Model to Determine Suitability of a Region for a Large Number of Crops

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Abstract

Agricultural crop distribution is rarely limited to a crop's native range. Increased crop range is largely the result of introduction of crops into new areas, which may in some cases be haphazard. The objective of this work was to develop a simple model to evaluate the suitability of many crops for Illinois conditions, but also with application for other geographic regions. Detailed physiological models would be most desirable for this task. However, a simple model was needed because of the scarcity of information to describe the climate and soil environment required by a large number of crops. The model described here included crop requirements and geographic distribution of soil properties (soil texture, soil pH, and soil drainage) and climate variables (daily maximum and minimum temperatures, precipitation, extreme minimum winter temperature, and growing days) to characterize the suitability of regions in Illinois for 414 crops. Crop requirements were linked to geographic distributions of soil and climate characteristics to describe the distribution suitability of Illinois conditions for each crop. Map algebraic routines in a geographic information system were used to compute the overall suitability of 2442 separate areas in the state. Application of the model to the State of Illinois demonstrates its utility for evaluating numerous crops using limited soil and climate characteristics, and the model can be expanded to any geographical area in the world with adequate soil and climate data.

Key Words: alternative crops, crop model, crop suitability, climate suitability, geographic information system, soil suitability, U.S. Corn Belt

Introduction

Alternative crops in farming systems provide diversification to combat the financial stress caused by an overabundant supply of a limited number of crops grown over a broad area. Often, selection of these crops is based on a limited number of species that have made their way into an area, either by progressive farmers' experimentation or by university or federal government research. There is a need for tools that will help screen a large number of crops across a region to identify potential alternative crops and locations of climate and soil conditions best suited for these crops. Existing tools that may be used, alone or in combination, include complex crop simulation models, geographic information systems (GIS), and expert systems.

Crop models, such as CERES-Maize (Jones and Kiniry, 1986) and SOYGRO (Wilkerson et al., 1983), rely on detailed crop physiological and precise soil and weather data at various stages of crop development to compute the growth and development of specific crops. Input variables include location latitude and longitude, planting date, plant density, solar radiation, daily temperature, daily precipitation, soil albedo, soil thickness, and soil-water-holding capacity, along with physiological/genetic variables that define crop development and response to the environment. These models, coupled with adequate long-term climate data, provide yield estimates for a location that can be used to evaluate the suitability of different locations for the crop. The computed yields can be used as input to economic models to evaluate the potential economic return of a particular crop at specified location. These and similar models have been used extensively to evaluate the potential impacts of climate change on shifts in production and growing regions of different crops (Easterling et al., 1993; Rosenzweig et al., 1995; Tubiello et al., 2000; Tubiello et al., 2002).

These crop simulation models require a thorough knowledge of the response of each crop to detailed soil and environment conditions. This in-depth knowledge is readily available only for most existing economic crops. Application of the models to lesser known and potential alternative crops that may be introduced into agricultural production systems is problematic due to the lack of knowledge of the specific edaphic (climate and soil) requirements.

Geographic information system (GIS) tools coupled with simple models of crop environment and soil conditions have been used to show the suitability of different crops for sub-state regions. Brooker and Gray (1990) used GIS to construct a temperature/crop map to display areas of Tennessee best suited for growing groups of vegetables with common temperature requirements. Their method combined weather station heat units, soil type (classed by potential for vegetable production) and soil slope information. Myers (1993) used GIS technology to create suitability maps for amaranth (*Amaranthus cruentus* L.) and canola (*Brassica napus* L. var. *napus*) based on soil classification, traditional crop production and estimated probability of disease in Missouri. Myers recognized that the suitability map for canola could be improved with greater understanding of the weather events associated with winter survival and the need to validate suitability maps. Young et al. (2000) used GIS to identify the suitability of the Wyoming Bighorn basin to grow 28 alternative crops. Their study included summer temperatures, precipitation, growing-degree days, length of frost-free season, and soil data developed using a predictive model based on surficial and bedrock geology and elevation. Finally, expert systems, such as VegSpec (USDA, U.S. Army COE, USGS, 2001), allow users to identify crop and plant species suitable for different locations by allowing them to input the climate and soil conditions of the location of interest.

The objective of this project was to develop a simple model that uses readily available specific crop edaphic requirements and climate and soil information in GIS format to evaluate the suitability of a region's conditions for a large number of crops. Although the model was applied to Illinois conditions, the approach and methods can be applied to many physiographic settings for which adequate climate and soil properties can be developed.

Methods

Soil and Climate Requirements

A literature search (Martin and Leonard, 1964; Duke, 1981; Galletta and Himelrick, 1990; Janick and Simon, 1993; Sauer, 1994; Annon, 2002) and numerous Internet Web pages (for example: Duke, 1983; California Rare Fruit Growers, Inc., 1995, 2002; Faucon and Faucon, 2000; USDA-NRCS, 2001a; USDA, U.S. Army COE, USGS, 2001; Janick, 2002) were used to identify potential alternative crops, and their soil and climate requirements. The three soil and four climate requirements most frequently found for the different crops were included in the model. Soil requirements included pH range (minimum and maximum), soil texture, and soil drainage information. Climate requirements included number of growing days, cardinal temperatures (absolute and optimum minimum and maximum temperatures), extreme winter minimum temperature, and minimum and maximum annual precipitation. While other climate (humidity and solar radiation) and soil characteristics (rooting depth) may limit crop growth at a location, these were not included in the model because these specific crop requirements generally were not available or known.

Regional Soil and Climate Characterization

Soil Data.

Ideally, geographically referenced soil-series data would be used for this application. The SSURGO database (USDA-NRCS, 2001c) provides such data on a limited basis for the United States. In Illinois, the SSURGO database is only available for a limited number of counties; therefore, the STATSGO database (SCS, 1993; USDA-NRCS, 2001b) was used for this study. There are 81 soil map units of similar geomorphic and topographic characteristics identified for the state of Illinois. Each STATSGO map unit is made up of 1- to 21-component soil taxonomic units (i.e., soil series) of known area. In addition to containing data that describe the soil, the STATSGO database contains georeferenced information that defines each map unit's shape, area, and location. This information was used to graphically represent attributes of Illinois soils using Arc-GIS software (ESRI, 2000).

The simplest method of characterizing the suitability of each map unit's soil properties was to represent each soil property as a single value. To obtain the mean map unit soil property (surface texture, pH, or drainage), the fraction of the total map unit land area occupied by each soil type was used to weight the soil property. The weighted mean for each map unit characteristic was computed using Equation 1,

$$S_i = \sum_{j=1}^{n} a_j S_j \qquad \textbf{(1)}$$

where S_i is the weighted mean soil property for the i^{th} map unit, n is the number of soils in the map unit, a_j is the fraction of the total map unit land area occupied by the j^{th} soil, and S_j is the soil characteristic for the j^{th} soil. Weighted soil property values for the STATSGO map units are used to generate a statewide coverage. The underlying assumption in adopting this procedure is that plant responses to the soil properties are linear; therefore, area weighting can be used to derive the landscape-soil properties.

Because not all soils are suitable for farming, certain soil series were not used to characterize the soil. Soil series containing more than 15 percent gravel and stone greater than 2 millimeters (mm), and aquatic components (water) typically are not farmed and therefore, were not included in computing the landscape-soil properties. Disturbed urban soils (urbanland and orthent) also typically are not farmed and were excluded. Soil series of very high organic soils (muck and sandy peat) are unique soils, and their inclusion in map unit descriptions skewed map unit pH, drainage and texture estimates such that unrealistic landscape-soil properties were defined. Therefore, they were not included in the general description of the map units.

Soil Texture. Map unit soil texture was estimated using the topsoil layer information from components of arable soils. Clay content, generally represented by soil material less than 0.002 mm in size (USDA-NRCS, 2001b), was provided as a STATSGO soil property. Sand and silt estimates were obtained by using the minimum and maximum percentages of soil material that passed through a number 10 (2.0 mm) and 200 mesh (0.075 mm) U.S. Standard sieve as listed in the STATSGO database. Sand was estimated as the difference between the amount of soil passing through a number 10 and number 200 mesh sieve. Silt content was the difference between 100 and the sum of the percentages sand and clay. The United States Department of Agriculture (USDA) soil classification defines sand as particles with diameters of 0.05-2.0 mm and silt as particles with diameters of 0.002-0.05 mm (Hillel, 1998, p. 61). Therefore, the percentage of sand is slightly underestimated while the percentage of silt is slightly overestimated, when compared to the USDA classification.

Texture for each map unit was estimated by weighting the sand, silt, and clay components using Equation 1. The map unit soil texture was determined by applying the sand and clay component percentages to a modified soil texture triangle (Saxton et al., 1986). The percentages of sand and clay are used as coordinates to identify the soil texture from the soil texture triangle.

Soil pH. Soil pH for each map unit was computed as the soil-series weighted average of each soil-series mean. The soil series-mean was computed using the STATSGO minimum and maximum pH values for each soil series.

Soil Drainage. Soil drainage classifications place major emphasis on the relative wetness of the soil under natural conditions as it pertains to wetness due to a water table (USDA Soil Survey Staff, 1993). Soil drainage classifications were sorted in order from most to least drained. An additional drainage class "Very well drained" was inserted between "Somewhat-excessively drained" and "Well-drained." This class was included because numerous plants required this soil drainage class. Soil drainage classes were assigned a numeric value to compute the weighted mean of a map unit's soil drainage. Some soil series in the STATSGO database were assigned two soil drainage classes. In this case, a single soil series value was computed by averaging the numerical value of the two classes.

Climate Characterization.

The climate was characterized using daily temperature and precipitation data for 86 National Weather Service Cooperative Observer Stations in Illinois. The 1971-2000 daily data were obtained from the Illinois State climatologist. In addition to characterizing the precipitation and temperature for the state, the data were used to characterize the extreme minimum winter temperature.

Maps of the 30-year mean annual climate variables were created using Surfer® (Golden Software, 1999) software. A data grid was created using the default kriging routine and smoothed using a 2 x 2 spline smoothing routine. Surfer® grids were converted to a format compatible with Arc-GIS software (ESRI, 2000), and 2000-meter (m) raster maps were created.

Precipitation. The 30-year mean annual precipitation was used to characterize the state's precipitation regime, because growing season precipitation requirements for specific crops were not generally available. In Illinois, approximately 66 percent of the annual precipitation occurs from April through October. Thus, the majority of precipitation occurs during the growing season.

Temperature. The 30-year mean temperature is most frequently used to represent the thermal environment. Assuming a normal distribution of temperature, this would represent the 50 percent probability of the 30-year mean temperature occurring on a specific date. Both the daily minimum and daily maximum temperatures were used to define the thermal environment. The median daily minimum and median daily maximum temperatures are the minimum and maximum temperatures expected one year in two, a relatively low risk tolerance. At Urbana, Illinois, for example, a median daily minimum temperature of 10°C is expected to be exceeded on 9 May, 50 percent of the time, and a median daily maximum temperature of 28°C is expected to be exceeded on 13 June, 50 percent of the time.

A more conservative risk tolerance of favorable conditions three years in four was chosen for this application. For the daily minimum temperature, this is represented by the 25 percent probability of not exceeding a given temperature (or the 75 percent probability of exceeding it). For the maximum temperature, the 75 percent probability of not exceeding a given temperature represents the three years in four event. Temperatures that represented the 25 and 75 percent probability for both the maximum and minimum temperatures for each day of the year were determined using 30 years of climate data and the Gumbel probability distribution (Wilks, 1995); thus, the number of observations used in computing each day's Gumbel distribution parameters was 30. The Gumbel distribution was chosen because of the ease of estimating its parameters using the methods of moments, and the fact that the Gumbel distribution can be analytically integrated. This makes it easy to compute the representative temperature for a desired probability level. At Urbana, Illinois, a 25 percent nonexceedence of a 10°C minimum temperature occurs on 23 May, 14 days later than if the mean daily minimum temperature had been used. A 75 percent exceedence of a 28 °C maximum temperature occurs on 29 May, 15 days earlier than if the mean daily maximum temperature had been used. Temperature probability thresholds such as, one year in 10 or one year in 20 could just as easily have been selected as thresholds.

Growing Season. The growing season length, defined as the number of growing days available for crop growth, was assumed to begin the day when the minimum temperature, with a probability of 75 percent, exceeded 0°C, or the daily maximum temperature exceeded the absolute minimum temperature required by the crop. The growing season was assumed to end when the daily minimum temperature, with a probability of 25 percent, after July 1 was less than 0°C, or the daily maximum was less than the absolute minimum temperature required by the crop.

Winter Minimum. Winter minimum temperature values at each station were computed using the lowest daily minimum temperature each year, and computing the minimum annual temperature expected one year in four. This conservative probability level was selected because of the costly consequences of temperatures below the minimum tolerance of a perennial crop.

Suitability Maps

Crop suitability maps were created using Arc-GIS (ESRI, 2000) to combine the climate and soil conditions in Illinois with the climate and soil requirements of each crop. The climate and soil variables included in the model used to develop the suitability maps were constrained by the crop climate and soil requirements available in the literature. Model development also was constrained by the need for it to apply the model to a large number of species. The result was the development of a simplified model that does not estimate biomass or yield.

Model Assumptions.

All models use simplifying assumptions. These assumptions need to be known in order to understand their effect on model results and to acknowledge model limitations. The discussion of the four major model assumptions explain how they may affect the results. The first three assumptions deal with the physiological response of crops to the environment. The fourth assumption deals with the extent to which management practices modify the environment.

Assumption 1. Within the range of their environmental requirements, all plants respond to environmental constraints in the same manner, and all varieties of a crop respond the same way. This assumption may result in a higher suitability classification for a species that may be more sensitive to a variable than the general response assigned.

Assumption 2. Temperatures exceeding the absolute maximum or those falling below the absolute minimum tolerated by a crop do not kill the plant, but rather stop or significantly reduce cell division or elongation. When temperatures return to a more favorable range cell division and elongation resume the same rate that occurred prior to the unfavorable temperatures. The longer the temperature remains outside the absolute maximum and minimum temperature range, the less suitable the environment is for the crop. This assumption may be violated by a crop that is especially temperature sensitive. Such a crop may be damaged severely by episodic hot or cold temperatures and thus would be unsuitable, while the model would indicate that the temperature conditions were suitable for the species. For example, in the case where the temperature sensitivity occurs during flowering, a crop may fail to set fruit, thus resulting in crop failure. This failure would make the location unsuitable for the species; however, the model would indicate it was suitable.

Assumption 3. Precipitation, growing days, and winter minimum temperature follow the "law of the minimum." This specifies that if a variable is limiting, the species cannot be grown, even if all the other variables are not limiting (Gardner et al., 1985, p. 190).

Assumption 4. Soil drainage and pH are variables that can be modified by management practices. For example, naturally poorly drained soil can be drained so that crops respond as though the soil were moderately well drained. Thus, a crop that requires moderately well-drained soil would be suited to poorly drained soil, because it is assumed that if the crop were to be grown on poorly drained soil, the producer would install drainage tile. Likewise, if the pH were not suitable, the producer, within limits, would use management practices that would make the pH more suitable. Therefore, these variables along with temperature and soil texture are additive and are weighted equally in the model. There are limits to how much the soil environment can be modified. For example, it is not practical to change excessively drained soil to well-drained soil.

There are also inherent assumptions with using GIS. The major assumption deals with the sharp boundaries of polygons and assumes that discrete lines between polygons adequately represent the changes in physical properties of the soil, climate, or both. Such a case rarely occurs in the real world. Generally, there is a gradient in a change in soil properties and temperature. Thus, suitability classifications near the boundaries may be suspect.

Model Limitations.

The model is limited to a general assessment of the suitability of a location for a crop. However, because other growth-limiting variables are not considered – for example, rooting depth and timing of precipitation during the growing period – the final suitability maps may not depict suitability of an established crop, as would be expected from soil and crop management research. Further, the limitation of soil texture and pH to the surface layer dilutes the total effect of these two variables on location suitability.

Soil characteristics were combined for a map unit, resulting in a representative soil characteristic that may or may not represent a given soil within the map unit. This limitation may result in a specific soil in a map unit being classified into a different suitability class than by mapping individual soil types separately.

Finally, there is considerable areal averaging of the climate variables. This is unavoidable, however, because 30-year climate data are used rather than data for a specific year. This averaging should not pose large problems. In locations where topographic and geographic features significantly modify the microclimate, specific small, localized areas where a species may be grown will be missed. These localized areas are also beyond the resolution of the STATSGO database.

Model Description.

The model consists of two basic components. The first component includes the procedures to evaluate the individual soil (texture, pH, and drainage) and climate variable (temperature, precipitation, winter minimum temperature, and growing days) suitability by comparing local conditions to crop requirements. The second component combines the soil and climate suitability scores into an overall suitability score that has both a quantitative (numerical value) and qualitative description. The numerical value ranged from 0 to 4, where <0.5 was unsuitable; ≥0.5 and <1.5, slightly suitable; ≥1.5 and <2.5, moderately suitable; ≥2.5 and <3.5, suitable; and ≥3.5, highly suitable. Suitability scores account for the soil and climate requirements of each crop and the soil and climate characteristics of the location. As a rule, it was assumed that as the soil and climate characteristics deviate from those required by a crop, the suitability of the specific soil or climate characteristic decreases.

Soil Texture Suitability. Soil texture suitability was determined for 21 crop-soil texture requirement groups (Table 1). Plant requirements of soil texture ranged from plants preferring a single soil texture class such as sand, silt, or clay, to crops that can grow in almost any soil. Soil texture suitability for a crop was assigned by mapping the percentage of sand and clay for the map unit on a graph representing the soil texture preferred by the crop.

Table 1. List of soil texture classes used to define texture suitability for crop soil texture requirements.

Crop Soil Texture Classes
All Soils
All to Sandy Soils
Clay Soils
Clay to Clay Loam Soils
Clay to Loam Soils
Clay to Sandy Loam Soils
Clay Loam Soils
Clay Loam to Loam Soils
Clay Loam to Sandy Soils
Clay Loam to Silt Soils
Loam Soils
Loam to Sandy Loam Soils
Medium Soils
Medium to Clay Soils
Medium to Sandy soils
Sandy Soils
Sandy to Sandy Loam Soils
Sandy Loam Soils
Silty Clay to Silty Clay Loam Soils
Silty Loam Soils
Silty Loam to Sandy Loam Soils

Soil pH Suitability. Crop pH preferences were separated into crops with narrow, medium, and wide pH ranges, based on the published preferences for each crop. A narrow pH range defines crops having a reported pH range of < 1 (maximum pH minus minimum pH), medium pH crops with a pH range of 1 to 2, and wide crops with a reported pH range greater than 2. Ten soil-pH classes, ranging from very strongly acidic soils to very strongly alkaline soils, were identified for crop soil-pH preferences. Suitability scores were determined by comparing the soil pH to the mean and deviation from the mean of the crop's preferred soil pH (Figure 1). In determining pH suitability classes, the suitability was related to the pH tolerance range of a crop, i.e., as the crop's pH range widened, the suitability also was widened. For example, if one assumes the mean preferred pH is 7, then soil pH ranges for the different suitability classes are those shown in Figure 1.

Soil Drainage Suitability. The model for the drainage suitability scores is depicted in Figure 2. Descriptions in the first row represent the drainage classifications of the soil at a location. Drainage classifications in the other represent the different crop requirements and the soil suitability for the crop's requirement at a location. Naturally poorly drained soils are given higher suitability classifications for plants that prefer moderately well-drained to poorly drained soils because the drainage of these soils can be modified by installing tile drainage.

Temperature Suitability. The air temperature model was designed to describe how a crop's temperature requirement matched the temperature environment for the year by using a single number. The single number for the year was obtained by using the daily maximum and minimum temperatures, which were further used to compute hourly temperature suitability values for each day. This weighted the daily suitability value by the time when the hourly suitability values were in a particular temperature suitability class. The maximum and minimum temperature expected three years in four for each day of the year were computed for 83 Illinois climate stations. The annual maximum and minimum temperature traces in Figure 3 represent the three years in four daily maximum and minimum temperatures for Urbana, Illinois. These temperature traces with the cardinal temperatures thresholds for *Miscanthus x giganteus* (Figure 3) show that both the maximum and minimum temperatures are within the optimum minimum and maximum temperature thresholds for 50 days. Thus, for half of the 100-day minimum growing season, the temperature at Urbana is highly suitable for *Miscanthus x giganteus*.

Hourly suitability scores (S_h) were determined by the relationship of the hourly temperature (T_h) to the four cardinal temperatures for a crop (absolute minimum, A_{mn}; optimum minimum, O_{mn}; optimum maximum, O_{mx}; and absolute maximum, A_{mx}). The hourly suitability scores were determined as:

Range	*Unsuitable* *pH*	*Slightly suitable* *pH*	*Moderately suitable* *pH*	*Suitable* *pH*	*Highly suitable* *pH*	*suitable* *pH*	*Moderately suitable* *pH*	*Slightly suitable* *pH*	*Unsuitable* *pH*
Narrow	< 6.15	6.15 - 6.25	6.25 - 6.45	6.45 - 6.75	6.75 - 7.25	7.25 - 7.55	7.55 - 7.75	7.75 - 7.85	>7.85
Medium	<5.75	5.75 - 6.00	6.00 - 6.25	6.25 - 6.50	6.50 - 7.50	7.50 - 7.75	7.75 - 8.00	8.00 - 8.25	>8.25
Wide	<5.50	5.50 - 5.75	5.75 - 6.00	6.00 - 6.50	6.50 - 7.50	7.50 - 8.00	8.00 - 8.25	8.00 - 8.50	> 8.50

Figure 1. Soil pH suitability classes for a crop with a preferred soil pH of 7 with different pH tolerances (top), generalized pH suitability ranges using the mean pH preference of the species (center), classification key for center figure (bottom).

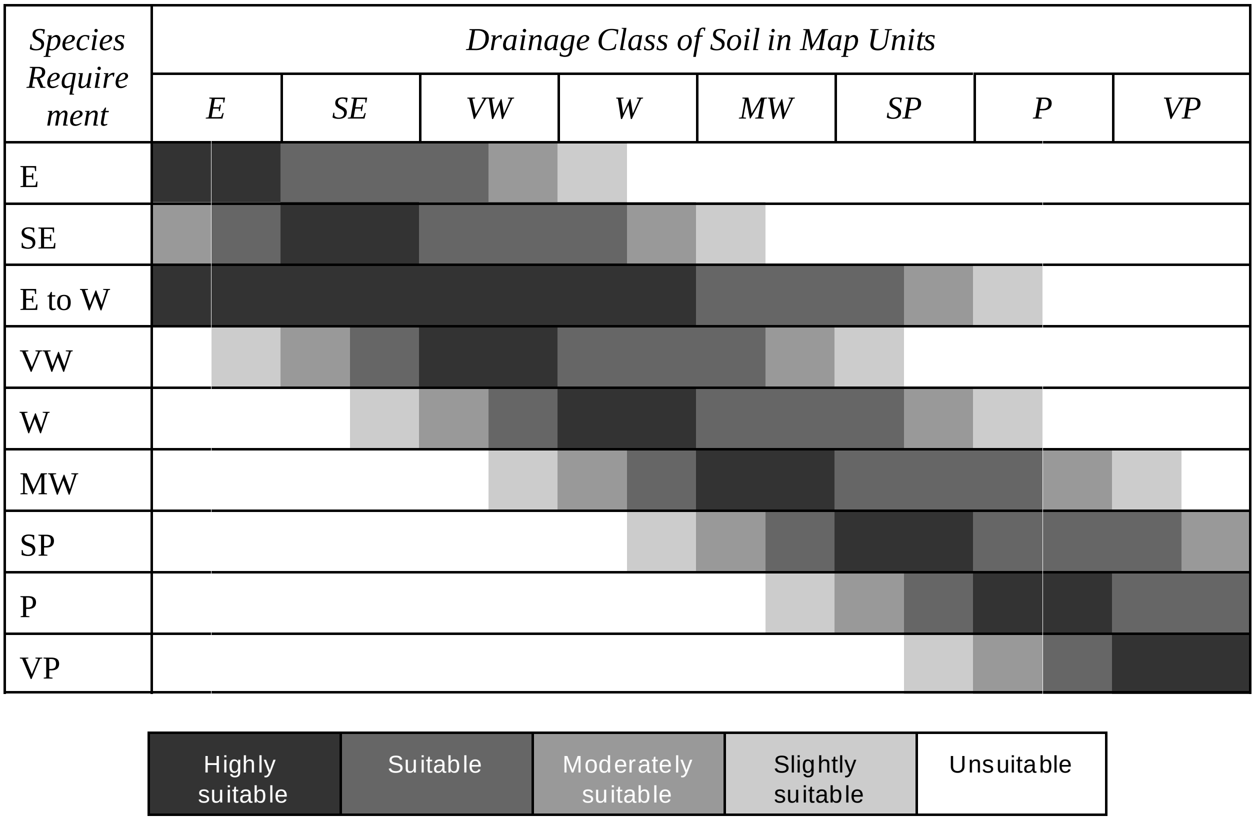


Figure 2. Diagram of soil drainage suitability for different crop requirements (E= escessively drained, SE = somewhat excessively drained, VW = very well drained, W = well drained, MW = moderately well drained, SP = somewhat poorly drained, P = poorly drained, and VP = very poorly drained).

$$\begin{gathered} T_h < A_{mn} \text{ then } S_h = 0 \\ T_h > A_{mn} \text{ and } < O_{mn} \text{ then } S_h = 3 \\ T_h > O_{mn} \text{ and } < O_{mx} \text{ then } S_h = 5 \\ T_h > O_{mx} \text{ and } < A_{mx} \text{ then } S_h = 3 \\ T_h > A_{mn} \text{ then } S_h = 0 \end{gathered} \qquad (2)$$

Hourly temperatures *(T_i)* for each day were estimated from original equations (Equations 3-5) developed for this application using the daily maximum (T_x) and minimum (T_n) temperatures and sine and cosine functions. For the period from sunrise (t_{sr}) to the time of occurrence of the maximum temperature for the day (assumed to be 1300 hours) a cosine function was used:

$$T_i = T_x - A\left(1 - \cos\left(\left[\frac{\pi/2}{13 - t_{sr}}\right](13 - t_i)\right)\right) \qquad (3)$$

where A is the amplitude of the temperature computed as the difference between the current days T_n and T_x, and t_i is the hour of the day between sunrise and 1300 hours expressed as hh, i.e, 09 hours. Between 1300 hours and midnight (0000), and midnight and t_{sr}, a sine function was used.

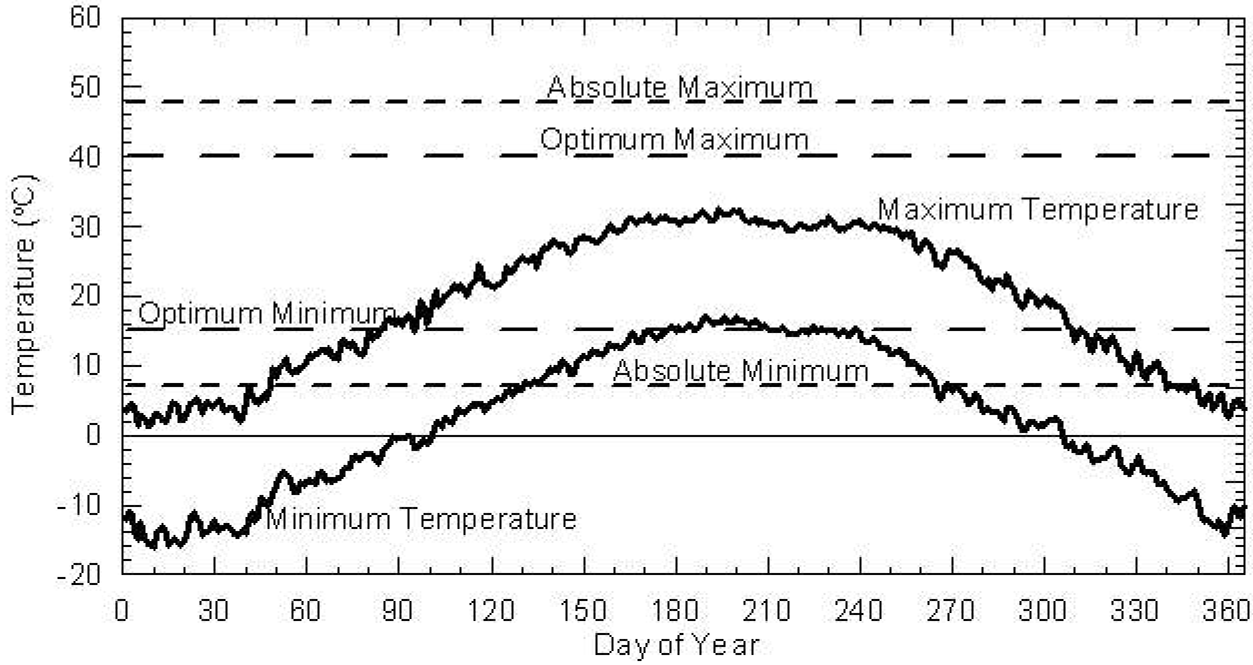


Figure 3. Comparison of *Miscanthus x giganteus* cardinal temperatures to daily minimum and maximum temperatures at Urbana, Illinois.

From 1300 hours to midnight, the function was:

$$T_i = T_x - A_n \sin\left(\left[\frac{\pi/2}{11 + t_{srn}}\right](t_i - 13)\right) \quad \textbf{(4)}$$

where A_n is the amplitude of the temperature between T_x of the current day and T_n of the following day, and t_{srn} is the time of sunrise on the next day. For the period from midnight to sunrise, the function was:

$$T_i = T_{xp} - A_p \sin\left(\left[\frac{\pi/2}{11 + t_{sr}}\right](t_i + 11)\right) \quad \textbf{(5)}$$

where T_{xp} is the maximum temperature of the previous day, and A_p is the amplitude of the temperature between T_{xp} and T_n. All functions assumed that sunrise was the time of the minimum temperature. Combining Equations (3)-(5) provides a smooth shape to the daily temperature curve (Figure 4). In the example, the previous day's maximum temperature was 27°C, the current day's minimum temperature was 20°C and the maximum 30°C, respectively, and the following day's minimum temperature was 21°C. For this temperature scenario and the cardinal temperatures for *Miscanthus* x *giganteus*, the hourly temperature scores are all equal to 5.

The daily temperature suitability for all days between the last spring frost and the first fall frost was the mean hourly suitability score. The temperature suitability for the year was the mean of the daily suitability scores between the last spring frost and the first fall frost.

For winter annual crops, the temperature suitability was the mean of the daily temperature suitability scores between the period of planting to harvest, exclusive of the dormancy period. Planting was assumed to occur in the fall on the last day that the optimum maximum temperature

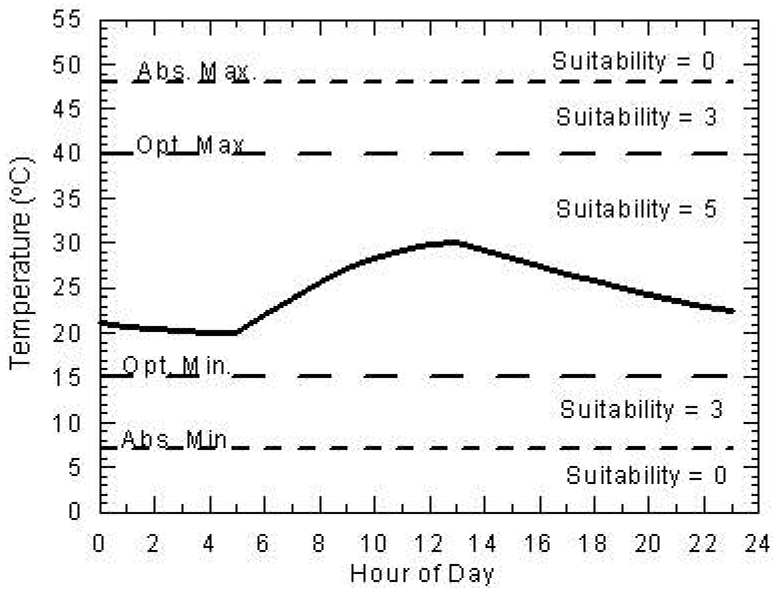


Figure 4. Example of hourly temperature distribution based on daily maximum and minimum temperature and cardinal temperatures for a hypothetical crop.

required by the species was exceeded one year in four. Harvest was assumed to begin in the spring or summer when the first day of the year that the maximum temperature exceeded the optimum maximum temperature three years in four. During the dormancy period, daily temperature suitability scores were not included in the growing season suitability score. The dormancy period was assumed to begin when there was less than a one year in four chance of the daily maximum temperature exceeding the absolute minimum temperature required by the crop, or the date that the minimum temperature was less than 0°C three years in four, whichever was earlier. The end of the dormancy period was assumed to occur on the first day that the maximum temperature exceeded the absolute minimum temperature required by the crop, or that the minimum temperature was above 0°C three years in four whichever was later. The growing season days, number of days between planting and harvest, were decreased by the number of days in the dormancy period. Exclusion of the dormancy days was justified because the daily suitability scores during the dormancy period were always 0, thus including the number of days of the dormancy period in the denominator underestimated the temperature suitability. Further, this method resulted in computing temperature suitability for the season only when the crop was growing actively .

Precipitation Suitability. Precipitation suitability was based on the range of the published annual precipitation requirements for each species. As the precipitation either increased above the maximum of the precipitation requirement range or the shortfall increased below the minimum of the precipitation requirement range, the suitability decreased (Figure 5). Two suitability scales were developed based on the reported crop precipitation requirements - one for crops with a wide precipitation requirement range (>300 mm), and one for crops with a narrow precipitation requirement range (≤ 300 mm). In the case of crops with a wide precipitation requirement range, the suitability for areas with excess precipitation decreased as a function of the precipitation range (Figure 5). For areas with a deficit, the suitability decreased by set precipitation deficit thresholds (150 and 350 mm). For crops with a narrow precipitation requirement range, the suitability for areas with precipitation deficits was a function of the precipitation requirement range, and the areas with excess precipitation had specified precipitation steps (350, 480, and 600 mm). For situations where actual precipitation was less than a crop's precipitation requirement, suitability scales were designed to allow up to 350 mm of water to be applied through irrigation, based on the assumption that the delivery mechanism and at least 350 mm of water were available for application to the land.

Winter Minimum Temperature Suitability. Overwintering crops (perennials, biennials, and winter annuals) were scored for cold tolerance — their ability to withstand extreme

Crops with precipitation range ≥300 mm yr^{-1}								
<Min-350 mm	≥Min-350 mm	≥Min-150 mm	≥Min	≥Min+1/3 of range	≤Max+range*1.25	≤Max+range*1.6	≤Max+range*1.8	>Max+range*1.25
Crops with precipitation range <300 mm yr^{-1}								
<Min-350 mm	≥Min-2/3 range	≥Min-1/3 range	≥Min	≥Min+1/3 of range	≤Max+350 mm	≤Max+480 mm	≤Max+600 mm	>Max+600 mm

Highly suitable	Suitable	Moderately suitable	Slightly suitable	Unsuitable

Figure 5. Precipitation suitability based on the range of the crop's precipitation requirement.

minimum temperatures. Based on the published extreme minimum temperature a crop can withstand, suitability was determined by comparing an area's extreme minimum winter temperature to the plant tolerance. This comparison may be done using any desired extreme minimum winter temperature probability, i.e., 1 year in 20, or 1 year in 4. For this work the one year in four extreme winter temperature for an area was used. The thresholds for different suitability classes were 1°C increments above the extreme minimum temperature tolerated by the crop. For example, the location would be unsuitable if the extreme winter minimum temperature tolerated by a crop was -30°C and the one year in four minimum temperature for an area was <-30°C; the location would be slightly suitable if the area's temperature was between –29 and -30°C; moderately suitable between –28 and -29°C; suitable between –27 and -28°C; and highly suitable greater than -27°C highly suitable. This approach was based on the USDA Plant Hardiness Zone Map (Cathey, 1990) that shows 5°F (2.8°C) temperature ranges for each suitability zone. Using a 1°C step for the five suitability classes provides a graduation across a region for suitability rather than a binary suitable-unsuitable classification. Annual crops do not overwinter and were considered highly suited to an entire region, based on the assumption that sensitivity to cold temperatures would be expressed in the temperature and growing days suitability scores.

Growing Days Suitability. Growing days (GD_e) were determined by the shorter of two periods defined either by the dates of the last spring frost (0°C) and the first fall frost, or by the first spring day and the last fall day that the daily maximum temperature exceeded than the absolute minimum temperature required by the crop. Thus, this component can be crop specific. A range of growing days (GD_r), defined by a minimum growing day requirement (GD_{mn}) and a maximum growing day requirement (GD_{mx}), was available for many crops. The suitability score for growing days (GD_{ss}) was determined as:

$$\begin{gathered} GD_e < GD_{mn} \text{ then } GD_{ss} = 0 \\ GD_e \geq GD_{mn} \text{ and } < GD_{mn} + 0.125GD_r \text{ then } GD_{ss} = 1 \\ GD_e \geq GD_{mn} + 0.125GD_r \text{ and } < GD_{mn} + 0.250GD_r \text{ then } GD_{ss} = 2 \\ GD_e \geq GD_{mn} + 0.250GD_r \text{ and } < GD_{mn} + 0.375GD_r \text{ then } GD_{ss} = 3 \\ GD_e \geq GD_{mn} + 0.375GD_r \text{ then } GD_{ss} = 4 \end{gathered} \qquad \textbf{(6)}$$

where 0 represents an unsuitable growing season length, 1 slightly suitable, 2 moderately suitable, 3 suitable, and 4 highly suitable. This approach assumes that if a region's growing season was less than the minimum days required by a crop, the region would be unsuitable. As the season length increases beyond the minimum growing season required, the region becomes more suitable for a crop. This is accounted for in Equation 6 by testing the minimum growing season requirement plus an increment of the crop's growing season range against the number of growing days in a region.

The above method was used to determine the growing season length suitability for annual, biennial, and perennial crops. For winter annuals, the growing season, defined by the date of planting in the fall and harvest in the next spring or summer, includes a dormancy period for most crops. Unfortunately, it was unknown if the reported growing season length did or did not include the dormancy period. Including the dormancy period in the analysis may have resulted in an inflated growing season length, while excluding the dormancy period may have resulted in a deflated growing season length. With inflated growing season length, the suitability scores became less limiting; thus, winter annual crops were deemed suitable in regions with climate conditions under which the crops were not normally grown. Deflated growing season length resulted in lower suitability scores, and winter annual crops were deemed unsuitable for regions with climate conditions under which the crops were known to thrive. Therefore, the growing season length was assumed to be suitable for all winter annual crops, and the limitation of the growth was determined by the minimum winter temperature.

Overall Suitability. Map algebra (ERSI, 2000) was used to create the overall suitability scores and component maps. Overall suitability was computed as the product of the average of the air temperature, soil drainage, soil texture, and soil pH suitability scores, and the product of the winter cold tolerance, number of growing days available, and precipitation suitability scores (Figure 6).

The four model components that were averaged represent components that at some time during the growing season meet the species requirements (air temperature), that affect growth and yield rates without killing the crop (air temperature, or soil texture), or that can be modified by management practices (soil drainage, or pH). The average of these four components has a 0-4 range but is rarely, if ever, 0.

The three components that are multiplied together individually can have extremely limiting effects on the suitability of a location for a crop. The law of the minimum was applied to these three components; thus, if precipitation was unsuitable, the location was unsuitable regardless of suitability of the other components. The 64 in the denominator scales the value of the expression on the right to a range of zero to one. The exponent of 0.3 distributes the suitability scores more evenly between an interval of 0 to 1.

Results

The model was applied to the climate and soils data of Illinois using climate and soil requirements for 414 potential crops. Limiting factors in Illinois were growing season length, temperature, precipitation, and winter minimum temperature. All soil texture and drainage classes were included in the Illinois conditions. Therefore, growth suitability for these two variables are localized within the state.

The range of the frost-free season across Illinois was 160 days in the northwestern part of

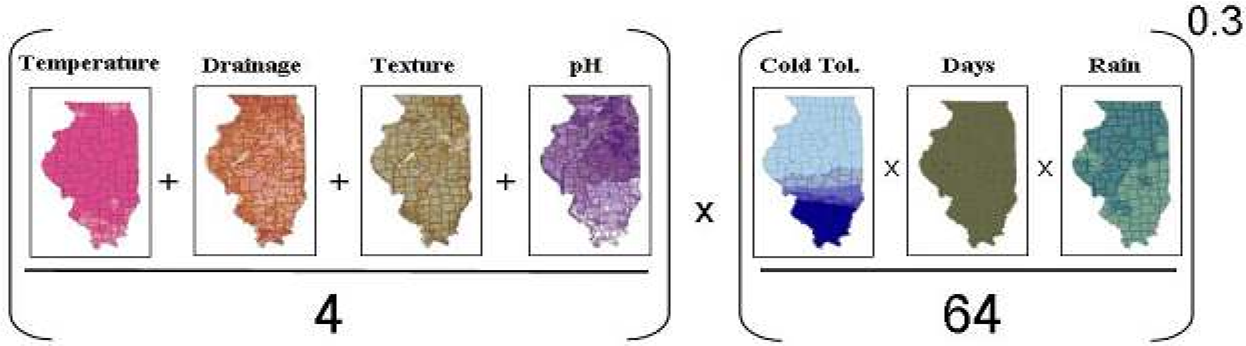


Figure 6. Map mathematics used to compute overall suitability score from soil and climate component maps.

the state and 200 days in the south. The minimum growing season required by the 414 potential crops ranged from 20 days to 365 days, and the maximum growing season required ranged from 55 days to 365 days. Only those crops that required more than 200 days to grow were classified as unsuitable in the entire state, while crops with growing season requirements between 160 days and 200 days would be unsuitable in only part of the state. Twenty-two crops had growing season requirements greater than 200 days and thus were unsuitable for Illinois conditions. A total of 35 crops had a growing season requirement between 160 and 200 days. An example is the European plum (*Prunus domestica* L. subsp. *domestica*) which has a minimum growing season requirement range of 180 to 210 days. With the rules in Equation 6, the growing season in Illinois is unsuitable (score = 0) for the European plum where the growing season is less than 180 days, slightly suitable (score = 1) where the growing season is between 180 and 184 days, moderately suitable (score = 2) where the growing season is between 184 and 188 days, suitable (score = 3) where the growing season exceeds 188 days and is less than or equal to 191 days, and highly suitable (score = 4) where the growing season exceeds 191 days.

Crop absolute minimum temperatures ranged from 2 to 19°C, and the absolute maximum temperatures ranged from 18 to 50°C. Crop optimum minimum temperatures ranged from 5 to 31°C, and optimum maximum temperatures ranged from 15 to 45°C. The Illinois maximum winter temperature range (-6 to 2°C) indicates that temperature conditions during the winter are unsuitable for all crop growth. At the same time, the minimum summer temperature (17 to 23°C) is suitable for crop growth for most crops. With a maximum summer temperature range of 29 to 33°C in Illinois, 92 crops with an absolute maximum temperature requirement of less than 29°C would experience some heat stress throughout the state. An additional 113 crops with a maximum absolute temperature requirement between 29 and 33°C would experience heat stress in those regions of the state where the summer maximum temperatures exceed the crop's absolute maximum temperature.

Annual precipitation in Illinois ranges from 877 to 1238 mm. Comparing this to the crop minimum annual precipitation requirements (50 to 2198 mm), and the maximum annual precipitation requirements (300 to 3807 mm) indicates that precipitation in Illinois is too high for 44 crops, and too low for 18 crops. The precipitation range allows for the ability to add an additional 350 mm of water through irrigation. The underlying assumption is that the water and methods to apply the water are available throughout the state.

Extreme minimum winter temperature suitability maps were prepared for 321 crops. The additional 93 crops for which extreme minimum winter temperature maps were prepared were annual or functional annual crops that would need to be planted at the start of each growing season. Extreme minimum winter temperatures are unsuitable in all of Illinois for 197 crops. An additional 14 crops may be grown in those regions of the state where extreme minimum winter temperatures exceed -20 °C.

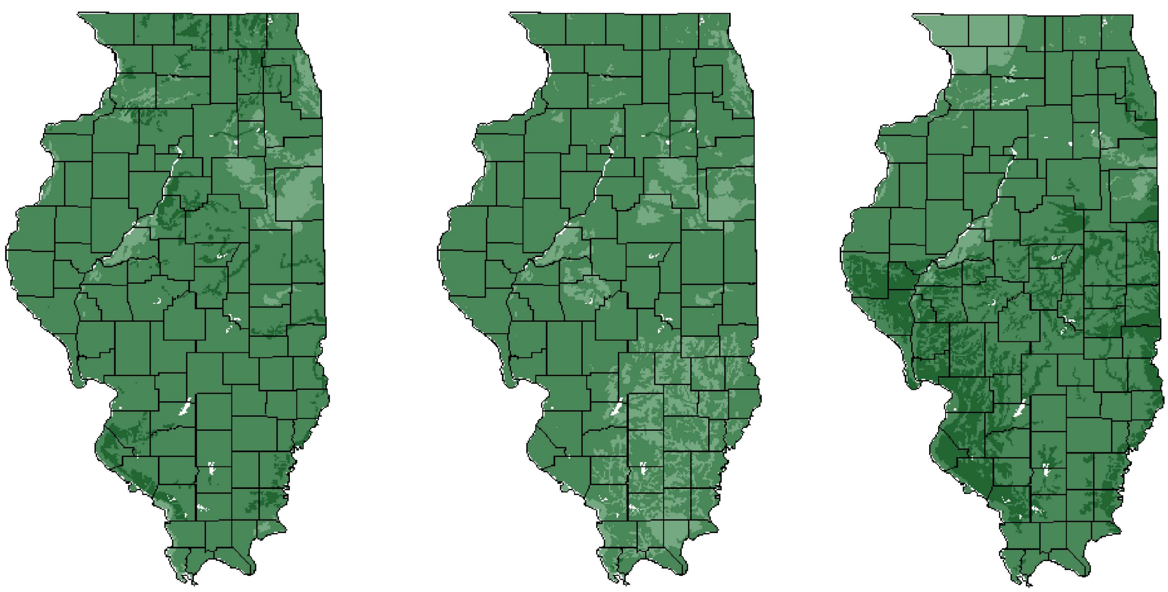
Examples of the model output for corn (*Zea mays* L.), soybean (*Glycine max* (L) Merrill), and miscanthus (*Miscanthus* x *giganteus*) are shown as examples (Figure 7) of model performance. Corn and soybean crops are grown widely in Illinois, while miscanthus is being investigated as a potential biofuel for generation of electricity. *Miscanthus* x *giganteus* is a vegetatively propagated hybrid cross between *Miscanthus sinensis* Andersson and *Miscanthus floridulus* (Labill) Warb. Ex K. Schm. & Lauterb. All three crops show suitability scores throughout the state ranging from moderately suitable (lightest shades on map) to highly suitable (darkest shades on map).

Conclusions

Soil (texture, pH, and drainage) and climate (temperature, precipitation, growing day, and minimum winter temperature) requirements were identified for 414 species. A model was developed to evaluate the suitability of a geographically referenced location's climate and soil conditions to the crop soil and climate requirements. The simple model accurately identifies corn and soybean as crops suitable for Illinois conditions. Further, it identified regions of the state that were less suitable for the crops. For corn, the main delimiting factor was soil texture (Figure 7), with less suitable areas occupied by sandy soils. For soybean, the main factors were soil texture in central Illinois and soil pH in southern Illinois (Figure 7). If the suitability scores are compared to historical corn and soybean yields, there are areas where recorded yields are greater than would be expected based on the suitability scores. Generally, those areas with suitable to highly suitable scores are associated with the higher yielding areas of the state. However, due to the limited model inputs, one would not expect suitability scores to replicate exactly the results of more complex models such as the CERES-Maize (Jones and Kiniry, 1986), SOYGRO (Wilkerson et al., 1983), or the DSSAT (Hoogenboom et al., 1995) models.

The model also shows *Miscanthus* x *giganteus* as being suitable to highly suitable throughout much of the state. In the central and southern regions of the state, soil texture and drainage are the main delimiters of suitability. Moderately suitable scores in the five-county area in the northwestern corner of the state are due to winter minimum temperature, which is cold enough to affect this perennial's ability to overwinter.

The model can be applied to a region or a specific location. Application to a region requires access to geographically referenced information, while application to a specific site requires knowledge only of the climate and soil for the location.



Corn Soybean Miscanthus

Figure 7. Examples of suitability scores for corn (*Zea mays* L.), soybean (*Glycine max* Merrill), and miscanthus (*Miscanthus x giganteus*). Lighter colors represent lower suitability scores.

Climate and soil requirements available for crops generally are not adequate to allow the development of a detailed model of crop yield. The greatest limitation is the lack of information relative to the crop precipitation requirements during the growing season. Therefore, the model results are an indication of the suitability of a location for a specific crop. The results should not be construed to indicate definitively that the crop can be grown in the area, nor that highly suitable locations will result in larger yields than suitable areas.

Application of the model should not be construed as an all inclusive process of identification of alternative crops. At best, it provides an indication of which crops may have the greatest success of being grown in a region. Final identification will require an in-depth study of other environmental factors that may limit crop growth and production. This will require the inclusion of many other academic and research disciplines.

The model also may be applied to other studies that require an understanding of regional crop growth such as the effects on climate change on crop distribution. Coupled with GIS programs and extensive databases, shifts in relative advantages of different regions to changes in annual precipitation and temperature may be identified by application of the model.

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