THE STUDY OF GLOBAL LAND SUITABILITY EVALUATION:
A CASE OF POTENTIAL PRODUCTIVITY ESTIMATION FOR WHEAT

Guoxin TAN, Ryosuke SHIBASAKI, K S RAJAN
Institute of Industrial Science, University of Tokyo
4-6-1 Komaba, Meguro-ku,Tokyo 153-8505 JAPAN
gxtan@skl.iis.u-tokyo.ac.jp
shiba@skl.iis.u-tokyo.ac.jp
rajan@skl.iis.u-tokyo.ac.jp

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ABSTRACT

In this paper, a GIS based global land suitability evaluation methodology is introduced. This methodology is combined GIS spatial analysis technique with a land evaluation methodology termed Agro-Ecological Zoning (AEZ) and a simulation model developed by FAO for calculating crop potential maximum biomass and yield. It divides global area of land into smaller grids, and calculates crop potential productivity by taking account of the crop characteristics, the climatic factors of radiation and temperatures within the growth periods together with the actual photosynthesis capacity of wheat and the fraction of the net biomass. Due to the potential maximum yield is mainly determined by temperature and precipitation characteristics, a new straightforward approach to interpolating weekly average air temperature and precipitation aided by monthly climatologically at unsampled points in space from weather-station observation is proposed. Finally a case of global potential productivity estimation for wheat is tested. Weekly average temperatures and precipitation are interpolated with quality control model from weather station network with time series of daily maximum, minimum temperature and precipitation. The growth period in which climate will permit rain-fed crop production and global wheat potential productivity is determined. The computed values of net biomass production and yield show the potential productivity estimation methodology is actually possible to be used for global land suitability evaluation.

1. INSTRUCTION

The ability of the world's natural resources to provide the needs of its growing population is a fundamental issue for the international community. The basic problem is one of mounting pressure on natural resources. Limits to the productive capacity of land resources are set by climate, soil and landform conditions and by the use and management applied to the land. Sustainable management of land resources requires sound policies and planning based on knowledge of these resources, the demands of the use to which the resources are put, and the interactions between land and land use. So it is very important for agriculture development planning to take land resources assessment.

The Food and Agriculture Organization of the United Nations (FAO) developed a methodological framework to assess food production, which widely known as the Agro-ecological zoning (AEZ) methodology (FAO, 1978-80). This methodology is an approach to determine the ecological potential of land resources for crop production and to estimates land suitability. It was first applied to land suitability estimates for 11 crops at three levels of inputs in five regions of the developing world. Due to AEZ methodology involves many spatial analysis, the application of Geographical Information System (GIS) in AEZ can provides a comprehensive framework for the appraisal and planning of land resources.

Climate pattern is one of the most important components for land productivity assessment. However climate and its space-time variability continue to be examined extensively by many researchers. A wide variety of approaches have been used (Washington and Meehl, 1986; Spencer and Christy, 1990; Dirks et al., 1998; Legates and Willmott, 1990). Observational biases at the station location are regarded as the most accurate or precise and have been investigated extensively (Karl et al., 1989). But weather station network with long-term records and good spatial coverage is uncommon (Willmott. 1991). Two problems arise from this paucity of well-conditioned observational networks. Estimating a time-averaged weather or climate variable at unsampled location by spatial interpolation is relatively unreliable, and in turn, areal averages made from the network observations can be biased. Some approaches have been studied intending to solve these problems (**Willmott and Matsuura, 1995**), in which Climatologically Aided Interpolation (CAI) is proved the best one. Unfortunately these methods cannot eliminate all the unreliable and bias especially in the fields where sampled stations are very sparely. How to solve these problems is crucial important for

weekly average temperature interpolation.

In this paper, firstly a Global Land Suitability Evaluation methodology and the assessment steps implemented in global land are brief discussed in section 2; then a weekly climate interpolation approach aided by interpolated monthly climatologically is proposed in section 3; A test of potential productivity estimation for wheat and conclusions will give late.

2. LAND SUITABILITY EVALUATION METHODOLOGY

2.1 Summary Of AEZ Methodology

Agro-ecological zoning (AEZ) divides an area of land into smaller units, which have similar characteristics related to land suitability, potential production and environmental impact (FAO/IIASA, 1991). It involves the inventory, characteristics, and classification of land resources for assessing the potential of agricultural production system. In its simplest form, the AEZ framework comprises three groups of compound activities.

2.1.1 Inventory of land utilization types (LUT) and their ecological requirements. LUTs are defined in terms of a product, or a specified range of products, and the management system, including the operations and inputs, used to produce these products. Their ecological requirements involve the climatic, soil and landform conditions necessary for the component crops and for the management system.

2.1.2 Definition and mapping of agro-ecological zones. The land resources inventory is based on combining different layers of information to define agro-ecological cells (AECs) with a unique combination of climate, soil and other related land attributes. It includes analyses length of growth period; define thermal zones; compile climatic resource inventory; compile soil and landform resource inventory; and compile present land use inventory.

2.1.3 Evaluation of the land suitability of each agro-ecological zone. Assessment of land suitability is carried out by a combination of matching constraints with crop requirements, and by modeling of potential biomass production and yield under constraint free conditions. This activity is normally carried out in two main stages, in which firstly the agro-climatic suitability is assessed, and secondly the suitability classes are adjusted according to edaphic or soil constraints.

2.2 GIS Based Land Suitability Evaluation Methodology

The AEZ concept is essentially a simple one. To facilitate the storage, manipulation and dealing of complex spatial information, it is very necessary to input all spatial data into a geographical information system. The nature of the analysis, which involves the data conversion, interpolation and overlay, can lend itself to the application of GIS. In our examinations, the spatial database of global land suitability evaluation is created and supported by ARC/INFO. With the aid of GIS, agro-ecological cells can be defined in grid, which form the basic unit of analysis used in AEZ applications, and a program, which combining overlaid spatial information with the calculation of crop productivity, is developed.

For estimation of potential productivity, AEZ uses the concept of a maximum attainable total biomass and yield. For a specified LUT, the potential maximum yield is determined by the radiation and temperature characteristics of a particular location, by the photosynthetic efficiency of the crop, and by the fraction of net biomass that the crop can convert to economically useful yield. Although some potential land productivity models have been developed, most of these are paid attention to regional model development. Here, a potential production biomass simulation model (FAO, 1978) is introduced to calculate the global potential maximum biomass and yield. In this model the photosynthetic efficiency and the maximum of gross biomass production are calculated from a very simple photosynthetically active radiation (PAR) on a perfectly clear day and the daily gross photosynthesis rate of crops canopies on very clear and overcast days given by de Wit.

Figure 1 gives a general overview of the flow and integration of information implemented in the global land suitability evaluation. In our examinations, the climate data is point distribution data based on whether station network. In order to interpolate high quality climate data, a climatologically aided interpolation method is proposed, and will be described late. For each crop type and grid cell, the optimum starting and ending dates of growth cycles are determined automatically based on air temperature, precipitation and the calculation of Potential Evaporation Transpiration (PET). Using potential production biomass simulation model, photosynthesis rate and photosynthetically active radiation is calculated, and then gross biomass production and net biomass production can be determined. The results are a series of estimated agronomically attainable yields for each land unit (grid). These estimates must be related to some correction

researches, are used to quantify the yield reductions. Finally land suitability class evaluation is estimated based on crop attainable productivity.
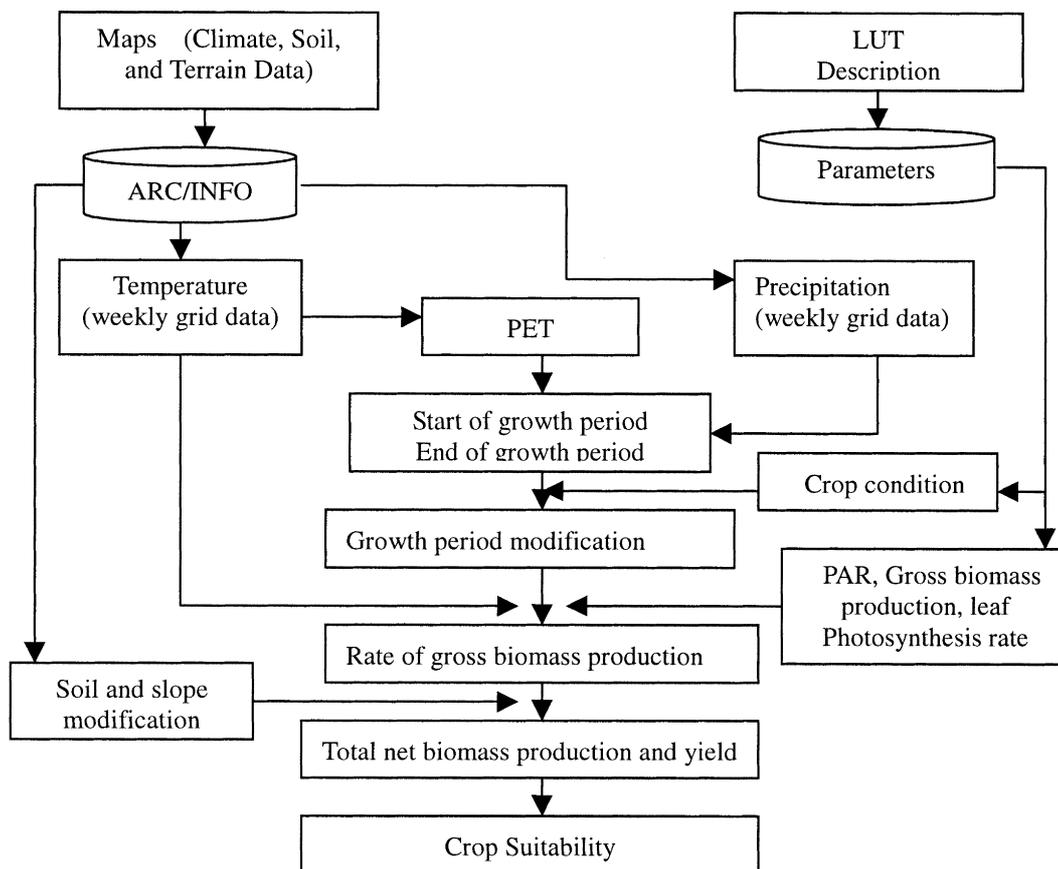

Figure 1. The flow of global land suitability evaluation

3. WEEKLY CLIMATIC DATA INTERPOLATION

Up to now, main researchers put their efforts on global annual-average or monthly-average climate estimate. There are a few researches put on weekly-average air temperature and precipitation interpolation. In this case, how to estimate weekly climate data using monthly-average high-resolution climatology and how to control interpolating quality are two very important problems for global air temperature and precipitation interpolation.

3.1 Principals

The principal for monthly climatologically aided global weekly air temperature and precipitation interpolation can be described as following several main steps.

3.1.1 Correcting air temperature to sea level. First step is to calculate weekly and monthly see level average air temperatures for all weather stations from daily air temperature records respectively.

3.1.2 Difference. It is needed to calculate monthly temperature and precipitation difference between sample stations and sea level climatology.

3.1.3 Interpolation. After traditional Interpolation methods such as Kriging (Oliver, 1990) with quality control models are introduced to interpolate weekly and monthly difference climate data respectively, CAI monthly air temperatures and precipitation can be estimated.

3.1.4 Space-Time Interpolation. After correcting weekly and monthly sea level interpolated average temperatures to real topography, a space-time interpolation technique then is used to estimate weekly air temperature and precipitation.

3.2 Quality Control In Climatic Interpolation

In order to reduce the uncertain in air temperature and precipitation interpolation such as no enough sample points and ill-distribution sample points in external interpolation, an interpolating quality control model is

$$\Delta \overline{T} = \frac{1}{n}\sum_{i=1}^{n}\Delta T_i$$
$$\Omega = \sqrt{\sum_{i=1}^{n}\left(\Delta T_i - \Delta \overline{T}\right)^2 \Big/ (n-1)} \tag{1}$$

Where ΔT_i is the climatic difference between the lower-resolution station temperature or precipitation of interest T_i and the climatological climate average temperature or precipitation $\hat{T}_i$ in high-resolution, n is the number of lower-resolution station, $\Delta \overline{T}$ is average difference temperature or precipitation, and Ω is standard deviation. If there are no enough stations in a fix searching distance area nearby grid j, then we use $\Delta \overline{T}$ instead of interpolation value $\hat{T}_j$. If $\hat{T}_j$ is more than $\Delta \overline{T} + 3\Omega$, we think interpolation in grid j is ill-condition and make $\hat{T}_j = \Delta \overline{T} + 3\Omega$. Otherwise if $\hat{T}_j < \Delta \overline{T} - 3\Omega$, then make $\hat{T}_j = \Delta \overline{T} - 3\Omega$.

3.3 Monthly Temperature Aided Weekly Air Temperature Interpolation

Because CAI monthly average temperatures and precipitation have a high accuracy, we can interpolate weekly air temperature and precipitation more accuracy by the aiding of CAI monthly temperature. This interpolation procedure is termed space-time interpolation. The formula is given follow

$$\overline{T}_{jm} = \sum_{w=k1}^{k2}(\hat{T}_{jw} \bullet \frac{d_{wm}}{N_m})$$
$$\hat{T}_{jw} = \sum_{m=m1}^{m2}[\hat{T}_{jm} + (\hat{T}_{jw} - \overline{T}_{jm})] \bullet \frac{d_{wm}}{7} \tag{2}$$

Where d_{wm} is the number of days in wth week on m^{th} month, N_m is the number of days on m^{th} month, k1 and k2 are the start-week and end-week on m^{th} month, m1 and m2 are the months that wth week spanned, $\hat{T}_{jw}$ and $\hat{T}_{jm}$ are weekly average air temperature or precipitation and CAI monthly average air temperature or precipitation at any location j correspondingly.

4   A CASE FOR GLOBAL WHEAT POTENTIAL PRODUCTIVITY ESTIMATION

Our tests of above-described methodologies are made by estimating wheat potential productivity. Climate data with time series of daily maximum, minimum temperature, precipitation and elevation for 6400 available terrestrial stations over the period from 1977 to 1991 is our lower-resolution network. Figure 2 is the distribution of the global weather station. A monthly long-term average air-temperature and precipitation that interpolated from nearly 18000 terrestrial stations recorded from 1890 to 1989 by Legates and Willmott (1990) serves as high-resolution climatoloy. A DEM at a spatial resolution of $5'$ by $5'$ is also used to obtain the georeferenced heights for grid networks. The soil data with different layer bulk-density, which provided by The Global Soil Data Task co-ordinating with the Data and Information System (DIS) framework activity of the International Geosphere-Biosphere Programme (IGBP), is used. The soil data resolution is also $5'$ by $5'$.

The global land resources inventory comprises 4320 by 2160 grid cells with resolution of $5'$ by $5'$. Figure 3 are some of the weekly air temperature interpolated by CAI and space-time interpolation methods respectively. In the same way, weekly precipitation was interpolated. There are many models to estimate evaporation rate. Here Linacre model is
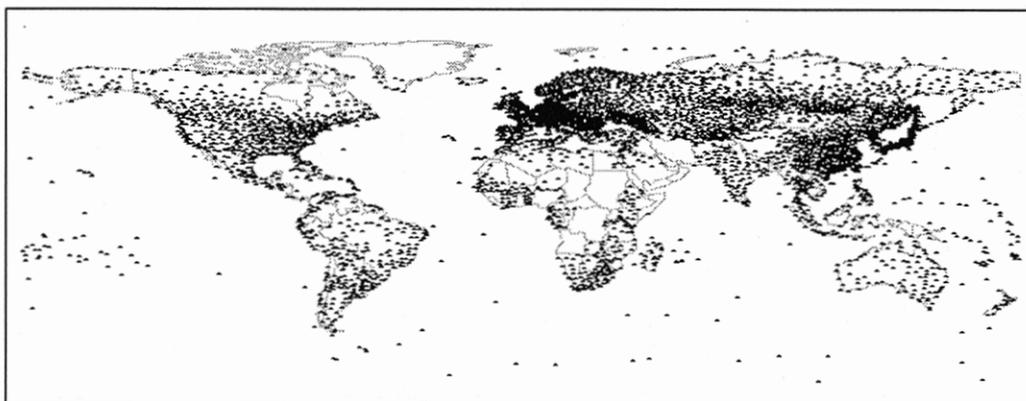
Figure 2. Spatial distribution of 6400 weather stations

-24   -18   -12   -6   0   6   12   18   24
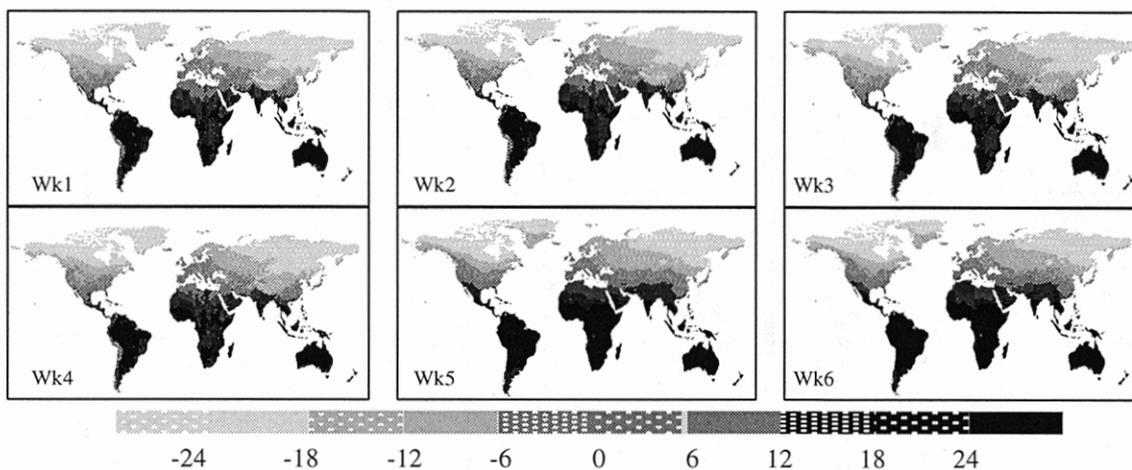
Figure 3. Weekly interpolated average temperature (First week to sixth week, Unit:degree)

Weeks: 1 6 12 18 24 29 35 41 47
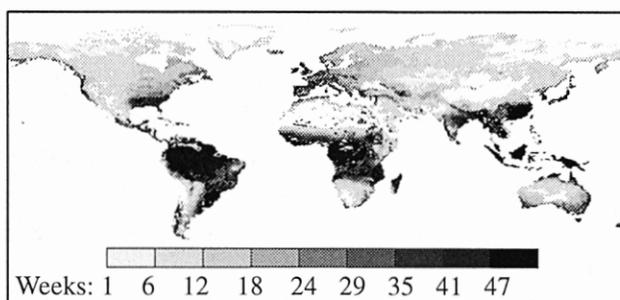
Figure 4. Growth weeks permitted by precipitation

Factor: 0   0.29   0.47   0.57   0.72   1.0
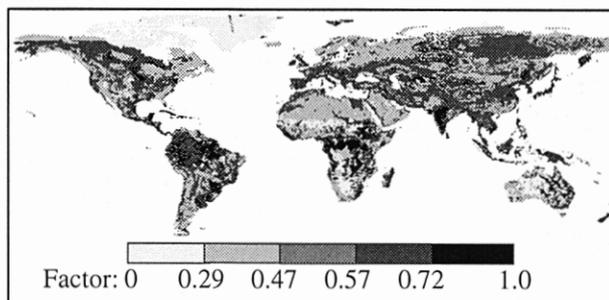
Figure 5. Soil constrain factor for wheat

Factor: 0 0.2 0.4 0.6 0.7 0.8 0.9 1.0
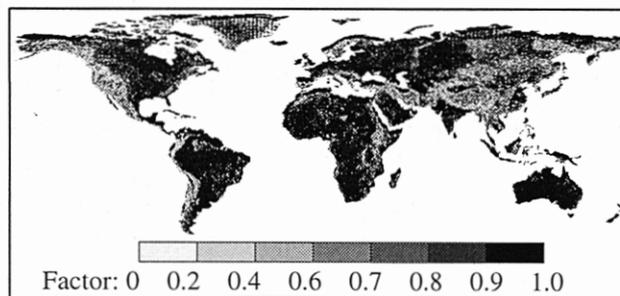
Figure 6. Slope constrain factor for wheat


Yield: 0   1.0   2.0   3.0   4.0
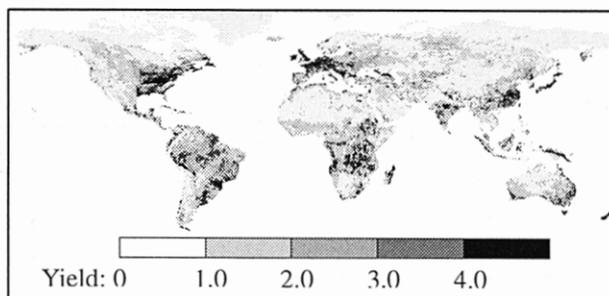
Figure 7. Wheat potential productivity (Unit: T/HA)

introduced due to this model can give evaporation estimates with the requirement of only temperature data. After estimating evaporation rate, the weeks of growth period in which climate will permit rain-fed crop production are determined (figure 4). Potential biomass production and yield can be calculated with simulation model. Then land suitability evaluation can be done by combining potential yield with several reduction factors (Tang and Ye, 1997). Figure 5 and figure 6 are soil and slope correct factors correspondingly. Finally, global potential wheat productivity has been grouped into five basic suitability classes according to attainable yield ranges: very suitable (more than 4 T/HA), suitable (3-4 T/HA), moderately suitable (2-3 T/HA), marginally suitable (1-2 T/HA), and not suitable (0-1 T/HA). The result is given in figure 7.

5. CONCLUSION

Due to the potential maximum yield is mainly determined by temperature and precipitation characteristics, any technique which can improve climatic data quality are of great benefit for the global land suitability evaluation. In order to improve weekly temperature and precipitation interpolation accuracy, a space-time interpolation method with quality control model is proposed. It estimates global weekly average temperature and precipitation by the aid of monthly climatology when high-resolution weekly average climatologicy is lack. Results show this interpolation method has a high quality and can be applied to other global interpolation of data from observational networks such as solar irradiances.

We wrote the test program to convince ourselves of the global land suitability evaluation. A case of global wheat potential productivity is tested. The results show the global wheat productivity evaluation methodology is feasible. It can be applied to other crop productivity evaluation and provide a framework for the appraisal and planning of land resources. Due to the complexity and widespread practice of multiple cropping systems, the future researches about this methodology are necessary.

REFERENCE

Dirks, K.N., Hay, J.E., Stow, C.D. and Harris, D., 1998. High-resolution study of rainfall on Norfolk Island, Part II: Interpolation of rainfall data. Journal of Hydrology, Vol.208, pp.187-193.

FAO, 1978-81. Report on the Agro-ecological Zones Project. Vol.1, Methodology and results for Africa; Vol.2, Results for Southwest Asia; Vol.3, Methodology and results for South and Central America; Vol.4, Results for Southeast Asia. [FAO] World Soil Resources Report 48/1,-4.

FAO/IIASA, 1991. Agro-ecological land resources assessment for agricultural development planning: A case study of Kenya: Resources database and land productivity. Main Report and 8 Technical Annexes. Rome, AGL-FAO. 9 vols. pp1150.

Karl, T. R., Tarpley, J. D., Quayle, R. G., Dias, H. F., Robinson, D. A. and Bradley, R. S., 1989. The recent climatic record: what it can and cannot tell us. Rev. Geophys, 27(3), pp.405-430.

Legates, D. R. and Willmott, C. J., 1990. Mean seasonal and spatial variability in global surface air temperature, Theor. Appl. Climatol., 41, pp.11-21.

Spencer, R. W., and Christy, J. R. 1990. Precise monitoring of global temperature trends from satellites, Science, 247, pp.1558-1562.

Tang, H., and Ye, L., 1997. Comparative Study on Methodology of Land Production Potential. China agriculture science and technique publishing company. Peking, China.

Washington, W. M. and Meehl, G. A. 1986. General circulation models CO_2 sensitivity experiments: snow-sea-ice albedo parameterization and globally averaged surface air temperature, Climatic Chang2, 8, pp.231-241.

Willmott, C. J., 1995. Climatologically aided interpolation (CAI) of terrestrial air temperature, International Journal of Climatology, Vol. 15, pp.221-229.

Willmott, C.J. and Matsuura K., 1995. Smart interpolation of annually averaged air temperature in the United States, Journal of Applied Meteorology, Vol. 34, pp2577-2586.