Postprint of Land Suitability Evaluation for Soybean Cultivation in the Sanjiang Plain

Authors: Bu Kun, Wang Zhiliang, Zhang Shuwen, Yang Jiuchun

Date: 2017-11-09T00:00:00+00:00

Abstract

Driven by global climate change, CO fertilization effects, and market demand, a series of domestic policies aimed at promoting soybean cultivation may lead to an increase in soybean planting area in the Sanjiang Plain. Against this backdrop, the key to fully utilizing local climatic conditions and fertile soil resources to promote rational allocation of agricultural land lies in conducting land suitability evaluation for soybean cultivation. Based on the GAEZ research framework published by FAO/IIASA, the authors: first, according to soybean requirements for climate and soil, conducted a climate inventory of meteorological data in the Sanjiang Plain to evaluate climate suitability for soybean cultivation; then, considering the influence of topographic factors on climatic conditions, used Fourier index and slope conditions to modify the evaluation results; subsequently, conducted a soil inventory, selecting soil layer thickness, texture, pH, drainage class, and waterlogging condition as evaluation indicators to assess soil suitability for soybean cultivation in the Sanjiang Plain, and performed suitability downgrade treatment for various soils containing an albic horizon; finally, performed layer overlay at the raster pixel scale to obtain land suitability evaluation results for soybean cultivation in the Sanjiang Plain. Additionally, the Suitability Index (SI) was introduced to conduct a spatial comparison of land suitability for soybean cultivation across 23 counties and cities in the Sanjiang Plain. The results indicate: (1) Except for mountainous areas with slopes greater than 30%, most areas of the Sanjiang Plain are suitable for soybean cultivation, with an area of 8.5×10 km^2, accounting for approximately 78.75% of the total area; (2) The gentle (2%~5%) and slightly undulating (5%~8%) areas along the banks of the Songhua River, Woken River, Muling River, etc., with good soil texture and drainage conditions, are most suitable for soybean cultivation; (3) In nine counties and cities—Boli, Yilan, Tangyuan, Jiamusi, Jixian, Huachuan, Youyi, Suibin, and Fujin—the Suitability Index exceeds 70%; followed by ten counties and cities: Tongjiang, Huanan, Hulin, Baoqing, Fuyuan, Qitaihe, Luobei, Jidong, Raohe, and Shuangyashan;

in four counties and cities—Hegang, Mishan, Jixi, and Muling—suitability is moderate; (4) The streamlined evaluation method of the GAEZ model can effectively achieve spatial differentiation analysis of soybean cultivation suitability at the regional scale, providing a scientific basis for rational allocation of land resources.

Full Text

Evaluation of Agricultural Land Suitability for Soybean Cultivation in the Sanjiang Plain, Northeast China

BU Kun[1], WANG Zhiliang[2,3], ZHANG Shuwen[1], YANG Jiuchun[1]

[1]Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130012, China
[2]College of Science, Qiqihar University, Qiqihar 161006, China
[3]Key Laboratory of Land Surface Pattern and Simulation, Chinese Academy of Sciences / Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Abstract: The Sanjiang Plain is one of China' s most important grain production bases. A series of domestic policies promoting soybean cultivation, driven by global climate change, CO fertilization effects, and market demand, may lead to expanded soybean planting areas in the region. Against this backdrop, the key to optimizing local climate advantages and fertile soil resources for rational agricultural land allocation lies in conducting land suitability evaluations for soybean cultivation. Following the GAEZ research framework published by FAO/IIASA, we first performed a climate inventory of meteorological data in the Sanjiang Plain based on soybean requirements for climate and soil, evaluating climate suitability for soybean cultivation. We then accounted for topographic influences on climatic conditions, applying Fourier index and slope conditions to modify the evaluation results. Next, we conducted a soil inventory, selecting soil layer thickness, texture, pH, drainage level, and flooding conditions as evaluation indicators for soil suitability, with downgrading applied to soil types containing albic horizons. Finally, layer overlay analysis at the grid cell scale yielded the land suitability evaluation results for soybean cultivation in the Sanjiang Plain. Additionally, a Suitability Index (SI) was introduced for spatial comparison of land suitability across 23 counties and cities. The results showed: (1) Except for mountainous areas with slopes exceeding 30%, most of the Sanjiang Plain is suitable for soybean cultivation, covering an area of 8.5×10 km^2 (approximately 78.75% of the total area); (2) The gentle (2%-5%) and undulating (5%-8%) areas along the Songhua, Woken, and Muleng Rivers, characterized by good soil texture and drainage, are most suitable for soybean cultivation; (3) Nine counties—Boli, Yilan, Tangyuan, Jiamusi, Jixian, Huachuan, Youyi, Suibin, and Fujin—achieved SI values exceeding 70%, followed by ten counties (Tongjiang, Huanan, Hulin, Baoqing, Fuyuan, Qitaihe, Luobei, Jidong, Raohe, and Shuangyashan) with moderate suitability, while Hegang, Mishan, Jixi, and

Muleng showed average suitability; (4) The streamlined GAEZ model evaluation approach effectively analyzes spatial variations in soybean cultivation suitability at the regional scale, providing a scientific basis for rational land resource allocation.

Keywords: GAEZ model; soybean cultivation; land ecological suitability; Sanjiang Plain

---

1. Introduction

With improving living standards in China, demand for non-GMO edible vegetable oil and livestock products has grown substantially, stimulating rapid development of the soybean processing industry and causing domestic soybean demand to surge dramatically. Zhang et al. [1] predicted that China' s soybean supply-demand gap would reach 1.38×10 tons by 2020, indicating this gap will continue widening in coming years. As a major soybean production region, the Sanjiang Plain in Heilongjiang Province ranks first nationally in soybean production potential [2-3]. With intensifying climate warming and drying trends [4], future global climate change and CO fertilization effects may benefit soybean production in Heilongjiang [5]. To fully leverage the region' s climatic and soil resource advantages, conducting agricultural land suitability evaluations for soybean cultivation is crucial for guiding local agricultural production and rational land resource allocation.

Previous studies on soybean cultivation suitability in Heilongjiang include Liu [6], who established a climate suitability evaluation index system in 1991. With advances in evaluation techniques, recent studies by Liu et al. [7], He et al. [8], and Li et al. [9] employed analytic hierarchy process and fuzzy mathematics methods to evaluate ecological suitability, using GIS technology to delineate planting zones. However, indicator system approaches suffer from substantial subjectivity, with weights typically derived from expert scoring and varying across regions. In the late 20th century, FAO and IIASA jointly developed the Agro-Ecological Zone (AEZ) model, widely used globally for assessing land production potential [10-11]. In 2009, IIASA released the latest version, Global AEZ (GAEZ 3.0), which features rigorous calculations and strong mechanistic representation, becoming one of the best models for expressing relationships between climate conditions and crop yields [3,12-16]. However, most GAEZ model applications focus on global, continental, or national scales, with limited research on how climate change affects land productivity in typical study areas [17]. This paper selects the Sanjiang Plain as a target region to explore GAEZ model application for soybean cultivation land suitability evaluation at the regional scale, providing scientific support for agricultural production and sustainable land resource utilization.

2. Materials and Methods

2.1 Data Sources This study utilized meteorological data, soil data, and DEM data for the Sanjiang Plain.

Meteorological data comprised daily observations from 1971-2010 at 20 meteorological stations in the Sanjiang Plain and adjacent counties, provided by the Heilongjiang Provincial Meteorological Bureau. Seven indicators were included: average temperature, maximum temperature, minimum temperature, precipitation, wind speed, sunshine duration, and cloud cover.

Soil data were derived from the *Heilongjiang Soil* atlas [18]. The paper soil map covering the Sanjiang Plain was scanned, digitized, geometrically corrected, and vectorized with soil type as the mapping unit. Based on collected and analyzed soil data for the Sanjiang Plain (Table 1), attributes were assigned by soil type, including A-layer thickness, texture, organic matter content, pH, and bulk density, generating vector soil type data for the study area.

DEM data were obtained from SRTM (Shuttle Radar Topography Mission) data jointly measured by NASA and NIMA, downloaded from http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp. Using ArcGIS software, the data were mosaicked and depression-filled for the study area to generate slope and slope length maps.

2.2 Methods

2.2.1 AEZ Methodology The Agro-Ecological Zone (AEZ) methodology, developed by Kassam in 1977 for FAO' s agricultural ecological zoning project [19], calculates crop photosynthetic-thermal production potential. Confronted with malnutrition and overpopulation affecting 400–500 million people in developing countries, FAO established the AEZ project to address food security. Over 30 years, AEZ has been applied globally and regionally, particularly in developing countries like China, Bangladesh, and Thailand, to address land carrying capacity, food production, crop suitability, and soil erosion degradation [20-22].

In 2009, IIASA released the latest AEZ model version, Global AEZ (GAEZ 3.0), which improved crop production potential simulation, land suitability evaluation, and water management calculations while updating global soil and land use data. Detailed technical documentation is available in relevant literature [23-25]. However, as a large-scale (national, global, or continental) evaluation method, certain GAEZ indicator settings may not be reasonable for specific small-scale regions [26].

While climate conditions determine plant survival and adaptation at broad scales [27], crop growth exhibits selectivity for site conditions including climate, topography, and soil, with growth varying across different environments [28]. Land suitability evaluation for crops thus determines model accuracy to some extent. The GAEZ model provides detailed indicators for land suitability evaluation and crop adaptation ranges for different climate, topography, and soil elements, effectively serving as a land evaluation framework for researchers [25].

2.2.2 Evaluation Process Following the GAEZ framework [29], we designed the evaluation process shown in Figure 1 [Figure 1: see original paper]. First, based on soybean requirements for climate and soil, we conducted a climate inventory of meteorological data (heat, radiation, water) to evaluate climate suitability. Next, considering topographic effects on climate, we applied Fourier index and slope conditions to modify results. Through soil inventory, we selected soil layer thickness, texture, pH, drainage level, and flooding conditions as evaluation indicators for soil suitability, downgrading suitability levels for soil types with albic horizons. Finally, layer overlay analysis at the grid cell scale (30 m × 30 m) using GIS technology produced the final land suitability evaluation, with cell values assigned according to the lowest suitability level.

(1) Climate Suitability Evaluation

1) **Soybean varieties and climate requirements:** Soybean is a short-day, temperature-loving crop with wide temperature adaptation but sensitive water requirements, needing more water than other dryland crops. Heilongjiang shows large interannual variations in active accumulated temperature. To fully utilize heat resources, Gao et al. [30] recalibrated heat indicators for major and newly bred soybean varieties in Heilongjiang, using the date when temperature stably passes 8°C with 80% guarantee rate as sowing date, and the earlier of either the date when temperature stably passes 10°C or the first frost date (minimum temperature 1°C) as growth season end. This revealed that except for northeastern Sanjiang Plain with accumulated temperature of 1,900–2,100°C · d (where only a few varieties mature), soybean varieties are widely distributed throughout the region (Table 2).

According to Wan et al. [31], the average difference between accumulated temperature stably passing 8°C and 10°C at 80% guarantee rate in Heilongjiang' s main agricultural areas is 70.6°C. Conventionally, accumulated temperature and duration days stably passing 10°C at 80% guarantee rate are used as heat division indicators for different maturity types. To accommodate this convention, we modified soybean climate suitability evaluation indicators by growth stage as shown in Table 3 .

Through climate inventory, the Sanjiang Plain shows 135–146 days with daily average temperature stably passing 10°C (Figure 2 [Figure 2: see original paper]A) and accumulated temperature of 2,411–2,778°C · d (Figure 2 [Figure 2: see original paper]B), both showing clear latitudinal distribution increasing from north to south and vertical zonation with terrain elevation at the same latitude [32]. Thus, climate conditions fully meet soybean growth needs. However, in local areas, water surplus or deficit caused by terrain or climatic year-to-year variation determines soybean yield, necessitating slope and water condition corrections.

2) **Slope correction:** Agricultural cultivation on steep slopes requires consideration of topsoil erosion and fertility decline. Without adequate protection measures, accelerated soil erosion seriously affects sustainable agricultural production. Under similar crop cover, soil erodibility, and crop/soil management conditions, soil erosion depends primarily on rainfall amount and intensity. Therefore, the GAEZ method establishes different precipitation variability indexes to apply different suitability evaluation rules for rainfed and irrigated crops [33].

To utilize available data and clearly explain total rainfall and intra-annual distribution, we used a modified Fournier index to reflect combined effects of rainfall amount and distribution [34]:

$$F_m = \frac{\sum_{i=1}^{12} P_i^2}{P_{ann}}$$

where F_m is the Fournier index (dimensionless), P_i is monthly precipitation, and P_{ann} is annual total precipitation. F_m characterizes both precipitation amount and distribution, constrained by $P_{ann} \leq F_m \leq 12P_{ann}$. In the GAEZ method, F_m results are divided into six classes: $F_m \leq 1,300$; 1,300-1,800; 1,800-2,200; 2,200-2,500; 2,500-2,700; and $F_m > 2,700$, with differentiation by input level.

This study used medium input level analysis. Based on multi-year average monthly precipitation, we calculated spatialized Fournier index values for Sanjiang Plain stations (Figure 3 [Figure 3: see original paper]), considering only the crop growth period from May to October.

The Sanjiang Plain shows two F_m situations: $F_m \leq 1,300$ and $1,300 < F_m \leq 1,800$. Combined with seven slope classes defined by GAEZ, we classified surface slopes based on rainfall as the main influencing factor (classification standards in Table 4). Then, at the grid cell scale, we conducted graded slope suitability evaluation for soybean cultivation (Figure 4 [Figure 4: see original paper]).

(2) Soil Suitability Evaluation

1) **Soil suitability indicators:** The GAEZ agricultural-soil suitability classification system follows the FAO' 90 classification system, established through comprehensive analysis of crop soil requirements and major soil conditions. However, our soil data came from Heilongjiang soil survey data using a different classification system from GAEZ. Therefore, GAEZ-provided suitability for different crops across soil types could not be directly applied. Instead, we adopted the GAEZ evaluation framework and basic principles with the following steps:

First, based on the FAO' 90 agricultural-soil suitability classification system, we established seven soil-related indicators: soil thickness (cm), texture (A-layer), bulk density (g・cm 3), organic matter content (g・kg 1), pH, drainage level, and flooding condition as criteria (Table 5).

Statistical analysis of Sanjiang Plain soil properties revealed that bulk density and nutrient content were suitable for soybean cultivation. Therefore, actual evaluation focused only on soil thickness, texture, pH, drainage level, and flooding condition.

Based on field conditions, we used expert judgment and semi-quantitative methods to determine crop soil requirements. Table 5 shows soybean soil condition requirements, with values representing optimal and marginal suitability thresholds.

Suitability evaluation for different crops on different soil types was obtained by comparing crop requirements with each soil mapping unit' s properties, producing a graded soil suitability map for soybean cultivation (Figure 5 [Figure 5: see original paper]).

2) **Soil constraint correction:** GAEZ corrections primarily address coarse fragments and soil phases. Based on the world soil map, GAEZ distinguishes 12 soil phases (lithic, petrocalcic, petrogypsic, petroferric, fragipan, hardpan, saline, alkaline, etc.) to correct agricultural land suitability. Sanjiang Plain soils have good texture, generally lacking coarse fragments, but albic horizons in albic bleached soils constitute limiting layers in some areas. Therefore, all soil types with agriculturally limiting albic horizons were downgraded by one suitability level.

(3) Land Suitability Evaluation

Finally, at the grid cell scale (30 m × 30 m), we overlaid the above evaluation results, assigning cell values according to the lowest suitability level to obtain the final land suitability evaluation for soybean cultivation in the Sanjiang Plain (Figure 6 [Figure 6: see original paper]).

To more intuitively express spatial differences in soybean cultivation suitability across counties, we calculated the Suitability Index (SI) using the GAEZ formula and generated normalized classification maps and statistical results for 23 counties (Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper]):

$$SI = \frac{\sum_{i=1}^{4} S_i \times i}{A}$$

where SI is the county-level land suitability index (dimensionless), A is county area (km^2), and S_i ($i = 1, 2, 3, 4$) is the area (km^2) of different suitability classes for soybean cultivation within the county.

3. Results

3.1 Climate Suitability and Slope Correction Results In the GAEZ method, crop climate suitability evaluation is crucial. Through climate inventory, matching soybean growth stage requirements with local climate conditions (thermal zones, growing season, accumulated temperature) and analyzing agro-climatic constraints (water conditions), we corrected climate suitability results using slope suitability classification standards to produce a topographic suitability map (Figure 4 [Figure 4: see original paper]). The results show most Sanjiang Plain areas are suitable for soybean growth, but constraints from topography and water conditions downgrade suitability to moderately or marginally suitable on steep slopes (>30%) in the Zhangguangcai, Wanda, Changbai, and Lesser Khingan mountain ranges.

3.2 Soil Suitability Evaluation Results Based on climate and topographic suitability, we conducted soil inventory and classification according to FAO' 90 standards and field conditions, generating a soil suitability map (Figure 5 [Figure 5: see original paper]). Compared with topographic suitability, soybean cultivation suitability varies significantly due to soil conditions. Particularly in the alluvial plains of the Bielahong, Nongjiang, and Naoli Rivers with heavy soil texture and poor drainage, suitability downgraded from very suitable to suitable. On sloping lands with excessive drainage, suitability decreased to moderately or marginally suitable.

3.3 Land Suitability Evaluation Results The GAEZ land evaluation procedure follows the principle that land quality decreases as limiting factors increase. We downgraded soil types with limiting albic horizons by one level. Overlaying evaluation results at 30 m × 30 m resolution and assigning values by the lowest suitability level produced the final land suitability map (Figure 6 [Figure 6: see original paper]). Areas along the Woken, Songhua, and Muleng Rivers, particularly gentle (2%-5%) and undulating (5%-8%) slopes with fertile soils, adequate moisture, and good drainage are very suitable. Areas with albic horizon constraints downgraded from very suitable to suitable or moderately suitable.

Statistical analysis by suitability class shows very suitable (S1) and suitable (S2) areas total 8.5×10 km^2, accounting for 78.75% of the Sanjiang Plain (Figure 7 [Figure 7: see original paper]).

3.4 Suitability Index Statistical Results Calculating SI for 23 counties and cities produced normalized classification maps and statistics (Figure 8 [Figure 8: see original paper]). Overall, all counties exceeded 58% normalized suitability index, indicating the Sanjiang Plain is generally suitable for soybean production. Based on the index, three categories emerge: (1) Nine counties along the Woken and Songhua Rivers—Boli, Yilan, Tangyuan, Jiamusi, Jixian, Huachuan, Youyi, Suibin, and Fujin—exceeded 70% suitability, representing optimal soybean cultivation areas; (2) Ten counties (Tongjiang, Huanan, Hulin, Baoqing, Fuyuan, Qitaihe, Luobei, Jidong, Raohe, and Shuangyashan) ranged 60%-70%; (3) Hegang, Mishan, Jixi, and Muleng ranged 58%-60%, showing average suitability.

4. Discussion and Conclusions

Following GAEZ land suitability evaluation procedures at 30 m × 30 m grid resolution, we conducted a detailed evaluation of soybean cultivation suitability in the Sanjiang Plain. The results show:

1) **Climate conditions:** The Sanjiang Plain is climatically suitable for soybean cultivation. However, topographic and water constraints downgrade suitability to moderately or marginally suitable on steep slopes (>30%) in the Zhangguangcai, Wanda, Changbai, and Lesser Khingan mountain ranges.
2) **Soil conditions:** Areas with heavy soil texture, poor drainage, or excessive drainage on steep slopes show reduced suitability (moderately or marginally suitable). Gentle (2%-5%) and undulating (5%-8%) areas along the Songhua, Woken, and Muleng Rivers are most suitable, with very suitable and suitable areas totaling 8.5×10 km^2 (78.75% of the plain).
3) **Suitability index:** Nine counties along the Woken and Songhua Rivers exceeded 70% normalized suitability (Boli, Yilan, Tangyuan, Jiamusi, Jixian, Huachuan, Youyi, Suibin, Fujin), followed by ten counties at 60%-70%, and four counties (Hegang, Mishan, Jixi, Muleng) with average suitability.
4) **Spatial differentiation:** The GAEZ method effectively distinguishes spatial differences in soybean cultivation suitability, providing reasonable scientific support for regional agricultural planning. Unlike indicator system methods, the streamlined GAEZ procedure avoids subjective interference, producing more objective and authentic results that are easily applied and compared across regions.

However, to more accurately estimate actual land productivity for soybean cultivation in the Sanjiang Plain, climate-based production potential must be further corrected considering local farming practices, irrigation proportions, agricultural input levels, and management methods. Due to data limitations, this study did not assess actual productivity; future research should evaluate both climatic and realistic production potential.

Acknowledgments: We thank the Earth System Science Data Sharing Platform (http://www.geodata.cn/) for supporting basic data collection.

References:

[1] Zhang Z H, Liu Z M. Predicting the supply and demand of soybean in China in 10 years later[J]. Soybean Science & Technology, 2009(4): 16–21

[2] Cai C Z, van Velthuizen H, Fischer G, et al. Analysis of soybean yield potential based on Chinese farming system zones by AEZ model[J]. Journal of Henan Agricultural Sciences, 2006, 35(5): 27-31
[3] Zhang X F, Wang H Z, Liu L, et al. Spatial-temporal characteristics of soybean production potential change under the background of climate change over the past 50 years in China[J]. Progress in Geography, 2014, 33(10): 1414-1423
[4] Sun F H, Yang S Y, Chen P S. Climatic warming-drying trend in northeastern China during the last 44 years and its' effects[J]. Chinese Journal of Ecology, 2005, 24(7): 751-755
[5] Ju H, Xiong W, Xu Y L, et al. Climate change and its' impacts in Northeast China[J]. Chinese Agricultural Science Bulletin, 2007, 23(4): 345-349
[6] Liu D H. Climatic suitability assessment index of main crops in Heilongjiang Province[J]. Heilongjiang Agricultural Sciences, 1991(4): 9-14
[7] Liu D, Du C Y, Yu C L. Ecological adaptability evaluation and planting division of soybean in Heilongjiang Province[J]. Soybean Science, 2008, 27(3): 433-436
[8] He Y B, Yao Y M, Li J P, et al. Precisely assessment on soybean growth suitability and analysis on its' cultivation reasonability—Taking the Northeast China as an example[J]. Chinese Journal of Agricultural Resources and Regional Planning, 2012, 33(1): 11-17
[9] Li H J, Yu Y N, Li Y G. Soybean planting zonation in Heilongjiang Province based GIS[J]. Technology Innovation and Application, 2013(2): 212
[10] Albersen P, Fischer G, Keyzer M, et al. Estimation of agricultural production relations in the LUC model for China[R]. IIASA RR-02-03. Laxenburg, Austria: IIASA, 2002
[11] Fischer G, van Velthuizen H T, Shah M M, et al. Global climate change impacts on agriculture: An integrated assessment, 1990-2080[J]. Philosophical Transactions of the Royal Society B: Biological Sciences, 2005, 360(1463): 2067-2083
[12] Liu L, Chen X, Xu X L, et al. Changes in production potential in China in response to climate change from 1960 to 2010[J]. Advances in Meteorology, 2014, 2014: 640320
[13] Liu L, Xu X L, Liu J Y, et al. Impact of farmland changes on production potential in China during recent two decades[J]. Acta Geographica Sinica, 2014, 69(12): 1767-1778
[14] Ge Y N, Liu L, Xu X L, et al. Temporal and spatial variations of Chinese maize production potential on the background of climate change during 1960-2010[J]. Journal of Natural Resources, 2015, 30(5): 784-795
[15] Zhou S D, Zhao M Z, Chen K, et al. Analysis on the potential grain productivity of the world' s major grain exporting countries[J]. Issues in Agricultural Economy, 2015(6): 91-104
[16] Zhao M Z, Zhu S Z. Analysis on the potential maize productivity of the world' s maize exporting countries[J]. World Agriculture, 2015(9): 121-130
[17] Yuan L L. Analysis of impact on Chinese main crop' s productivity of climate change during 1961-2010[D]. Wuhan: Central China Normal University,

2015
[18] Heilongjiang Land Administrator Agency, Heilongjiang Provincial Office of Soil Survey. Heilongjiang Soil[M]. Beijing: Agriculture Press, 1992
[19] Kassam A H. Net biomass production and yield of crops[R]. Rome: FAO, 1977
[20] Chen F. Evaluation on the land suitability in Fujian based on AEZ/GIS[J]. Fujian Geography, 2002, 17(3): 11–13
[21] FAO. Agro-ecological zoning and GIS applications in Asia-with special emphasis on land degradation assessment in drylands[R]. Rome: FAO, 2005
[22] Fischer G, Sun L X. Model based analysis of future land-use development in China[J]. Agriculture, Ecosystems & Environment, 2001, 85(1/3): 163–176
[23] Fischer G, Shah M M, van Velthuizen H T, et al. Global agro-ecological assessment for agriculture the 21st century[R]. Laxenburg, Austria: IIASA, 2001
[24] Fischer G, Shah M, Tubiello F N, et al. Socio-economic and agro-ecological assessment for agriculture in the 21st century: Methodology and results[R]. IIASA RR-02-02. Laxenburg, Austria: IIASA, 2002
[25] Fischer G, Shah M, van Velthuizen H, et al. Agro-ecological zones assessments[M]//Fischer G, Shah M, van Velthuizen H, et al. Land Use, Land Cover and Soil Sciences. Oxford, UK: EOLSS Publishers, 2006
[26] Fischer G, Granat J, Makowski M. AEZWIN: An interactive multiple-criteria analysis tool for land resources appraisal[R]. IIASA IR-98-051. Laxenburg, Austria: IIASA, 1998
[27] Hudson G, Birnie R V. A method of land evaluation including year to year weather variability[J]. Agricultural and Forest Meteorology, 2000, 101(2/3): 203–216
[28] Han X L. Crop Ecology[M]. Beijing: China Meteorological Press, 1991
[29] Zhang X C. The methodology of AEZ program[J]. Chinese Journal of Agricultural Resources and Regional Planning, 1992, 13(4): 56–62
[30] Gao Y G, Wang Y G, Nan R, et al. Identification and application of thermal indexes of main cultivated soybean varieties in Heilongjiang Province[J]. Chinese Journal of Agrometeorology, 2005, 26(3): 200–204
[31] Wan M W, Liu X Z. Chinese Phenological Observation Method[M]. Beijing: Science Press, 1979: 1–17
[32] Bu K. Agro-ecological land resources evaluation of the Sanjiang Plain[D]. Changchun: Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, 2008: 17–81
[33] Xie J Q, Cai Y M, Zheng Z Y, et al. AEZ-based assessment for food productivity potential of cultivated land in China[J]. China Land Science, 2004, 18(4): 31–37
[34] Arnoldus H M J. Methodology used to determine the maximum potential average annual soil loss due to sheet and rill erosion in Morocco[J]. FAO Soil Bulletin, 1977, 34: 39–51

Note: Figure translations are in progress. See original paper for figures.