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Prediction of Aboveground Net Primary Productivity and Foliage Projective Cover in an Arid Area of China

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It appears that two main factors hinder the effective incorporation of ecological information derived from computer modeling in resource management at large spatial scales: (1) some models are not ecologically sound and (2) most models based on ecological principles are often too sophisticated or detailed, having complex structures and requiring a large range of input data. This paper employs a generic model based on well-established ecological principles, but with appropriate detail, to better serve decision-making in sustainable resource management. The model was used to simulate aboveground net primary productivity (ANPP), foliage projective cover (FPC), and the evaporation coefficient (k) for large arid areas in northwest China, where there has been serious desertification recently. Observation data of ANPP and FPC in the study area were used to validate the model, and the model results were in good agreement with observation data and other published data. The model was then used to simulate the evaporation coefficient, FPC, and ANPP for the study area. The simulation results indicated that except for several sites, the k parameter was lower than 0.35×10^{-2} and implied a typical arid climate in the study area. Estimated FPC of the plant community was lower than 50% at most sites, and the annual ANPP was very low—less than 1 tons $\cdot$ $ha^{-1} \cdot yr^{-1}$ at 93.8% of sites. These simulation results could serve as references for vegetation restoration and livestock husbandry management in arid areas of China.

Keywords aboveground net primary productivity, plant community, simulation model, vegetation coverage

Desertified land accounts for 27% of the continental territory of China, with desertification affecting 498 counties in northern China (China National Committee for the Implementation of the UN Convention to Combat Desertification, 2006). It is

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even more disturbing that about 2460 km^2 of land is estimated to convert to desertified land each year in China, equivalent to the loss of a medium-sized county (Liu et al., 2005; Yang et al., 2005). Fortunately, desertification was mitigated from a 10,400 km^2 increment per year in the late twentieth century to a 7585 km^2 decrement per year during 1999–2004 (China National Committee for the Implementation of the UN Convention to Combat Desertification, 2006). This paper focuses on arid areas in China, many of which have experienced rapid land degradation, termed sandification (desertification in the case of sandy soil) in China, including part of the Xinjiang Autonomous Region, part of Qinghai Province, the west of the Inner Mongolia Autonomous Region, and northwestern Gansu Province (Zhu & Liu, 1988). Along the middle reach of the Tarim River in Xinjiang, for example, the proportion of degraded area increased from 59% (1553 km^2) in 1960 to 63% in 1990, the severity of sandification has significantly increased, and it has been estimated that the annual reduction of grassland in the period 1983–1990 was 2% (Wang & Cheng, 2000; Wang et al., 2002).

Sandification has serious adverse effects on the ecological and economic values of ecosystems in these arid regions. Although arid areas are generally characterized as having low productivity and a harsh environment, it is argued that many ecosystems that are of low direct economic value deliver critical ecosystem services that benefit humans in other ways, such as the delivery of clean water, carbon storage, cultural benefits, soil conservation, and biodiversity (Millennium Ecosystem Assessment, 2003). This might be true in our study area in northwestern China. The large daily temperature variation and high solar radiation in these arid regions of China provide conditions suitable for special agricultural products (such as small carrots and grapes) in the oases scattered within the grazing land of the majority of the country. These oases depend on a stable hydrological regime and it is of direct economic importance to maintain the natural landscape and rehabilitate degraded ecosystems in order to maintain the oases (Thomas et al., 2000).

To rehabilitate degraded land effectively, it is pertinent to understand why ecosystem degradation occurs. It is common knowledge that mismanagement is largely responsible for current sandification in the aforementioned areas (Mitchell et al., 1998; Thomas & Middleton, 1994; Zhu, 1995; Thomas et al., 2000). The main causes of sandification in the studied area are thought to be overcultivation, overgrazing, and excessive collection of wood for fuel (Zhao, 1988; Zhu & Liu, 1988; Zhu, 1989). Infringement on oases by sandification is a major threat (Thomas et al., 2000). To protect the area from overgrazing, sustainable grazing management should be emphasized and knowledge of aboveground net primary productivity (ANPP) would be useful.

Net primary productivity (NPP) is a key functional parameter for an ecosystem (Roxburgh et al., 2004). The NPP estimation not only indicates the grazing capacity (Holecheck, 1988; Miehe et al., 2010), but also assists in the determination of the appropriate level of vegetation cover in vegetation restoration projects. Vegetation cover in well-managed landscapes reflects disturbances such as grazing and fire but is also strongly affected by climate and soils. Some vegetation restoration projects implemented to combat sandification in China have established extremely dense vegetation that may not be sustainable into the future and may also have negative effects in the more immediate term. For example, the "Three North" Shelterbelt Development Program was initiated by the government in 1978. Although it is difficult to assess the shelterbelt stability at this time, it is argued that problems may arise owing to the falling water table and deteriorating water quality due to the high-density vegetation, which may not be maintained naturally in arid and semi-arid areas (Mitchell et al., 1996). Therefore, to ensure sustainable vegetation restoration, suitable vegetation coverage should be determined.

On the basis of the aforementioned, two measurements are of particular importance in the sustainable management and rehabilitation of degraded land in our study area: estimation of the ANPP for grazing control and determination of the optimal vegetation coverage according to the environment. Measurements and simulations of NPP and land capability have been conducted for arid areas of China over the past decade; for example, grassland yield estimation (Li et al., 1998), simulation of regional vegetation dynamics using remote sensing data (Gao et al., 2000), simulation of NPP in China by BIOME3 (Ni et al., 2000), and simulation of the land capability of Fukang County, Xinjiang (Thomas et al., 1994). However, application of the simulations of these studies to sustainable management is somewhat constrained, owing to their complicated methods, inputs, and/or inaccessibility.

In this paper, an effective process-based model of the plant community growth with simple input, meteorological and basic soil information is used to predict the vegetation coverage and ANPP of a plant community. We believe the model results could be used as references for the restoration of degraded lands and livestock control management in arid areas. We first describe the structure and function of the model; second, validate the modeled predictions against observation data; and, finally, assess the potential of the model in the estimation of land capability.

Methods

Model Acquisition

COMSIM is a simple equilibrium model that predicts vegetation cover and production from basic climatic and edaphic parameters using long-term monthly average data, with the computation of constraints due to water supply/demand for ecosystem production being fundamental to the model (Specht, 1981). The upper limits of plant biomass and production are set using biophysical parameters such as the amounts of water, rainfall, soil moisture, and evaporation, with work over many years having established that many aspects of plant communities are determined by such factors (Harris, 2002). The model focuses on the transfer of biomass throughout the system. Its core principle is the control of water flow through the soil–plant–atmosphere continuum of the plant community, which governs and is governed by the leaf coverage throughout the landscape. According to the input type, it is most similar to the CenW and 3PG models evaluated by Roxburgh et al. (2004) (i.e., monthly long-term climatic averages, water balance models, edaphic data inputs, no incorporation of satellite data). The model falls into the biogeochemical/vegetation group of models reviewed by Cramer et al. (1999), having some aspects of the dynamic nature of vegetation in its response to the environment proposed by Cramer et al. (2001). It has much in common with the approach of the water-centered models discussed by Churkina et al. (1999). These models have been used at global scale to calculate carbon sequestration by vegetation but have been little tested for arid areas, which have proved problematic owing to poor on-ground datasets for validation and a high degree of spatial (and temporal) variation (Roxburgh et al., 2004).

The use of foliage projective cover (FPC) of the vegetation as the primary interceptor of solar radiation distinguishes COMSIM from many other models, which use the leaf area index or plant cover type (e.g., broadleaf) in the prediction of photosynthetic activity or production. FPC represents the horizontal cover of vegetation over the land surface, regardless of overlapping layers, and thus approximates the optimal photosynthetic potential of the vegetation (ignoring the diminishing efficiencies of the lower layers of the canopy integral to using the leaf area index). FPC incorporates all strata of the vegetation (there are established relationships between overstory and understory foliage cover), which is particularly appropriate for low-cover vegetation, and FPC is positively correlated with the normalized difference vegetation index (Danaher et al., 1992).

On the basis of ecological principles, the relationships between FPC, ANPP and environmental factors were established, and the COMSIM model was developed (Specht, 1981; Specht & Specht, 1999). We used this model to analyze ANPP and FPC in a huge arid area of China. The main equations are

$$E_a/E_0 = kW, \tag{1}$$

$$W = P - D + S_{ext}, \tag{2}$$

where E_a is the actual monthly evapotranspiration (mm), E_0 is monthly pan evaporation (mm), k is the evaporation coefficient, W is available soil water (mm) in a month, P is monthly rainfall (mm), D is monthly drainage (mm), and S_{ext} is soil water stored in the root zone at the beginning of each month (mm).

S_{max} is used to calculate k in the COMSIM model. Because E_a and k cannot be directly calculated using Eqs. (1) and (2), an iterative mathematic algorithm is used to estimate their values in the equilibrium state. The iteration process is well described by Specht (1981). For S_{ext} and D, only initial values needed to be set, and they were then updated during the iteration in this research. Here, $D = S_{max}/2$ and $S_{ext} = 10$ mm were set initially during the iterative process.

$$FPC\text{over} = 9770 \times k/100 - 7.15, \tag{3}$$

$$FPC\text{under} = 5880 \times k/100 + 10.04, \tag{4}$$

$$FPC\text{total} = FPC\text{over} + FPC\text{under}, \tag{5}$$

where FPCtotal (%), FPCunder (%) and FPCover (%) are the total, understory and overstory FPC (Specht & Specht, 1999).

$$MI = E_a/E_0, \tag{6}$$

where MI is the moisture index.

$$LI = 1 - e^{(-3.5 \times L/750)}, \tag{7}$$

where LI is the light index, L is the total monthly solar radiation (cal cm^{-2} day^{-1}), and e is the base of the natural logarithm (Specht, 1981).

$$TI = 0.049 \times 10^{(0.044 \times T)}, \tag{8}$$

where TI is the thermal index and T is the monthly average temperature (°C).

$$NPI\text{over} = FPC\text{over} \times TI \times MI \times LI, \tag{9}$$

$$NPI\text{under} = FPC\text{under} \times TI \times MI \times LI, \tag{10}$$

where NPIover and NPIunder are the understory and overstory monthly net production indices, and NPI is the sum of NPIover and NPIunder.

$$CMGI = NPI \times OptCAGI, \tag{11}$$

where $OptCAGI$ is the optimal current annual growth increment ($\text{tons} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$) (when there are no constraints on water availability, temperature, and light) and $CMGI$ is the actual monthly biomass production ($\text{tons} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$) (Specht & Specht, 1999).

$$OptCAGI = 0.86 + 0.1AvAnnT, \tag{12}$$

where $AvAnnT$ denotes the annual average temperature.

$$ANPP = \int_1^{12} (CMGI)dt, \tag{13}$$

where $ANPP$ is the aboveground net primary productivity ($\text{tons} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$).

Study Area

The study area includes the majority of the arid areas of China (Figure 1 and Appendix 1). The annual precipitation in this region varies from 15.0 to 411.7 mm, the average monthly temperature varies from −26.7°C to −4.7°C in January and from 7.7°C to 32.3°C in July, and the annual mean temperature ranges from −4.6°C to 14.3°C in different places.

The study area has a continental climate and precipitation is low. The temperature is high in summer, resulting in high evaporation. Turpan in the Xinjiang Autonomous Region is a typical case and is commonly called the "fire stove" in China. To the west of the Tianshan Mountains, there are several basins. The western terrain of the basins is lower and affected by moist westerly winds, whereas the eastern terrain is obstructed by the Tianshan Mountains to the east and thus has higher precipitation. Annual precipitation is higher in some mountain areas or some basins between high mountains; for example, Zhaosu, which is located between branches of the western Tianshan Mountains, has higher precipitation. In general, the climate of the study area (especially the Xinjiang Uyghur Autonomous Region, XUAR) is characterized by three huge mountains (Altai in the north, Tianshan in the middle, and Kunlun in the south), and two big basins (Taklimakan and Jungar). The centers of the two basins are extensive desert, while there are oases irrigated by snow-melted waters of the high mountains scattered at the basin edges and along rivers. The oases are also important locations for farming and grazing in the XUAR. However, a lack of forage in spring and winter limits animal husbandry supported by oases and high-mountain grazing systems.

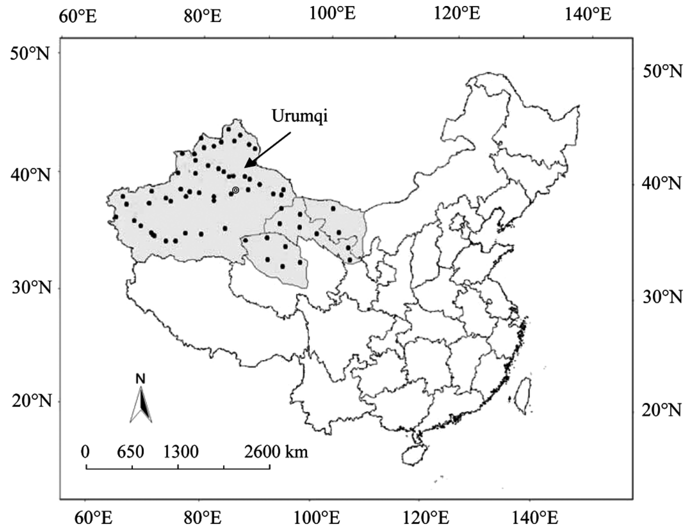


Figure 1. Localities of the 65 study sites in the study area of China. The shaded area represented the study area.

Climatic and Edaphic Data

Monthly average data were obtained from 65 weather stations in the area for the 38-year period from 1961 to 1998. Solar radiation was estimated from the product of percentage sunlight and the maximum solar radiation using trigonometry. The locations of stations are shown in Figure 1. S_{max} was derived from a soil map of China (1:1,000,000) and the description of soil properties for the corresponding zone given in a textbook (Xiong & Li, 1987).

Actual Aboveground Net Primary Productivity (ANPP)

The observed ANPP data were gathered in two ways at 14 sites. Four sites were monitored by a local researcher using the International Biological Program method (personal communications) (Milner & Hughes, 1968) and 10 sites were monitored by the authors.

The sites were selected to represent soil and vegetation conditions as different as possible; for example, conditions of grassland, shrubland, and relatively moist and dry sites. At each site, sample plots were set randomly in relatively intact areas (without obvious degradation) to obtain data for potential vegetation. Data were measured over several years (1–4 years). After field data were collected, climate data for that year were compared with average data. If climate data deviated greatly from the average data, the field measurement was continued the next year until the climatic conditions were similar to average conditions, especially in terms of precipitation. Therefore, our field data represent average conditions in the local area.

At each site, a 1 km^2 sample site was defined, within which 3–5 sample plots were established (the actual number at each site is given in Table 1), each having an area of 1600 m^2(40 × 40 m) to get an adequate representation of each plant community. Three plots of 4 m^2(2 × 2 m) were set in each 1600 m^2 plot (Milner & Hughes, 1968; Specht & Specht, 1999). In each 4 m^2 plot, the plant community height and species composition were recorded, and the aboveground biomass was obtained both in April and August. The ANPP was calculated by subtracting the biomass in April from the biomass in August (Milner & Hughes, 1968).

After completion of the observations, the average ANPPs in 4 m^2 plots and then in 1600 m^2 plots were calculated.

All measurement ANPP data were translated into units of tons $\cdot$ $ha^{-1} \cdot yr^{-1}$ and are presented in Table 1.

FPC

The plant community FPC was measured within each 40×40 m plot through a sample line (40 m in length) in August when the aboveground biomass was measured. The FPC is the percentage horizontal foliage cover determined by FPC crosswire sighting tubes in the field (Ashton, 1976; Specht & Specht, 1999). The average FPC was derived for each plot over several years and is presented in Table 1.

Regression Analysis

Regression analysis was carried out for 65 predicted k, ANPP, and FPC data against mean annual rainfall, and multiple regression incorporating both temperature and rainfall was carried out for predictions of ANPP and FPC using SPSS 10.0 software (SPSS, 2000).

Results

Measured ANPP and FPC

The measured ANPP was between 0.02 and 2.41 tons $\cdot$ $ha^{-1} \cdot yr^{-1}$, the measured FPC was between 26.4% and 75.2%, and the highest values for FPC and ANPP were found in Zhaosu with high precipitation and the lowest in Lenghu with low precipitation (Table 1).

Model Performance against Measured ANPP and FPC

ANPP and total FPC data were gathered to test the performance of the model. A lack of data in this area is a great challenge for model evaluation, although it is a general problem for modeling of ecosystem processes (Armstrong et al., 1997), especially in arid zones (Roxburgh et al., 2004). Of the 65 sites selected for climatic and edaphic data, ANPP and FPC data were only available for 14 sites. The observation and simulation data are compared in Figures 2 and 3. The differences between the observation and simulation data were between 10% and 25%, which were greater than the 11% difference in a study by Armstrong et al. (1997). To further evaluate the model performance, a measure used by Qiu et al. (1998) was adopted to examine the correlation between the modeled and observed ANPP and FPC. Employing this method, the observation and estimation data were used to derive a linear regression equation ($y = a + bx$), which was then compared with the 1:1 observed data line ($y = x$). It is clear from Figures 2 and 3 that the simulation data are in good agreement

Table 1. Information on measured aboveground net primary productivity (ANPP, $tons \cdot ha^{-1} \cdot yr^{-1}$) and total foliage projective cover data (FPC, %) in the study area. SE represents standard error for averaged data

Sites	Latitude (°N)	Longitude (°E)	Precipitation (mm)	Year	Average ANPP	SE	Total FPC (%)	SE	Number of plots ($40 \times 40\,m^2$)/measured duration (years)
Akesualaer	40.05	81.05	42.4	Average	0.32	0.07	49.6	3.8	5/3
			83.5	1993	0.46	0.09	56.3	3.3	
			32.9	1994	0.21	0.04	43.1	2.7	
			48.5	1995	0.3	0.07	49.4	3.1	
Fuyun	46.98	89.52	158.6	Average	0.41	0.02	55.7	0.9	5/2
			235.1	1994	0.43	0.04	56.8	4.0	
			164.5	1995	0.39	0.05	54.6	3.6	
Geermu	36.42	94.90	38.8	Average	0.08	0.02	40.6	2.2	3/1
Kuerle	41.75	86.13	50.1	Average	0.17	0.03	36.2	2.5	5/2
			58.6	1993	0.21	0.02	39.2	1.4	
			42.4	1994	0.13	0.02	33.1	0.9	
Lenghu	38.08	93.38	17.6	Average	0.02	0.02	26.4	2.5	3/1
Luntai	41.78	84.25	47.4	Average	0.3	0.05	50.1	1.6	5/2
			72.7	1993	0.36	0.07	52.1	1.0	
			42.7	1994	0.24	0.06	48.1	0.5	

Ruoqiang	39.03	88.02	17.4	Average	0.05	0.05	32.1	1.6	5/2
			23.5	1996	0.07	0.01	34.1	3.9	
			13.9	1997	0.03	0.01	30.1	2.7	
Shache	38.43	77.27	43.2	Average	0.21	0.02	38.4	1.0	5/2
			32.4	1997	0.17	0.05	37.2	2.5	
			45.5	1998	0.24	0.1	39.6	3.5	
Shihezi	44.32	86.05	199.1	Average	0.84	0.08	58.2	0.8	3/2
			208.8	1995	0.95	0.3	59.1	5.5	
			197.9	1996	0.73	0.15	57.2	4.6	
Subeiyemajie	41.58	96.88	85.2	Average	0.16	0.05	37.1	2.8	3/1
Tacheng	46.73	83.00	291.6	Average	1.51	0.2	65.3	2.2	3/3
			367.5	1990	1.79	0.2	68.7	3.7	
			230.9	1991	1.19	0.1	61.1	2.9	
			329.4	1992	1.55	0.2	66.1	3.2	
Tulufan	42.93	89.20	16.4	Average	0.08	0.03	38.7	4.4	5/4
			8.5	1991	0.04	0.01	34.1	1.5	
			23.2	1992	0.09	0.02	46.2	2.1	
			7.2	1993	0.05	0.01	30.4	1.3	
			21.3	1994	0.14	0.03	44.2	2.2	
Yining	43.95	81.03	257.5	Average	1.95	0.25	67.2	1.9	5/3
			311.2	1994	2.24	0.2	69.3	6.1	
			154.4	1995	1.45	0.1	63.3	5.6	
			279	1996	2.15	0.2	68.9	6.0	
Zhaosu	43.15	81.13	512.1	Average	2.41	0.15	75.2	1.2	5/3
			464.3	1994	2.21	0.3	73.1	6.1	
			535.5	1995	2.71	0.24	77.2	7.1	
			494.7	1996	2.32	0.31	75.3	6.5	

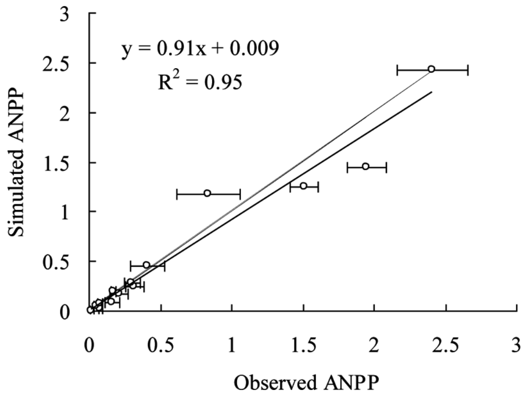


Figure 2. Comparison of observed and simulated ANPP (tons · ha^{-1} · yr^{-1}). Error bars indicate the standard error of the observed data. The dashed line shows the 1:1 relationship, the complete line, and the fitted relationship.

with observations of ANPP and FPC. Therefore, the model is acceptable and valuable in simulating ANPP and FPC in the study area.

Prediction of ANPP and FPC

The simulation data show that among the 65 sites, the evaporation coefficient k was less than 0.35×10^{-2} at the majority of sites (53/65), between 0.35×10^{-2} and 0.45×10^{-2} at nine sites, and between 0.45×10^{-2} and 0.55×10^{-2} at three sites (Figure 4). These three k ranges represented arid, semi-arid, and subhumid arid areas, respectively, according to the criteria of Specht and Specht (1999). Figure 4 shows that k was less than 0.35 in most areas, and the locations with k greater than 0.35 were mostly in the central western region affected by moist westerly winds. Therefore, the k values indicate clearly that the study sites had a dry nature. Simulated ANPP was very low, being nearly zero at some sites, less than 0.1 tons · ha^{-1} · yr^{-1} at 21.5% of sites, less

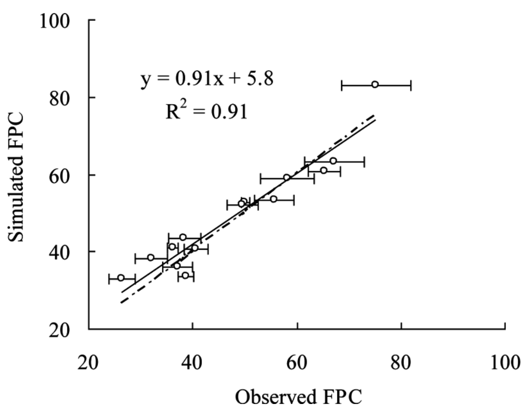


Figure 3. Comparison of observed and simulated total foliage projective cover (FPC, %). Error bars indicate the standard error of the observed data. The dashed line shows the 1:1 relationship, the complete line, and the fitted relationship.

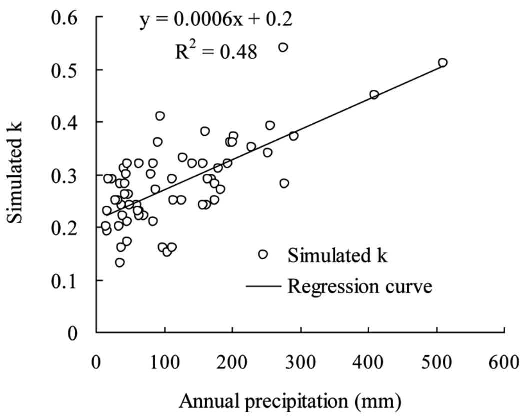


Figure 4. Observed and simulated k ($\times 10^{-2}$) by COMSIM model and regression curve for the 65 study sites in the study area of China.

than 0.5 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1} at 75.4% of sites, and less than 1 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1} at 93.8% of sites. Only four sites had ANPP greater than 1 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1}(Figure 5). FPC total ranged 0.20%–0.50% in most areas and had a trend similar to that of k. FPC total of the plant community was less than 50% at 64.6% of the study sites (Figure 6). Vegetation cover and ANPP were naturally very low, as evidenced by the observation data (Table 1 and Figures 2 and 3), and modeling showed how widespread this low productivity was across the study area.

Regression analysis indicated that it was possible to quickly estimate k (Figure 4, $P < 0.01$, n = 65), ANPP (Figure 5, $P < 0.01$, n = 65) and FPC (Figure 6, $P < 0.01$, n = 65) from rainfall in the study area. Stepwise regression analysis indicated that both temperature and annual rainfall significantly affected ANPP ($ANPP = 0.004 \times rainfall + 0.03 \times temperature - 0.35$, $P < 0.01$, n = 65), and FPC was significantly affected by rainfall, but not by temperature.

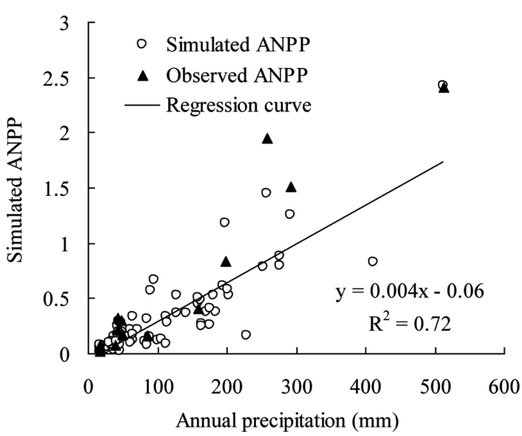


Figure 5. Observed and simulated ANPP (tons $\cdot$ ha^{-1} $\cdot$ yr^{-1}) by COMSIM model and regression curve for the 65 study sites in the study area of China.

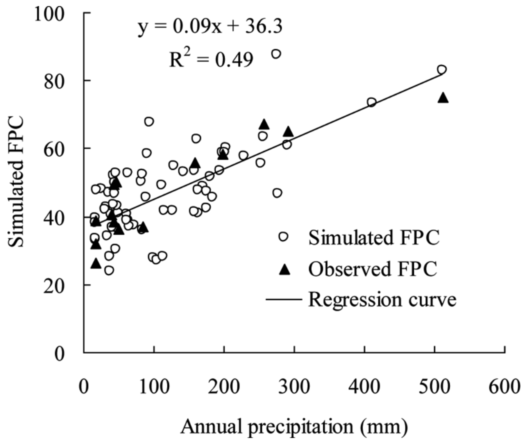


Figure 6. Observed and simulated total foliage projective cover (FPC, %) by COMSIM model and regression curve for the 65 study sites in the study area of China.

Discussions and Conclusions

The simulation results obtained using the COMSIM model based on the water balance indicated that the FPC was lower than 50% in most areas, and because dense vegetation would consume much water owing to high transipiration, vegetation coverage should be lower than 50% to ensure sustainable vegetation restoration. Although model evaluation showed that the accuracy of the simulation results obtained in this paper was only 75%–90% compared with observation data, the simulated FPC could serve as a reference. Overgrazing, together with agricultural land exploitation, has resulted in serious environmental problems in huge areas in China. To maintain a sustainable ecosystem, the Chinese government launched projects to restore ecosystems. However, owing to lack of knowledge of suitable vegetation coverage, some of the projects were probably unsustainable. Therefore, it is important to assess and communicate such information to the government. Low simulation FPC and ANPP might tell us that we may have to leave most areas (e.g., the Gobi Desert) as they should be and appreciate their biodiversity and environmental values. Any economic activity will be limited and should not exceed the capability of the environment. Because of the low ANPP, livestock husbandry should be managed carefully so as not to exceed holding capacity.

There have been numerous reports related to NPP prediction; our results generally agree with published results for similar areas. Kogan et al. (2004) reported that the biomass of Mongolian grassland with annual precipitation of 243 mm is 1.4 tons $\cdot$ ha^{-1}. Bai et al. (2007) reported that the ANPP for meadow steppe (with annual precipitation of 350 mm) averages 1.8 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1} and ranges from 0.36 to 3.3 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1}, that for typical steppe (with annual precipitation of 249 mm) averages 0.48 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1} and ranges from 0.12 to 1.5 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1}, and that for desert (with annual precipitation of 168 mm) averages 0.2 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1} and ranges from 0.06 to 0.41 tons $\cdot$ ha^{-1} $\cdot$ yr^{-1} on the Xilingol steppe of Inner Mongolia. The average live biomass on the Xilingol steppe is 1.3 tons(ha^{-1} as derived from the MODIS vegetation index (Kawamura et al., 2005), which is a little lower than data reported by Bai et al.

(2007). Fernandez-Gimenez and Allen-Diaz (1999) reported that biomass for desert steppe is 0.08 tons · ha^{-1} and vegetation coverage is 14% in a dry year, whereas the values are 0.36 tons · ha^{-1}, and 51% or higher in a wet year. Ni (2001) reported that vegetation carbon storage in temperate deserts in China is 6 tons · ha^{-1}, which converts to aboveground biomass of 12 tons · ha^{-1} · yr^{-1} (assuming that half of plant biomass is carbon); in this area, however, both aboveground and belowground biomass are higher, and the ANPP should be much lower. Wesche et al. (2010) reported that biomass was 0.2–0.5 tons · ha^{-1} in 2005 with 101 mm precipitation in Gobi Gurvan Saykhan National Park in southern Mongolia, and that vegetation cover has been 1–60% with 100–150 mm annual precipitation. The coverage of plant communities predicted in our research is similar to the coverage in those reports.

In our study area, the annual rainfall was less than 50 mm at 26% of the sites, less than 100 mm at 54%, and less than 200 mm at 86%. The predicted ANPP ranged from 0.01 to 2.42 tons · ha^{-1} · yr^{-1}; these results are similar to data reported by Bai et al. (2007) for different areas, including areas of meadow steppe, typical steppe and desert, and data presented in other reports for similar climate zones.

Significant improvements in NPP prediction have been achieved with the help of new remote-sensing technology and vegetation indices (Purevdorj et al., 1998; Tucker et al., 2005). There are global-scale gross primary productivity (produced by the Distributed Active Archive Center for Biogeochemical Dynamics, the Oak Ridge National Laboratory (ORNL DAAC), http://daac.ornl.gov) and NPP products (published by the Global Land Cover Facility (GLOPEM), Prince & Goward, 1995). Data downloaded from the GLOPEM website and field data were compared for three sites: the Xilingol steppe of Inner Mongolia (43.7°N, 116.6°E), Kuerle (41.75°N, 86.13°E), and Zhaosu (43.15°N, 81.13°E). Data downloaded from GLOPEM are 7.2, 3.2, and 6.1 tons C · ha^{-1} · yr^{-1} for 1998 for the aforementioned three sites, and observation data were 2.5 (data from ORNL DAAC), 0.2 and 2.4 tons · ha^{-1} · yr^{-1} (Table 1), equivalent to 1.2, 0.1, and 1.2 tons C · ha^{-1} · yr^{-1}. Because data from GLOPEM are of NPP, they are much higher than our results for ANPP. Considering that much biomass is allocated to the root system in an arid area, this difference is reasonable (Milner & Hughes, 1968).

It should be noted that ANPP and FPC predictions reflect potential vegetation adapting to long-term climatic conditions. Therefore, these predictions should be higher than actual data in a degraded area. Furthermore, vegetation degradation usually results in changes in soil and the microclimate. At such locations, plant species and vegetation coverage should differ from those for native vegetation in the early stages of restoration projects. The data should be carefully referenced in such areas. Because of large fluctuations in climate, especially annual precipitation in an arid area (Thomas et al., 2000), our results derived for the equilibrium state should differ from observations in different relatively dry and wet years as reported by Huxman et al. (2004) and Vetter (2005).

It is also important to point out that the presented model is more applicable than many available models at large scales. Armstrong et al. (1997) reported a model that predicts plant community growth dynamics on a monthly scale for different vegetation types; however, this model requires specific inputs of vegetation type and its application is thus limited. Other models could be used to simulate ANPP; however, such models also require relatively detailed inputs (Hanson et al., 1988), and thus, it is difficult to use them at large spatial scale. The present model is based on monthly climate data, which can be collected from normal weather stations, and the model could be easily applied with large spatial extent. Therefore, it may be more suitable for regional environment management.

The simple input requirements of the present model are especially important for the present study area. Although NPP observations have been significantly improved by a program of the China Ecological Research Network and a forestry observation network (Gao et al., 2000), observation data are still too sparse for extension to a regional level and regional environment management. Therefore, few models have been built for such a purpose. As examples, biomass estimation of grassland through remote sensing and GIS technologies (Gao et al., 2000) and carbon storage estimation (Ni et al., 2000; Feng et al., 2001; Ni, 2002) may be useful for monitoring the NPP dynamics, but insufficient validation limits their utility. A study of the land capacity of Fukang County in Xinjiang Province (Thomas et al., 1994) integrated both theoretical and empirical methods and provided a good estimation of NPP in that particular area, obtaining results similar to our results; however, it is unclear whether the approach can be extended to all arid areas. The validation of presented model indicates that it can be used in arid areas in Central Asia and can provide a good estimation of annual production.

A simplification is made for the presented model. An oasis maintained by the water supply from melted mountain snow and ice is an important component in arid ecosystems, but is azonal. However, the presented model is concerned with zonal vegetation only, and interaction between an oasis and desert is not considered. It might be helpful for the interaction to be incorporated in future studies.

Finally and most importantly, the Chinese government has started a large national-level program called "Exploitation in Western China," which will bring enormous change to the ecological environment in the study area. To ensure sustainable development, reasonable measurements, including those of reasonable vegetation cover and reasonable livestock numbers, are urgently needed for this area, and our model could be the first of many to come.

References

Ashton, D. H. 1976. The development of even-aged stands of *Eucalyptus regnans* F. Muell. In Central Victoria. *Australia Journal of Botany* 24: 397–414.

Armstrong, H. M., I. J. Gordon, S. A. Grant, N. J. Hutchings, J. A. Milne, and A. R. Sibbald. 1997. A model of the grazing of hill vegetation by sheep in the UK. I. Prediction of vegetation biomass. *Journal of Applied Ecology* 34: 166–185.

Bai, Y. F, J. G. Wu, Q. M. Pan, J. H. Huang, Q. B. Wang, F. S. Li, A. Buyantuyev, and X. G. Han. 2007. Positive linear relationship between productivity and diversity: evidence from the Eurasian Steppe. *Journal of Applied Ecology* 44: 1023–1034.

China National Committee for the Implementation of the UN Convention to Combat Desertification. 2006. *China national report on the implementation of the united nation's convention to combat desertification*. Ministry of Forestry, Beijing.

Churkina, G., S. W. Running, A. L. Schloss, and the participants of the Potsdam NPP Model Intercomparison. 1999. Comparing global models of terrestrial net primary productivity (NPP): the importance of water availability. *Global Change Biology* 5(Suppl. 1): 46–55.

Cramer, W., A. Bondeau, F. I. Woodward, I. C. Prentice, R. A. Betts, V. Brovkin, P. M. Cox, V. Fisher, J. Foley, A. Friend, C. Kucharik, M. R. Lomas, N. Ramankutty, S. Sitch, B. Smith, A. White, and C. Young. 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. *Global Change Biology* 7: 357–373.

Cramer, W., D. W. Kicklighter, A. Bondeau, B. III. Moore, G. Churkina, B. Nemry, A. Ruimy, A. L. Schloss, and the participants of the Potsdam NPP Model Intercomparison. 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. *Global Change Biology* 5(Suppl. 1): 1–15.

Danaher, T. J., J. O. Carter, K. D. Brook, A. Peacock, and G. S. Dudgeon. 1992. Broadscale vegetation mapping using NOAA-AVRRR imagery. In *Proceedings of the 6th Australian Remote Sensing Conference*, 2–6 November 1992, Wellington, New Zealand, 3: 126–137.

Feng, Q., G. Cheng, and K. Endo. 2001. Carbon storage in desertificated lands: A case study from North China. *GeoJournal* 51: 181–189.

Fernandez-Gimenez, M. E., and B. Allen-Diaz. 1999. Testing a non-equilibrium model of rangeland vegetation dynamics in Mongolia. *Journal of Applied Ecology* 36: 871–885.

Gao, Q., M. Yu, and X. Yang. 2000. An analysis of sensitivity of terrestrial ecosystems in China to climate change using spatial simulation. *Climate Change* 47: 373–400.

Hanson, J. D., J. W. Skiles, and W. J. Parton. 1988. A multi-species model for rangeland plant communities. *Ecological Modelling* 44: 89–123.

Harris, G. 2002. Simple rules underlie the complex and non-linear dynamics of terrestrial and aquatic ecosystems: implications for catchment biogeochemistry and modeling. *C.S.I.R.O. Land and Water Technical Report* 11/02.

Holecheck, J. L. 1988. An approach for setting the stocking rate. *Rangelands* 10: 10–14.

Huxman, T. E., M. D. Smith, P. A. Fay, A. K. Knapp, M. R. Shaw, M. E. Loik, S. D. Smith, D. T. Tissue, J. C. Zak, J. F. Weltzin, W. T. Pockman, O. E. Sala, B. M. Haddad, J. Harte, G. W. Koch, S. Schwinning, E. E. Small, and D. G. Williams. 2004. Convergence across biomes to a common rain-use efficiency. *Nature* 429: 651–654.

Kawamura, K., T. Akiyama, H. Yokota, M. Tsutsumi, T. Yasuda, O. Watanabe, and S. Wang. 2005. Comparing MODIS vegetation indices with AVHRR NDVI for monitoring the forage quantity and quality in Inner Mongolia grassland, China. *Grassland Science* 51: 33–40.

Kogan, F., R. Stark, A. Gitelson, L. Jargalsaikhan, C. Dugrajav, and S. Tsooj. 2004. Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices. *International Journal of Remote Sensing* 25: 2889–2896.

Li, J., T. Liang, and Q. Chen. 1998. Estimating grassland yields using remote sensing and GIS technologies in China. *New Zealand Journal of Agricultural Research* 41: 31–38.

Liu, A. X., Z. J. Liu, Z. Y. Wang, Z. Niu, and D. M. Yan. 2005. Monitoring of desertification in central Asia and western China using long term NOAA-AVHRR NDVI time-series data. *IEEE International* 4: 2278–2280.

Miehe, S., K. Jürgen, H. V. Wehrden, and V. Retzer. 2010. Long-term degradation of Sahelian rangeland detected by 27 years of field study in Senegal. *Journal of Applied Ecology* 47: 692–700.

Millennium Ecosystem Assessment. 2003. *Ecosystems and Human Well-being*. Island Press, Washington.

Milner, C., and R. E. Hughes. 1968. *Methods for the Measurement of the Primary Production of Grassland. IBP Handbook No. 6*. Blackwell, Oxford.

Mitchell, D. J., W. Fearnehough, M. A. Fullen, and I. C. Trueman. 1996. Ningxia desertification, reclamation and development. *China Review* 5(Autumn/Winter): 27–31.

Mitchell, D. J., M. A. Fullen, I. C. Trueman, and W. Fearnehough. 1998. Sustainability of reclaimed desertified land in Ningxia, China. *Journal of Arid Environments* 39: 239–251.

Ni, J. 2001. Carbon storage in terrestrial ecosystems of China: estimates at different spatial resolutions and their responses to climate change. *Climatic Change* 49: 339–358.

Ni, J. 2002. Carbon storage in grasslands of China. *Journal of Arid Environments* 50: 205–218.

Ni, J., M. T. Sykes, I. C. Prentice, and W. Cramer. 2000. Modelling the vegetation of China using the process-based equilibrium terrestrial biosphere model BIOME3. *Global Ecology and Biogeography* 9: 463–479.

Prince, S. D., and S. J. Goward. 1995. Global primary production: a remote sensing approach. *Journal of Biogeography* 22: 316–336.

Purevdorj, T., R. Tateishi, T. Ishiyama, and Y. Honda. 1998. Relationships between percent vegetation cover and vegetation indices. *International Journal of Remote Sensing* 19: 3519–3535.

Qiu, G. Y., T. Yano, and K. Momii. 1998. An improved methodology to measure evaporation from bare soil based on comparison of surface temperature with a dry soil surface. *Journal of Hydrology* 210: 93–105.

Roxburgh, S. H., D. J. Barrett, S. L. Berry, J. O. Carter, I. D. Davies, R. M. Gifford, M. U. F. Kirschbaum, B. P. McBeth, I. R. Noble, W. G. Parton, M. R. Raupach, and M. l. Roderick. 2004. A critical overview of model estimates of net primary productivity for the Australian continent. *Functional Plant Biology* 31: 1043–1059.

Specht, R. L. 1981. Growth indices-their role in understanding the growth, structure and distribution of Australian vegetation. *Oecologia* 50: 347–356.

Specht, R. L., and A. Specht. 1999. *Australian plant communities*. Oxford University Press, Victoria.

SPSS. 2000. SPSS 10.0 for windows. SPSS Inc. Chicago, Illinois, USA.

Thomas, D. A., and N. J. Middleton. 1994. *Desertification: Exploding the Myth*. John Wiley and Sons, Chichester.

Thomas, D. A., X. M. Sun, J. P. Zhang, J. Z. Zhu, M. Lewis, and P. Xu. 1994. Land capacity of Fukang county, Xinjiang province, People's Republic of China. *Arid Soil Research and Rehabilitation* 8: 373–387.

Thomas, F. M., S. K. Arndt, H. Bruelheide, A. Foetzki, D. Gries, J. Huang, M. Popp, G. Wang, X. Zhang, and M. Runge. 2000. Ecological basis for a sustainable management of the indigenous vegetation in a central-Asian desert: presentation and first results. *Journal of Applied Botany* 74: 212–219.

Tucker, C. J., J. E. Pinzon, M. E. Brown, D. Slayback, E. W. Pak, R. Mahoney, E. Vermote, and N. El Saleous. 2005. An Extended AVHRR 8-km NDVI Data Set Compatible with MODIS and SPOT Vegetation NDVI Data. *International Journal of Remote Sensing* 26: 4485–4498.

Vetter, S. 2005. Rangelands at equilibrium and non-equilibrium: recent developments in the debate. *Journal of Arid Environments* 62: 321–341.

Wang, G., and G. Cheng. 2000. The characteristics of water resources and the changes of the hydrological process and environment in the arid zone of northwest China. *Environmental Geology* 39: 783–790.

Wang, X., Y. Ma, H. Wang, and Z. Tao. 2002. Analysis on climate characteristics of sandstorms in North Xinjiang. *Acta Scientiarum Naturalium Universitatis Pekinensis* 38: 681–687 (in Chinese with English abstract).

Wesche, K., K. Ronnenberg, V. Retzer, and G. Miehe. 2010. Effects of herbivore exclusion in southern Mongolian desert steppes. *Acta Oecologica* 36: 234–241.

Xiong, Y., and Q. K. Li. 1987. *Soils of China.* 2nd edition. Science Press, Beijing (in Chinese).

Yang, X., K. Zhang, B. Jia, and L. Ci. 2005. Desertification assessment in China: An overview. *Journal of Arid Environments* 63: 517–531.

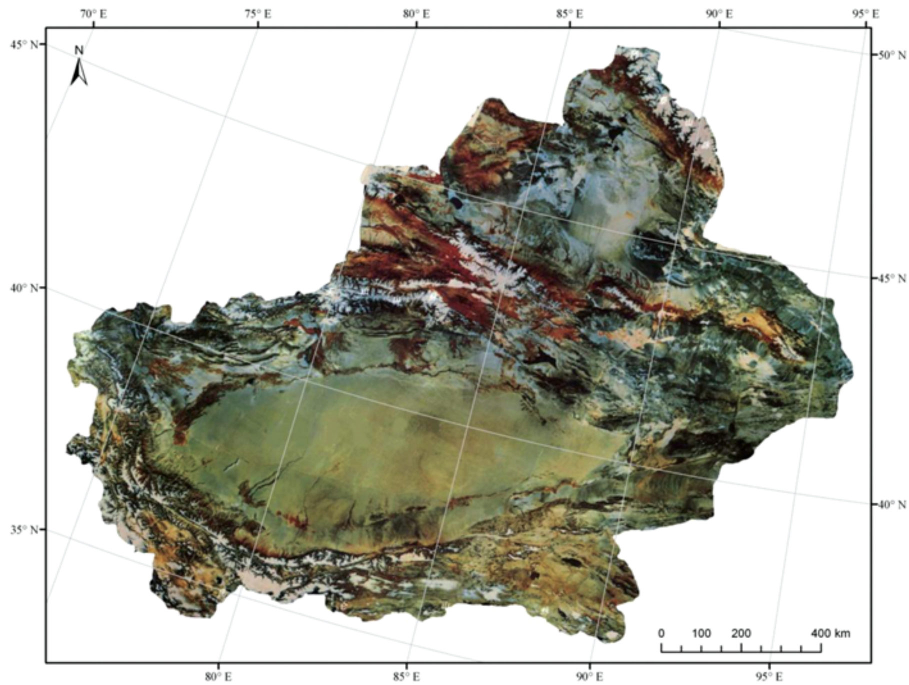
Zhao, S. 1988. Human impact on northwest arid China: desertification or de-desertification? *Chinese Journal of Arid Land Research* 1: 105–116 (in Chinese with English abstract).

Zhu, F. 1995. Study on land desertification in the middle reaches of the Tarim River, Xinjiang. *Arid Zone Research* supplement: 406–419.

Zhu, Z. 1989. Advances in desertification research in China. *Journal of Desert Research* 9: 1–13 (in Chinese with English abstract).

Zhu, Z., and S. Liu. 1988. Desertification processes and their control in Northern China. *Chinese Journal of Arid land Research* 1: 27–36 (in Chinese with English abstract).

Appendix



Appendix 1. Satellite image of main part of arid area (Xinjiang Uygur Autonomus Region) to show topography of the study area. (Figure available in color online.)