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# Methodology for Assessment of Desertification based on Vegetation Degradation Using Net Primary Productivity (NPP) as a Key Indicator

By

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Summary

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Up to now, a "structured informed opinion analysis" based on subjective information has often been used to assess regional desertification and land degradation. Although this might be the most appropriate assessment method given limitations of time, money and labor, the method is neither objective nor quantitative; objectivity and quantitativeness often have a trade-off relationship with efficiency. In the present study, we propose a new methodology for monitoring and assessing regional desertification/land degradation that is both objective and quantitative. This new method relies on net primary productivity (NPP) as a key indicator of biological productivity.

We compared the potential NPP (determined from climatological parameters) and actual NPP using a dataset for the 20 years from 1981 to 2000. To estimate the potential NPP, we used the Chikugo model. To estimate the actual NPP, we used a modified Carnegie-Ames-Stanford Approach (CASA) model, a type of Production Efficiency Model (PEM), which is driven by satellite

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observations. This modified model, the "Dryland-adjusted CASA" (D-CASA) model, was used to estimate the actual NPP of Asian drylands.

We identified potential desertification/land degradation hotspots in Asia based on vegetation degradation. Specifically, these were the regions of central Inner Mongolia (China), mid-latitudinal and south Mongolia, northwest India, and the Deccan Plateau (India). We also identified vegetation degradation regions that were not identified by the Global Assessment of Human Induced Soil Degradation (GLASOD) database as being affected by soil degradation in mid-latitudinal Kazakhstan and Betpak-Dala (southwest of Lake Balkhash). Because we were able to assess desertification by objective and reproducible methods and were able to identify desertification hotspots not identified by the existing soil degradation map (GLASOD), we conclude that the new methodology proposed here for desertification assessment is valid and useful.

## Introduction

How can we assess regional desertification and land degradation objectively? In the early 1990s, two assessments of global desertification/land degradation were published under the auspices of the United Nations. First, the World Atlas of Desertification (UNEP 1992) assessed desertification from the viewpoint of soil degradation using the Global Assessment of Human Induced Soil Degradation (GLASOD) database (OLDEMAN & al. 1991). Second, the International Center for Arid and Semi-Arid Land Studies (ICASALS) of Texas Tech University, Lubbock, TX, USA, used a vegetation degradation dataset. The UN-authorized value of 3.6 billion hectares published in Agenda 21 (UN 1992) and reported by UNEP to the United Nations Conference on Environment and Development (UNCED) as the area affected by desertification corresponds to the area assessed by the second report (global vegetation degradation). The area of soil degradation in drylands recognized by GLASOD is no more than 1.0 billion hectares (UNEP 1992).

The method used by both studies was a "structured informed opinion analysis" (DREGNE 1998) based on subjective information. This might be the most appropriate assessment method given limitations of time, money, and labor. However, although efficient, the method is neither objective nor quantitative; objectivity and quantitativeness often have a trade-off relationship with efficiency.

In the present study, we propose a new methodology for monitoring and assessing regional desertification/land degradation that is both objective and quantitative. This new method relies on net primary productivity (NPP) as a key indicator of biological productivity.

The United Nations Convention to Combat Desertification (UN 1994) defines desertification/land degradation as a "reduction or loss, in arid, semi-arid, and dry subhumid areas, of biological or economic productivity and complexity." By this definition, a reduction in biological productivity can be the main criterion used to assess desertification from the viewpoint of vegetation degradation.

It is appropriate to assess desertification/land degradation on the basis of vegetation degradation, because vegetation degradation results in reduced production of biological resources, on which people in villages in developing countries strongly depend for their food, fodder, fuel, fertilizer, and building materials (TSUNEKAWA & al. 2003, ANANTHA RAM & al. 1999). VITOUSEK & al. 1986 estimated that nearly 40 % of potential terrestrial NPP is used directly (e.g., for food, fuel), co-opted (e.g., converting open land to cities), or foregone because of human activities. For this reason, biological productivity as represented by NPP is often used as an indicator of sustainability (CARDOCH & al. 2002). DEFRIES 2002 suggests that global terrestrial NPP is sensitive to human modifications of the landscape. This observation is highly appealing, and we share the basic idea.

We have identified two major approaches to the assessment of desertification/land degradation based on the reduction in NPP. The first compares potential NPP based on climate with actual NPP in a particular region. The second approach is to examine long-term trends of NPP in a particular region. In the present study, we focus on the first approach, and attempt to detect potential hotspots of desertification/land degradation in Asia using the dataset for the 20 years from 1981 to 2000.

## Material and Methods

### Model for estimating actual NPP

To estimate regional NPP, we used a Production Efficiency Model (PEM; MONTEITH 1972, 1977). We modified the Carnegie-Ames-Stanford Approach (CASA) model, which was developed by POTTER & al. 1993 and is driven by satellite observations, and used our modified "Dryland-adjusted CASA" (D-CASA) model to estimate the actual NPP of Asian drylands. We needed to modify the CASA model because it was not validated for Asian drylands and the soil moisture estimates obtained from the CASA soil-moisture submodel were not satisfactory when compared with our field observations.

We modified the soil-moisture submodel by using observations from Inner Mongolia, China (see NEMOTO & al. 2003 for details). In the case of original CASA model, the maximum of Relative Dry Rate (RDR), that is, evaporation efficiency has a very low value, resulting in a suppressed evaporation. To avoid this problem, we modified the equation so that RDR ranges from 0 (corresponding to hygroscopic point) to 1 (field capacity). This means when soil moisture reaches field capacity, actual evapotranspiration equals to potential evapotranspiration (PET). The basic formula for estimating monthly NPP (kg dry weight $m^{-2}$ $month^{-1}$, including both aboveground and belowground biomass) is the same as in the original CASA model:

$$NPP = PAR \times FPAR \times W_s \times T_{s1} \times T_{s2} \times \varepsilon_{max},$$

where $PAR$ (MJ $m^{-2}$ $month^{-1}$) is photosynthetically active radiation (the incoming solar radiation in the photosynthetically active spectral region, about 400 to 700 nm); $FPAR$ is the fraction of PAR absorbed by plants, which is estimated from normalized difference vegetation index (NDVI) data obtained from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA satellite; $W_s$, $T_{s1}$, and $T_{s2}$ are scalar variables that account for the effects of water stress, temperature stress due to high or very low temperatures, and temperature stress related to the difference between the optimum and actual temperature, respectively, as in the CASA model; and $\varepsilon_{max}$ is the maximum value of light-use efficiency (0.389 g C $MJ^{-1}$).

### Model for estimating potential NPP

Generally, the variability of NPP is greatly affected by climatic factors. Thus, we sought to eliminate the NPP variability caused by climatic factors by comparing potential NPP estimated from climatic conditions with actual NPP.

Several models have been developed to estimate NPP based on climatic conditions; among them, the Miami model developed by LIETH 1975 and the Chikugo model developed by UCHIJIMA & SEINO 1985 are well known. We used the Chikugo model because we considered that model, which uses Budyko's radiative dryness index to take into account the surface heat and water balance induced from solar radiation and precipitation, to be superior to the Miami model, which is an empirical model based on precipitation and temperature. The equations of the Chikugo model are:

$$NPP = 0.29[exp\{-0.216(RDI)^2\}]\ R_n$$
$$RDI = R_n / (l \times P),$$

where *RDI* is radiative dryness index, *Rn* is annual net radiation (kJ $cm^{-2}$ $yr^{-1}$); *P* is annual precipitation (cm $yr^{-1}$); and *l* is latent heat of evaporation (0.058 kJ $cm^{-3}$).

Calibration of actual and potential NPP using a gridded NPP dataset

The modeled NPP values were calibrated using a gridded NPP dataset distributed by the Oak Ridge National Laboratory (ZHENG & al. 2003). The dataset contains 2335 cells with total observed NPP. We used 90 cells located in our study region to calibrate our D-CASA model and 16 cells to calibrate the Chikugo model. The observed NPP in the cells used to calibrate the Chikugo model was more than 10 t dry weight $ha^{-1}$ $yr^{-1}$ and was estimated to be near to the potential NPP values judging from their biome type (forests) and high NPP values. Using regression techniques, we established calibration equations that related NPP values observed on the ground (Oak Ridge dataset) and those modeled by the D-CASA and Chikugo models.

The calibration equations were:

$y = 0.7878\ x + 1.6238$ for the D-CASA model ($R^2 = 0.3418$, $p<0.01$)
$y = 0.4511\ x + 2.8209$ for the Chikugo model ($R^2 = 0.3412$, $p<0.05$),

where $y$ is observed NPP (t dry weight $ha^{-1}$ $yr^{-1}$), and $x$ is modeled NPP (t dry weight $ha^{-1}$ $yr^{-1}$).

Estimation of actual and potential NPP

We estimated NPP for the region between 16°N–64°N and 32°E–152°E using a 0.2° grid for actual NPP and a 1° grid for potential NPP. We used the following datasets: precipitation from the Global Precipitation Climatology Center (GPCC); temperature, PAR and Rn from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis products; NDVI from NOAA/AVHRR/United States Geological Survey (USGS) 1-km AVHRR Global Land dataset; vegetation type from our original dataset based on the NOAA global vegetation index (GVI) and the classification scheme developed by NEMANI & RUNNING 1997; and soil texture from the UN Food and Agriculture Organization (FAO) soil map.

Extent of drylands and identification of desertification/land degradation hotspots

We overlaid the map of average actual NPP for the 20 years from 1981 to 2000 estimated by the D-CASA model on the map of the average potential NPP for the 20 years estimated by the Chikugo model and identified 4 regions: non-degraded or negligibly degraded areas; slightly degraded areas; moderately degraded areas; and heavily degraded areas, depending on the ratio of actual NPP to potential NPP (R=actual/potential), that is, $R \geq 1.0$; $1.0 > R \geq 0.75$; $0.75 > R \geq 0.5$; and $0.5 > R$, respectively.

Then, we identified areas of land degradation in drylands as potential desertification hotspots by overlaying the land degradation map on a drylands map. Following UNEP (1992), we defined drylands as regions where the ratio of annual precipitation (P) to mean annual potential evapotranspiration (PET) is between 0.05 and 0.65, excluding cold regions.

## Results and Discussion

Actual and potential NPP in Asia from 1981 to 2000

Actual NPP was estimated as more than 10 t ha$^{-1}$ yr$^{-1}$ in Assam (India) and other regions; as 5 to 10 t ha$^{-1}$ yr$^{-1}$ in the Huabei Plain (China), around the border between Russia and Kazakhstan, Hyderabad (India), and other regions; and as less than 5 t ha$^{-1}$ yr$^{-1}$ in Baotou (China), around the Aral Sea, western Iran, and other regions (Fig. 1). The distribution pattern of actual NPP estimated by the D-CASA model was similar to the average annual NPP of the 18 NPP models in the Potsdam NPP Model Intercomparison (PIK-NPP) project (CRAMER & al. 1999).

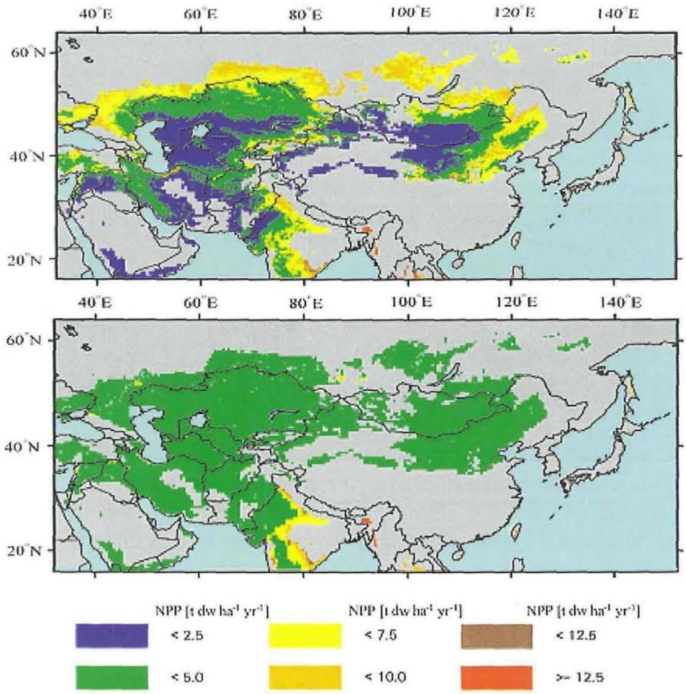


Fig. 1. Actual NPP estimated by the D-CASA model (upper) and potential NPP estimated climatologically by the Chikugo model (lower), average from 1981 to 2000 in Asian drylands.

Potential NPP showed a geographical distribution similar to actual NPP. However, potential NPP values were lower than actual NPP values in the regions of southern Russia, eastern Ukraine, and the Huabei Plain in China. By contrast, potential NPP was higher than actual NPP in southern Kazakhstan, southwestern Mongolia, and northwestern India. Most regions where actual NPP was higher than potential NPP correspond to areas dominated by irrigated agriculture.

Identifying potential desertification/land degradation hotspots in Asia

The degraded regions from India to Central Asia shown on the map of potential desertification/land degradation hotspots in Asia (Fig. 2 [upper]), correspond well with those on the soil degradation map of GLASOD (Fig. 2 [lower]; OLDEMAN & al. 1991).

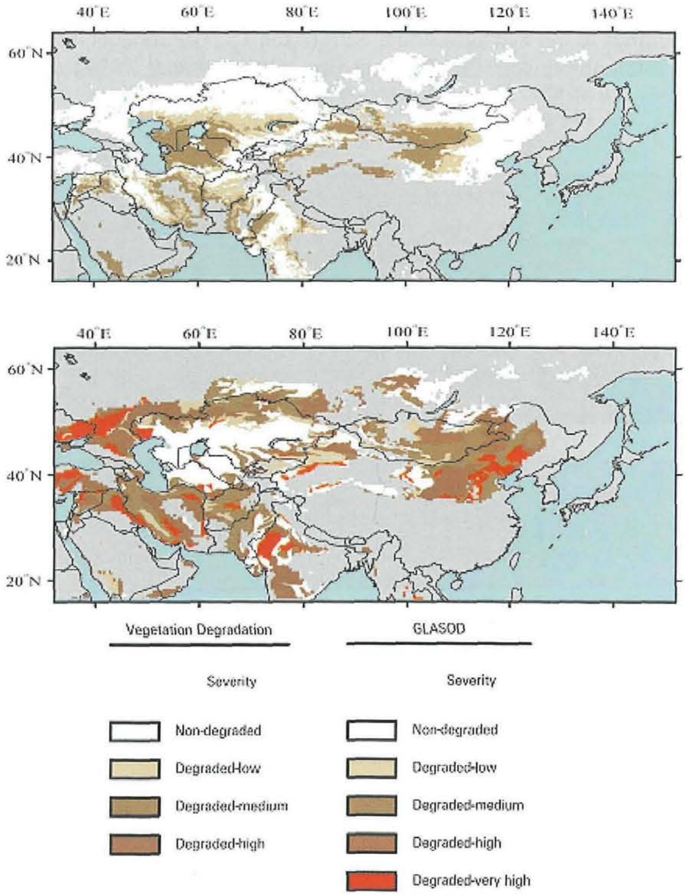


Fig. 2. Upper map: Potential desertification/land degradation hotspots in Asia from the viewpoint of vegetation degradation. The hotspots were identified by overlaying a map of regions showing land degradation (where actual NPP was less than potential NPP) on a map of drylands (where the ratio of annual mean precipitation to annual mean potential evapotranspiration was between 0.05 and 0.65, excluding cold regions).

Lower map: Soil degradation in drylands mapped by overlaying the GLASOD map of soil degradation regions (OLDEMAN & al. 1991) on the drylands map.

The regions of central Inner Mongolia (China), mid-latitudinal and south Mongolia, northwestern India, and the Deccan Plateau (India) are included in the area showing both vegetation degradation and soil degradation. The main differences between the two maps are in northeastern Inner Mongolia, Hebei Province (China), and northeastern China, where croplands and grazing lands predominate. In these regions, we evaluated degradation to be less than that determined by GLASOD.

YOUNG & WANG 2001 analyzed NDVI trends in China using satellite data from 1982 to 1992 and showed that the major decrease in NDVI occurred in the forest regions of southern China, whereas NDVI tended to increase in agricultural regions, especially in northeastern China. DEFRIES 2002 compared current and undisturbed vegetation and also reported an increase in NDVI in the agricultural region around Bo Hai in northeastern China. Thus, our estimates of vegetation degradation are consistent with those of previous studies.

On the other hand, some regions, including mid-latitudinal Kazakhstan and Betpak-Dala (southwest of Lake Balkhash), were estimated by the present study to be areas of vegetation degradation, but were not considered by GLASOD to be areas of soil degradation. Consistent with our results, the Map of Current Desertification in Central Asian Arid Zones (BABAEV & KHARIN 1999), based on a comprehensive evaluation including vegetation and soil degradation, shows "intensive and severe" or "moderate" desertification southwest of Lake Balkhash.

## Conclusions

In the present study, we achieved the following two outcomes:

(1) We identified potential desertification/land degradation hotspots in Asia for the 20 years from 1981 to 2000 from the viewpoint of vegetation degradation. Specifically, these were the regions of central Inner Mongolia (China), mid-latitudinal and south Mongolia, northwestern India, and the Deccan Plateau (India).

(2) We identified regions of vegetation degradation not identified by GLASOD as being affected by soil degradation in mid-latitudinal Kazakhstan and Betpak-Dala (southwest of Lake Balkhash).

Because we were able to assess desertification by objective and reproducible methods which do not need much time, money and labor, and were able to identify desertification hotspots not identified by the existing soil degradation map (GLASOD), we conclude that the new methodology proposed here for desertification assessment is valid and useful.

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