International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:3, No:6, 2009

Classification of Soil Aptness to Establish of *Panicum virgatum* in Mississippi using Sensitivity Analysis and GIS

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***Abstract*—**During the last decade Panicum virgatum, known as Switchgrass, has been broadly studied because of its remarkable attributes as a substitute pasture and as a functional biofuel source. The objective of this investigation was to establish soil suitability for Switchgrass in the State of Mississippi. A linear weighted additive model was developed to forecast soil suitability. Multicriteria analysis and Sensitivity analysis were utilized to adjust and optimize the model. The model was fit using seven years of field data associated with soils characteristics collected from Natural Resources Conservation System - United States Department of Agriculture (NRCS-USDA). The best model was selected by correlating calculated biomass yield with each model's soils-based output for Switchgrass suitability. Coefficient of determination (r2) was the decisive factor used to establish the 'best' soil suitability model. Coefficients associated with the 'best' model were implemented within a Geographic Information System (GIS) to create a map of relative soil suitability for Switchgrass in Mississippi. A Geodatabase associated with soil parameters was built and is available for future Geographic Information System use.

***Keywords*—**Aptness, GIS, sensitivity analysis, switchgrass, soil.

I. Introduction

THE U.S. Department of Energy (DOE) believes that biofuel—made from crops of native grasses, such as fast-growing *switchgrass*—could reduce the nation's dependence on foreign oil, curb emissions of the "greenhouse gas" carbon dioxide, and strengthen America's farm economy. ‘Alamo’ Switchgrass (Panicum virgatum L.), is a summer, perennial pasture grass which is native to North America [1].

There are two main ecotypes of Switchgrass; a thicker stemmed lowland hybrid that is better acclimatized to warmer, moist conditions and a finer- stemmed, up-land hybrid that is more often found in middle to northern regions [1].

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Switchgrass is resistant to a number of pests and diseases, and it is able to generate high yields of biomass with little to no applied fertilizer [1]. In recent years, this pasture grass has been investigated widely because of its potential as alternative forages and especially as biofuel source [2]. Switchgrass crops may able to improve the soil quality by reducing nutrient loss and sequestering carbon underground [3].

Nutrient uptake and loss are significant aspects for high-biomass producing of Switchgrass. Increases in plant N concentration with increasing applied N have been observed [4]. Biomass production of Switchgrass is directly correlated with high levels of soil moisture, water holding capacity and Nitrogen, thus these variables are the primary limiting factors [5]. Soil bulk density and strength are important variables that affect both shoot and root growing of Switchgrass. In hard soils a reduction in the elongation rate of the roots has been observed, while in weak soils elongation rates increase [4]. Consequently, the result of high soil bulk density is decreased Switchgrass growth and decreased water and nutrient attainment [6]. The influence of soil *pH* on productivity of *Panicum virgatum* seems to fluctuate with factors which are related with *pH*; however this pasture grass has a wide range of *pH* tolerance (4.8 to 7), but the optimum *pH* varies between 5.5 to 6 [1]. Favorable weather conditions and soil characteristics of Mississippi make Switchgrass a viable option for farmers. Because growing conditions are not uniform across the State, assessment of site suitability is an important prerequisite to recommendations to farmers. The significance of this research is that it permits forecast soil suitability for establishment of Alamo Switchgrass in Mississippi. To complete this task, sensitivity analysis was used to determine how sensitive the model output is to changes in the value of the soil-parameters used [7]. Research, literature review, discussion with experts, and statistical analyses were all employed to select the candidate soil parameters for modeling and for determining the relative importance (weight) of each soil parameter that would likely result in highest yield for Panicum virgatum L. Literature indicates that *water holding capacity* (*awc*) [8] and *organic nitrogen* (*o.c.*) are the most important parameters to consider for modeling Switchgrass soil suitability [9]. Other soil variables chosen for analysis included *pH* (*pH*) and bulk density (*bd*), [10]. Most of the data used were obtained from the Natural Resources Conservation System - United States Department of Agriculture (NRCS-USDA). In addition, some data used for modeling were developed using the Soil Plant Atmosphere and Water (SPAW) computer model developed by USDA and the Department of Biological Engineering of Washington State University, and combined with supplementary statistically-based methods. The input of the model consisted primarily of functions and parameters that were obtained from the NRCS-USDA and which were held constant [11]. Mississippi is comprised of 21 Ecoregions at level IV in EPA's management system classification which is indicative of significant ecological and biological diversity within the State [12]. The objective of this study was to determine site suitability for 'Alamo' Switchgrass in Mississippi. Although weather conditions are important in the timing of planting and yield variability, this project was oriented toward the determination establishment and cropping of Switchgrass as a function of soil properties only.

II. Data and Methodology

A. Study Area

The region considered for this study is the State of Mississippi, which is located in the southeastern region of the United States of America. Mississippi is bordered on the east by Alabama, on the north by Tennessee, on the west by Arkansas and Louisiana and on the south by Louisiana and the Gulf Coast. Most of the State is composed of low hills; known as the North Central Hills in the north, and the Pine Hills in the south. Higher elevations and steeper topography exist in the Fall Line Hills and the Pontotoc Ridge in the northeast region, this region expands into a fertile black soil terrain known as the Black Belt. The coast of Mississippi, Costal Plains, encompasses Pascagoula, Biloxi and Bay Saint Louis, and is in part divided from the Gulf of Mexico by barrier islands, Cat, Horn, Ship and Petit Bois islands. The Mississippi Alluvial Plain, also known as the Mississippi Delta extends from the northwest and west central part of the State; this section has fertile soils formed by stream deposition [12].

The climate of Mississippi is hot and humid. It is categorized as a subtropical climate with long hot summers and short mild winters. Average temperature is around 29 C in July and 10 C in January. Mississippi supports large areas of forest vegetation including wild trees such cottonwood, pines, elm, oak, pecan, sweet gum, etc, thus forest products is one of the most important industries in the State. The dominant soils in Mississippi are Aquepts, Aqualfs, Aquents, Udolls, and Udalfs. These soils are deep and medium textured. Most of them have udic or aquic moisture regime, termic temperature and smectitic or mixed mineralogy [12].

B. Data

Modeling Switchgrass suitability using GIS requires a variety of data formats and levels. Data formats used in this study include vector, attribute, and raster. Data measurement levels included ratio, interval, ordinal, and nominal.

1. Raster Data

Surface analyses, associated with the generation of *hillshades, contours, slope,* and *aspect* and were interpreted from Digital Elevation Model (DEM) data acquired from the United States Geological Survey (USGS) and MARIS. The statewide DEM was mosaiked from the assemblage of several 10 m^2 horizontal resolution DEMs then resampled to 30 m^2 horizontal resolution to optimize modeling performance.

2. Attribute Data

C. Methodology

Research associated with soil suitability for the establishment and cropping of Switchgrass in Mississippi and discussion of general Switchgrass suitability with experts was carried out for the first phase of the project. Initial investigation concentrated on developing soil-related criteria that influence plant growth in general and specific to Alamo Switchgrass when available. An examination of the soil taxonomy classification in the US was completed to determine at what level of categorization we would develop our study. NRCS-USDA set the Soil taxonomy classification in United States of America has six levels of categorization, these are: Order (12 classes), Suborder (63 classes), Great group (250 classes), Sub group (1400 classes), Family (8000 classes) and Series that has more than 20,000 classes. Soil series-level information was not complete for the entire state, so association-level information was chosen for modeling purposes. Soil association polygons were obtained in digital form MARIS. Each polygon represents one unique *soil association,* which is composed of three soil *series*. For example, Bigbee, Bibb, and Quitman individual soil series collectively comprise one soil association. Soil series represent the most homogenous unit in the system of soil taxonomy (USDA-NRCS). The soil digital map of Mississippi includes as part of its metadata an attribute table that contains spatial information associated with each soil series, but it does not includes data associated with any of the soil parameters that are regularly used to determine soil quality. Attribute tables that digital maps contain are needed to complete a number of spatial operations, such as spatial analysis, queries, and Boolean calculations. To improve the original attribute table (stgo.dbf), 54 fields from the NRCS-USDA database that are associated with soil properties and characteristics were joined to the digital soil map. Soil Plant Atmosphere and Water (SPAW) software, Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model, and statistical methods were used to develop soil properties data that were also included in the soils 'Geodatabase' assembled for this study. To accomplish this task a linear weighted additive model was developed and later implemented within a Geographic Information System (GIS) to predict site suitability based on soil properties for the entire State [13]. To determine the optimal combination of the parameters weights in the model, multicriteria analysis and sensitivity analysis were utilized [14]. Sensitivity analysis methods were employed for determination of the number of parameters and weighting of the parameters selected for the model [15]. The parameters (predictors) selected to complete the analysis were: potential water holding capacity (awc) measured in cm/dm (in/feet), potential bulk density (bd) measured in g c^{-3} , hydrogen ion acidity of soil solution (pH), and active organic nitrogen (o.n.). The weighted linear model created to determine soil suitability for Switchgrass is as follows:

$$Suit = w1 * (awc) + w2 * (bd) + w3(ph) + w4(on) \quad (1)$$

Where:

$Suit$ = soil suitability to crop Switchgrass in Mississippi indicator;

$w1$ = range of weights for water holding capacity (unitless);

$w2$= range of weights for bulk density (unitless);

$w3$= range of weights for pH (unitless);

$w4$ = range of weights for active organic nitrogen (unitless);

awc = water holding capacity (unitless, normalized value);

bd = bulk density (unitless, normalized value);

ph = hydrogen ion acidity (unitless, normalized value);

on. = active organic nitrogen (unitless, normalized value);

Factors that are within the parenthesis represent intervals of potential coefficient values each parameter can take on during simulations. This process is useful to evaluate how sensitive the solution to the equation is when the assumptions (weights) vary. The coefficient of variation (c.v.) was used to determine the intervals over the specified weight ranges that were significant. The c.v. is used to determine the variance in the input data, and permits comparison of the standard deviation with the average for the data set. For this study the higher the c.v. the lower the significance of the parameter in the model and vice versa. The intervals selected for the range of weights for each coefficient and the increments at each factor level of the model is presented below:

- $w1$: 0.35 to 0.5. Increments of 0.02 units.

- $w2$: 0.1 to 0.2. Increments of y 0.01 units.

- $w3$: 0.05 to 1.5. Increments of 0.145 units.

- $w4$: 0.3 to 0.5. Increments of by 0.02 units.

Assignment of initial variable weighting ranges cited above was developed from a combination of literature review, statistical analysis, and discussion with experts. As mentioned in the review of literature in the introduction, awc and on. are considered the primary parameters that influence growing and yield of switchgrass and the other parameters used have secondary influence. Additionally, advice from Dr. Brian Baldwin, Associate professor at the Department of Soils and Plant Science at Mississippi State University, who has extensive experience investigating Panicum virgatum pasture, was considered; we determined potential weights for each parameter on an interval from zero to one. The initial weights used were: 0.42 for awc, 0.12 for bd, and 0.12 for ph, 0.08 and 0.4 for on. Then from these initial references we predicted empirically the potential range of each interval to weight each parameter; Table I displays the predicted values.

TABLE I
POTENTIAL VARIABLE WEIGHTS (MIN/MAX) AND INITIAL WEIGHTS (IW)

Potential Parameters Weights

Parameter	min	max	iw
awc	0.35	0.50	0.40
bd	0.10	0.20	0.12
pH	0.05	0.15	0.05
o.n.	0.30	0.50	0.30
o.c.	0.10	0.30	0.11

To validate the empirical values we calculated the c.v. associated with yield for each parameter to determine if our empirical prediction was reasonable. The statistical results corroborated our choice for the initial coefficient ranges and that the coefficient of determination for each parameter was proportionally correlated with the initial weights assigned. The data input for the parameters (predictors) was imported from the soil attribute matrix (54 columns x 1369 rows) developed to enhance soil attribute information. To simplify the calculations the 1369 rows were reduced to 103 because many rows (soil associations) have the same soil series as primary soil series. Next, sensitivity analysis was implemented to enable parameterization of the model described above (Eq. 1). Sensitivity analysis was used to complete a series of tests in which each potential unique model that resulted from varying the weights, based on the intervals specified, was compared with simulated yield information derived from the ALMANAC model. To implement the sensitivity analysis a programming statement in MATLAB 7R software was developed. The result was a 103 row by 1296 column matrix where each column represents one of the unique model mentioned above. Each model signifies a unique relation between the output variable ('suit') and the five soil property parameters used in the simulation. The c.v. of each parameter was evaluated and compared with the others to validate and adjust the initial weights set in the model, which were heuristically determined. Each potential model was evaluated using simulated biomass yield for Switchgrass as estimated by the ALMANAC yield model. The 'ALMANAC model' is a computer simulation model that permits estimation of the potential biomass yield for agricultural systems under conditions specified by the user. The model simulates soil water balance, the nutrient balance, weather, and interception of solar radiation. For this study soil properties were used as model drivers; interception of solar radiation and weather conditions were held constant. Five hundred seventy eight yield sites were randomly assigned across Mississippi. Random site selection for yield calculations was performed for each soil association. Randomization was carried out using proportional allocation of plots by area for each of the 103 unique soil associations in Mississippi. Fig. 1 is a display of the distribution for the sites selected to simulate the biomass yield for Switchgrass in Mississippi.

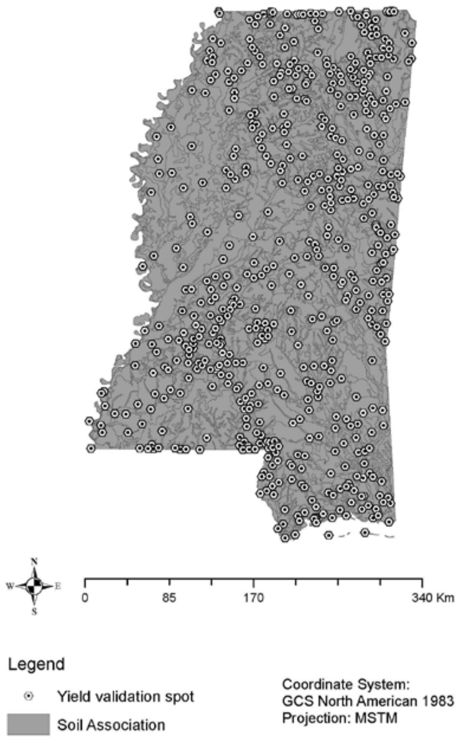

Fig. 1 Sites set to validate biomass yield in Mississippi

The soil suitability model was validated in two phases. First, the mean values of the coefficients for each parameter were used as weights to obtain the soil suitability model for Alamo Switchgrass. Then the coefficient of determination (r2) between the soil suitability (suit.dbf) and biomass yield (yield.dbf) variables was estimated. For the second phase, the variable biomass-yield was correlated with each of the possible suitability models obtained in the sensitivity analysis matrix output. The highest r2 was identified to determine the best model. To simulate biomass yield, data was imported into the ALMANAC from the soils 'Geodatabase'. Simulations resulted in calculations of mean biomass yield for each soil series and were recorded in a matrix (1 column x 103 rows). Next; this column was added as new column in the matrix obtained in the sensitivity analysis, resulting in a final matrix (Fmatrix.txt) with 7777 columns and 103 rows. After that, each model was correlated with biomass yield to determine the highest r2. For this case the highest r2 represents the best model. To complete this task a programming statement was developed within R Statistical software environment. Next, FMatrix.txt was used as input data. The parameters and coefficients (weights) obtained from the sensitivity analysis were used to build the Switchgrass site suitability spatial model using ESRI's ArcToolbox within the ArcMap software. ArcGIS ModelBuilder was used to implement the 'optimal' model in the GIS environment resulting in output of a geo-referenced Switchgrass site suitability map. Output from the GIS model was aggregated from a continuous variable to five categories of site suitability: very good, good, moderate, poor, and very poor. The output classes were obtained by implementing the Natural-breaks (Jenks)' classification method for the continuous variable's output frequency distribution. The raster model inputs for each soil variable in the model were created from the enhanced digital soil map of Mississippi. Four new raster files were created; one for each of the four soil parameters. The data for each parameter were normalized using the maximum score normalization method (2) [14].

$$Normalized\ value = \left(\frac{Original\ value}{Maximum\ maximum}\right) * 100 \qquad (2)$$

Some soil property values were quite small, e.g., 0.369 and 0.361. Each raster layer was multiplied by 100 to avoid loss of information during the normalization process. After normalization the site suitability model was run and the output raster values were aggregated into five suitability classes: very good, good, moderate, poor and very poor.

III. Results

The results obtained for each of the four variables evaluated to complete the soil suitability model for Switchgrass are described below. The c.v. for awc is 7.72463. In the plot obtained for awc as part of the statistical output of the sensitivity analysis procedure, the vertical axis represents the standardized values for soil suitability while the horizontal axis represents the six levels of weighting (coefficients) that were analyzed for each variable during the simulation. Each number on the horizontal axis represents the lower/upper limit of one of the five sub-intervals developed within the main interval. The main interval contains the potential weights for awc. There are an infinite number of potential weights possible within this main interval. However, to implement the simulation only six potential weights were tested, thus five sub-intervals were chosen and implemented in the programming statement. The same criteria were applied for each parameter. The weights used for awc are 0.35, 0.38, 0.41, 0.44, 0.47, and 0.5 and the step interval used for this parameter was 0.03. According to the plot obtained for awc, when the coefficient for awc varies, the soil aptness for establishment and cropping of Alamo Switchgrass shows considerable fluctuation.

The c.v. for bd is 9.66711. The weights used for bd are 0.06, 0.084, 0.108, 0.132, 0.156 and 0.18 and the step interval used for this parameter was 0.024. According to the plot output, when the weight for bd varies, the soil suitability for establishment and cropping of Alamo Switchgrass shows non-significant fluctuation. Consequently, the influence of bulk density in the model is considerably lower than the influence of awc. The difference of the c.v. obtained for each case supports this conclusion. Table II summarizes the discrete weights used for each soil parameter during the simulation and the c.v. obtained for each soil parameter from the sensitivity analysis.

TABLE II
WEIGHTS USED FOR COEFFICIENTS AND *C.V.* OUTPUT IN THE SENSITIVITY ANALYSIS PROCESS

Parameter	Number of observations	w1	w2	w3	w4	w5	w6	Coeff. Var (*c.v.)*
awc	800928	0.35	0.38	0.41	0.44	0.47	0.5	7.35455
o.n.	800928	0.3	0.34	0.38	0.42	0.46	0.5	7.73861
bd	800928	0.1	0.12	0.14	0.16	0.18	0.2	9.06811
pH	800928	0.05	0.07	0.09	0.11	0.13	0.15	9.11278
o.c.	800928	0.1	0.14	0.18	0.22	0.26	0.30	9.11544

The c.v. obtained for each parameter was used to determine the degree of influence that each parameter has in the soil suitability model for Switchgrass. As illustrated in Table II awc and on have the lowest c.v. followed by bd, and ph. respectively. According to the results, we can conclude that on and awc are the parameters that are more significant in the model and that bd, and ph have less influence. The level of influence determined for each parameter as a function of its c.v. corroborates the previous heuristic analysis in which we assigned a similar arrangement for the parameters, this means that the c.v.'s are directly correlated with the weights that were assigned initially. The final output in the sensitivity analysis was a matrix (data_suit matrix) with 103 rows (all soil series present in Mississippi) and 1296 columns (where each column represents one soil suitability model), thus 133497 values were placed in a matrix. In the first modeling phase, the r2 was 0.7163, which indicates an acceptable quality correlation between the variables biomass-yield and soil-suitability and that the initial soil suitability model, which was generated taking in account heuristic and statistical analysis, represents an efficient model to evaluate and map soil suitability for Switchgrass in Mississippi. In the second phase the highest r2 was found in the fourteen column number of data_suit matrix and the value is 0.8177. This value is higher than the value obtained in the 'first phase' analysis. Fig. 2 presents the plot for this correlation,

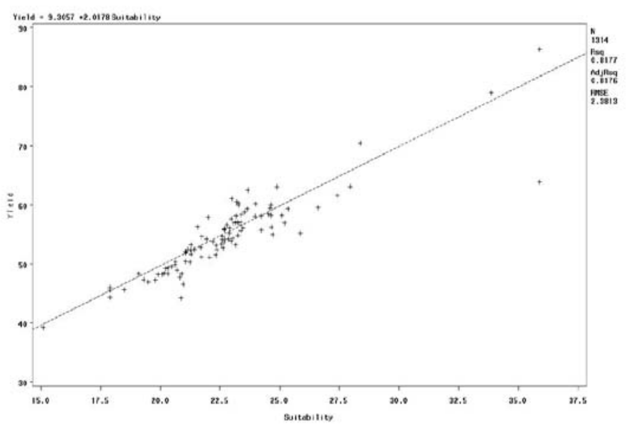

Fig. 2 Plot of validation after sensitivity analysis

The best coefficients for each parameter in the soil suitability model for establishment and cropping of Switchgrass at Mississippi are presented below as factors of (3).

$$Suit = 0.41 * (awc) + 0.1 * (bd) + 0.07(ph) + 0.36(on) \quad (3)$$

The GIS-based spatial site suitability model resulted in the suitability map for Switchgrass in Mississippi shown in Fig. 3.

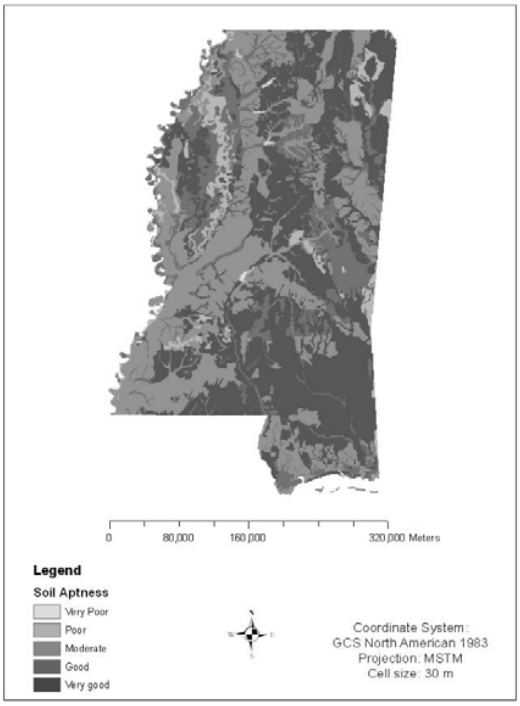

Fig. 3 Soil suitability map to crop Switchgrass in Mississippi

Fig. 4 illustrates how the soil suitability output is related to the Omernik's Ecoregions (red lines). This result is consistent with the fact that each Ecoregion is comprised of similar soil associations.

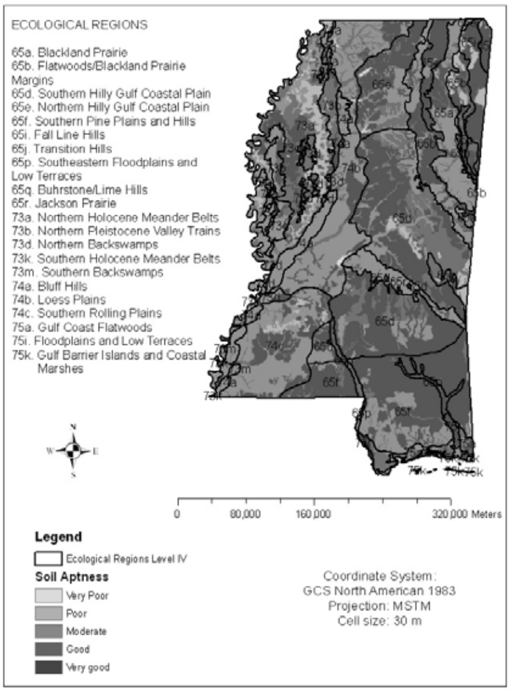

Fig. 4 Soil suitability map to crop Switchgrass and ecoregions in Mississippi (Level IV)

Fig. 5 illustrates a similar relationship that exists between physiographic regions and the similarity of soil properties within individual physiographic regions.

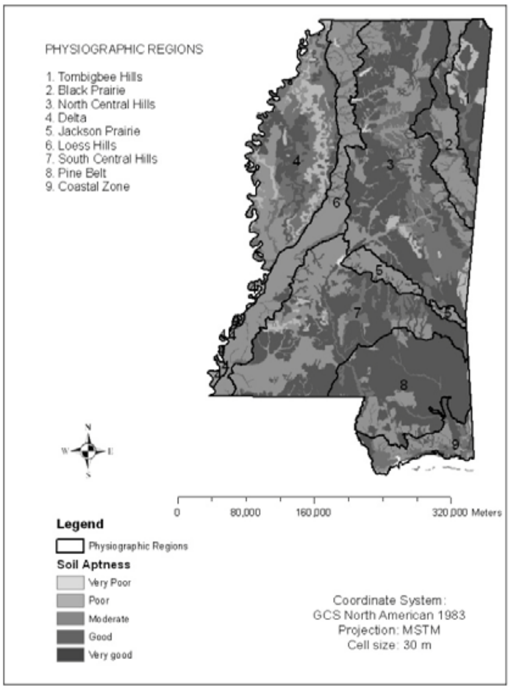

Fig. 5 Soil suitability map to crop Switchgrass and physiographic regions

IV. Conclusion

This research employed GIS spatial modeling techniques joined with Sensitivity Analysis to map site aptness for establishment of Alamo-Switchgrass in Mississippi, US. The need for better characterization of soil properties at the soil association level resulted in development of an improved set of soil characteristics for the soil association map of Mississippi. The data that were developed for this project are preserved in a relational database that is expected to be useful for many other projects that require more complete soils information at the soil association level. Many GIS-based models are built on heuristic decisions regarding variable importance and variable interactions are rarely considered during model fitting. Sensitivity analysis makes available an important method for quantitatively assessing variable weights and variable interactions that are important criteria when attempting to develop a spatial model that optimizes the input data.

The ALMANAC model is a functional tool for estimating yield biomass and served as a surrogate for validation data in the absence of any field data. Holding interception of solar radiation and weather conditions constant enabled assessment of how soil properties only affect the potential Switchgrass yield. Future efforts could benefit by allowing variation of these meteorological inputs. Most of the soils in Mississippi have moderate to good soil aptness for the establishment and cropping of Alamo-Switchgrass. However, there are some sites that exhibit poor and very poor soil aptness. Comparison of the model output results to the physiographic regions of Mississippi reveals that the majority of the Delta region in Mississippi presents moderate to good soil conditions for establishment and cropping of Switchgrass. The Loess Hills region generally encompasses moderate Switchgrass aptness with a few areas that are categorized very good, and only a few areas characterized as good, very good and poor. Most of the North Central Hills and Tombigbee Hills present moderate, good and very good soil aptness while the Black Prairie is characterized by moderate and some very good soil aptness as well as South Central Hills. The largest part of Jackson Prairie contains areas of moderate soil aptness. Approximately eighty percent of the Pine Belt presents very good soil aptness and some areas have poor soil aptness. The Coastal Zone regions are characterized by moderate soil aptness; however some areas present good soil conditions to establish switchgrass. Analyzing patterns of soil aptness compared with the Ecological map of Mississippi (Level III) reveals that most of the Southern Coastal Plains and the southern region of the Southeastern Plains are characterized by moderate and good Switchgrass site aptness. The majority and the northern region of the Southeastern Plains ecoregions are characterized by moderate to very good soil suitability with some patches of good site aptness. The Mississippi Alluvial Plain ecoregion is characterized by moderate soil aptness in the central region and a few patches of poor site aptness over the northwest of this region. Finally, most of the Mississippi Valley Loess Plains presents moderate to very good site suitability for the establishment and cropping of Alamo-Switchgrass.

ACKNOWLEDGMENT

This research was supported by the US Department of Energy's Sustainable Energy Center. We would also like to thank the Department of Geosciences of Mississippi State University, US Department of Agriculture (USDA-NRSC), Jim Kiniry at the USDA-ARS Grassland, Soil, and Water Research Laboratory for his and his staff's support in the operation of the ALMANAC model, and Dr. Brian S. Baldwin (Associate professor of Plant and Soil Sciences Department at Mississippi State) for his assistance with data and heuristic analysis associated with Switchgrass and its relationship with soil and environmental parameters.

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