.06	0.21 ± 0.04
	Seeded: 54 lb N/ac	0.20 ± 0.06	0.24 ± 0.04
	Seeded: 107 lb N/ac	0.16 ± 0.06	0.17 ± 0.04
	Plug: 0 lb N/ac	63 ± 4.22	54 ± 4.09
	Plug: 54 lb N/ac	72 ± 4.22	62 ± 4.09
	Plug: 107 lb N/ac	78 ± 4.22	69 ± 4.09
	Effects: d.f.	*p-values*	
	Planting Method: 1	**0.0001**	**0.0001**
	Fertilizer N: 2	0.7670	0.4685
	Planting Method × Fertilizer N: 2	0.7649	0.4655
Switchgrass 'Alamo'	Seeded: 0 lb N/ac	0.10 ± 0.04	0.22 ± 0.05
	Seeded: 54 lb N/ac	0.07 ± 0.04	0.10 ± 0.05
	Seeded: 107 lb N/ac	0.17 ± 0.04	0.20 ± 0.05
	Plug: 0 lb N/ac	30 ± 4.16	64 ± 4.34
	Plug: 54 lb N/ac	26 ± 4.16	67 ± 4.34
	Plug: 107 lb N/ac	43 ± 4.16	74 ± 4.34
	Effects: d.f.	*p-values*	
	Planting Method: 1	**0.0001**	**0.0001**
	Fertilizer N: 2	0.2560	0.7076
	Planting Method × Fertilizer N: 2	0.2640	0.7080
Woodland Sunflower	Plug: 0 lb N/ac	72 ± 5.29	31 ± 3.96
	Plug: 54 lb N/ac	86 ± 5.29	33 ± 3.96
	Plug: 107 lb N/ac	88 ± 5.29	34 ± 3.96
	Effects: d.f.	*p-values*	
	Planting Method: 1	0.1065	0.8640

Results obtained from plots established with seeds and plugs revealed that the planting method (PM) significantly influenced stand density percentages for all three feedstock species ($P < 0.05$). Stand densities for all feedstocks were not significantly influenced by FR treatments in the 2017 and 2018 growing seasons (see table 10). All feedstocks showed improved stand density with plots grown using plugs regardless of the year of observation. Conversely, results showed that plots established with seeds did not completely germinate as evidenced by the small stand density percentages (< 1 percent). The disparity observed between stand density percentages of plots established using plugs and seeds could be due to factors such as growing conditions, amount of seed used, growing season duration, and harvest timing. Overall, results showed that seeds sown for the selected feedstocks were more sensitive to growing conditions than plugs and that feedstock established with plugs have a higher chance of developing a higher density stand due to having a more established root system at time of planting.

Plots were categorized by poor, fair and good depending on the stand density percentage. Plots with a stand density percentage lower than 33 percent were classified as poor. Plots with stand density percentages between 33 and 66 were classified as fair, and plots with percentages greater than 66 were classified as good. When considering the total number of seed treatment plots across all replications for big bluestem (n=15), it was observed that 100 percent of the plots were considered poor in both years 1 and 2 (see table 11). Conversely, when assessing the total number of plug treatment plots at harvest (n=15), it was determined that 20 percent of the plots would be considered poor, while 80 percent would be considered good in year 1. Plug treatments in year 2 resulted in 55 percent of the plots being considered fair, with 45 percent being considered good. Of seed treatment plots for switchgrass, 100 percent were considered poor in years 1 and 2 (see table 11).

Table 11. Status of treatment plots at harvest (poor, fair, or good).

		2017			***2018***		
	Treatment (N=15):	**Poor**	**Fair**	**Good**	**Poor**	**Fair**	**Good**
Big Bluestem	Seed	15	0	0	15	0	0
	Plug	3	1	11	0	11	4
Switchgrass 'Alamo'	Seed	15	0	0	0	0	15
	Plug	6	8	1	0	8	7
Woodland Sunflower	Plug	0	1	14	13	1	1

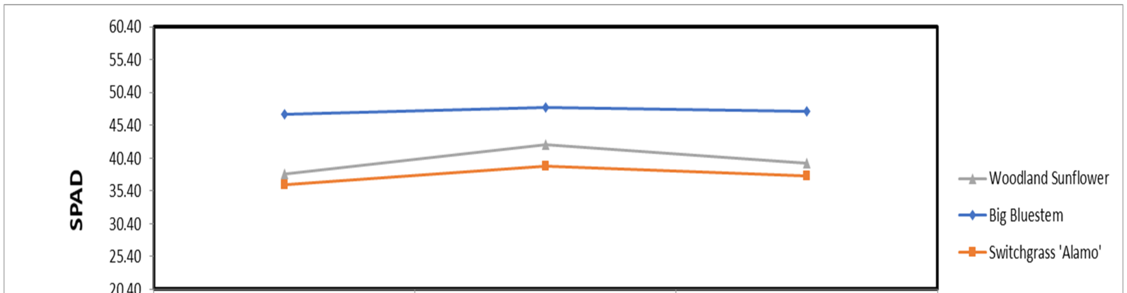
For switchgrass, it was determined that 40 percent were poor, 53 percent were fair, and 7 percent were good. In year 2, 54 percent of plots with plugs were considered fair and 47 percent were considered good (see table 11). These results highlight that plots grown with plugs were able to generate more biomass than plots established with seeds during the period of record.

PLANT QUALITY AND HEALTH EVALUATION USING SPAD AND NDVI

The third objective of the pilot study was to observe plant quality and overall health for the established crops during the two selected seasons and the contribution of N fertilizer treatments to the overall plant health. Results from the plant analysis (SPAD measurements) showed that chlorophyll concentrations of woodland sunflower, switchgrass, and big bluestem were not significantly influenced by FR treatment levels (d.f. = 2; $p > 0.05$). SPAD values over all FR treatments for woodland sunflower plants in 2017 had an average of 36.7, while measurements taken in 2018 had an average of 30.4. For each growing season, woodland sunflower exhibited a 17.2 percent decrease between 2017 and 2018 (see table 9). SPAD values over all FR treatments for big bluestem plants in 2017 had an average of 38.1, while measurements collected during the 2018 season had an average of 41.2. Comparing averages between growing seasons showed that big bluestem exhibited an 8.1 percent increase between 2017 and 2018. SPAD values averaged over all FR treatments for switchgrass in 2017 was 38.7, while in the 2018 season the SPAD value average was 38.2. When comparing these averages between growing seasons, switchgrass exhibited a decrease of 1.47 percent between 2017 and 2018 (see table 9). The SPAD results demonstrate that chlorophyll concentrations and overall leaf quality of the feedstocks were mildly responsive to varying FR treatments. SPAD values for woodland sunflower were 24 percent higher than those reported in research with sunflower feedstocks grown in Georgia (Pfister et al. 2017). Switchgrass SPAD values for plots with no fertilizers were higher than common SPAD values reported in a previous study (Tubeileh et al. 2017). Overall, results indicated that the feedstock leaves were healthy and contained adequate chlorophyll content.

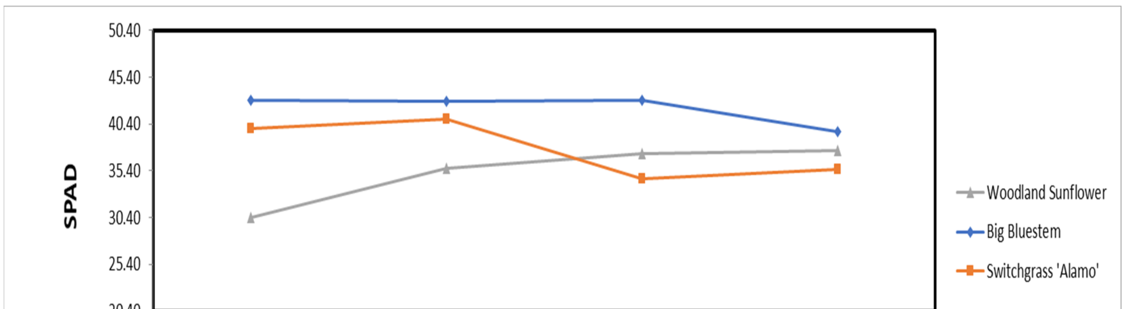
Results from the NDVI analyses showed that canopy health of woodland sunflower, switchgrass and big bluestem feedstocks were not significantly influenced by FR treatment levels (d.f. = 2; $p > 0.05$). The NDVI mean value for all FR treatments for woodland sunflower was 0.6 for 2017 and 0.65 for 2018. In the growing seasons, woodland sunflower exhibited an 8.3 percent increase between 2017 and 2018 (see table 9). The mean NDVI value for all 2017 FR treatments for big bluestem plants was 0.56 and for 2018 it averaged 0.73. When comparing these averages between growing seasons, big bluestem exhibited a 30.4 percent increase between 2017 and 2018. For switchgrass, the mean NDVI values for all 2017 FR treatments was 0.49, and 0.69 for 2018. Between growing seasons, switchgrass exhibited a decrease of 40.8 percent between 2017 and 2018 (see table 9). NDVI results demonstrated that the canopy health of these feedstocks was associated with other variables different from N fertilizer treatments.

When assessing SPAD values temporally over the 2017 season (September–November), it was observed that leaf quality was highest in October before tapering off into November. In most cases, for woodland sunflower, chlorophyll concentrations increased until anthesis (flowering), as woodland sunflower and switchgrass displayed similar SPAD distributions over the 2017 growing season (see figure 18a). Conversely, SPAD distributions for big bluestem appear to deviate from switchgrass and woodland sunflower for 2017. When averaging SPAD values collected over the growing season, big bluestem generated high-quality biomass with an average SPAD of 47.6 over the 2017 season (see figure 18a). SPAD measurements collected over the 2018 growing season highlight increasing chlorophyll concentrations from the onset of the growing season until flowering period for woodland sunflower (see figure 18b). For switchgrass, chlorophyll concentrations fluctuated between July and September with observed minimum and maximum SPAD values of 34.5 to 40.9, respectively (see figure 18b). Alternatively, chlorophyll concentrations for big bluestem appeared consistent between July and September with observed minimum and maximum SPAD values of 39.6 to 42.8, respectively (see figure 18b). Overall, SPAD values for all feedstocks appear more responsive to the 2018 growing season when compared with 2017, as more variability was observed monthly. Overall, these results suggest that plant health improved during the second year once all feedstocks were well established during the second year.



	Sep	Oct	
Woodland Sunflower	37.97	42.47	39.68
Big Bluestem	47.11	48.09	47.60
Switchgrass 'Alamo'	36.35	39.15	37.75

(a)

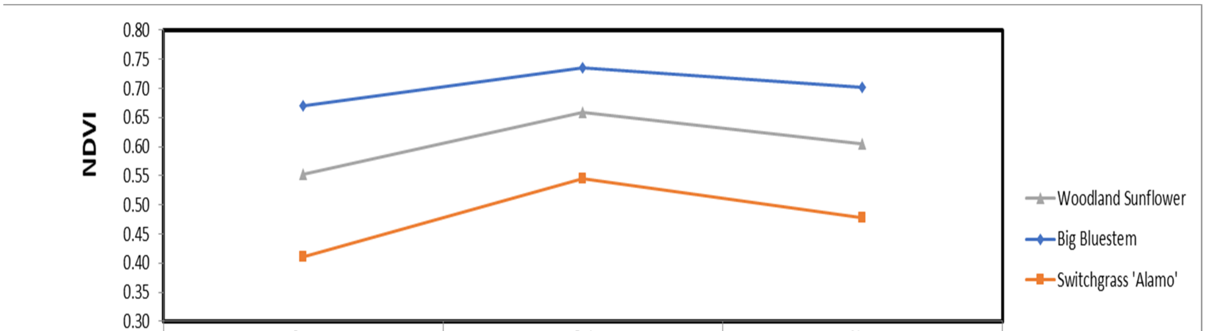


	Jun	Jul	Aug	Sep
Woodland Sunflower	30.40	35.63	37.23	37.54
Big Bluestem	43.00	42.82	42.99	39.57
Switchgrass 'Alamo'	39.90	40.96	34.54	35.58

(b)

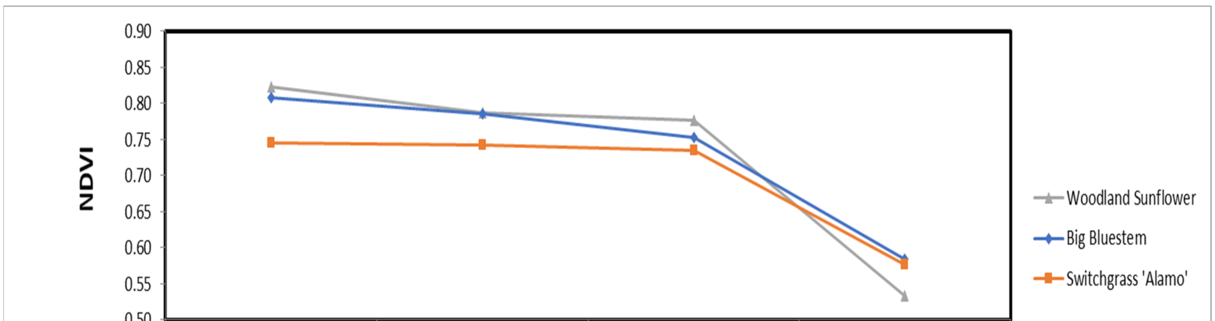
Figure 18. Graphs. SPAD measurements collected on feedstocks for: (a) 2017 (September – November); and (b) 2018 (June – September).

NDVI values from the 2017 season (September–November), showed that canopy quality improved the highest in October for all feedstocks (see figure 199a). In most cases, solar radiation was being absorbed and utilized more effectively by the feedstock canopies in the latter part of the 2017 growing season. When comparing NDVI values between feedstock species, canopy health among feedstocks were somewhat comparable over the growing season. NDVI collected in 2018 displayed a steady decrease from June to August before tapering off considerably in September probably as a result of less radiation during the early fall (see figure 199b).



	Sep	Oct	Nov
Woodland Sunflower	0.55	0.66	0.61
Big Bluestem	0.67	0.74	0.70
Switchgrass 'Alamo'	0.41	0.55	0.48

(a)



	Jun	Jul	Aug	Sep
Woodland Sunflower	0.82	0.79	0.78	0.53
Big Bluestem	0.81	0.79	0.75	0.58
Switchgrass 'Alamo'	0.74	0.74	0.73	0.58

(b)

Figure 19. Graphs. NDVI measurements collected on feedstocks for: (a) 2017 (September – November); and (b) 2018 (June – September).

EVALUATING BIOMASS FEEDSTOCKS USING HEAT OF COMBUSTION

The fourth objective of the pilot study was to assess feedstock energy (calorific value) of switchgrass, big bluestem, and woodland sunflower biomass when combusted. Energy yields results showed that the energy content of woodland sunflower was comparable to that of wood waste material used in pulp and paper mills. For example, the caloric value (energy content) for woodland sunflower was just 3.8 percent lower than that of wood splints and 19 percent lower than coal (Lunguleasa, 2007), suggesting that combustion of dried woodland sunflower material generates power comparable to more established biomass resources (i.e., wood wastes from forestry and industry). For big bluestem, the observed energy content was 4 percent higher than coal (Lunguleasa, 2007). Interestingly, the feedstock energy derived from burning big bluestem was 10 and 23 percent higher than switchgrass, for non-fertilized and low fertilized plots respectively (see table 9).

Results obtained from aggregating energy yield means across all sampling sites for each feedstock, woodland sunflower, big bluestem, and switchgrass revealed that overall energy yields were not significantly influenced by fertilizer levels (see table 9). It should be noted that woodland sunflower energy yields increased with all fertilizer levels with a minimum and maximum energy content of 18.6 and 20.1 kj/g respectively. Big bluestem energy yields increased with fertilizer levels up to 60 kg-N/ha with a minimum and maximum energy content of 25.1 and 27.4 kj/g. Alternatively, switchgrass energy yields slightly decreased with fertilizer levels. Switchgrass provided a minimum and maximum energy content of 22.1 and 22.9 kj/g respectively. These results indicated that higher rates of fertilizer will not result in significant energy gains per mass of feedstock suggesting that the observed energy content of these feedstocks may be related to other factors such as chemical composition. It should be noted that the bioenergy yield of the selected feedstocks depends on the conversion process (i.e., biochemical, thermochemical, or direct combustion) used to obtain energy. For example, in a scenario where direct combustion processes are used for the selected feedstocks, this study concluded that big bluestem would the most attractive feedstock to implement in ROW areas from an energy production standpoint.

BIOMASS FEEDSTOCKS NUTRIENT EFFICIENCY RATIO

The fifth objective of the pilot study was to determine the nutrient efficiency ratio associated with each feedstock to correlate the availability of macro and micronutrients in the soils and their respective plant uptake to identify possible nutrient deficiencies. Results from all FR treatments revealed that woodland sunflower is an efficient nutrient utilizer of soil nitrogen, potassium, and manganese with NER values of 35.04, 14.88, and 12.69, respectively (see table 12). Similar trends were also demonstrated for big bluestem, as the feedstock was also efficient in utilizing N, K, and Mn; NER values were 18.33, 8.21, and 5.39, respectively (see table 12). Switchgrass exhibited high nutrient absorption for soil N with an NER of 14.13, followed by K with an NER of 11.05 and finally Mn with 5.39 (see table 12). For all feedstocks, NERs for phosphorus (P) and iron (Fe) were quite low, suggesting these ROW soils had limited capability of supplying these nutrients for plant growth.

Table 12. Nutrient use efficiencies of feedstocks under different N rates across two years.

	Fertilizer Treatment	*Nutrient Efficiency Ratio (NER)* Nitrogen (N)	*Phosphorus (P)*	*Potassium (K)*	*Iron (Fe)*	*Manganese (Mn)*
Woodland Sunflower	0 lb N/ac	26.42	3.95	14.08	0.28	8.91
	54 lb N/ac	48.64	5.53	13.07	0.71	18.10
	107 lb N/ac	30.06	4.64	17.50	0.38	11.06
	Average					
		35.04	**4.71**	**14.88**	**0.45**	**12.69**
Big Bluestem	0 lb N/ac	13.50	3.24	8.73	0.43	5.64
	54 lb N/ac	15.08	2.25	4.65	0.39	5.00
	107 lb N/ac	26.40	3.22	11.25	0.51	5.54
	Average					
		18.33	**2.90**	**8.21**	**0.44**	**5.39**
Switchgrass 'Alamo'	0 lb N/ac	16.82	3.10	11.99	0.27	5.14
	54 lb N/ac	10.14	3.94	8.84	0.24	5.69
	107 lb N/ac	15.42	2.26	12.32	0.22	5.34
	Average					
		14.13	**3.10**	**11.05**	**0.24**	**5.39**

When analyzing the data for patterns associated with different FR levels, soil N utilization by woodland sunflower increased until FR levels were 54 lb N/ac. With the exception of K, this phenomenon was also observed with all other nutrients (i.e., P, Fe, and Mn). In a similar fashion, soil N utilization by big bluestem also increased with increased FR levels. This trend was not observed for other nutrients (i.e., P, K, Fe, and Mn), as NERs for P and Mn were highest for the control (0 lb N/ac), while NERs for K and Fe were highest with FR levels of 107 lb N/ac. When analyzing the data for patterns associated with different FR levels, soil N utilization by switchgrass was highest without the presence of N fertilizer, as NER values decreased from the control (0 lb N/ac) to low (54 lb N/ac) FR rates. This trend was also observed for K and Fe, as switchgrass appeared to have higher adsorption of these nutrients with no N fertilizer application. P and Mn nutrient utilization by switchgrass increased with FR levels up to 54 lb N/ac before decreasing with the excessive FR rate of 107 lb N/ac. These results suggested that the soils in the

ROW areas selected were N limited, therefore, when N based fertilizers were applied, the feedstock nutrient uptake and subsequent plant growth increased due to the availability of nitrogen.

ENVIRONMENT EFFECTS ON BIOMASS FEEDSTOCKS PRODUCTION

In this study, results showed that switchgrass, big bluestem, and woodland sunflower, apart from switchgrass yields in 2018, did not require high fertilization to adapt to the poorly drained sandy loam soils present in the highway ROW. Therefore, other factors such as weather, soil quality, allelopathy (i.e., plant competition), and weeds could be contributing to differences in yields at improved fertilizer levels, as these factors can influence a plant's ability to properly absorb and utilize nutrients effectively, thereby affecting plant establishment and growth (Balligar et al. 2001).

Weather Factors

From these factors, it is possible that weather (e.g., rainfall, ambient temperature, and solar radiation) is contributing meaningfully to the reduced yield responses to fertilizers for switchgrass and big bluestem stands. The weather data for the ROW sampling sites are presented in table 13 and table 14.

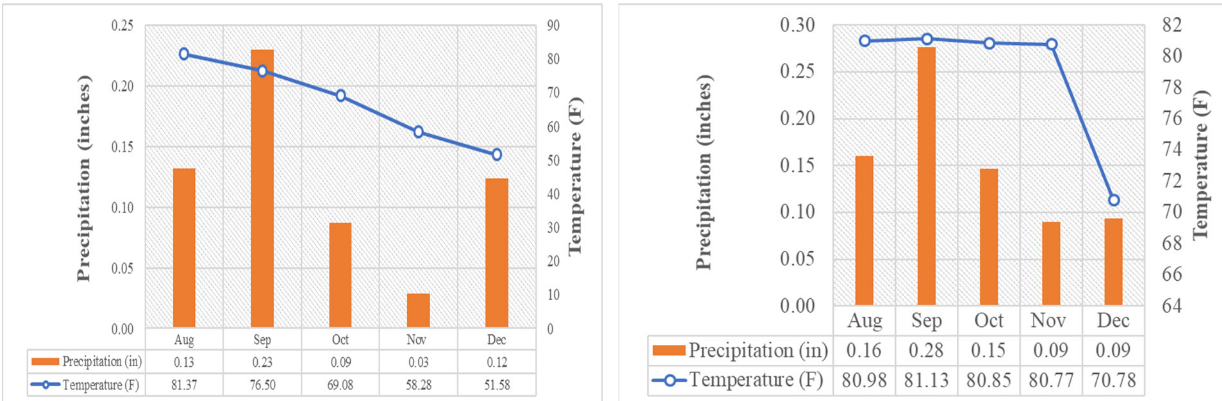
Table 13. Weather data for each pilot study site for the 2017 growing season.

	2017									
	Precipitation (in)					***Temperature (F)***				
Location	August	September	October	November	December	August	September	October	November	December
MM90	0.113	0.233	0.075	0.029	0.123	81.4	76.3	69.1	58.3	51.6
MM102	0.123	0.231	0.082	0.027	0.123	81.4	76.3	69.0	58.3	51.6
MM108	0.128	0.230	0.085	0.026	0.123	81.4	76.4	68.9	58.3	51.6
MM121	0.142	0.228	0.094	0.027	0.123	81.4	76.6	69.0	58.3	51.6
MM130	0.153	0.226	0.100	0.032	0.123	81.4	76.8	69.2	58.3	51.6

Table 14. Weather data for each pilot study site for the 2018 growing season.

	2018									
	Precipitation (in)					***Temperature (F)***				
Location	August	September	October	November	December	August	September	October	November	December
MM90	0.160	0.275	0.147	0.089	0.093	80.687	81.0	80.7	80.8	70.8
MM102	0.160	0.276	0.147	0.090	0.093	80.850	80.9	80.7	80.8	70.8
MM108	0.160	0.276	0.147	0.090	0.093	80.930	81.0	80.8	80.8	70.8
MM121	0.160	0.277	0.147	0.090	0.093	81.142	81.2	80.9	80.8	70.8
MM130	0.160	0.277	0.147	0.090	0.093	81.308	81.5	81.1	80.8	70.8

Collected weather data showed that monthly precipitation levels across the study area were different during August and October, as mile markers 90 and 130 saw 3 percent differences in rainfall. Throughout the 2017 growing season, precipitation levels trended downward during the months of September, October, and November, with a high of 0.23 inches in September and a low of 0.03 inches in November (see table 13). Unlike precipitation, temperature levels during each month of growth were much more homogeneous across the pilot study sites. During the 2018 growing season (see table 14), results show that precipitation levels during the month analyzed were similar across the study area, with precipitation levels being highest in September and lowest in November. Temperature levels for the 2018 season were relatively steady tending up to October before dropping off by 14 percent in November and December. When averaging weather data from all five sites it was apparent that precipitation was seasonally low for the US southeast, with 0.12 inch and 0.15 inch of rain received during the first (see fFigure 20a) and second growing season (see Figure 20b), respectively.



(a) (b)

Figure 20. Graphs. Representative climate graph for all pilot study sites for: (a) 2017 growing season; (b) 2018 growing season.

Precipitation data shows that rainfall distribution was more sporadic in the first growing season, which may have had adverse residual effects on switchgrass, big bluestem, and woodland sunflower canopy development and overall yield. This has been suggested in prior sunflower research in which Patil et al. (2015) showed that yields for sunflower plants grown in low soil moisture and nutrient availability conditions can be quite low. Regarding switchgrass and big bluestem, Sanderson et al. (2012) suggested that rainfall frequencies may be more important than overall amounts received for adequate woodland sunflower root development, while Owsley (2002) stated that big bluestem tends to decrease plant N allocation to shoots and increase allocation to rhizomes during drought conditions. Additionally, it has been shown that irregular distribution of rainfall can adversely affect N utilization by plants (Liu and Wiatrak 2011). Despite of the differences observed during the first year, results show the biomass yields in the ROW appear to be sustainable with low amounts of precipitation throughout the growing season.

Weather-related results further revealed that PM treatments introduced significant responses from switchgrass and big bluestem stand density. This could be attributed to the fact that switchgrass establishment through seed is more susceptible to factors such as inadequate moisture at planting and excessive seed dormancy. Southeastern trials of big bluestem grown in Georgia, produce elevated amounts of dormant seed (Owsley 2002). Furthermore, successful stands of switchgrass using seeds will initially be sparse during establishment and can lead to false conclusions that it was a failure (Hancock 2009). Overall, results showed that that switchgrass and big bluestem were able to establish with the southeast US rainfall patterns regardless of the PM.

The steady decline in NDVI measurements for the second year of observation of switchgrass, big bluestem, and woodland sunflower could be attributed to higher temperatures observed earlier in the growing season (see figure 21), as this reflects more days of full sunlight. NDVI measurements are very sensitive to sunlight availability due to the requirement of the NDVI meter to quantify sunlight reflectance from canopies. This has been supported in previous research by which Davenport et al. (2005) which showed that NDVI measurements need to be taken with full sunlight and are somewhat sensitive to the time of day the measurement is made. Woodland sunflower did not see increased yields in the second year of production and results did not show a high canopy height. It is possible that photosynthetic efficiency influenced NDVI readings, as it has been acknowledged that NDVI tends to increase with canopy height (Liu and Wiatrak 2011).

Nutrient Dynamics and Allopathy

Changes in SPAD values for woodland sunflower in the first and second year of observation were likely due to nutrient dynamics associated with maturation throughout the growing season. This has been acknowledged in prior research, as Mathers and Stewart (1982) reported that nitrogen accumulation in leaves and stems of sunflowers can increase until seed filling (anthesis). This could explain why woodland sunflower experienced a decrease in SPAD, but an increase in NDVI from year one to year two. Changes in NDVI measurements for big bluestem during the second year may be attributed to nutrient dynamics, including a high nutrient utilization of soil N (see table 12), high nitrogen to phosphorus ratio (N:P) (see table 15), and nutrient availability from soil. Big bluestem had an N:P ratio of 4.16 on control (0 lb N/ac) plots, symbolizing limited N adsorption. This is supported by the results from the soil analysis of samples collected from underneath these feedstocks, with an average pH value of 4.8, which reflects acidic soils and low nutrient availability for plants. The difference between the N:P ratios for low (54 lb N/ac) and high (107 lb N/ac) in big bluestem plots reflects the ability of the feedstock to utilize nutrients. Similar results have been observed where Zhang et al. (2015b) noted that big bluestem responds well to N, P, and K fertilizers, which can result in increased canopy quality, and would subsequently increase NDVI.

Table 15. Plant tissue macronutrients (%) in response to fertilizer treatments.

Species	*Fertilizer N Treatment*	*Calcium (Ca)*	*Potassium (K)*	*Magnesium (Mg)*	*Phosphorus (P)*	*Carbon (C)*	*Nitrogen (N)*	*Iron (Fe)*	*Sulfur (S)*
WS	0 lb N/ac	0.95	0.70	0.45	0.20	49.07	1.32	0.01	0.21
	54 lb N/ac	2.59	0.65	0.91	0.28	46.47	2.43	0.04	0.28
	107 lb N/ac	1.53	0.88	0.55	0.23	48.54	1.50	0.02	0.20
BB	0 lb N/ac	0.53	0.44	0.28	0.16	50.72	0.68	0.02	0.16
	54 lb N/ac	0.45	0.23	0.25	0.11	50.75	0.75	0.02	0.14
	107 lb N/ac	0.59	0.56	0.28	0.16	50.10	1.32	0.03	0.19
SW	0 lb N/ac	0.46	0.60	0.26	0.16	50.24	0.84	0.01	0.15
	54 lb N/ac	0.37	0.44	0.28	0.20	50.57	0.51	0.01	0.14
	107 lb N/ac	0.39	0.62	0.27	0.11	50.56	0.77	0.01	0.14

WS = Woodland Sunflower; BB = Big Bluestem; SW = Switchgrass 'Alamo'

The low responses of SPAD and NDVI to N fertilizer treatments for switchgrass and woodland sunflower could be attributed to nutritional dynamics regarding plant nutrient composition, as the N:P ratio for switchgrass was low in comparison to big bluestem and did not display a linear relationship with applied N fertilizer (see table 15). The N:P ratio of woodland sunflower did not increase with N fertilizer applications. The smaller N concentrations associated with switchgrass plant material could be attributed to biomass partioning to other plant components in response to N stresses without the presence of N fertilizer. Nitrogen stress reduces the production of chlorophyll that is involved in the photosynthesis, which can have adverse impacts on SPAD and NDVI readings from treatments without N application (Liu and Wiatrak 2011). Despite crops such as switchgrass and big bluestem having high photosynthetic N-use efficiencies, N supply and plant N composition can have significant influences on leaf area development (Kakani and Reddy 2010). Thus, SPAD and NDVI values for switchgrass were likely affected by biomass partitioning throughout the growing season in response to nutrient dynamics.

Finally, stands that were considered "poor" in this study were likely more susceptible to allopathy from competing vegetation. This is especially true for switchgrass, as it is considered a bunch grass and, until it becomes well established, will not provide substantial ground cover (Griffith et al. 2014). It is inferred that competing in situ plants were able to reduce external nutrient concentrations to lower levels under conditions of nutrient stress. This can be expected for these soils, as roadsides contain few regionally rare species but have relatively high richness of disturbance-tolerant species (i.e., weeds) (Forman and Alexander 1998).

DIFFERENCE IN ENERGY YIELDS

Based on the yield and subsequent energy analysis performed in this study, big bluestem and switchgrass biomass grown and harvested over an acre of ROW with no fertilizer can produce approximately 74,000 and 106,000 MJ of energy, respectively (see table 16). In addition, an acre of woodland sunflower could produce approximately 38,000 MJ of energy from combustion of its dried matter. These results can help GDOT develop criteria for what constitutes adequate ROW acreage (based on the proposed project type) to make a ROW bioenergy project attractive to an end user, such as a biomass processing company and/or a utility company. Poe et al. (2012) noted that Oregon and Ohio DOTs—in coordination with utility companies in their areas—determined that at least 1 MW (3,600 MJ) needs to be produced to make a solar highway project economically feasible. Ohio DOT has concluded that amount requires approximately 5 acres of land.

In terms of ethanol production, which is another option for energy generation, by referencing previous research by Stork et al. (2009) on ethanol production from switchgrass and big bluestem, the research team determined the potential ethanol production from switchgrass and big bluestem on the I-16 ROW of Emanuel, Candler, and Bulloch Counties. Results show the potential biofuel production associated with processing feedstocks grown along the continuous ROW of I-16 (see table 16). Based on the observed yields for this study, projected ethanol yield per acre for big bluestem and switchgrass would be approximately 63,000 gallons per acre of converted biomass. This would offset approximately 5 percent of all ethanol consumed by annual traffic volume in the study area (USDOT, 2019).

It should be noted that energy generation from woodland sunflower, big bluestem, and switchgrass depends on which process is used to extract energy (e.g., biochemical, thermochemical, or direct combustion processes). In a scenario where direct combustion processes (method used in this study) are used for energy extraction, this study shows that big bluestem produced in the ROWs would be the best option from an energy production standpoint.

Table 16. Estimate of bioenergy production in right of way.

	Fertilizer Treatment	Yield (tons/ac)	Energy Production (MJ/ac)	Study Area ROW (ac)	Potential Study Area Production (ton)	Potential Energy Production Study Area (MJ)	Ethanol per ton (gal)	Potential Ethanol from Study Area (gal)
WS	0 lb N/ac	2.24	37796	1976.4	4427.2	74703415	-	-
	54 lb N/ac	2.84	49209	1976.4	5613.1	97259314	-	-
	107 lb N/ac	4.00	72973	1976.4	7905.8	144228656	-	-
BB	0 lb N/ac	3.23	73548	1976.4	6383.9	145363623	19723	125910288
	54 lb N/ac	5.78	143777	1976.4	11423.8	284167747	11021	125910288
	107 lb N/ac	5.91	120954	1976.4	11680.8	239059535	10779	125910288
SW	0 lb N/ac	5.12	106458	1976.4	10119.4	210408882	11932	120750030
	54 lb N/ac	5.26	106076	1976.4	10396.1	209654748	11614	120750030
	107 lb N/ac	7.62	152702	1976.4	15060.5	301807607	8017	120750030

WS = Woodland Sunflower; BB = Big Bluestem; SW = Switchgrass 'Alamo'

ENVIRONMENTAL ASSESSMENT

This section details the environmental impacts of establishing bioenergy feedstocks in the ROW sites.

Stormwater Nutrients

The total organic carbon concentrations were measured in runoff surrounding each feedstock species in all sampling sites. Overall, TOC concentrations in water samples did not exhibit significant spikes when fertilizer was applied (see table 17). In the same way, TN concentrations in runoff surrounding switchgrass and big bluestem were not significantly affected by the application of fertilizer at the proposed rates.

TN concentrations in water samples collected around woodland sunflower were significantly different at low and medium levels of fertilizer; however, concentrations diminished with high levels of N fertilizer (see figure 21). TN concentrations for woodland sunflower were 45 percent lower than TN concentrations in runoff outside the ROW sampling sites. Big bluestem and switchgrass TN concentrations for plots with no fertilizer were 28 and 2 percent higher than TN concentrations in runoff from surrounding ROW areas.

Table 17. Effects of fertilizer treatment on TOC and TN concentrations in runoff from feedstock soils.

	Fertilizer Treatment	*TOC (mg/l ± S.E)*	*TN (mg/l ± S.E)*
Woodland Sunflower	0 lb N/ac	14.14 ± 1.67	4.85 ± 0.87
	54 lb N/ac	17.24 ± 1.67	8.48 ± 0.87
	107 lb N/ac	15.65 ± 1.67	4.44 ± 0.87
	df	*p-values*	
	2	0.4585	**0.0206**
Big Bluestem	0 lb N/ac	18.61 ± 1.85	9.86 ± 1.43
	54 lb N/ac	13.61 ± 1.85	6.58 ± 1.43
	107 lb N/ac	12.61 ± 1.85	6.88 ± 1.43
	df	*p-values*	
	2	0.1048	0.2595
Switchgrass 'Alamo'	0 lb N/ac	14.9 ± 1.74	7.2 ± 1.04
	54 lb N/ac	14.77 ± 1.74	7.19 ± 1.04
	107 lb N/ac	15.53 ± 1.74	7.34 ± 1.04
	df	*p-values*	
	2	0.9478	0.9939

**Significant differences were observed at the 0.05 probability level ($p < 0.05$). The significant ($p < 0.05$) main factor p-values are bolded.*

TOC concentrations for woodland sunflower were 35 percent lower than TOC in runoff from ROW adjacent areas, while TOC from big Bluestem and switchgrass plots with no fertilizer were 2.3 and 27.8 percent lower than TOC in runoff from nearby ROW areas. These results suggest that TOC and TN in runoff near these feedstocks will not be significantly affected by introducing fertilizers at the studied rates. It is possible that these feedstocks have the capacity to quickly assimilate nitrogen as nitrogen in ROW soils is naturally low. These findings show the potential of high-value feedstocks in improving stormwater runoff quality by decreasing nutrient concentrations in surface waters. In short, the selected feedstocks can work as natural filters to remove various pollutants through biochemical processes present in perennial feedstocks and soils in ROWs. These findings can inform highway departments, urban and transportation planners, and developers that excessive nutrients should not be transported downstream as a result of the tilling and fertilizer activities associated with producing biomass feedstocks in the ROW. Using these deep-rooted feedstocks to decrease nutrients and other pollutant that come in contact with these feedstocks presents to GDOT with a low-cost, solar energy–driven cleanup alternative that can be easily replicated along highways in Georgia.

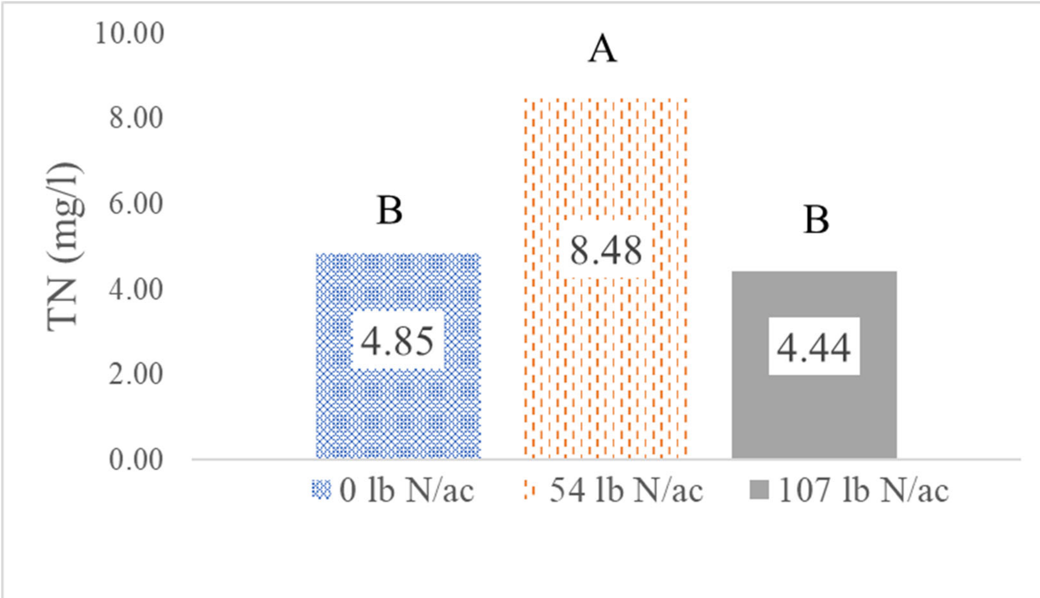
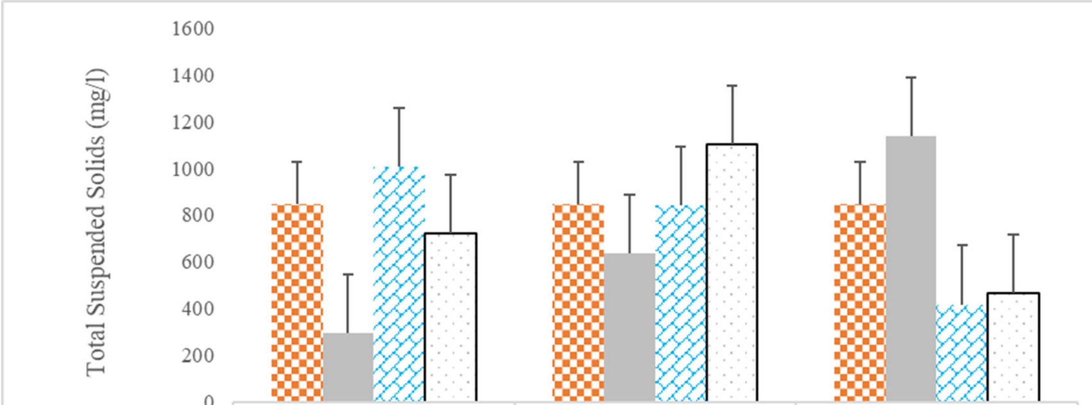


Figure 21. Graph. Mean TN (mg/l) in runoff under woodland sunflower in response to three fertilizer applications (control [0 lb N/ac], low [54 lb N/ac], and high [107 lb N/ac]). Bars with different letters indicate significant differences at the 0.05 probability.

Total Suspended Solids

Total suspended solids were measured in the soils of these feedstock following rainfall events. Results revealed that TSS in runoff from native vegetation was higher than runoff from the perennial feedstocks used in this study (see figure 22). Woodland sunflower, big bluestem, and switchgrass reduced baseline TSS concentrations by 186, 33, and 103 percent, respectively. The observed TSS decreases reflect the filtering capacities associated with the biomass feedstocks planted as a vegetative barrier, which can result in sediment reductions in the ROW. These findings can inform GDOT administrators that excessive sediment will not be transported downstream as a result of the tilling activities associated with establishing the ROW sites for biomass feedstock production. Using the biomass feedstocks as a medium through which stormwater passes in order to remove various waterborne pollutants such as TSS present a low-cost sustainable cleanup technique for GDOT to implement on the highway ROWs. Utilizing these feedstocks on the ROW for filtration of TSS could be a more sustainable and cheaper stormwater best management practice (BMP) option when compared to other BMPs such as detention basins, dry ponds, wet ponds, swales, and constructed wetlands.



	Woodland Sunflower	Big Bluestem	Switchgrass
Native Vegetation	848	848	848
Control	296.67	637.33	1140
Low	1006.67	841.33	417.33
High	720	1101.33	466.67

Figure 22. Graph. Comparison of TSS (mg/L) in runoff from native roadside vegetation against TSS in runoff from woodland sunflower, big bluestem, and switchgrass sampling sites treated with three different fertilizer applications.

Carbon Capture and Storage

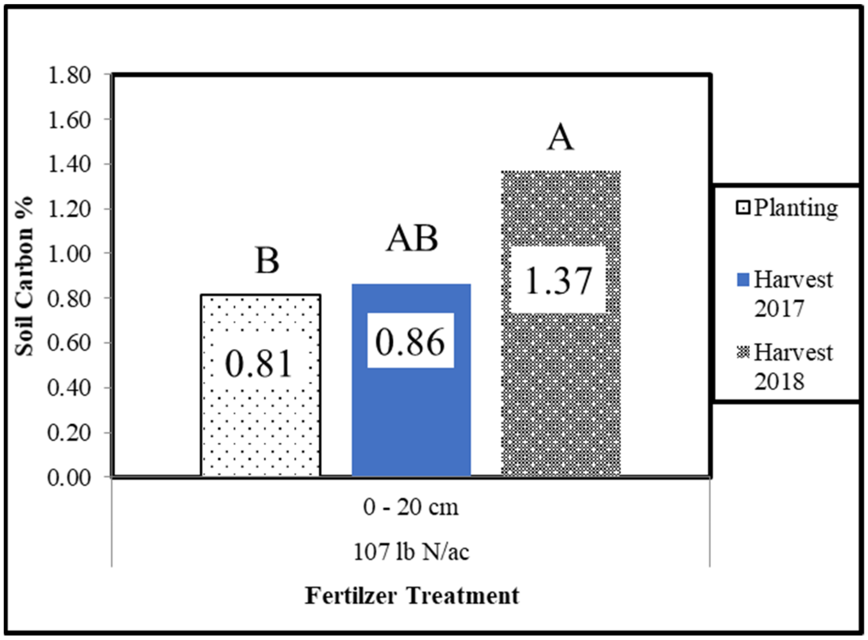
In addition to assessing the capacity of the selected feedstocks to reduce erosion in roadside soils, an assessment was performed on the atmospheric carbon sequestration potential of these feedstocks. The rationale was that these feedstocks have the ability to capture CO_2 from the atmosphere and deposit it as organic carbon in the soils through natural processes. The soil organic carbon percentages from 50-mg soil samples analyzed throughout the project show all feedstocks influenced SOC concentrations with varying degrees of intensity. Woodland sunflower increased initial SOC accounts by 34.3 and 80.3 percent for control (0 lb N/ac) and low (54 lb N/ac) fertilizer treatments, respectively (see table 18). SOC percentages were significantly influenced by woodland sunflower at plots containing high amounts of fertilizer (107 lb N/ac) (see figure 23a). Big bluestem stands established using seed increased initial SOC accounts by 72.2, 11.0, and 68.3 percent for control, and low and high fertilizer treatments, respectively. Big bluestem stands established using plugs increased initial SOC accounts by 77.8 and 38.2 percent for low and high fertilizer treatments, respectively (see table 18). SOC percentages were significantly influenced by big bluestem at plots containing no amounts of fertilizer (see figure 23b). Switchgrass stands established using seed increased initial SOC accounts by 65.1, 42.6, and 59.5 percent for control, and low and high fertilizer treatments, respectively. Switchgrass stands established using plugs increased initial SOC accounts by 75.3, 63.2, and 92.9 percent for control, and low and high fertilizer treatments, respectively.

Table 18. Mean soil organic carbon (%) in soils under feedstock species over two-year period.

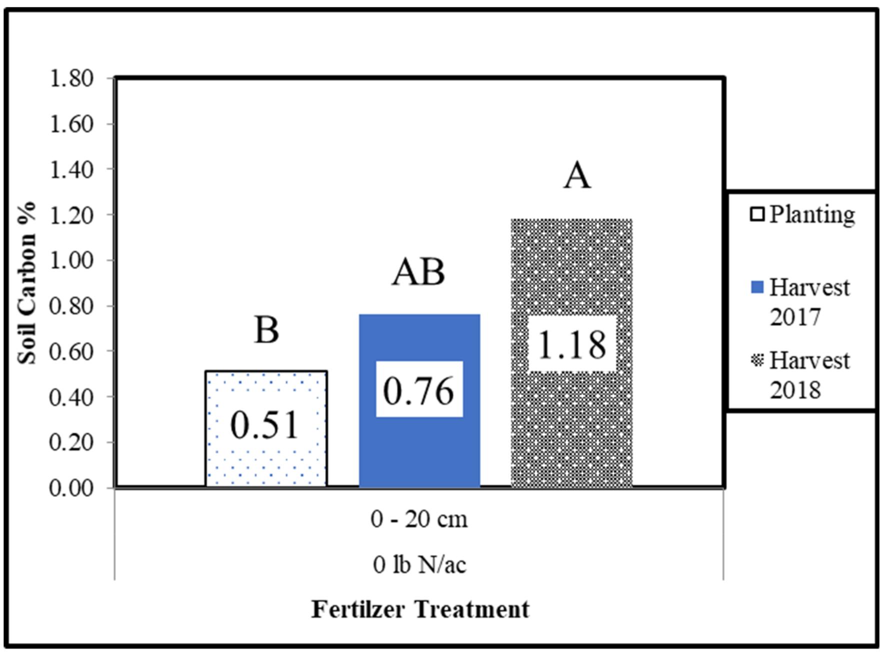
		0 lb N/ac		***54 lb N/ac***		***107 lb N/ac***	
		Seed	***Plug***	***Seed***	***Plug***	***Seed***	***Plug***
	Time	***SOC (% ± S.E)***					
WS	Planting	-	0.7 ± 0.11	-	0.71 ± 0.18	-	0.81 ± 0.15
	Harvest 2017	-	0.78 ± 0.11	-	0.95 ± 0.18	-	0.86 ± 0.15
	Harvest 2018	-	0.94 ± 0.11	-	1.28 ± 0.18	-	1.37 ± 0.15
	df	*p-values*					
	2	-	0.3236	-	0.0973	-	**0.0287**
BB	Planting	0.72 ± 0.17	0.51 ± 0.18	1 ± 0.16	0.72 ± 0.22	0.82 ± 0.19	0.76 ± 0.22
	Harvest 2017	0.81 ± 0.17	0.76 ± 0.18	0.92 ± 0.16	0.78 ± 0.22	0.97 ± 0.19	1.24 ± 0.22
	Harvest 2018	1.24 ± 0.17	1.18 ± 0.18	1.1 ± 0.16	1.28 ± 0.22	1.38 ± 0.19	1.05 ± 0.22
	df	*p-values*					
	2	0.101	**0.0402**	0.7247	0.1754	0.1201	0.3156
SW	Planting	0.63 ± 0.13	0.77 ± 0.24	0.61 ± 0.10	0.57 ± 0.13	0.79 ± 0.20	0.85 ± 0.25
	Harvest 2017	0.75 ± 0.13	0.79 ± 0.24	0.69 ± 0.10	0.76 ± 0.13	0.82 ± 0.20	0.77 ± 0.25
	Harvest 2018	1.04 ± 0.13	1.35 ± 0.24	0.87 ± 0.10	0.93 ± 0.13	1.26 ± 0.20	1.64 ± 0.25
	df	*p-values*					
	2	0.1114	0.1743	0.1697	0.185	0.185	0.383

WS = Woodland Sunflower; BB = Big Bluestem; SW = Switchgrass 'Alamo'

**Significant differences were observed at the 0.05 probability level (p < 0.05). The significant (p < 0.05) main factor p-values are bolded.*



(a)



(b)

Figure 23. Graphs. Two-year period mean soil organic carbon in soils from: (a) woodland sunflower; (b) big bluestem; (c) switchgrass. Bars with different letters indicate significant differences at the 0.05 probability level.

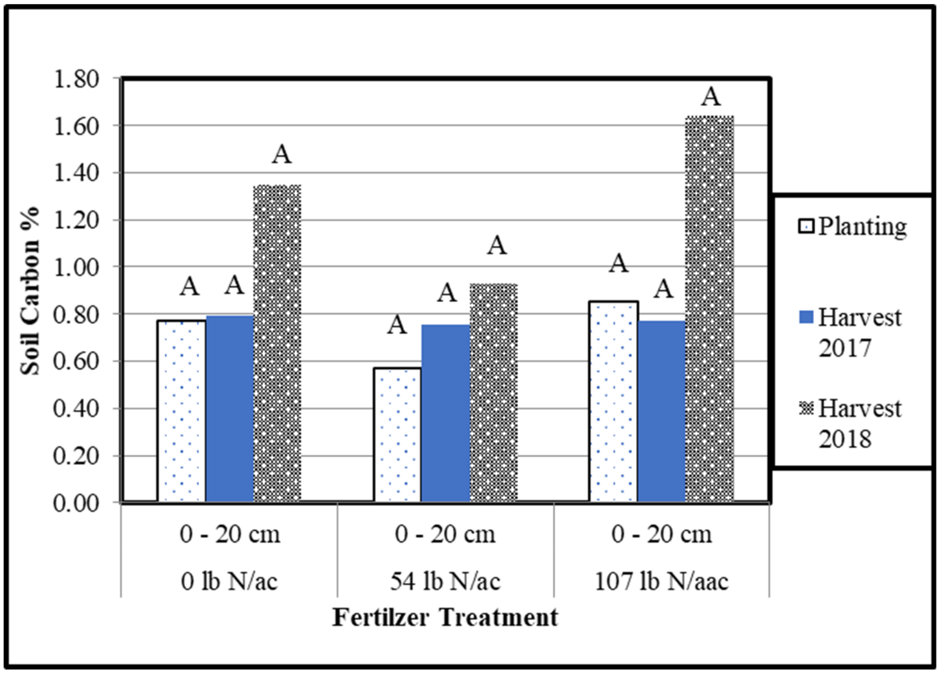
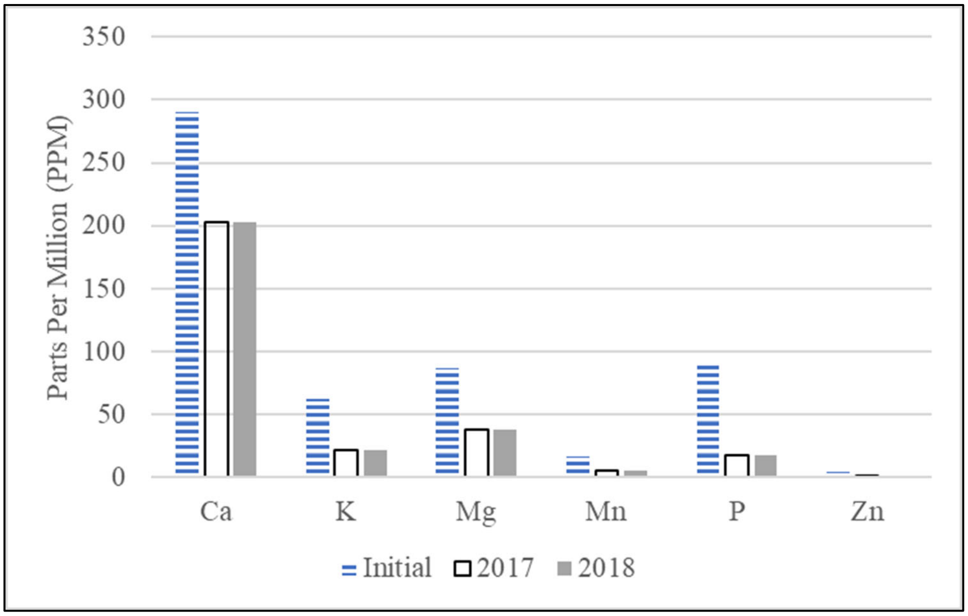


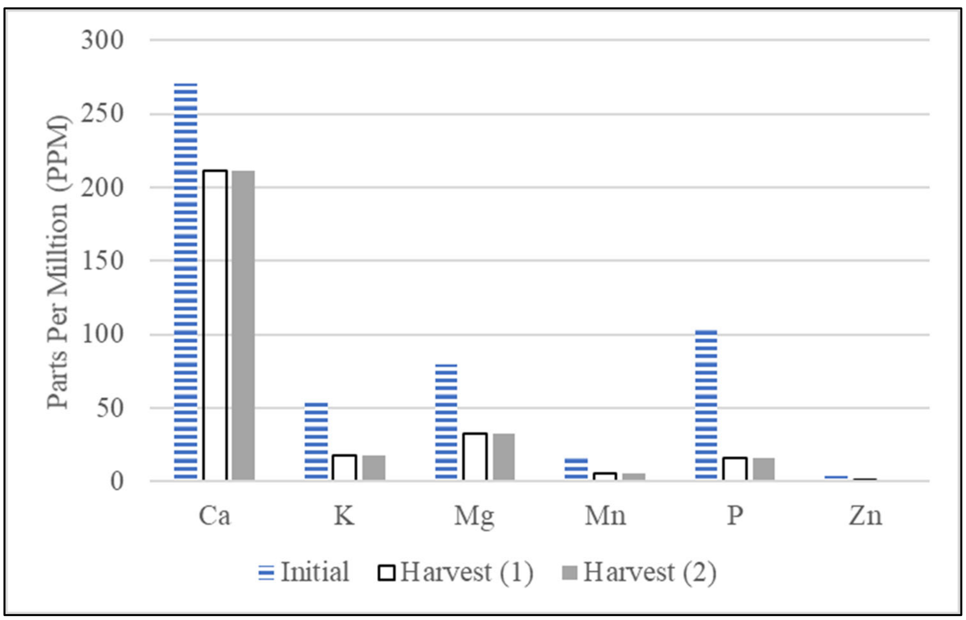
Figure 23. Graphs. Two-year period mean soil organic carbon in soils from: (a) woodland sunflower; (b) big bluestem; (c) switchgrass. Bars with different letters indicate significant differences at the 0.05 probability level. (Continued)

Soil Nutrient Composition

Nutrient concentrations were measured throughout the pilot study by analyzing soil samples collected at the onset of the pilot study. These initial soil samples were compared with additional samples analyzed at the first and second (last) harvest periods. The results showed that biomass feedstocks established along the highway ROW had an impact on soil nutrient compositions over subsequent growing seasons. When comparing soil samples collected over the duration of the pilot study, it was observed that calcium, potassium, magnesium, manganese, phosphorus, and zinc concentrations were depleted over the two-year growing period (see figure 24). Overall, these results suggest that macronutrients such as phosphorus and potassium as well as important micronutrients such as magnesium, manganese and zinc should be replenished through fertilizer application in a period of three years to produce significant amount of biomass in ROW areas.

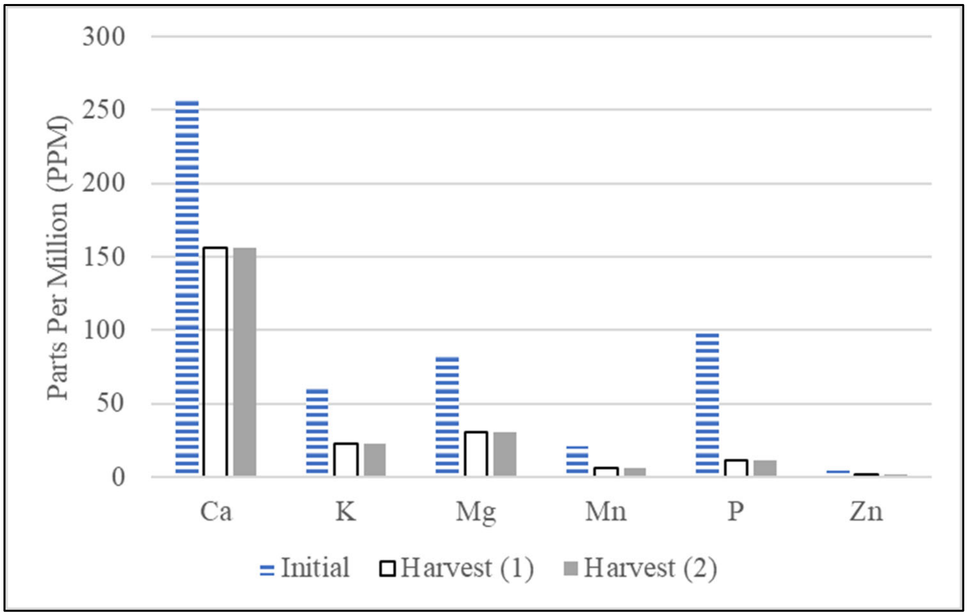


(a)



(b)

Figure 24. Graphs. Nutrient concentrations (Ca, K, Mg, Mn, P, and Zn) in ROW soils throughout the pilot study for: (a) woodland sunflower; (b) big bluestem; (c) switchgrass.



(c)

Figure 24. Graphs. Nutrient concentrations (Ca, K, Mg, Mn, P, and Zn) in ROW soils throughout the pilot study for: (a) woodland sunflower; (b) big bluestem; (c) switchgrass. (Continued)

In general, calcium levels decreased in the pilot study by 43.2, 28.3, and 66.0 percent for woodland sunflower, big bluestem, and switchgrass, respectively. Manganese levels decreased by 129.4, 146.8, and 167.1 percent for woodland sunflower, big bluestem, and switchgrass, respectively. Phosphorus levels were depleted by 405.1, 566.0, and 776.0 percent for woodland sunflower, big bluestem, and switchgrass, respectively. Despite this study being conducted over a two-year period, the results from the soil analyses indicate that feedstocks being produced over longer periods of time (>5 years) will take up some essential elements from the soil through their roots and from the air (primarily nitrogen and oxygen) through their leaves. This was reflected in the soil analysis results, as the biggest drop in nutrient levels was observed between the initial and first harvest period (see figure 24). It appears that some elements will be absorbed by feedstocks in higher concentrations than others, as potassium, manganese, and phosphorus were depleted at higher rates than magnesium, calcium, and zinc. As a result, producers entering a long-term contract (≈10 years) with an end user may want to consider incorporating soil amendments (i.e., fertilizers, legumes, etc.) in between contract periods to improve depleted soils that have been used for ROW feedstock production or consider any current agricultural best management to recycle some of the macro- and micronutrients adsorbed by the bioenergy crops. For instance, a small fraction of the harvested bioenergy crops should be left at each site for nutrient recycling through plant decomposition.

In summary, TSS, TN, and TOC results from the environmental assessment highlighted the environmental benefits of these feedstocks on ROW areas. Sediment concentrations in runoff waters can be reduced through the implementation of these feedstocks. In addition, TN and TOC in runoff will not be significantly altered by establishing these feedstocks on ROW areas. The SOC results from the soil analysis suggested that every feedstock had a positive effect on soil quality by increasing soil organic carbon through photosynthesis. Increases in SOC can improve overall soil quality by decreasing nutrient loss, reducing soil erosion, increasing water conservation, and generating greater biomass feedstock production in subsequent growing seasons as a result of increasing the amount of carbon stored in ROW soils. Woodland sunflower was able to generate significant increases in SOC concentrations at higher levels of N fertilizer. This could be due to larger belowground biomass (root) development due to enhanced nutrient from the fertilizer. Furthermore, the NER results of the feedstock species showed that woodland sunflower is capable of high rates of nutrient acquisition and utilization as evident by the high NERs for nitrogen, phosphorus, and potassium (see table 12).

Big bluestem was also able to generate significant increases in SOC concentrations using no-N fertilizer application. When considering the high root:shoot ratio of 3.23 associated with big bluestem, along with the high NERs (see table 12), it can be concluded that the belowground root system is responsible for storing atmospheric carbon belowground. The ability of big bluestem to sequester CO_2 without the application of fertilizer may be considered as a bonus for ROW biomass production, as it presents an environmental incentive in addition to all its other energy-generation benefits. Switchgrass was also able to produce high concentrations of SOC with no fertilizers during the establishment and second year of observation. This is important as switchgrass grown without fertilizers will be more cost-effective from a management perspective while also mitigating greenhouse gases emitted from vehicular traffic.

VEGETATION TAXONOMY

A vegetation taxonomy study was done to assess if the existing vegetation on the ROW (sampling sites) had any energy production potential. Overall, results showed that the existing vegetation was highly diverse and non-homogenous and did not include any bioenergy crop in significant quantities to be harvested for energy generation purposes. The vegetation taxonomy produced the identification of 55 roadside species along Bulloch, Candler, and Emanuel Counties. Results show that bahiagrass (*Paspalum notatum*) is the most prevalent roadside species, while partridge pea (*Chamaecrista fasciculata*), petiteplant (*Lepuropetalon spathulatum*), Southern dewberry (*Rubus trivialis*), Mexican petunia (*Ruellia simplex*), muscadine (*Vitis rotundifolia Michx.*), and Carolina canarygrass (*Phalaris caroliniana*) represented the smallest percentages (<1 percent) of roadside vegetation (see figure 25). The most prevalent roadside vegetation throughout the study area are presented in table 19.

Results show that I-16 contains relatively diverse roadside plant communities, as evident by the Simpson's diversity index score. Bahiagrass is the most prominent plant along the rights of way of Bulloch, Candler, and Emanuel Counties. While bahiagrass is serviceable as a livestock feed that can provide forage for cattle, purpletop vervain (*Verbena bonariensis*), clasping Venus' looking glass (*Triodanis perfoliata)*, roughfruit scaleseed (*Spermolepis divaricate*), and Italian ryegrass (*Lolium multiflorum*) present no applications of interest and are considered common weeds.

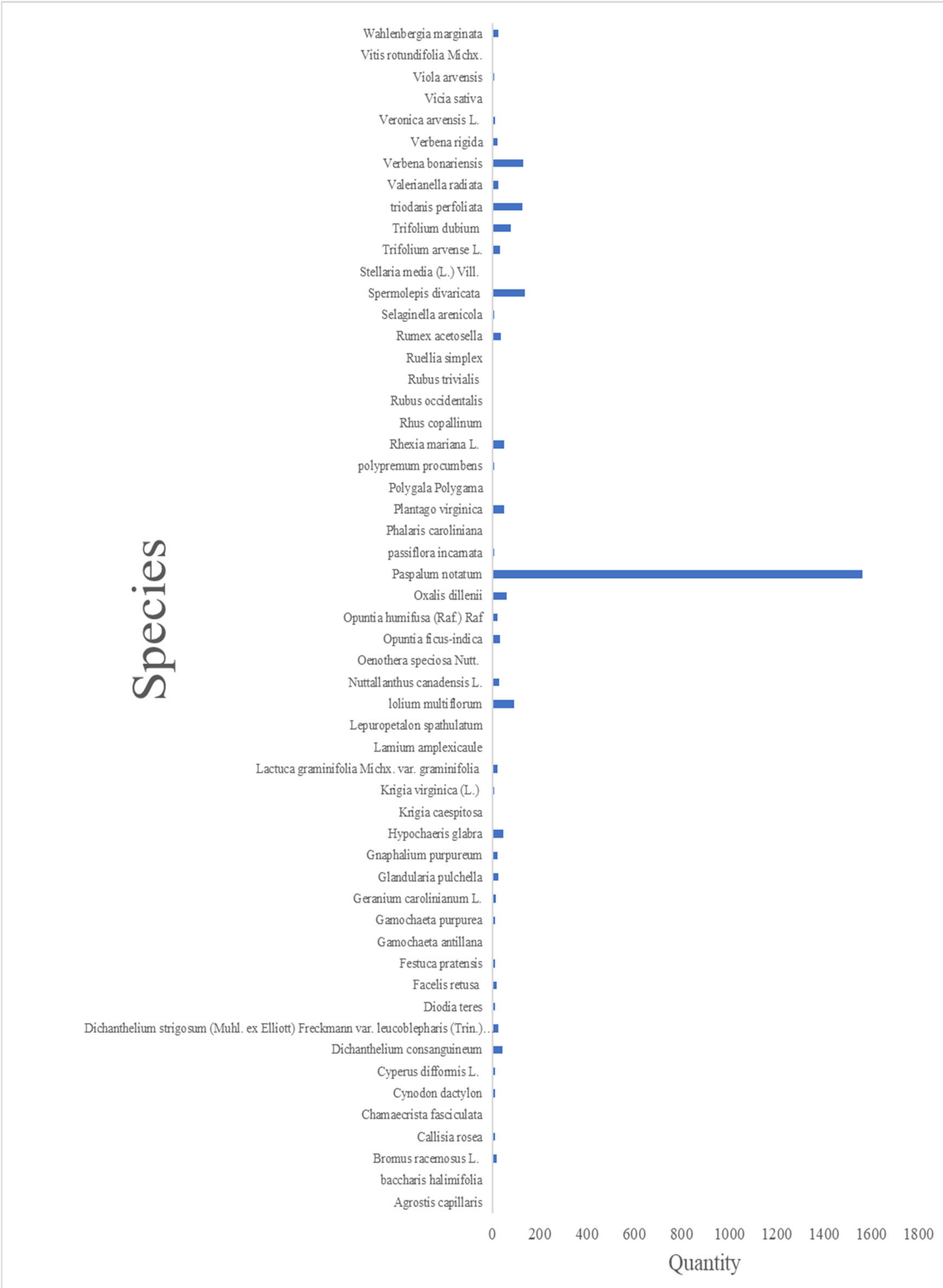


Figure 25. Graph. Vegetation taxonomy of right-of-way sites.

Table 19. Top 10% most abundant right-of-way vegetation: description and applications.

Paspalum notatum

By: Harry Rose

Family: Poaceae
Genus: Paspalum
Common Name: Bahiagrass
Duration: Perennial
Growth Habit: Graminoid
Applications: Erosion control; Turf/Lawn in areas requiring low-maintenance and heavy foot traffic; Use for livestock as a source of hay
Percentage of observed vegetation: 54.2%

Spermolepis divaricata

By: Russ Kleinman & Richard Felger. Apr. 20, 2010

Family: Apiaceae
Genus: Spermolepis
Common Name: Roughfruit scaleseed
Duration: Annual
Growth Habit: Forb/herb
Applications: N/A
Percentage of observed vegetation: 4.75%

Verbena bonariensis

Source: http://flowers3.la.coocan.jp. July 2006

Family: Verbenaceae
Genus: Verbena
Common Name: Purpletop vervain
Duration: Annual/Biennial/Perennial
Growth Habit: Forb/herb
Applications: N/A
Percentage of observed vegetation: 4.47%

Triodanis perfoliata

Source: http://www.missouriplants.com. May 6, 2005

Family: Campanulaceae
Genus: Triodanis
Common Name: Clasping Venus' looking glass
Duration: Annual
Growth Habit: Forb/herb
Applications: N/A
Percentage of observed vegetation: 4.33%

Lolium multiflorum

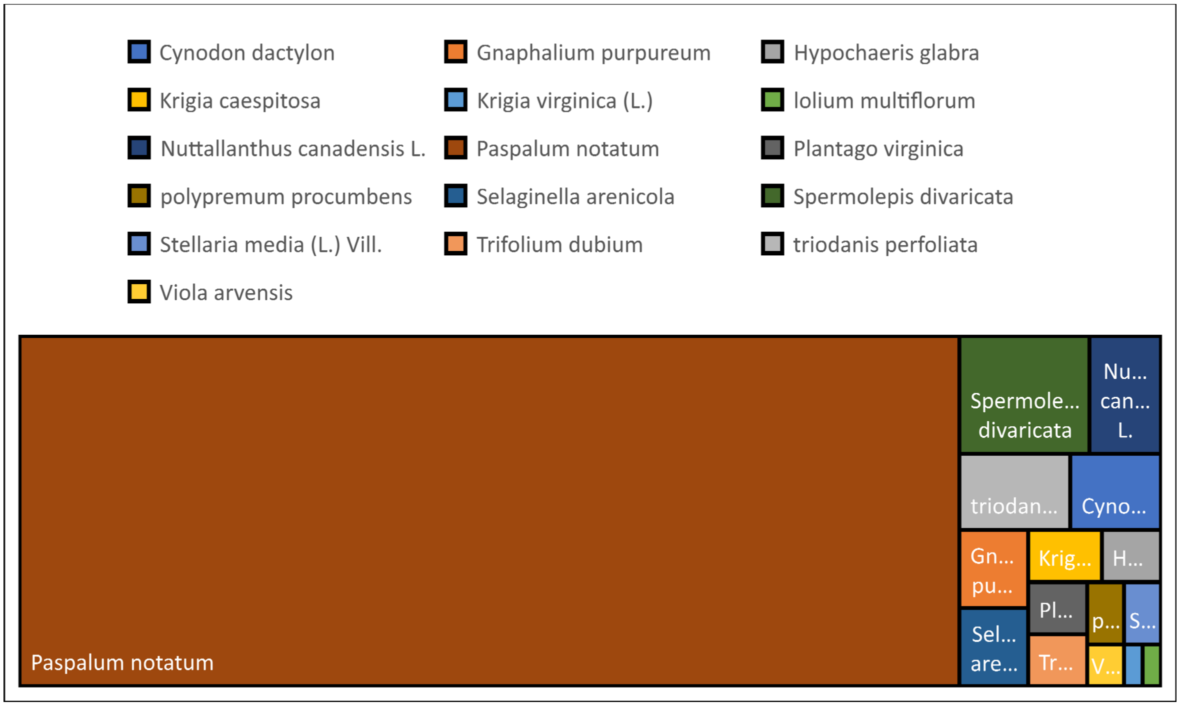
By: Trevor James

Family: Poaceae
Genus: Lolium
Common Name: Italian ryegrass
Duration: Annual/Perennial
Growth Habit: Graminoid
Applications: N/A
Percentage of observed vegetation: 3.19%

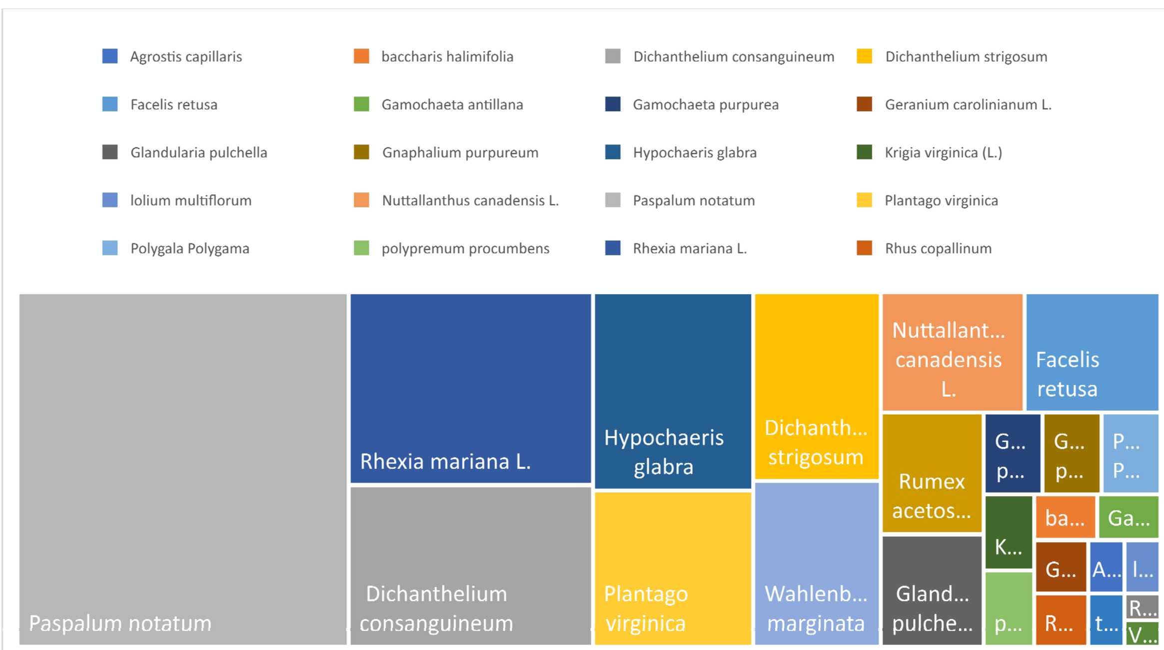
Simpson's Diversity Index

The Simpson's diversity indexes determined for each site were 0.32, 0.87, 0.65, 0.88, and 0.51 for mile makers 90, 102, 108, 121, and 130, respectively. The Simpson's diversity indexes for mile marker 90 suggest that there is a small number of distinct species making up the plant community at the ROW site. Alternatively, the higher diversity indexes reported for mile markers 102, 108, 121, and 130 suggest that the plant communities populating these locations are rich with diverse species present. The observed diversity indexes for these sites could be attributed to factors such as soil type and ROW configuration. Mile marker 90 was the only site position on an interchange configuration. The communities present at this location could be sparse due to the subgrade used to construct the interchange and due to exposure to more pollutants, as the on-ramp flanks this site to the north while the highway flanks it to the south. To further clarify, a visual representation of the plant community distribution at each site is presented in figure .

The treemaps presented above illustrate the distribution of plant communities along the ROW sites. Mile markers 102, 108, and 121 appear to have a more even dispersal of plant species, while the vegetation at mile markers 90 and 130 mostly comprises bahiagrass (*Paspalum notatum*). Most of the identified vegetation along the ROW contained no biomass/bioenergy generation potential, as the specimens collected for this taxonomy comprised weedy vegetation. There were some notable specimens identified in the ROW taxonomy that may present value to the ROW if properly managed. Partridge pea (*Chamaecrista fasciculata*) found at mile maker 108 (figure 26c) has been used as a root medicine to prevent fatigue in athletes. Purple passionflower (*Passiflora incarnata L.*), which populated mile marker 121, has ethnobotany applications, as Native Americans used the poultice root for boils, cuts, earaches, and inflammation.

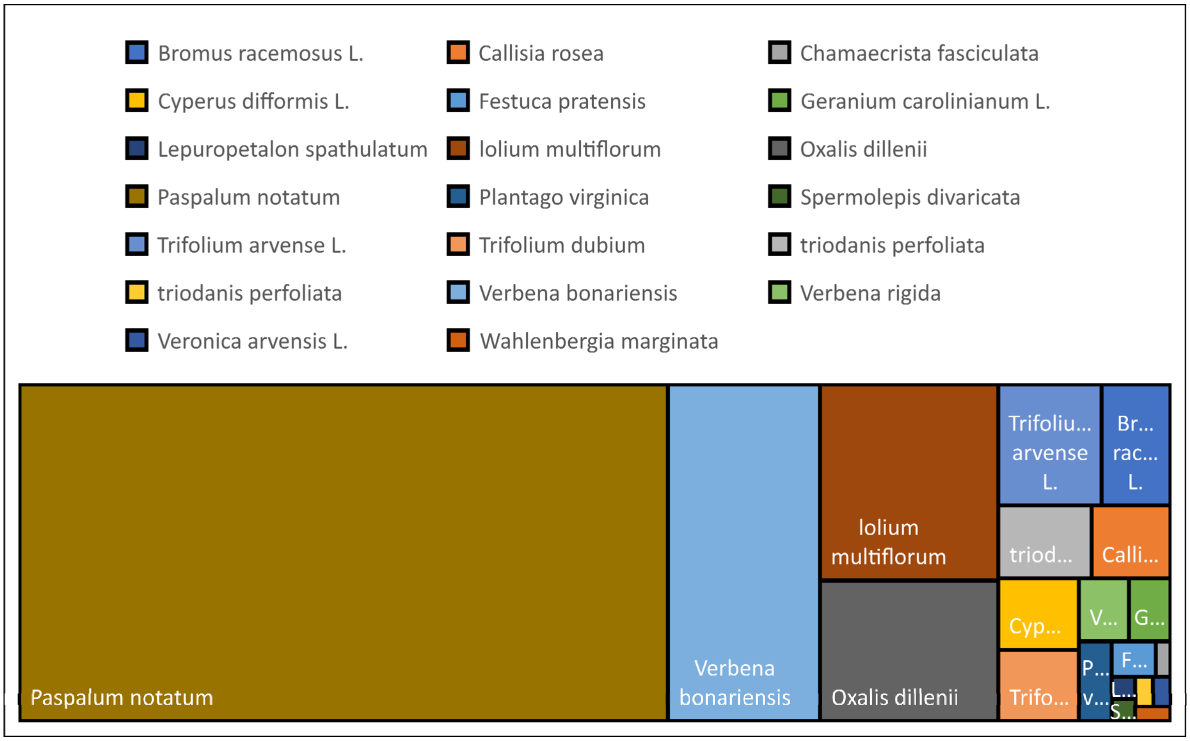


(a)

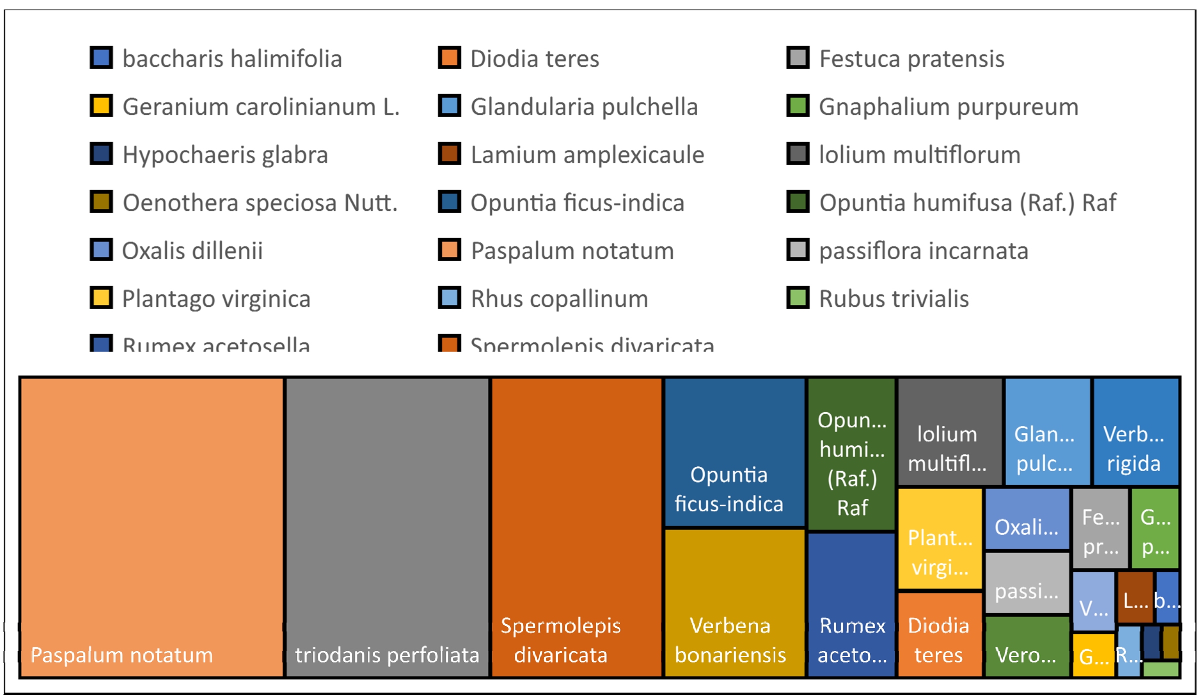


(b)

Figure 26. Diagrams. Treemaps representing distribution of plant communities present at:(a) mile marker 90; (b) mile marker 102; (c) mile marker 108; (d) mile marker 121; (e) mile marker 130.

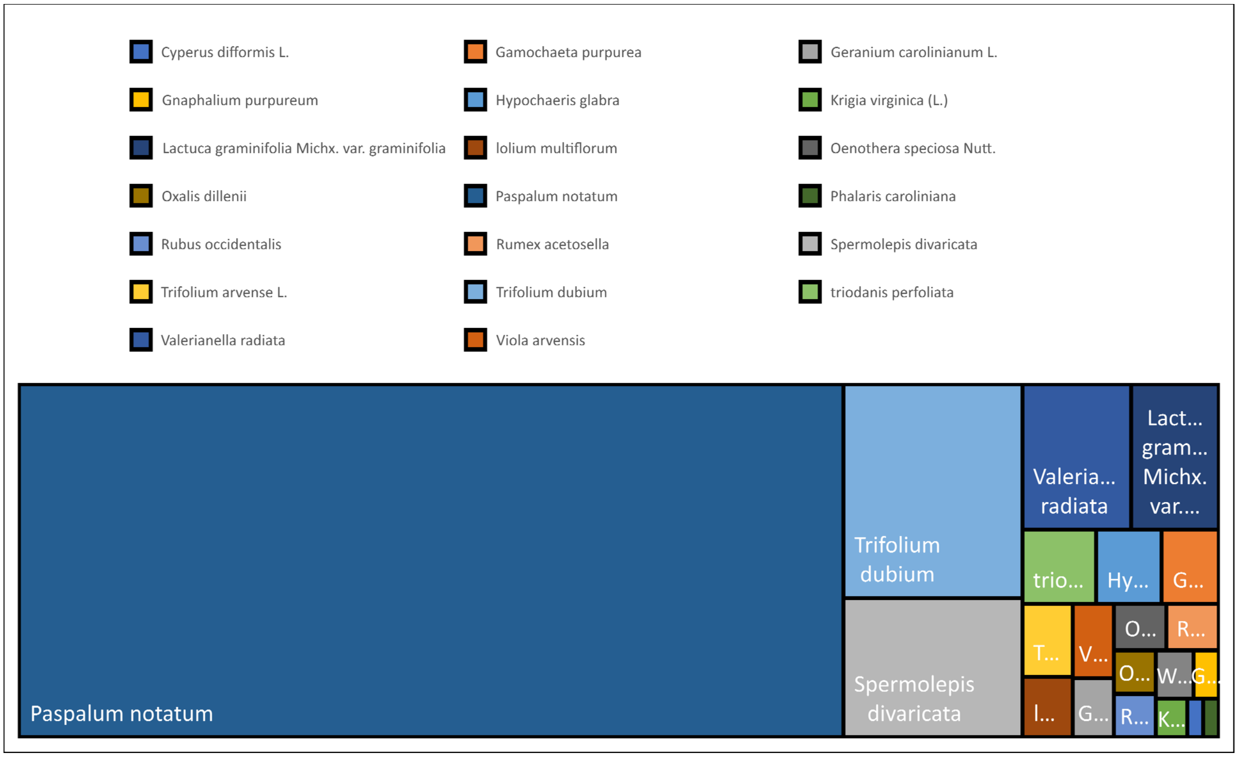


(c)



(d)

Figure 26. Diagrams. Treemaps representing distribution of plant communities present at: (a) mile marker 90; (b) mile marker 102; (c) mile marker 108; (d) mile marker 121; (e) mile marker 130. (Continued)



(e)

Figure 26. Diagrams. Treemaps representing distribution of plant communities present at: (a) mile marker 90; (b) mile marker 102; (c) mile marker 108; (d) mile marker 121; (e) mile marker 130. (Continued)

In addition, the dried leaves boiled with water have been used to treat insomnia (USDA 2008). *Opuntia ficus-indica*, commonly known as the prickly pear cactus, is a drought-resistant plant that also populated mile marker 121 (figure 26d). The plant has drawn interest from researchers due to its potential as a second-generation carbohydrate feedstock, and a recent feasibility study examined using an enzymatic hydrolysate to pretreat the stems prior to fermentation. These results suggest that the highway ROW contains some high-diversity sites that offer modest-value vegetation for GDOT to investigate.

PERFORMING A FEASIBILITY ASSESSMENT ON ROW BIOMASS PRODUCTION

Breakeven Payback Period

Unit production costs for a 10-yr period for big bluestem and switchgrass production were determined for the following cases: (1) seeding with no fertilizer, (2) seeding with 54 lb N/ac fertilizer, (3) seeding with 107 lb N/ac fertilizer, (4) plug installation with no fertilizer, (5) plug installation with 54 lb N/ac fertilizer, and (6) plug installation with 107 lb N/ac fertilizer. For this analysis, individual costs were calculated for establishment, harvest, and transportation so GDOT authorities could see a distribution of the costs associated with the main activities identified in this study. Breakeven payback periods under an assumed 10-year contract for big bluestem planted by sowing seeds ranged from 2.2 years with no fertilizer inputs to 2.7 years with excessive fertilizer inputs (see table 20). When averaging the annualized unit production costs associated with growing big bluestem from seed over all fertilizer input levels, harvest was the largest cost component with 55 percent of the final cost. Transportation represented the next largest cost component with 28 percent. Establishment represented the smallest cost component with 17 percent of the total cost. Breakeven payback periods under an assumed 10-year contract for big bluestem planted by installing plugs ranged from 12.7 years with fertilizer input equivalent to 107 lb N/ac to 20.5 years with no fertilizer inputs (see table 20). When averaging the annualized unit production costs associated with growing big bluestem from plugs over all fertilizer input levels, establishment costs represented the majority (90 percent) of final cost. Harvest was the next largest cost component with 7 percent of the final cost. Transportation represented the smallest cost component with 3 percent of the final cost.

Breakeven payback periods under an assumed 10-year contract for switchgrass planted by sowing seeds ranged from 2.9 years with no fertilizer inputs to 3.6 years with excessive fertilizer inputs (see table 20). When averaging the annualized unit production costs associated with growing switchgrass from seed over all fertilizer input levels, harvest was the largest cost component with 57 percent of the final cost. Transportation represented the next largest cost component with 30 percent. Establishment represented the smallest cost component with 13 percent of total cost. Breakeven payback periods under an assumed 10-year contract for switchgrass planted by installing plugs ranged from 16.1 years with excessive fertilizer inputs to 21.5 years with no fertilizer inputs (see table 20). When averaging the annualized unit production cost associated with growing switchgrass from plugs over all fertilizer input levels, establishment was the largest cost component with 91 percent of the final cost. Harvest represented the next largest cost component with 6 percent. Transportation represented the smallest cost component with 3 percent of the total cost.

Table 20. 10-yr production life span with outdoor storage environment: breakeven payback period for big bluestem and switchgrass grown as a bioenergy crop using seeded and plug methods of installation.

			Annualized Unit Production Cost ---------------------------- $/ac------------------------------				
Species	***Method***	***Fertilizer N Treatment***	***Establishment***	***Harvest***	***Storage***	***Transportation***	***Breakeven Period (years)***
BB	***Seed***	0 lb N/ac	$21.48	$72.66	-	$34.32	2.2
		54 lb N/ac	$32.60	$117.66	-	$61.41	2.62
		107 lb N/ac	$43.52	$119.96	-	$62.79	2.73
	Plug	0 lb N/ac	$1344.94	$72.66	-	$34.32	20.52
		54 lb N/ac	$1356.06	$117.66	-	$61.41	12.86
		107 lb N/ac	$1366.98	$119.96	-	$62.79	12.74
SW	***Seed***	0 lb N/ac	$17.23	$106.01	-	$54.40	2.94
		54 lb N/ac	$28.36	$108.49	-	$55.89	3.08
		107 lb N/ac	$39.28	$150.14	-	$80.96	3.63
	Plug	0 lb N/ac	$1747.00	$106.01	-	$54.40	21.46
		54 lb N/ac	$1758.13	$108.49	-	$55.89	21.11
		107 lb N/ac	$1769.05	$150.14	-	$80.96	16.08

BB = Big Bluestem, SW = Switchgrass

A second alternative was analyzed using the same economic model where the harvested biomass would be stored in an indoor facility near the highway for a given period in the annualized unit production cost as shown in table 21. The assumptions for this scenario involved the use of a 1-acre indoor structure (43,560 ft^2) with an assumed cost of $12 per square foot. In addition, a yearly ownership cost at 12 percent of the storage structure cost was assumed. Table 21 illustrates the same concept as table 20, with the exception of the use of an indoor storage facility, rather than an outdoor storage environment. After accounting for the cost of an indoor storage facility, breakeven payback periods for the production scenario increase by 43 percent overall. Combined, Table 20 and table 21 illustrate the yearly expenses associated with producing ROW feedstocks under different growing scenarios over a 10-year contract period.

Table 21. 10-yr production life span with indoor storage environment: breakeven payback period for big bluestem and switchgrass grown as a bioenergy crop using seeded and plug methods of installation.

			Annualized Unit Production Cost ---------------------------------- *$/ha* ----------------------------------				
Species	***Method***	***Fertilizer***	***Establishment***	***Harvest***	***Storage***	***Transportation***	***Breakeven Period (years)***
BB	**Seeded**	0 lb N/ac	$21.48	$72.66	$164.04	$34.32	4.12
		54 lb N/ac	$32.60	$117.66	$293.55	$61.41	4.54
		107 lb N/ac	$43.52	$119.96	$300.15	$62.79	4.64
	Plug	0 lb N/ac	$1344.94	$72.66	$164.04	$34.32	22.43
		54 lb N/ac	$1356.06	$117.66	$293.55	$61.41	14.77
		107 lb N/ac	$1366.98	$119.96	$300.15	$62.79	14.65
SW	**Seeded**	0 lb N/ac	$17.23	$106.01	$260.03	$54.40	5.28
		54 lb N/ac	$28.36	$108.49	$267.14	$55.89	5.43
		107 lb N/ac	$39.28	$150.14	$386.99	$80.96	5.98
	Plug	0 lb N/ac	$1747.00	$106.01	$260.03	$54.40	23.8
		54 lb N/ac	$1758.13	$108.49	$267.14	$55.89	23.45
		107 lb N/ac	$1769.05	$150.14	$386.99	$80.96	18.42

BB = Big Bluestem, SW = Switchgrass

Table 22 illustrates an example of the calculation metrics listed in chapter 4 (Calculation Metrics for Model) to generate the enterprise budget for establishing switchgrass using seed and high inputs of fertilizer. Table 22 shows that total cash expenses for year 1 will be $243 followed by $397 for year 2 and $524 per acre from year 3 onward. The revenue stream from delivering switchgrass to an end user during consecutive growing seasons is $640 for year 2, followed by $1,069 from the third year onward. With an assumed market value of $84 per ton of biomass, the profits associated with producing switchgrass over a 10-year period are shown to be $244/ac of harvested biomass in year 2, followed by $545 from the third year of production onward. Using the developed economic model, the same type of analysis can be done using different production scenarios including different feedstocks, market values, investment costs, operational costs, etc. The computational model used for this analysis will be given to GDOT as part of the final deliverables.

Table 22. Enterprise budget example for Switchgrass grown with seed using high amounts of fertilizer.

Enterprise Budget - Seed		QTY	Unit	Price /Unit	Yr 1 (Establishment)	Yr 2	Yr 3	Yr 4-10	Total	Present value[1]
SELECT CASH EXPENSES										
Plant Material										
	Seed	6	lbs PLS/acre	$ 14.00	$84.00	$0	$0	$0	$84	$84
Soil Fertility										
	Nitrogen	314.71	lb/expected ton per acre	$ 0.47	$148	$0.00	$0.00	$0.00	$147.91	$148
	P_2O_5	0.00	lb/expected ton per acre	$ -	$0	$0.00	$0.00	$0.00	$0.00	$0
	K_2O	0.00	lb/expected ton per acre	$ -	$0	$0.00	$0.00	$0.00	$0.00	$0
Weed Control										
	Spray (Bcast/HB) 13' Rigid	1	acre	$ 5.63	$5.63	$0.00	$0.00	$0.00	$5.63	$6
Establishment & Maintenance										
	Disk Harrow 14'	1	acre	$ 5.40	$5	$0	$0	$0	$5.40	$5.40
Harvesting										
	Mowing/conditioning	1	acre	$ 125.15	$0	$125	$125	$125	$1,001.17	$780.21
	Staging	1	acre	$ 24.99	$0	$190	$318	$318	$2,416.41	$1,862.08
Storage										
	Outdoor Storage	1.00	acre	$ -	$0	$0	$0	$0	$0.00	$0
Transportation										
	Delivery to biorefinary	1.00	acre	$ 80.96	$0	$81	$81	$81	$647.70	$504.76
TOTAL CASH EXPENSES					$243	$397	$524	$524	$4,308	$3,389.99
REVENUES										
Biomass	Mature yield (estimation)	12.73	dry ton/acre		0.92	7.62	12.73	12.73		
	Revenue Stream			$ 84.00	$0	$640	$1,069	$1,069	$8,122.62	$6,259.25
REV ABOVE EXPENSES					-$243	$244	$545	$545	$3,814	**$3,841.59**
				EQUAL ANNUAL REVENUE (Annualized over 10 years)						$932.81
				BREAK EVEN PAYBACK PERIOD[2]						**3.63**

Sensitivity Analysis

A sensitivity analysis was performed on the breakeven payback period for growing switchgrass and big bluestem feedstocks under a 10-yr contract. The sensitivity analysis was implemented to measure the impacts of fluctuations in parameters related to management conditions on the feasibility or breakeven payback period of producing bioenergy crops in the ROW. Parameters used for the sensitivity analysis included cost of plug (seedling), seed, fertilizer, and market value of delivered biomass. The breakeven payback associated with using fertilizer inputs of 54 lb N/ac to establish feedstock production would be the baseline for the sensitivity analysis, as this level of input represents a realistic amount for perennial feedstocks being managed for bioenergy purposes, should fertilizers be used during establishment (year 1) (Rinehart 2006). When evaluating the results of the sensitivity analysis on production breakeven periods for switchgrass grown using plugs, a 25 percent decrease in plug prices would decrease the breakeven payback period by nearly 20 percent below the base scenario (see table 23). Conversely, a 25 percent increase in plug prices would increase the breakeven payback period nearly 20 percent. A decrease in price for N fertilizer to $0.24/lb would reduce the breakeven payback period by just 0.26 percent, while an increase in N fertilizer price to $0.71/lb would inflate the breakeven payback period by only 0.26 percent. When evaluating the results of the sensitivity analysis on production breakeven periods when switchgrass is grown using seeds, variability in seed price does not appear to significantly alter breakeven payback periods, as a 25 percent decrease for switchgrass seed prices would only decrease the breakeven payback period by 0.74 percent, while an increase in seed price of 25 percent would result in a 0.55 percent increase over the base scenario (see table 23). A decrease in price for N fertilizer to \$0.24/lb would reduce the breakeven payback period by just 1.1 percent, while an increase in N fertilizer price to \$0.71/lb would inflate the breakeven payback period by only 1.1 percent. Regardless of the use of plugs or seeds for switchgrass establishment, uncertainty in the market value for switchgrass appears to have a big impact on the feasibility of production. A 25 percent decrease in market value would prolong the time in which producers can expect a net income of zero by 33 percent. Alternatively, a 25 percent increase in the market value for switchgrass would diminish the breakeven payback period by 20 percent below the base scenario.

According to the results of the sensitivity analysis on production breakeven periods, when big bluestem is grown using plugs, a 25 percent decrease in plug prices would decrease the breakeven payback period by nearly 18 percent below the base scenario (see table 23). Conversely, a 25 percent increase in plug prices would increase the breakeven payback period nearly 18 percent. A decrease in price for N fertilizer to \$0.24/lb would reduce the breakeven payback period by just 0.27 percent, while an increase in N fertilizer price to \$0.71/lb would inflate the breakeven payback period by only 0.34 percent. For production breakeven periods when big bluestem is grown using seeds, variability in seed price does not appear to significantly alter breakeven payback periods, as a 25 percent decrease for big bluestem seed prices would only decrease the breakeven payback period by 0.88 percent, while an increase in seed price of 25 percent would result in a 0.66 percent increase over the base scenario (see table 23). A decrease in price for N fertilizer to \$0.24/lb would reduce the breakeven payback period by just 1.1 percent, while an increase in N fertilizer price to \$0.71/lb would inflate the breakeven payback period by only 0.88 percent. Fluctuations in the market value for big bluestem can have a considerable impact on the feasibility of production, as a 25 percent decrease in market value would prolong the breakeven payback period by 33 percent. Conversely, a 25 percent increase in the market value for big bluestem would diminish the breakeven payback period by 20 percent below the base scenario.

Table 23. Sensitivity analysis of 10-yr breakeven payback period for switchgrass (SW) and big bluestem (BB) grown as a bioenergy crop using a fertilizer rate of 54 lb N/ac in year 1.

Species	*Scenario*	*Breakeven Payback Period (years)*	*Change from Base Scenario* (%)*
SW	Change in plug price from $1.30/plug		
	25% decrease	17.02	−19.36%
	25% increase	25.20	19.36%
	Change in seed price from $14/lb PLS		
	25% decrease	3.06	−0.74%
	25% increase	3.10	0.55%
	Change in N price from $0.47/lb for plug treatment		
	50% decrease	21.06	−0.26%
	50% increase	21.16	0.26%
	Change in N price from $0.47/lb for seed treatment		
	50% decrease	3.05	−1.10%
	50% increase	3.11	1.10%
	Change in biomass price from $84/ton for plug treatment		
	25% decrease	28.15	33.35%
	25% increase	16.89	−20.00%
	Change in biomass price from $84/ton for seed treatment		
	25% decrease	4.11	33.33%
	25% increase	2.46	−20.07%
BB	Change in plug price from $1.00/plug		
	25% decrease	10.60	−17.54%
	25% increase	15.12	17.54%
	Change in seed price from $12.5/lb PLS		
	25% decrease	2.60	−0.88%
	25% increase	2.64	0.66%
	Change in N price from $0.47/lb for plug treatment		
	50% decrease	12.83	−0.27%
	50% increase	12.90	0.34%
	Change in N price from $0.47/lb for seed treatment		
	50% decrease	2.59	−1.10%
	50% increase	2.64	0.88%
	Change in biomass price from $103/ton for plug treatment		
	25% decrease	17.15	33.38%
	25% increase	10.29	−19.97%
	Change in biomass price from $103/ton for seed treatment		
	25% decrease	3.49	33.26%
	25% increase	2.09	−20.04%

** Baseline breakeven payback periods for SW produced from seed and plug was 3.08 and 21.11 years, respectively*
** Baseline breakeven payback periods for BB produced from seed and plug was 2.62 and 12.86 years, respectively*

The results of the economic assessment highlight that fertilizer price fluctuations have a negligible effect on breakeven payback periods when using plugs for switchgrass and big bluestem establishment. Conversely, costs associated with fertilizer applications will have a bigger impact on expected breakeven payback periods for these feedstocks when seeds have been used. This is relevant when considering fertilizer prices increase with fertilizer rate. With the knowledge that production costs can increase with improved yield, fertilizer has been associated with successful biomass feedstock production. This was shown by Haque, Epplin, and Taliaferro (2009) who found that switchgrass yields increased with FR levels up to 54 lb N/ac when averaged over 3 years of harvest, and by Kering et al. (2011) who observed increasing switchgrass yields up to N fertilizer rates of 110 lb N/ac. Furthermore, Zhang et al. (2015a) highlighted that big bluestem yields can be responsive to N fertilizer rates up to 135 lb N/ac. While the breakeven payback period depends not only on the price of N fertilizer inputs, this analysis highlights a substantial impact on breakeven payback periods using different planting methods as well. It was observed that uncertainty in market value for switchgrass and big bluestem had a considerable influence on feasibility of production. Despite making significant strides in developing native warm-season grasses such as switchgrass and big bluestem for biomass, a reliable market has not been established in the southeastern United States. In the scenario where a bioenergy market is established, demand for these feedstocks for biofuels will likely fluctuate with the world energy prices (Christopher et al. 2015).

CHAPTER 7. CONCLUSIONS

There are many acres of highway right of way that could be used to grow bioenergy crops. Continuous bioenergy crop production along the highway ROWs will be challenging due to some areas having limited parcel size. Some areas of highway ROW have poor nutrient compositions due to the pH levels associated with the soils. In addition, highway ROW soils for this study were classified as some variant of sand, resulting in low water-holding capacity, poor soil structure, and lack of chemical properties (fertility). Most of these limitations can be mitigated or reduced with proper management. Most of the identified current vegetation along the ROW contain no biomass potential as the specimens collected for this taxonomy comprised weedy vegetation. There were some notable specimens identified in the ROW taxonomy that may present value to the ROW if properly managed.

In field and laboratory research conducted over this two-year study, results showed that switchgrass, big bluestem, and woodland sunflower adapted well to the poorly drained sandy soils present throughout the highway ROW. However, it was shown that a limiting factor of the biomass plots was compaction, as feedstock productivity decreased with bulk density increases. This study shows that the depth of seed placement and the level of soil compaction is critical to feedstock establishment and growth. The use of fertilizers for agronomic management of switchgrass (*Panicum virgatum L.* 'Alamo'), big bluestem (*Andropogon gerardii*), and woodland sunflower (*Helianthus divaricatus*) being grown on the ROW produced different results depending on the feedstock. Fertilizer treatments did not produce significant yield increases for big bluestem and woodland sunflower. However, switchgrass did see significant yield increases up to 7.6 tons/ac from high levels of fertilizer. Overall biomass production increased for all feedstocks upon the second year of production, which could be anticipated as a result of maturing root structures. Switchgrass production experienced a considerable increase between the first and second year of observation. It can be concluded that switchgrass would generate higher biomass yield over a 10-yr production life based on the yield observed in year 2.

Big bluestem biomass production does not appear to be as high as switchgrass, which is reflective of a slower growth rate. No fertilizer application would be appropriate for biomass production from these feedstocks based on the results of this study, as increases in yield over the first two to three years can be expected regardless of fertilizer application levels. Despite no significant response to fertilizer levels, it can be concluded from this report that long-term production of big bluestem will result in yields slightly lower than switchgrass at all levels of fertilizer. In a scenario where fertilizer would be incorporated in the roadside development of these feedstocks, this report shows that low (54 lb N/ac) levels of fertilizer would be adequate for biomass production. Woodland sunflower also exhibited increased biomass production over the two-year study, however, yields were not comparable with big bluestem and switchgrass. Despite the lower production, woodland sunflower is still capable of providing additional benefits to the roadside by providing pollination sources and increasing biodiversity. Plant quality was not significantly affected by fertilizer application, which shows that GDOT would not need to exert resources in maintaining plant vigor and health over a production life span. The observed energy production levels associated with combusting these feedstocks would likely be attractive to stakeholders and investors in a scenario where a mature bioenergy market exist.

ROW production of the biomass feedstocks had no considerable impact on the amount of organic matter and nutrients being transported downstream as a result of site preparation and management activities to prepare the ROW for biomass production. Total suspended solids concentrations in water samples collected beneath these alternative crops were lower than TSS concentrations from water samples collected outside the cropping system used for this study. In addition, soil organic carbon concentrations in soils beneath these alternative crops increased over the two-year growing period, indicating that these feedstocks can have a positive effect on soil quality (i.e., SOC) while also contributing to reduction of greenhouse gases associated with highway corridors. Despite the improvements in SOC and soil N, results from supplemental soil analysis indicate long-term (i.e., >5 years) production of these feedstocks will require eventual soil amendments, as the feedstocks absorbed some essential elements through their root system over the two-year period.

Regardless of the production scenario, establishing biomass feedstocks using plugs (seedlings) resulted in breakeven payback periods four times longer than feedstocks established using seed, on average. Budgeting for long-term feedstock production using plugs for establishment will be difficult for producers entering the market. In a scenario where GDOT is interested in investing resources toward the production of switchgrass and big bluestem, administrators should use seeds as the primary planting method for establishing feedstocks. Seeds were most cost-effective for all production scenarios and can be recommended for feasible production of switchgrass and big bluestem feedstocks under a 10-year contract with an end user. By evaluating different feedstock management inputs, it will be possible to operate and budget with more flexibility with seeds as the primary method of planting; however, uncertainty in market value for biomass will need to be accounted for.

Based on the study results, any of the provided feedstock can be implemented and established in Georgia ROWs. However, each option will present advantages and limitations based on the needs and requirements defined by each GDOT district office. From the feedstock analyzed in this study, switchgrass and big bluestem performed better from a biomass yield and energy generation perspective for a given set of conditions observed in the ROWs. In addition, depending on the time required for plant establishment and the initial investment costs, planting switchgrass and big bluestem crops from seeds provided a better option if costs are a constraint at the initial stages. If GDOT is planning to generate revenue over a longer period of time with a higher initial investment, then big bluestem, planted from plugs, provides a better alternative in the long run. Specific advantages and disadvantages for each feedstock analyzed in this study are summarized below:

<u>Switchgrass</u>

- Establishment with seeds offers the most cost-effective pathway of production.
- Establishment with plugs ensures higher stand density and subsequent biomass production.
- Long-term (>5 years) production is the best use due to its projected yield over multiple growing seasons.
- Higher acreage of production required to compare with the energy levels of big bluestem.
- High fertilizer input rates are necessary to generate significant increases in biomass production.

Big Bluestem

- Establishment with seeds offers the most cost-effective pathway of production.
- Establishment with plugs ensures higher stand density and subsequent biomass production.
- Energy content extracted from biomass is high compared to switchgrass
- Cost-effectiveness is higher when compared with switchgrass.
- Fertilizer inputs are not required to generate significant energy content.

Woodland Sunflower

- Short-term (<5 years) production is the best use due to its slower growth rate.
- Enhanced biodiversity makes it an ideal option.
- Fertilizer inputs are not required to generate significant energy content.

In general, utilizing bioenergy crops in ROW areas along highways in the state of Georgia as a green sustainable solution to offset maintenance costs associated with the management of ROWs offers other benefits, including:

- Utilizing nontraditional cropland in the form of ROWs to generate bioenergy crops that do not compete for arable land typically used for the food crops.
- Growing bioenergy crops that have the potential to generate economic activity and jobs on land that currently does not generate income or jobs.
- Providing potential revenue/savings for GDOT, depending on the market for bioenergy crops.
- Allowing the potential for GDOT to run their fleet on biodiesel produced from bioenergy crops grown on highway ROW.
- Offering reduced dependence on fossil fuels.
- Providing environmental benefits:
    - Soil stabilization.
    - Reduced greenhouse gas emissions.
    - Reduced total suspended solids.
    - Soil quality improvement.
    - Water pollution mitigation.

- Reducing the maintenance of ROW due to replacement of unwanted vegetation (i.e., weeds) with high-value bioenergy crops.

Some constraints associated with growing these bioenergy crops in ROW areas include:

- Access to farming equipment on and off the highways.
- Fair to poor soils along the highways.
- Economic uncertainty due to undeveloped markets for bioenergy crops.
- Lack of registered herbicides for weed control for some bioenergy crops.
- Lack of knowledge about growing some bioenergy crops.
- Minimal biomass production due to limited parcel size in ROWs in some highway areas.

CHAPTER 8. IMPLEMENTATION

CHECKLIST FOR ALTERNATIVE USES OF THE ROW

The following checklist includes questions that GDOT administrators might consider when assessing the feasibility of implementing a program to accommodate renewable energy production in the state highway ROW. The checklist is not meant to communicate particular roles and responsibilities or imply that these are the only considerations necessary. Instead, it should help GDOT identify important components that are already in place versus those that might yet be necessary to accommodate providing alternative uses of GDOT's ROWs.

Yes? No?

1. **Does GDOT have leadership support to explore the accommodation of renewable energy programs in the highway ROW?** ____________

   A committed project champion within GDOT leadership is vital to overcoming barriers and keeping projects on the paths forward.

2. **Are there state requirements or incentives for state agencies to acquire a certain percentage of their electricity from renewable sources? Are there state requirements or incentives for state agencies to reduce their GHG emissions?** ____________

   The presence of such requirements or incentives can help GDOT justify the goal of pursuing alternative uses of highway ROW. If the answer to this question is no, accommodating alternative uses of the ROW could still be practicable; the justification would likely need to focus on *economic or other environmental stewardship–related purposes.*

3. **Does GDOT have an encroachment policy or other similar policy that might discourage some alternative uses of the ROW?**

   If so, GDOT should assess whether the policy pertains to all potential alternative uses and/or whether the policy still aligns with current priorities. GDOT could consider the development of an ***interdisciplinary team*** *to identify and address the unique issues—including those related to design, construction, and safety—that alternative uses of the ROW present in the state.*

4. **Are GDOT's ROW property maps available electronically and/or in geospatially enabled format(s)?**

   Having electronically available ROW property maps would likely facilitate analyses of potential sites for biomass production within the ROW. Electronically accessible ROW property maps that could be incorporated into a GIS would facilitate the development of a site suitability model for feedstock establishment, as was observed in this study.

5. **Does GDOT have staff qualified and available (likely GIS staff) to review data related to resources location(s)? Does the state have natural resource data that GDOT can use/leverage?**

   If no, is GDOT in a position to hire a consultant to perform analyses of natural resource location data in relation to GDOT property maps? For potential renewable energy projects, not all suitable locations from a transportation perspective will necessarily be in locations with suitable natural resource (e.g., soil resources) availability. Open-source natural resource information would be available through the Soil Survey Geographic Database (SSURGO). In a scenario where suitable locations are being scouted for a ROW biomass energy project, SSURGO would be a source of spatial information pertaining to available natural resource distributions over a given area of land where GDOT may be considering the establishment of ROW biomass feedstocks.

6. **For renewable energy projects, has any utility company or private developer(s) shown interest in partnering with GDOT for the implementation of this kind of project?**

   GDOT will need to find a location(s) of sufficient size(s) to ensure the economic feasibility of the alternative use of the ROW being considered. Developing criteria for what constitutes adequate acreage (based on the proposed project type) would be a useful activity for GDOT to consider. For solar projects, for example, Oregon and

Ohio DOTs—in coordination with utility companies in their areas—have determined that the ability to produce at least 1 MW is necessary to make a solar highway project economically feasible. Ohio DOT has concluded that requires approximately 5 ac of land. This metric will continue to evolve as new technologies that allow more energy to be generated on a smaller footprint become available.

7. **Does GDOT legal staff have experience working with agreements related to renewable energy projects?**

   Renewable energy projects can involve complex legal documents that GDOT may not be able to develop given current areas of in-house expertise. Therefore, GDOT may need to utilize outside legal counsel or consultants to help guide the development process of these agreements.

POTENTIAL PARTNERS IN UTILIZING ROW PRODUCTS FOR ENERGY USE

The following section includes information on potential partners to utilize GDOT's ROW products for energy use. In it, the research team assumes that a bioenergy market is fully materialized in Georgia and that GDOT is able to coordinate long-term (~10 years) contracts with end users (partners) in proximity to dedicated highway ROW production areas. This section is meant to communicate proximity of potential end users to interstate highways and to highlight the product type (e.g., wood or herbaceous biomass) used at each facility. It is expected that these end users would be capable of generating and selling energy from the ROW products to utility companies (e.g., Georgia Power) in the state of Georgia. Figure 27 illustrates various biomass facilities in Georgia capable of processing and converting delivered switchgrass, big bluestem, and woodland sunflower biomass into usable products, such as electricity, biofuel, or heat. It is assumed that these facilities would be capable of condensing switchgrass and big bluestem into fuel pellets for combustion. These facilities are located throughout the state and would provide an outlet for biomass material generated within highway ROWs across the state of Georgia. Table 24 lists available biomass processing facilities in Georgia by output type. Studies have suggested utilizing biomass from the three feedstock species in this study is possible by briquetting and admixing wood residue delivered for paper factories with lignin remains from cellulose factories (Lunguleasa 2009).

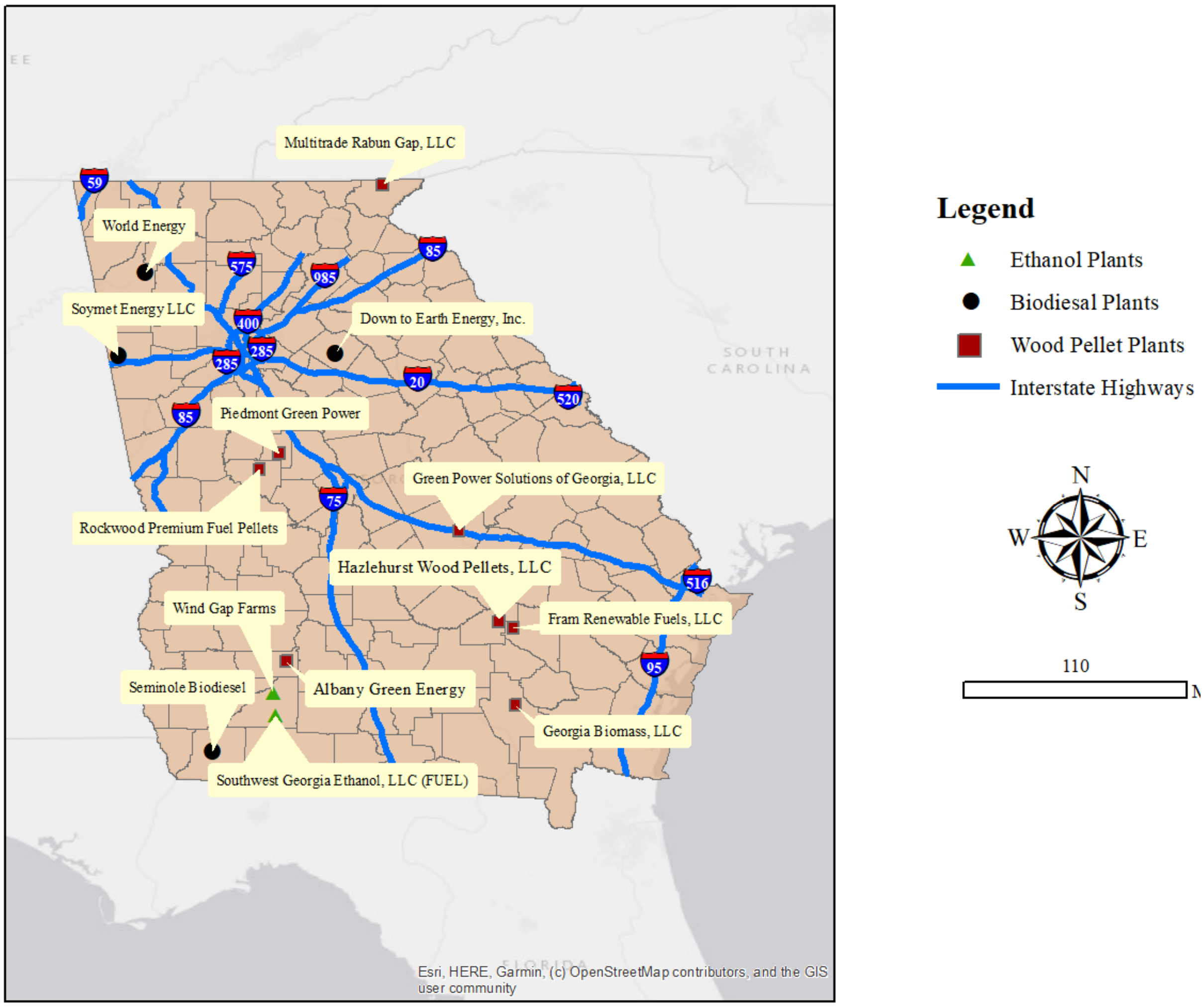


Figure 27. Map. Biomass processing facilities in Georgia.

Table 24. List of biomass processing facilities in Georgia.

Company (End User)	Biomass	Output	Address	Contact Person	Credentials	Email	Phone
Albany Green Energy	Wood	Wood-Using Renewable Energy Plant	508 Liberty Expressway SE Albany, GA 31705	Stuart Glenn	Operations Manager	-	229-352-6402
Camilla Ethanol Plant (Southwest Georgia Ethanol, LLC)	Herbaceous	Biodiesel	4433 Lewis B. Collins Road Pelham, GA 31779	-	-	CamillaFlintHills@fhr.com	229-522-2822
Down to Earth Energy / Clean Energy Biofuels	Herbaceous	Biodiesel	941 Monroe Jersey Road Monroe, GA 30655	-	-	-	678-318-1785
Fram Renewable Fuels, LLC (Appling County Pellets)	Wood	Wood pellet mill	248 Sweetwater Drive Baxley, GA 31513	-		-	912-366-1422
Georgia Biomass, LLC	Wood	Wood pellet mill	3390 Industrial Boulevard Waycross, GA 31503	-	-	-	912-490-5293
Green Power Solutions of Georgia, LLC	Wood	Wood-Using Renewable Energy Plant	709 Papermill Road Dublin, GA 31027	- -		-	478-272-1600
Hazlehurst Wood Pellets, LLC	Wood	Wood pellet mill	430 Hulett Wooten Farms Road Hazlehurst, GA 31539	-	-	-	912-551-9251
Multitrade Rabun Gap, LLC	Wood	Wood-Using Renewable Energy Plant	1585 Yorkhouse Road Rabun Gap, GA 30568	Bill Gravley -	Branch Manager	-	706-746-3170
Piedmont Green Power, LLC	Wood	Wood-Using Renewable Energy Plant	100 Commerce Place Barnesville, GA 30204	Kathy Oxford	Executive Director	kathy.oxford@cityofbarnesville.com	770-872-3773
Rockwood Premium Fuel Pellets	Wood	Wood pellet mill	4737 Barnesville Hwy The Rock, GA 30285	-		info@rockwoodpellets.com	706-656-5292
Seminole Biodiesel, LLC	Herbaceous	Ethanol	310 Commodore Industrial Blvd Bainbridge, GA 39817	Roger Whitworth	Manager	-	229-246-2307
Soymet Energy, LLC	Herbaceous	Biodiesel	4451 Alabama Hwy Rome, GA 30165	Joe Harrison -	-	joe.harrison@soymetenergy.com	706-524-8395
World Energy, LLC	Herbaceous	Biodiesel	555 West Hermitage NE Rome, GA 30161	Greg Hopkins	Managing Director, Engineering and Technology Services	info@worldenergy.net	617-889-7300

BEST MANAGEMENT GUIDELINES

Based on the findings of this study, implementation best management practices have been developed for switchgrass, big bluestem, and woodland sunflower production by GDOT in the highway ROW. It is recommended to grow biomass feedstocks from the roadside to the ROW boundary in height steps. By design, low-growing perennials (e.g., woodland sunflower) would be closest to the road, then taller crops (i.e., switchgrass and big bluestem) could be grown in the next step of the mosaic. Finally, as line-of-sight issues for motorists decrease with increased distance from the roadside, taller or denser crops could be grown. Producers entering a long-term contract (≈10 years) with an end user may want to consider incorporating soil amendments (e.g., fertilizers, legumes, etc.) in between contract (replanting) periods to improve depleted soils that have been used for ROW feedstock production. Additional practices include:

Establishment

- A site analysis using the Soil Survey Geographic Database (SSURGO) and electronically available ROW property maps is recommended before planting.
- Reduced tillage is recommended for feedstock site preparation on the ROWs. Reduced tillage leaves 15–30 percent residue cover after planting. Weed control would be accomplished with herbicides and/or cultivation.
- Avoiding the use of fertilizer during the establishment year is recommended to minimize excessive weed growth (which can slow growth of the grasses planted) and potential runoff into streams and wetlands.

Switchgrass and Big Bluestem

- Plant perennial grasses 2 or 3 weeks before to 2 or 3 weeks after the recommended planting dates for corn, typically from mid-April to early June.
- Consider using seeds for biomass feedstock establishment.
- Seed big bluestem using a grass drill or broadcasting onto the surface of a prepared seedbed. Drilled plantings should be set at a depth of ¼ to ½ inch and broadcast plantings should be packed with a packer roller to improve seed-to-soil contact. Using NRCS-recommended seeding rates, big bluestem should be seeded at 9 lb/ac.

- Using NRCS-recommended seeding rates, seed switchgrass at 6 lb/ac. Seed should be planted ¼ inch deep.

Woodland Sunflower

- Plant 2 or 3 weeks before to 2 or 3 weeks after the recommended planting dates for corn, typically from mid-April to early June.
- Plant woodland sunflower using 2-ft spacing to avoid overcrowding and to facilitate farm equipment access to plots.

Maintenance

- Maintaining switchgrass and big bluestem planted by seed may be difficult not only because of seed dormancy, but because of competition from weeds. Perennial warm-season grasses such as bahiagrass (*Paspalum notatum*) germinate in the warmer ROW soils present throughout Georgia and can have an impact on feedstock stand establishment.
- Feedstock quality on the ROWs can be maintained by utilizing cultural and mechanical control measures to reduce weed pressure. For instance, annual cropping with small grains and field peas for one or two years could provide an opportunity to control weeds several times during the season while building soil organic matter. An example of annual crops could be nitrogen-fixing legumes that could contribute to nitrogen availability in the ROW in the range of 50 to 150 lb/ac/year, depending on the species and percent composition of legumes in the field.

Harvesting

- Harvest late in the growing season (December), if possible, as studies have shown that biomass harvested during winter exhibits higher structural carbohydrates and lignin as well as lower protein and ash compared to earlier-harvested crops. These characteristics are desirable for bioenergy production.
- Late harvest timing may also promote sustainability of switchgrass and big bluestem by facilitating the translocation of nutrients such as nitrogen, phosphorus, and potassium

from the aboveground biomass into the root system following crop senescence, which results in a reduction of nutrient replacement for subsequent growing seasons.

- Leave at least 4- to 6-inch stubble after harvest to elevate windrows (aid airflow and speed up drying).
- Use conventional hay equipment for harvesting biomass.
- Use a rectangular baling system for harvested biomass.

Storage

- Options range from uncovered storage of round bales to an indoor storage structure.
- For an outdoor storage environment, consider using tarps for harvested biomass configured as rectangular bales to avoid the potential for wet bales.
    - This choice has a cost trade off: $ invested vs. $ lost in dry matter.
- Indoor storage environment may be considered for covering rectangular bales if biomass is not being delivered to end user immediately after harvest and is being stored off-site for an extended period of time (>100 days).

APPENDICES

VEGETATION TAXONOMY BY SITE (MILE MARKER)

MM 130	**Count**	1	7	4	2	8	2
	Species	*Cyperus difformis L.*	*Gamochaeta purpurea*	*Geranium carolinianum L.*	*Gnaphalium purpureum*	*Hypochaeris glabra*	*Krigia virginica (L.)*
MM 121	**Count**	2	11	7	3	14	6
	Species	*Baccharis halimifolia*	*Diodia teres*	*Festuca pratensis*	*Geranium carolinianum L.*	*Glandularia pulchella*	*Gnaphalium purpureum*
MM 108	**Count**	16	11	1	11	3	5
	Species	*Bromus racemosus L.*	*Callisia rosea*	*Chamaecrista fasciculata*	*Cyperus difformis L.*	*Festuca pratensis*	*Geranium carolinianum L.*
MM 102	**Count**	2	3	41	25	17	3
	Species	*Agrostis capillaris*	*baccharis halimifolia*	*Dichanthelium consanguineum*	*Dichanthelium strigosum (Muhl. ex Elliott) Freckmann var. leucoblepharis (Trin.) Freckmann*	*Facelis retusa*	*Gamochaeta antillana*
MM 90	**Count**	9	7	4	5	1	1
	Species	*Cynodon dactylon*	*Gnaphalium purpureum*	*Hypochaeris glabra*	*Krigia caespitosa*	*Krigia virginica (L.)*	*Lolium multiflorum*

MM 130	Count	21	5	4	3	479	1	3
	Species	*Lactuca graminifolia Michx. var. graminifolia*	*Lolium multiflorum*	*Oenothera speciosa Nutt.*	*Oxalis dillenii*	*Paspalum notatum*	*Phalaris caroliniana*	*Rubus occidentalis*
MM 121	Count	1	3	17	1	31	20	8
	Species	*Hypochaeris glabra*	*Lamium amplexicaule*	*Lolium multiflorum*	*Oenothera speciosa Nutt.*	*Opuntia ficus-indica*	*Opuntia humifusa (Raf.) Raf*	*Oxalis dillenii*
MM 108	Count	1	67	48	418	5	1	24
	Species	*Lepuropetalon spathulatum*	*Lolium multiflorum*	*Oxalis dillenii*	*Paspalum notatum*	*Plantago virginica*	*Spermolepis divaricata*	*Trifolium arvense L.*
MM 102	Count	5	3	12	5	33	4	2
	Species	*Gamochaeta purpurea*	*Geranium carolinianum L.*	*Glandularia pulchella*	*Gnaphalium purpureum*	*Hypochaeris glabra*	*Krigia virginica (L.)*	*Lolium multiflorum*
MM 90	Count	11	429	4	3	7	20	3
	Species	*Nuttallanthus canadensis L.*	*Paspalum notatum*	*Plantago virginica*	*polypremum procumbens*	*Selaginella arenicola*	*Spermolepis divaricata*	*Stellaria media (L.) Vill.*

MM 130	**Count**	4	41	6	63	9	26	5	3
	Species	*Rumex acetosella*	*Spermolepis divaricata*	*Trifolium arvense L.*	*Trifolium dubium*	*Triodanis perfoliata*	*Valerianell a radiata*	*Viola arvensis*	*Wahlenbergia marginata*
MM 121	**Count**	115	8	13	2	1	19	75	89
	Species	*Paspalum notatum*	*Passiflora incarnata*	*Plantago virginica*	*Rhus copallinum*	*Rubus trivialis*	*Rumex acetosella*	*Spermolepis divaricata*	*Triodanis perfoliata*
MM 108	**Count**	11	13	1	98	6	1	1	
	Species	*Trifolium dubium*	*Triodanis perfoliata*	*Triodanis perfoliata*	*Verbena bonariensis*	*Verbena rigida*	*Veronica arvensis L.*	*Wahlenbergia marginata*	
MM 102	**Count**	18	122	26	5	4	49	3	1
	Species	*Nuttallanthus canadensis L.*	*Paspalum notatum*	*Plantago virginica*	*Polygala Polygama*	*Polypremum procumbens*	*Rhexia mariana L.*	*Rhus copallinum*	*Ruellia simplex*
MM 90	**Count**	4	11	2					
	Species	*Trifolium dubium*	*Triodanis perfoliata*	*Viola arvensis*					

MM 130	Count				
	Species				
MM 121	Count	31	14	8	4
	Species	*Verbena bonariensis*	*Verbena rigida*	*Veronica arvensis L.*	*Vicia sativa*
MM 108	Count				
	Species				
MM 102	Count	13	2	1	22
	Species	*Rumex acetosella*	*Triodanis perfoliata*	*Vitis rotundifolia Michx.*	*Wahlenbergia marginata*
MM 90	Count				
	Species				

PROJECT PHOTOGRAPHS

Figure 28. Photo. Preliminary soil sampling of right-of-way sites.

Figure 29. Photo. GDOT site preparation at mile marker 90. Photo taken on 06/17/2017.

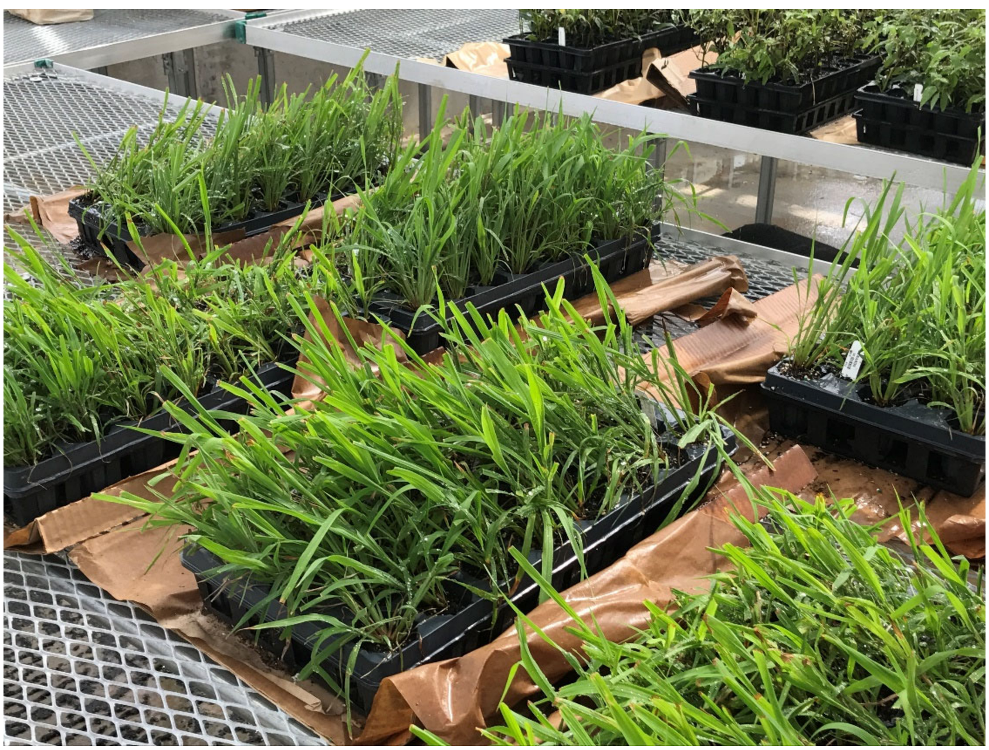


Figure 30. Photo. Big bluestem plugs upon arrival at GSU. Taken on 08/01/17.

Figure 31. Photo. Woodland sunflower plugs upon arrival at GSU. Taken on 08/01/17.

Figure 32. Photo. Switchgrass plugs upon arrival at GSU. Taken on 08/01/2017.

Figure 33. Photo. Row spacing delineation. Taken on 08/02/17.

Figure 34. Photo. Initial planting of feedstocks. Taken on 08/02/17.

Figure 35. Photo. Big bluestem in 2nd month of growing season.

Figure 36. Photo. Woodland sunflower in 3rd month of growing season.

Figure 37. Photo. Switchgrass in 4th month of growing season.

Figure 38. Photo. Soil pant analysis development (SPAD) measurements of woodland sunflower.

Figure 39. Photo. Harvesting of switchgrass in December.

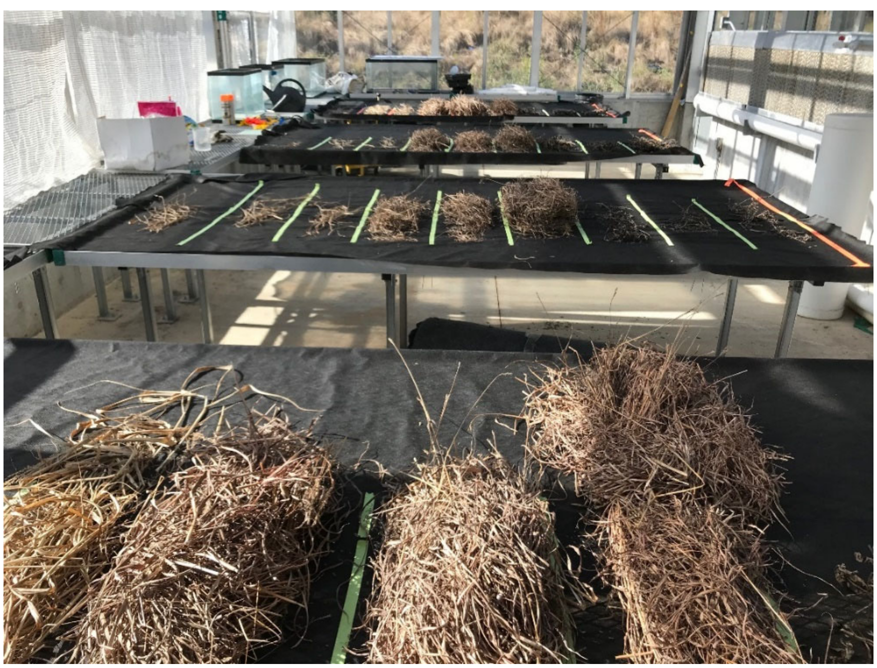


Figure 40. Photo. Greenhouse environment for storage/drying of harvested feedstocks.

Figure 41. Photo. Calorimeter (energy) analysis of switchgrass.

Figure 42. Photo. Total suspended solid analysis on water samples collected beneath feedstocks.

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