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Forage Species Suitability Mapping for China Using Topographic, Climatic and Soils Spatial Data and Quantitative Plant Tolerances

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Abstract

Selecting plants adapted to the climatic and soil conditions of specific locations is essential for environmental protection and economic sustainability of agricultural and pastoral systems. This is particularly true for countries like China with a diversity of climates and soils and intended uses. Currently, proper species selection is difficult due to the absence of computer-based selection tools. Climate and soil GIS layers, matched with a matrix of plant characteristics through rules describing species tolerances would greatly improve the selection process. Better matching will reduce environmental hazards and economic risks associated with sub-optimal plant selection and performance. GIS-based climate and soil maps have been developed for China. A matrix of quantitative species tolerances has been developed for example forage species and used in combination with an internet map server that allows customized map creation. A web-based decision support system has been developed to provide current information and links to original data sources, supplementary materials, and selection strategies.

Key words: Geospatial, Climate, Soils, Eco-physiology, Internet map server (IMS), Dynamic mapping system, Decision support system (DSS), Perennial ryegrass, *Lolium perenne* L., Orchardgrass, *Dactylis glomerata* L., Tall fescue, *Lolium arundinaceum* (Schreb.) Darbysh.

INTRODUCTION

Sustainability is a major focus today in agriculture and natural resource systems-seeking to utilize plant, animal, soil, and water resources in the most-productive and least-damaging manner. Consequently, land managers frequently request recommendations on which species and varieties would best fit into their production system[1,2]. Species selection tools, however, have been too generalized and have lacked the wealth of knowledge available from different disciplines. Improved plant selection tools would: (1) better capture and disseminate the collective knowledge of agronomists, grassland ecologists, GIS specialists, climatologists, soil scientists, information science specialists, farmers, and ranchers, and (2) facilitate improved, individually tailored decision making.

Traditional suitability zone maps typically show general zones where species are being grown. Usually these maps are produced by a graphicsartist working with a crop specialist or agro-meteorologist and depict gen-

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eral agricultural concepts and broad groupings of precipitation and temperature and/or soils. These maps are of minimal value in decision-making. There is a need for maps that are more specific, consider more information, and can be readily changed to reflect the most current state of knowledge.

CREATING FORAGE SUITABILITY ZONE MAPS FOR CHINA: A NEW APPROACH

Creating improved, plant species suitability maps for China involves integrating spatial topographic, climatic, soil, and plant information in a "quantitative ecology" approach. This quantitative tolerances approach is used to define the highly productive range and survival limits of example forage species (i.e., minimum, maximum, and optimal ranges for temperature, precipitation, pH, and drainage)[3,4].

This approach differs from traditional species adaptation and selection approaches in two ways. First, it involves developing a matrix (database table) of plant growth limitations and matching these quantitative tolerances with the spatial data layers (GIS coverages) for climate, soil, and geophysical elements (temperature, precipitation, pH, drainage, slope, aspect, etc.). This approach allows for geographically explicit and individually tailored recommendations for land managers in predicting suitability zones for specific crop and restoration species.

Second, spatial suitability maps are developed digitally, based on the best spatial information available, then evaluated and improved with field trial data and expert knowledge. Traditionally, species suitability information has been extrapolated spatially from a small number of field trials.

However, field trials are expensive and difficult to implement and manage, and suffer from variations in weather conditions from year to year.

CURRENT TOOLS

Current computer-based tools, including geographic information systems (GIS), internet map servers (IMS) and "dynamic mapping," expert systems (ES), decision support systems (DSS), and web-based delivery systems can be combined to develop and display better maps of plant species needed for various agricultural and natural resource management applications.

GIS

GIS is a family of powerful and dynamic computer software systems that manipulate and display layers of spatially variable data. A variety of data types are used including climate factors (precipitation, temperature, radiation), geo-physical features (topography, mineral and soil traits, ground and surface water), biological characteristics (plant and animal information and tolerances), socio-economic factors (demographics, values for inputs and products), and geo-political information (political boundaries, urban centers, transport infrastructure). By integrating these individual spatial data layers in a GIS, it's possible to better understand their interrelationships and create more useful maps.

Internet map server (IMS) and dynamic mapping

Internet map servers allow maps to be displayed in web-based applications. There are both proprietary, commercially distributed versions and "open source" IMS programs available. For applications involving considerable customization and multi-national cooperation, the open source versions have compelling advantages.

One of the recent developments for improving mapping is the capability to develop "dynamic" maps via an IMS application. This paper reports the development of an 'open source' dynamic mapping system (based on the Minnesota Map Server; http://mapserver.gis.umn.edu/) that allows for refinement of the suitability maps by cooperating plant species experts. This application allows translation of "mental maps" into quantitative tolerance-based digital maps.

DSS and ES

Integration of GIS layers within a decision support system (DSS) or expert system (ES) permits agriculture and natural resource management decision makers to see the context of any specific action. This is important for protecting fragile ecozones, minimizing inputs of fertilizers and pesticides, optimizing the use of land for agricultural production, and improving economic returns. This paper reports on the development of a DSS for species selection that integrates spatial information into typical scenarios involving forage-livestock systems, soil conservation, and urban greening. The result is that the decision-making process is made simpler and more ecologically-based.

Web-based delivery

Delivering information 24 hours a day, 7 days a week (24-7) through web-based information systems offers significant benefits, especially when developers and cooperators are located in different countries and time zones. Web-based systems also offer the benefit of providing various types of tools in an integrated and easy-to-use format. Multiple language versions are also possible, with significant savings over separate, independent systems. The forage information system[5], hosted by Oregon State University (http://forages.oregonstate.edu/), was an early leader in developing and delivering forage-based information. The applications reported in this paper have been integrated into the FIS.

METHODS

The creation of improved suitability maps for China involved producing detailed climate and soils maps, and combining this information with quantitative tolerance estimates in a GIS environment. The maps are validated with results from field-based trials and expert knowledge.

Climate and soils mapping

The development of detailed, state-of-the-science climate maps for China was a major part of the overall effort. Climate maps available at the time were highly generalized, and did not adequately represent the detailed spatial variability in climate produce by physiographic variations, such as terrain, coastal effects, and others. In this project, detailed climate maps were developed by: (1) collecting station climate data from all possible sources and performing quality checks; and (2) interpolating the station data to a 4-km resolution grid using the PRISM climate mapping system.

Station climate data were collected from the People's Republic of China and neighboring countries. Totaling 3 274 stations for precipitation and 2 562 stations for minimum and maximum temperature, they represent one of the most comprehensive station data sets currently available for this region.

The mean monthly station data were checked for reasonableness by applying a version of PRISM that performs jackknife cross-validation on each station in the dataset. Stations with large observation-prediction errors were identified. The PRISM Graphical User Interface was then used to display climate-elevation scatterplots in the vicinity of the questionable stations to determine if the station "fit in" with the others, or was an obvious outlier. Outliers were removed from the dataset. A number of station location coordinates were found to be in error, but in general, few outliers were found, giving us confidence that the climate data were of good quality.

Spatial modeling of the climate data was performed at 2.5-minute (- 4-km) resolution. A 2.5-minute digital elevation model (DEM) was derived from the GTOPO-30 DEM series. GIS was used to prepare supplementary grids used in the interpolation. These included a coastal proximity grid, estimates of wintertime temperature inversion heights, and a terrain profile grid.

The PRISM (Parameter-elevation Regressions on Independent Slopes Model) knowledge-based system[6,7] was used to grid precipitation and minimum and maximum temperature over China. PRISM is a sophisticated climate mapping technology that has been used in several major climate mapping efforts in the US. PRISM has also been used to create state-of-the-science climate maps in Europe[8,9].

PRISM uses point observational data, a digital elevation grid, and other spatial data sets to generate estimates of climatic variables on a regular grid that is GIS-compatible. The model is a moving-window linear regression of climate vs. elevation that is calculated for each grid cell in the digital elevation grid. Stations surrounding the grid cell provide data points for the regression. The heart of the model is the extensive spatial climate knowledge base that calculates station weights upon entering the regression function. These weights are based on each station's climatological similarity to the grid cell being estimated. The knowledge base and station weighting functions currently account for spatial variations in climate due to terrain height and steepness, rain shadow effects, proximity to the coast, and temperature inversions[10].

PRISM was parameterized to produce the most physically realistic maps by starting with model settings th at gave the lowest mean absolute cross-validation error, then modifying these settings as experience with China's complex climate patterns increased over time. Experience was gained by consulting publications on Chinese climate, using the station data themselves (via the PRISM graphical user interface), and by using knowledge from other regions, as applicable. General expectations of climatic patterns in China were formed, and served as a guide for the evaluation of the PRISM modeling runs. Limited peer review of the draft maps by Chinese climatologists provided much needed expert input to the process.

The end result of the China climate mapping effort was a set of GIS maps of 1961-1990 mean monthly and annual precipitation (Fig.1), and minimum and maximum temperature. (See the following URL for the searchable database of climate images developed by this project: http://forages.oregonstate.edu/is/ssis/main.cfm?PageID=100). High-resolution, GIS-compatible climate grids for China can be obtained through license agreement from http://www.climatesource.com.

Soil characteristics information was obtained with the assistance of personnel from the Soil & Fertilizer Institute, Chinese Academy of Agricultural Sciences in Beijing, and the Soil Institute, Chinese Academy of Sciences in Nanjing. Soil surveys for China began in the early 1930s under the guidance of an American soil scientist, J. Thorp [11]. Since then, regional and national surveys have been conducted by teams of Chinese and international scientists. The first China national soil survey was completed in the late 1950s. The second national soil survey was completed in the mid-1990s after 16 years of work in compiling thousands of datasets. The soils in 2 444 counties, 312 national farms, and 44 forests were surveyed. Soil maps were developed from these surveys, the first at a scale of 1:10 000 000[12,13]. Subsequently, a 1:4 000 000 national soil map was developed and digitized for widespread use by research scientists[14]. Mapping units for this 1:4 M scale map were delineated using a genetic soil classification system which was described by Shi et al [15]. This classification system was initially conceived in 1953 and its current form was finalized in 1978 by Gong et al[16]. Information contained in *Soils of China* publication[17] was compiled from provincial soil survey reports and includes: (1) soil formation, classification, and distribution; (2) soil type and properties; (3) soil fertility, and (4) soil resources and use. The 1:4 M soils map and soil characteristics information was used in the project reported in this paper. It is anticipated that future species suitability mapping projects will utilize the 1:1 M scale spatial and attribute data recently reported by Shi et al[18].

Maps now include national and provincial maps for soil type, texture, drainage, pH, salinity and alkalinity at 1:4 000 000 scale. (See the following URL for the searchable database of soil maps developed by this project: http://forages.oregonstate.edu/is/ssis/).

Species suitability mapping

Quantitative species tolerances were defined for nine example forage crop species (URL: http://forages.oregonstate.edu/is/ssis/main.cfm? PageID=103). Resources used to develop initial estimates were based on the American Society of Agronomy monographs for cool season forage grasses[19] and clover science and technology[20], and National Range and Pasture Handbook for the natural resources conservation service[21]. These quantitative species tolerances are being refined with the help of global cooperators using web-mapping tools. Example climatic and soil tolerances for three species [perennial ryegrass, *Lolium perenne* L.; orchardgrass, *Dactylis glomerata* L.; tall fescue, *Lolium arundinaceum* (Schreb.) Darbysh.] are shown in Tables 1, 2, and 3.

Using climatic and soils spatial data layers and quantitative tolerances, GIS-based species suitability maps were created for the example forage crop species. Example maps using climatic tolerances only for perennial ryegrass, orchardgrass, and tall fescue are shown in Figs.2, 3, and 4.

Table 1 Quantitative climatic and soil factor tolerances for perennial ryegrass (*Lolium perenne* L.)

	July max temp (°C)		Jan min temp (°C)		Annual precip. (mm)		Soil pH		Soil drainage (categories) 2)		Soil salinity (mm hos cm-1)	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Well adapted	22	30	-5	9999 1)	625	9999	5.75	7.5	MWD	MWD	0	2
Moderate	20	32	-10	9999	525	9999	5.5	7.75	SPD	MWD	0	8
Marginal	18	34	-15	9999	450	9999	5.25	8.0	PD	WD	0	8

1) For the high values for Jan minimum temperature and annual precipitation: 9999 is entered to indicate no limit to the high values for this tolerance category.
2) For soil drainage categories, abbreviations are used for soil drainage categories: VPD (very poorly drained), PD (poorly drained), SPD (somewhat poorly drained), MWD (moderately well drained), WD (well drained), SED (somewhat excessively drained), ED (excessively drained).
The same as below.

This new generation of maps is more specific, considers more information, and can be adapted to incorporate additional spatial data layers and revised to reflect revised quantitative tolerances. The project design allows for refinement of the species suitability maps by subject experts using the on-line dynamic mapping IMS. As additional information becomes available for other environmental and economic data, these components will be reflected in the suitability maps.

Part of the China project work has been the deve-

Table 2 Quantitative climatic and soil factor tolerances for orchardgrass (*Dactylis glomerata* L.)

	July max temp (°C)		Jan min temp (°C)		Annual precip. (mm)		Soil pH		Soil drainage (categories)		Soil salinity (mm hos cm^{-1})	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Well adapted	22	31	-7.5	9999	625	9999	5.75	7.5	MWD	MWD	0	2
Moderate	20	33	-10	9999	490	9999	5.25	7.75	MWD	WD	0	8
Marginal	18	35	-17.5	9999	375	9999	4.75	8.25	SPD	ED	0	8

Table 3 Quantitative climatic and soil factor tolerances for tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh.]

	July max temp (°C)		Jan min temp (°C)		Annual precip. (mm)		Soil pH		Soil drainage (categories)		Soil salinity (mm hos cm^{-1})	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Well adapted	22	32	-10	9999	625	9999	5.5	8.0	MWD	MWD	0	8
Moderate	20	34	-15	9999	450	9999	5.0	8.5	PD	WD	0	16
Marginal	18	36	-20	9999	300	9999	4.0	9.5	VPD	ED	0	16

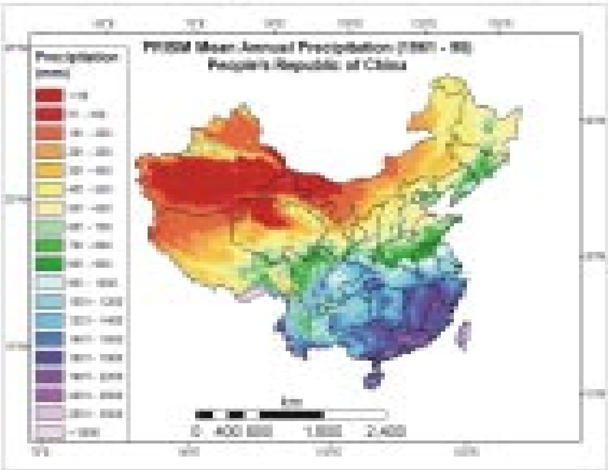

Fig. 1 Mean annual precipitation for the People's Republic of China based on PRISM modeling

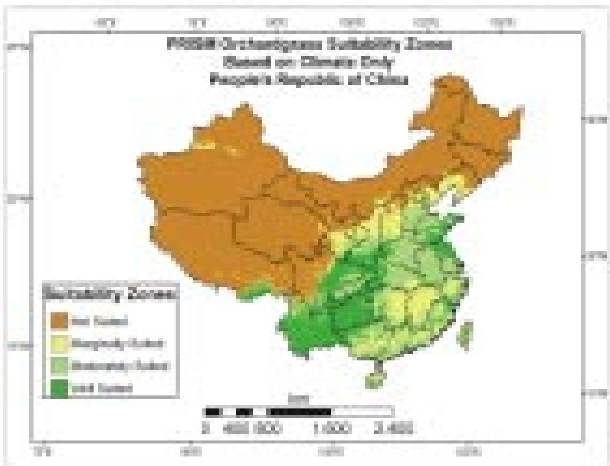

Fig. 3 Orchardgrass (*Dactylis glomerata* L.) climate-based suitability map for China

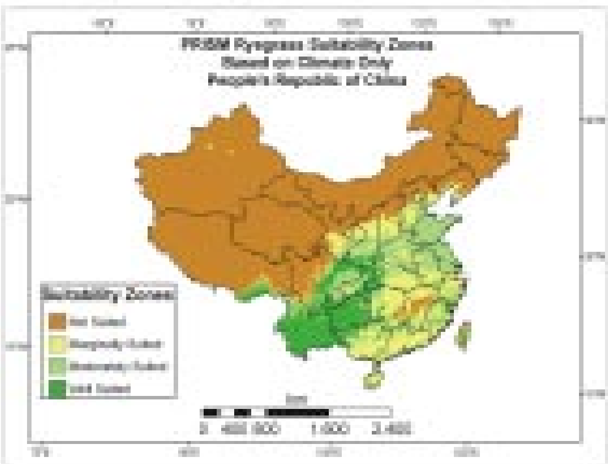

Fig. 2 Perennial ryegrass (*Lolium perenne* L.) climate-based suitability map for China

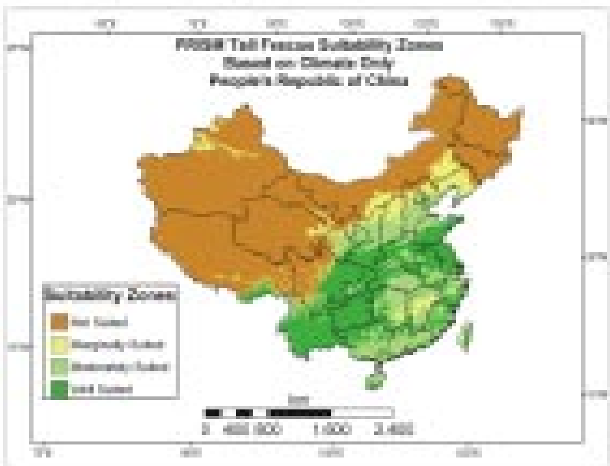

Fig. 4 Tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) climate-based suitability map for China

lopment of the capability to create “dynamic” maps via an internet map server application. Dynamic in this instance means the maps can be changed to reflect new data almost instantaneously. This allows for refinement of the suitability maps by subject experts located anywhere in the world. Experts can translate their “mental map” of what they believe to be true from experience in the field into quantitative tolerance-based digital maps.

With the internet map server presented on the web with drop-down menus and easy-to-use forms, an expert can adjust the measurements to be reflected in a map. Then with the computer making thousands of calculations, the revised map appears. Maps generated in this manner are completely different from old, static maps that were out-of-date as soon as they were published. Dynamic maps are more current but also can depict many more factors and handle the changes that elevation creates. This dynamic mapping software application, like PRISM, is a one-of-a kind system that could be applied to any other similar type project. The URL for the internet map server that contains the password protected dynamic mapping component is: http://mistral.coas.oregonstate.edu/forages/.

Additional validation is accomplished with the help of collaborators in collecting data from field-based research trials, including those developed specifically for this project and those adapted from other projects.

With the help of expert knowledge and field-based data, adjustments will be made to the maps and field measurements refined, resulting in even more accurate and useful maps. If you would like to participate in revising quantitative tolerance estimates or field validation, please contact the USA corresponding author for procedures in obtaining a password for collaborative work.

DISCUSSION AND CONCLUSIONS

This paper describes the development and application of current computer technologies to model and map climatic, soil, and species suitability. The result has been the most detailed climate, soil, and species suitability maps in the world.

Unique, state-of-the-science climate modeling software (PRISM) was used to develop monthly precipitation, maximum and minimum temperature spatial data layers. Digital soil information was developed from soil surveys for pH, drainage, salinity and alkalinity. Quantitative tolerance estimates were developed from research-based information resources. Species tolerances were then applied to the climate and soil spatial layers. In this way geospatial data were used to solve an important, practical, sustainability problem of optimal matching of plants species to specific environments, intended uses, and management level.

Individual data layers (climate, soil, plant, etc.) were placed within a web-based information system and integrated within a DSS with various scenarios. A dynamic mapping application, developed with open source software, now allows rapid revision of maps when new quantitative tolerance values are selected. Validation, using field-based trials and expert knowledge, allows for continued improvement of suitability maps.

Developing integrated systems for the delivery of huge amounts of data from many subject matter topics in a way that is understandable and easy to use presents two fundamental challenges: 1) accessing, assembling and organizing input data, and 2) working together in ways that are efficiently collaborative. This project has successfully accomplished the overall project goal and specific objectives, but improvements are still needed if further refinements are to be made efficiently and without undue delays.

Accessing, assembling, and organizing data

Much of the required plant eco-physiology information was scattered throughout many research papers and isolated plant species literature so that profitable use was greatly hindered. In many cases, quantitative estimates conflicted among various sources, and estimates were often provided in broad ranges that made the data of less value. Assembling and making these data more readily usable is an immediate and continuing need for developing more ecologically-based selection process applications for plant suitability zones[4]. Hundreds of species could be readily mapped if the quantitative tolerance information was available.

Accurate spatial layers of climate data were critical to the success of this project. While sophisticated methods such as PRISM exist for interpolating and extrapolating climate information to locations where there are no data, these methods rely on point observations at station locations. Unfortunately, access to these data is sometimes limited, even to the research community. Limited access to such basic data for China presented a serious obstacle to this project. Data were not only hard to access, but were often in non-electronic formats, requiring extensive keypunching.

Working together

Although it is widely recognized that it is inefficient to duplicate work instead of sharing information and working cooperatively, scientists are trained to work in a particular subject matter specialty and are most often rewarded for individual accomplishments rather than joint efforts. Thus, it is both a technical and social challenge for scientists to work collaboratively, especially in multinational teams. Another challenge that works against cooperation is the funding shortfalls that exist in many research institutes, universities, and commercial company research and development departments. Often data must be sold to obtain funding for future projects. Thus, projects needing many years of data for many stations often must find significant funds for obtaining the necessary data.

Nevertheless, collaborative networks provide a wonderful system for development and validation of research findings. This paper provides a “success story” of collaborative research between US and Chinese scientists with expertise in numerous fields and disciplines to create and integrate spatial data for an applied agricultural problem; that of appropriate plant species selection for forage and livestock systems and soil erosion control.

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