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Did climate drive ecosystem change and induce desertification in Otindag sandy land, China over the past 40 years?

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Abstract

The process of desertification in the Otindag sandy land has increased dramatically over the past several decades. While there has been an increase in research on recent changes, little is known about the historical vegetation cover, the soils and the past biogeographical patterns, which are important for understanding the desertification causes and for effective desertification control. This research explores two relevant issues: (1) what are the major causes for ecosystem change and desertification; and (2) what are the implications for developing management policies, including those related to engineering projects. For these purposes, a meta-process model is developed to simulate several key parameters of plant community, including foliage projective cover (FPC) and net primary production (NPP). Their dynamics over the past 40 years are analysed. It is found that if only climate is considered, the simulated NPP and FPC of vegetation community show an increasing trend, although the increase is not statistically significant. This indicates that climate may not be the key cause for desertification in this area. Instead, socio-economic factors should be mainly responsible for such changes, as is confirmed by our further analysis. Two measurements are

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proposed for sustainable environment management: development and maintenance of suitable vegetation coverage of at least 46.7% and implementing a reasonable sheep stocking of 1.5 per hectare, respectively.

Keywords: Desertification; Net primary production; Otindag sandy land; Simulation model; Vegetation coverage

1. Introduction

There are eight large deserts and four large sandy lands in China, and the four sandy lands contain most of the desertified areas and areas vulnerable to desertification (Zha and Gao, 1997). One of the sandy lands, Otindag, has become an increasingly active in terms of movement over the past several decades (Zhu and Wang, 1993; Zha and Gao, 1997). Otindag covers a total area of 21,400 km^2, within which the proportion of moving sandy land increases from only 2% in 1950s to 20% in 1990, and 46.6% in 1999 (Song, 2002). The Normal Difference Vegetation Index (NDVI) changes from 0.57 in 1996 to 0.33 in 2001, also showing a decreasing trend of vegetation coverage (He and Lu, 2003). Another remote sensing study (Wulan et al., 2001) in this area reports that the desertified land covers 58.8% in 2000, and the coverage proportions of heavy-, medium-, and light-desertified land are 20.5%, 27.2%, and 52.3%, respectively. Compared with the situation in 1995, the light-desertified land increases 29%, heavy-desertified land increases 11%, and the medium-desertified land decreases 17%. Although these researches conclusions vary, an overall trend of increasing desertification is obvious. After the original vegetation was destroyed, there was an increase in xerophyte and shrub species in the herbal vegetation community. The pasture edibility for livestock declined, and the amount of *Artemisia* species increased significantly (Wulan et al., 2001). The land productivity was reduced from 0.8–3.9 ton $ha^{-1} yr^{-1}$ in 1950s to less than 0.7 ton $ha^{-1} yr^{-1}$ in 1990s in most areas (Yang and Chen, 1991). Further, Otindag sandy land is becoming one of the major sources of sandy dust storms with increasingly severe adverse environmental impacts on extensive areas in North China including two major metropolises: Beijing and Tianjin, especially in recent years (Jin et al., 2001; Liu et al., 2003). China has launched several engineering projects in an attempt to reverse this loss of vegetation cover.

However, cautions need to be taken in implementing such projects. Although desertification can be caused by both natural and socio-economic factors, mismanagement is responsible for most current desertification (Zhu and Liu, 1988; Mitchell et al., 1998). In particular, major corrective engineering projects are genuinely very complex and inappropriate strategies and methodologies may produce unexpected results, e.g. possible falling water-tables and deteriorated water quality (Mitchell et al., 1996). Two such cases have been observed in China in 'land reclamation' projects using Scotch pine in Zhanggutai, Horqin sandy land, and Yulin, Mu Us sandy land. These projects were started in the 1950s. In early reclamation stages, the Scotch pine grew very well, but recently some of them have began to die in both areas. At the same time, it is found that the underground water-table in some places dropped significantly during this reclamation period. In the 1950s, the water-table was between 1 and 3 m beneath the surface, but today the water-table is from 30 to 50 m beneath the surface. One convenient, although inconclusive, explanation that has been suggested is that the two phenomena are related; the semi-arid climate cannot support high density vegetation (Jiao, 1987, 1989).

To reach sound sustainable management policies in Otindag sandy, a clear picture of its historical vegetation, soil, and other biogeographical patterns is necessary. However, Otindag sandy land has not been well studied. Current research emphasizes techniques for cultivating grasses and shrubs to control grassland desertification (Hui et al., 1996), soil water regime (Chen et al., 2000), photosynthetic pathways, life-forms of certain species (Wang, 2002), classification and ordination analysis of plant communities in interdune lowland (Liu and Guo, 2003). More research is needed to fully understand the main driving forces and causes for increasing desertification in Otindag sandy land before suitable measures for combating desertification in that area can be established.

Although information about historical vegetation cover does not exist, long-term meteorological data has been collected for the past 40 years. To explore the dynamics of vegetation in this area, one feasible approach for now is through the ecological models that can effectively link climatic factors with processes of plant community. Obviously, an appropriate ecological model is the key. However, the available models are characterized by either being: (1) readily transportable, but not ecologically sound; or (2) too sophisticated or detailed for decision makers to take advantage in developing management policies (Specht and Specht, 1999). This paper proposes a simple but effective process-based plant community growth model to simulate key parameters of plant community, including the foliage projective cover (FPC) and the net primary production (NPP), based on meteorological data, in Otindag sandy land. The simulation results are used to examine the dynamics of plant community processes over the past half-century and to explore possible causes of desertification. Some measures are also suggested for vegetation rehabilitation and grazing management to effectively combat desertification in Otindag.

2. Methods

2.1. Study area

Otindag sandy land is located at central-eastern inner-Mongolia, north of Beijing (Fig. 1), between 41°56′ and 44°24′ North latitude and 112°22′ and 117°57′ East longitude, about 360 km along west–east and 30–100 km along north–south direction. The elevation is between 1100 and 1400 m above sea level, decreasing from south-east to north-west. The climate is a continental semi-arid temperate type,

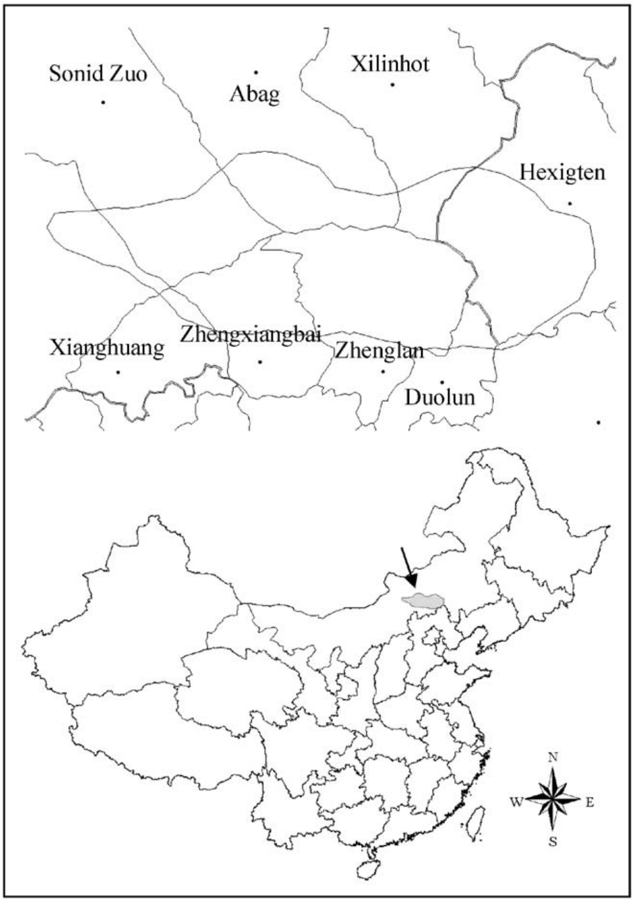

Fig. 1. The study area location in North China. Names of banners (counties) are displayed.

with a frigid, windy spring and winter. Precipitation is concentrated in summer and fall, and the annual average precipitation varies from 350–400 mm at south-east to 100–200 mm at north-west, influenced by south-east monsoon. The major soil type is sandy soil type formed by Eolian processes (Wulan et al., 2001). The vegetation in Otindag is characterized by woodland prairie and meadow prairie in the east, semi-arid grassland in the central area and desert prairie in the west. A total of 952 flowering plant species have been recorded, from 75 families and 348 genera. The two largest families are Compositae and Gramineae, with 48 genera, 150 species, and 42 genera, 124 species, respectively. In eastern Otindag, there are rich species in the meadow prairie and woodlands and the species composition varies with micro-landforms. On sunward southern slopes of large sand dunes, the vegetation is relatively sparse, and mainly include *Salix gordejevii*, *Prunus armeniaca*, *Caragana microphylla*, *Hedysarum fruticosum*, *Agropyron cristatum*, *Thalictrum squarrosum*. The plant community in the northern slopes includes these in southern slopes as well as some semi-shrub and herbal species, such as *Artemisia intramongolica*, *Bromus inermis*, *Agropyron cristatum*, *Poa ochotensis*, etc. In the flat sandy land area, the major species include *Ulmus pumila* var. *sabulosa*, *Populus davidiana*, *Betula platyphylla*, *Picea meyeri* var. *mongolica*, *Ostryopsis davidiana*, *Rosa xanthina*, *Lonicera microphylla*, etc. The dominant species of meadow prairie include*Triglochin palustre*, *Halerpestes ruthenica*, *Potentilla anserine*, *Sanguisorba officinalis*, *Polygonum sibiricum*, etc. The major plant species in central semi-arid prairie area include *Stippa grandis*, *Cleistogenes squarrosa*, *Leymus chinensis*, *Agropyron cristatum*, *Thalictrum petaloideum*, *Poa sphondylodes*, *Leymus secalinus*, *Bromus inermis*, etc. The western desert prairie area is mainly occupied by *Artemisia intramongolica*, *Caragana microphylla*, *Artemisia desertorum*, *Psammochloa villosa*, etc. The vegetation coverage are 65–75% in east, 35–50% in central area, and only 30–35% in the west in 1950s (Editor Committee of Flora of Inner Mongolia, 1998).

2.2. NPP field observation

Field NPP is measured, for the purpose of model validation, at selected sample sites within the semi-arid prairie area in the central Otindag. The sample sites are chosen in places where rare human disturbances are imposed and therefore can be thought of as typical undisturbed semi-arid prairie.

The sample site size is $1 \times 1\,km^2$. The average vegetation height is 80 cm, and the major plant species include *Stippa grandis*, *Cleistogenes squarrosa*, *Leymus chinensis*, *Agropyron cristatum*.

Within the $1 \times 1\,km^2$ sample site, we set up 8 sample plots, each of $40 \times 40\,m^2$. A smaller sample plot of $1 \times 1\,m^2$ is placed in each $40 \times 40\,m^2$ plot, and the vegetation coverage, height, and species composition are recorded every half a month, from April to October, through 2000–2002. The above ground plant parts are gathered and weighted after dried 3 days in oven. The annual NPP can thus be calculated as the sum of the positive increments of above-ground biomass, in $ton\,ha^{-1}\,yr^{-1}$ (Milner and Hughes, 1968), i.e., NPP = sum (positive increments in AGbiomass).

At the end of the 3-year observation period, the average NPP within each $1 \times 1\,m^2$ plot and subsequently each of the eight $40 \times 40\,m^2$ are calculated. In this way, we are able to get the NPP of the zonal vegetation in the study area, i.e. $0.87 \pm 0.11\,ton\,ha^{-1}\,yr^{-1}$.

2.3. FPC field observation

The FPC of vegetation community was measured by setting a sample line (50 m in length) within each of the eight $40 \times 40\,m^2$ sample plots. The FPC was measured once a month, from June to September, during the period between years 2000–2002. The Specht and Specht (1999) method was used to measure the FPC. The total FPC in each sample plot was calculated as the average FPC over the 3 years. Finally, the average FPC of the 8 sample plots was derived: $41.7 \pm 4.3\%$.

2.4. Model development and description

In order to model an ecosystem process, predictive linkages need to be established between available resources (water, nutrients, and so on) and biotic products (height, cover, NPP). These linkages are essential to understanding requirements for ecosystem reconstruction and continued survival. The model in this study is developed in STELLA (High Performance Systems, Inc., 2000). To illustrate the basic terms and typical implementation, one of the modules is presented in Fig. 2, which simulates the relationship between water balance and the evaporation coefficient k. In the figure, an accumulation (e.g. water, carbohydrate, etc.) is represented with a rectangular ''stock'' or ''state variable'' symbol. The value of an accumulation is calculated as the sum of its initial value and the balance of inward and outward flows over a specified period. A flow is represented using a pipe with a spigot (valve), and flow direction is shown with an arrow. Sometimes, a flow can be bi-directional. Other variables and constants are represented with circular ''convertor'' symbols. A simple directional line (with arrow) is used to represent relationships between other variables (symbols). Note that no relationship affects the ''stock'' symbols, by definition.

This ecosystem model is a meta-process model describing, in general terms, the functions of an 'average' ecosystem throughout a year, with a monthly time-step, and it is centered on plant community. Based on Huggett (1993) and Battaglia and Sands (1998), a meta-process model falls between a traditional ecosystem model and a deterministic (process-based) landscape ecological model. This model is based on two fundamental axioms of ecosystem functions: the conversion of light to carbohydrate by the plant component of the ecosystems and the use of those carbohydrates for plant survival and growth.

The capacity of vegetation to trap light and to convert carbohydrates produced in photosynthesis to new tissues is dependent on several factors: number of leaves exposed to sunlight, water and nutrients available, and average temperature and temperature variation through the year. These environmental factors vary with location (due to difference in latitude, longitude, coastal or inland locations, and soil, etc.), and they change with seasons, or over long-term periods.

The spatial distribution of foliage in the horizontal plane, i.e. FPC is primarily determined by the evaporative coefficient, a variable expressing control of water loss by a plant community (Specht and Specht, 1999). The anatomical and physiological attributes of all the leaves in a plant community are influenced by atmospheric water stress during the brief period of leaf formation.

Distribution of carbohydrates to various parts of a plant community (roots, shoots, stems, leaves) is dependent on overall resource availability, genetics of plants, and consumer population, whose diversity and seasonal cycles are closely coupled with growth rhythms of various organs within a plant community upon which consumers depends.

Many equations have been developed to describe relationships among components of an ecosystem, and they have been gradually incorporated in ecosystem models (Specht, 1981a; Specht and Specht, 1989, 1999).

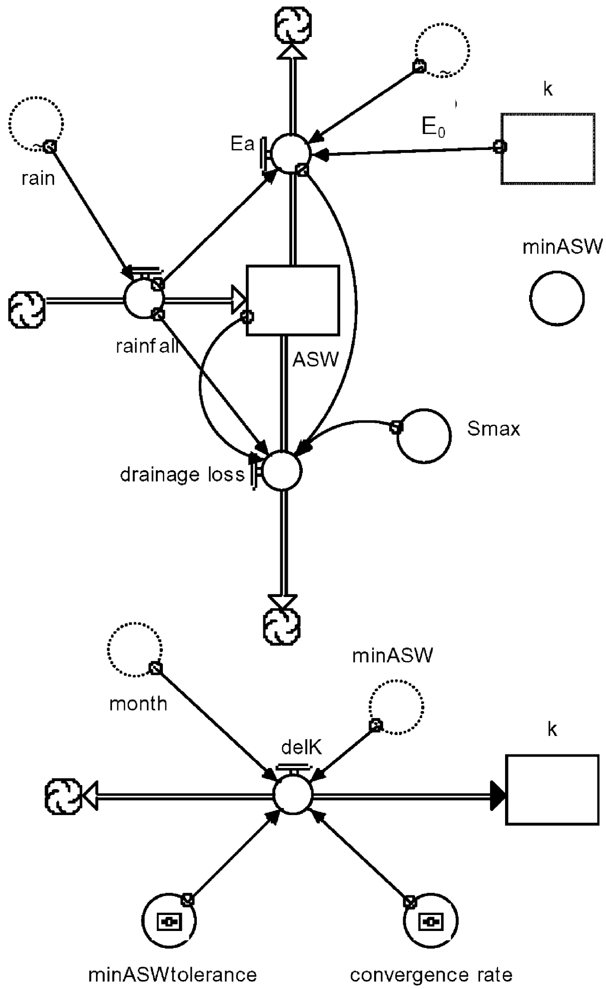

Fig. 2. Illustration of Stella model for a module simulating water balance. Where, rain, rainfall, E_a, E_0, ASW, min ASW, k, drainage loss, S_{max}, month, del K, min $ASW_{tolerance}$, convergence rate stand for monthly rainfall (mm), monthly rainfall (mm), monthly evapo-transpiration (mm), monthly pan evaporation (mm), available soil water (mm), minimum available soil water (mm), evaporation coefficent, drainge soil water loss, soil water-holding capacity, month, value for calculating k by iterative method, minimum available soil water tolerance, convergence rate for iterative method.

2.4.1. Moisture, evapo-transpiration and FPC

As stated above, the primary factors influencing plant community development include water, light, temperature and nutrient availability. Within a plant community, the number of leaves determines photosynthesis potential as well as possible resource demands for growth (nutrients, etc.), and these are dependent on available water and evaporation. In our study site, a semi-arid area in China, water is the most important factor and its effects are thus first discussed (Longworth and Williamson, 1993; Zhang, 1994).

It is assumed that a plant community will grow as long as soil moisture conditions are favorable. In practice, soil moisture is calculated as a simple, one-layer water balance, with rainfall as input and actual evapo-transpiration and drainage as output. Soil moisture may increase up to soil moisture storage capacity before drainage occurs. Once soil is fully charged with water, i.e. soil moisture reaches soil water storage capacity (S_{max}), internal drainage to aquifers will occur and water will be lost from an ecosystem in sandy land. S_{max} is the maximum amount of water that can be held in soil, and it is influenced by soil depth, volume of rock and soil water-holding capacity of each horizon in the soil profile.

Water will be used as much as the atmosphere will allow, i.e. if evapo-transpiration can continue, and the water usage is related to the evaporative power of the atmosphere (expressed by evaporation from a Class A pan), with a small contribution by plants to resist water loss.

The amount of water passing through a plant community is constrained by leaf distribution throughout the entire plant community. The ratio of actual to potential monthly evapo-transpiration (E_a/E_0) is assumed to be linearly related to soil moisture level (Specht, 1972; Specht, 1981a, b), and the slope of this E_a/E_0 vs. soil moisture function, termed evaporation coefficient (k) characterizes horizontal distribution of combined foliage in overstorey plus understorey strata in a plant community. As stated before, a key assumption in our model is that plant communities tend to maximize utilization of available soil moisture, with the constraint of not exhausting soil moisture to the permanent wilting point. This assumption is realized during the initial model "calibration" phase, when the slope (k) of the E_a/E_0 vs. soil moisture function is optimized to ensure as much water as possible is used by the plant community, but without exhausting soil moisture in any month. A simple optimization algorithm, named iterative technique (Specht, 1983), is used to achieve convergence on an appropriate slope value.

As might be expected, when soil water storage is limiting, the rate of water loss from a plant community through evapo-transpiration is closely related to leaf cover and particularly the horizontal surface exposed to atmosphere, expressed by

$$E_a/E_0 = k \times W, \tag{1}$$

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

where E_a is monthly actual evapo-transpiration (mm), E_0 represents monthly pan evaporation (mm), k is evaporative coefficient, and W is available soil water (mm) over a month. W is calculated using Eq. (2), where P is monthly rainfall (mm), D is monthly drainage loss (mm), and S_{ext} is water stored within the root zone of the soil at the beginning of a month and extractable by the plant community (mm).

When water is non-limiting, E_a tends to equal E_0

$$E_a/E_0 = 1.0. \tag{3}$$

The foliage architecture of all strata in a plant community provides an estimate of the photosynthetic potential of landscape (Specht, 1983). FPC represents the optimal photosynthetic surface for a plant community and thus is a powerful predictor of many aspects of community structure and function. We will mainly deal with structural attributes in this paper.

Total FPC is the same under same evaporative conditions, unless there is an excess water supply when E_a equals to E_0 (Specht and Specht, 1999). Both under- and over-storey FPC are related to the value of k (Specht and Specht, 1989):

$$\mathrm{FPC_{over}} = 9770 \times k/100 - 7.15, \tag{4}$$

$$\mathrm{FPC_{under}} = 5880 \times k/100 + 10.04. \tag{5}$$

The amount of foliage and its associated transpiration potential can be assumed to be in balance with the potential evapo-transpiration, which is consistent with the above assumption. While lower values of FPC may leave some moisture unexploited by the plant community, higher values of FPC will lead to exhaustion of soil moisture.

2.4.2. Growth indices

Growth indices, such as the monthly NPI and the Current Annual Growth Index (CAGI), describe relative growth response of plants when all other environmental factors are optimal. Growth indices are derived from Climatic Indices, which express relative development of some aspects of an ecosystem with reference to climatic variables (Prescott et al., 1952). These climatic factors act simultaneously, and their impacts may be assumed to be multiplicative (Fitzpatrick and Nix, 1970).

In this study, we adopted a plant community growth model developed by Specht and Specht (1999). In their model, four climatic factors account for plant growth, including average monthly temperature, solar radiation, rainfall and pan evaporation. Their effects on monthly net primary productivity are characterized by a moisture index (MI), a light index (RI) and a thermal index (TI). Their definitions are shown in Eqs. (6)–(8), respectively:

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

where moisture index (MI) is defined as the relative dry matter production of the leaf canopy under water stress when contrasted with production achieved when water is in adequate supply; all other factors are assumed non-limiting.

$$\mathrm{RI} = 1 - \mathrm{e}^{(-3.5 \times R/750)}, \tag{7}$$

where light index (RI) is the fractional dry matter production of the leaf canopy expressed on a scale from zero to unit (the maximal production when no factor is limiting), R is the total monthly solar radiation, and e is the base of the natural logarithms (Specht, 1981a):

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

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

Once the three monthly indices and FPC are derived, monthly NPI can be calculated for both over- and under-storey strata of the plant community according to Eqs. (9) and (10). Monthly Net Photosynthetic Index (NPI) represents the total reserve of carbohydrates available to a plant community at any time under any conditions, and its value ranges from 0 to 1 (Specht, 1981a). FPC is included because it qualifies the LI according to the amount of leaves intercepting light in the canopy

$$\mathrm{NPI}_{\mathrm{over}} = \mathrm{FPC}_{\mathrm{over}} \times \mathrm{TI} \times \mathrm{MI} \times \mathrm{RI}, \tag{9}$$

$$\mathrm{NPI}_{\mathrm{under}} = \mathrm{FPC}_{\mathrm{under}} \times \mathrm{TI} \times \mathrm{MI} \times \mathrm{RI}. \tag{10}$$

It is then possible to calculate monthly NPP (Eq. (11)). The optimal NPP is related to temperature and is calculated using Eq. (12).

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

where CMGI is sum of actual current monthly growth increment of overstorey and understorey NPP (monthly NPP, above ground), OptCAGI is current optimal monthly growth increment (Specht and Specht, 1999):

$$\mathrm{OptCAGI} = 0.86 + 0.1 \times \mathrm{AvMon}\,T \tag{12}$$

where, AvMon T denotes monthly average temperature (Specht and Specht, 1999)

$$\mathrm{NPP} = \int_{1}^{12} (\mathrm{CMGI})\,\mathrm{d}t, \tag{13}$$

where NPP is the annual NPP (ton $\mathrm{ha^{-1}\,yr^{-1}}$).

NPP measures the amount of matter that has accumulated, per unit area of land, in the producer, consumer or decomposer section of an ecosystem in one year. Thus NPP along with FPC, can be used to describe the structure of a plant community.

2.4.3. Model evaluation

To evaluate the effectiveness of our model, the simulated vegetation community parameters are compared with their field observation in the study area.

The model inputs come from 40-year averages (from 1960 to 1999) of monthly temperature, precipitation, pan evaporation and solar radiation in the study area. Simulated results for k, NPP and total FPC were 0.29 (value $\times\,10^{-2}$ per mm of available water), 0.96 (ton $\mathrm{ha^{-1}\,yr^{-1}}$) and 46.7%, respectively. In the study area, observed NPP is 0.87 (0.87 ± 0.11, measured by the IBP Standard Method (Milner and Hughes, 1968)) ton $\mathrm{ha^{-1}\,yr^{-1}}$. Total FPC is $41.7 \pm 4.3\%$. Obviously, simulated NPP and total FPC values are rather consistent with the observed ones. K-value validation requires long-term water balance observation using a lysimeter. Since lysimeter data was not available in Otindag, it is impossible to directly validate k-value. However, since FPC is derived from k and total NPP is also calculated based on the empirical equation related to k, the close correspondence between simulated and observed FPC and NPP should indirectly validate the simulated k-value.

The two Eqs. (4) and (5) used in the model are experimental equations based on the vegetation data in the whole Australia (Specht and Specht, 1999). It is ideal to establish such equations based on information in study area. Due to lack of sufficient field FPC measurement, the only feasible alternative is to adopt equations developed under similar natural environments. Fortunately, the vegetation in many regions of Australia has similar structures as these in Otindag, and it is not unreasonable to apply the two equations in Otindag. In fact, Jiang et al. (2004) already tested the two equations in Xinjiang Uygur Autonomous Region in China and they demonstrated that the equations can be directly applied in arid areas in China. In our study, the good correspondence between the observed and simulated FPC also proves the applicability of the two equations in the study area.

After validation, the model developed above is used to simulate several parameters of plant community in Otindag sandy land. For each of the 40 years, observed climatic data, including monthly precipitation, monthly temperature, monthly pan evaporation, and monthly solar radiation are used as inputs, and evaporative coefficient (k), NPP and FPC are output by the simulation. Then simple linear regression is used to analyse the dynamic trend of the three parameters (k, NPP, FPC) over the past 40 years. The analysis was carried out using SPSS 10.0 (SPSS, 2000).

3. Results

As shown in Fig. 3, in the past 40 years in Otindag, the maximum annual precipitation is 546 mm at 1992, the minimum is 244 mm at 1989, and the average is 372 mm. Before 1970s, the dry–wet years are evenly distributed, and the dry–wet year interval is about 1–2 years. From 1970s to 1980s, the rhythm is 1–2 wet years (annual rainfall exceeds average yearly rainfall) followed by 3–4 dry years (annual rainfall is less than average yearly rainfall). The dry year period increases to 4–5 year for 1980–1990, however, the annual precipitation is still close to average, except at 1989.

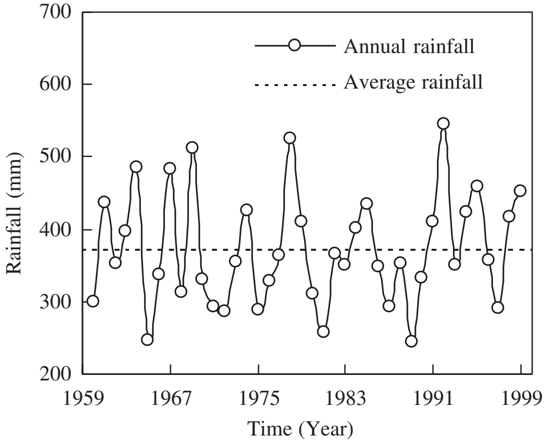

Fig. 3. The annual rainfall (mm) over 40 years.

Since 1990s, the precipitation increases and the wet–dry year interval are reduced to 1–2 years. Consequently, the annual precipitation is indeed relatively lower in 1970–1990. It is still well above 300 mm. Therefore precipitation reduction is not sufficient to explain why desertification has been increasingly enhanced in the past several decades, especially the fast desertification in the past decade. The simulated results also support this argument.

As discussed in previous sections, the simulated k in Otindag sandy land is 0.29 (value $\times 10^{-2}$ per mm of available water), which indicates an arid area according to the criteria proposed by Specht and Specht (1999). The simulated total FPC reaches only 46.7%, and NPP is 0.96 (ton $ha^{-1} yr^{-1}$). Apparently under natural conditions, both vegetation cover and productivity are quite low.

When examining long-term dynamics of simulated plant community parameters, k shows a trend of slightly increase (Fig. 4). This implies that moisture condition of ecosystems in this area did not turn drier, but a little bit wetter. Simulated FPC and

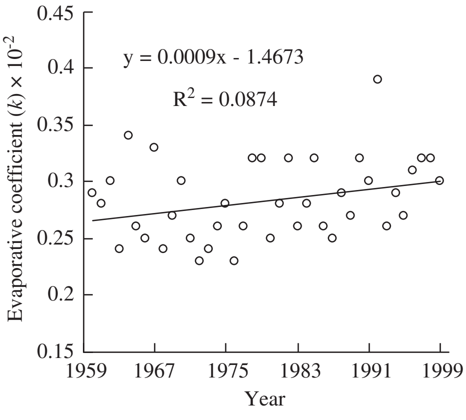

Fig. 4. Changes of simulated evaporative coefficient (k) over 40 years.

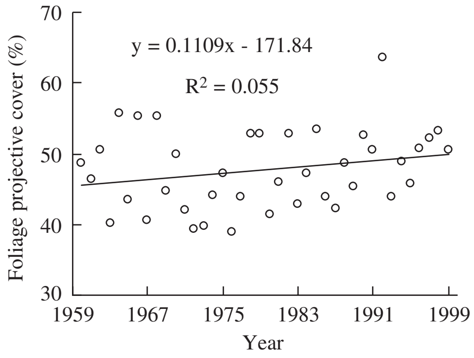

Fig. 5. Changes of simulated FPC (%) over 40 years.

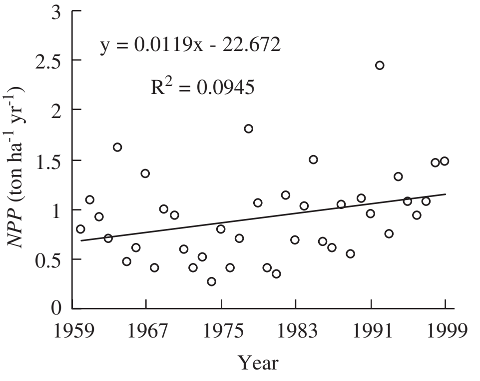

Fig. 6. Changes of simulated NPP (ton ha^{-1} yr^{-1}) over 40 years.

NPP show similar trends as *k* (Figs. 5 and 6). In other words, the climate should have increased the density of vegetation and should have produced more NPP, instead of enhanced desertification. Although the increasing trends of these parameters of plant community are not significant, it is sufficient to conclude that climate is not the main factor responsible for vegetation degradation and desertification in this area.

4. Discussions and conclusions

The model developed in this study has advantage for management purposes. As discussed in previous sections, there are few readily transportable models that are ecologically sound and some existing ecological models are frequently too sophisticated or detailed for decision makers to incorporate them into a larger management framework, such as one for desertification control. For example, Armstrong et al. (1997) developed an excellent computer model which can predict monthly growth, senescence, litterfall and standing biomass of ungrazed herbage in seven dwarf shrub-dominated and five grass-dominated vegetation types commonly found in the hilly areas of UK. However, the inputs needed by the model are very complex, including areas of each vegetation type present at the site, temperature zone in which the site is located, percentage ground cover of the two components within vegetation mosaics and the average altitude. Some other models can predict biomass and growth (Sibbald et al., 1987; Hanson et al., 1988). They also either need relative detailed information, or they are unable to show environmental variations. In the model developed by Sibbald et al. (1987), detailed input data are used to predict growth, senescence and litterfall of *Agrostis-Festuca* grassland, but grass growth cannot be distinguished under varied environmental conditions. Hanson et al.'s (1988) model requires daily precipitation, maximum and minimum temperature, as well as the setting of a large number of model parameters for simulating each species. Grassland yield estimation using remote sensing and GIS technologies (Li et al., 1998; Gao et al., 2000) may be a good idea to monitor temporal NPP change, although lack of feasible field validity and the high expense of remote sensing data make it of limited use. BIOME3 (Ni et al., 2000) is another good tool for simulating NPP. Still it needs detailed climate, soil and vegetation data, which are not readily available. Carbon storage estimation in desertified lands in China (Feng et al., 2001) and in grasslands of China (Ni, 2002) could also provide useful references for grass production, but detailed observed data is also needed. In contrast, our model requires much less detailed inputs and can produce reasonably accurate outputs. It therefore is more appropriate for decision makers.

There are several simplifications of our model. First, nutrients are very limited in most arid and semi-arid regions. This may possibly reduce the potential NPP. As nutrient content data is not available, it was not considered in this model. However, as we discussed, since water availability is the main constraint factor in arid areas, estimated FPC and NPP based on the well justified water balance process is still quite informative. Secondly, little information is available on rate of senescence and litterfall for arid ecosystem in study area, the live biomass and dead biomass cannot be distinguished by this model.

In our simulation, all three parameters k, NPP and FPC show increasing trends over the past 40 years. Although the increasing magnitude is not significant, it is sufficient to conclude that natural conditions might not be key causes of desertification in the study area. NPP, FPC and evaporation coefficient show an apparent decreasing trend from 1960 to 1975, but there was no obvious desertification process at work in Otindag sandy land in this period.

The significant desertification since 1980s seems coupling with the household-based production system, which might induce overuse of land resources (Zhu and Liu, 1988; Zhu and Wang, 1993). In the household-based production system, the land and other production resources are still mainly the property of collectives. However, the basic production unit is the household. Each household leases land and other resources from collectives, and in return each household pays relevant taxes. Since farmers are free to manage the land in the lease period, they are much more motivated to increases the agriculture productivity. However, the lack of collaboration among farmers results in dispersed usage of resources and limited scale of production. At the same time, the land resources tend to be exploitatively utilized, e.g. illegally converting grassland into farmland, over-grazing, without sufficient inputs to maintain the land sustainability. This might indicate that mismanagement could be mainly responsible for land degradation and desertification. Further, it has been argued that tension between declining land productivity induced by desertification, and increasing demands imposed by population, is often the primary cause of land overuse. This in turn causes further desertification, resulting in a vicious circle (Longworth and Williamson, 1993; Thomas and Middleton, 1994). This might also be the case in Otindag sandy land. For example, in Zhenglan Banner (a typical county-level administrative area in Inner Mongolia), where desertification is severe, the population, cropland area and livestock number increased dramatically in the past 40 years. Population almost tripled from 29,879 in 1957 to 78,999 in 1999. Out of the total population, urban population, farmers, and grazers increased from 1640, 12,811, and 15,428 in 1957 to 13,965, 20,763, and 44,214 in 1996, respectively

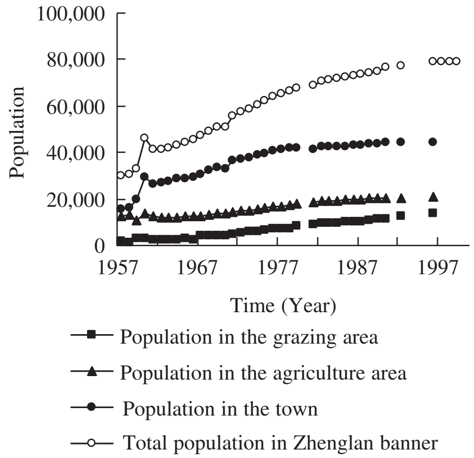

Fig. 7. Changes of human population from 1957 to 1999.

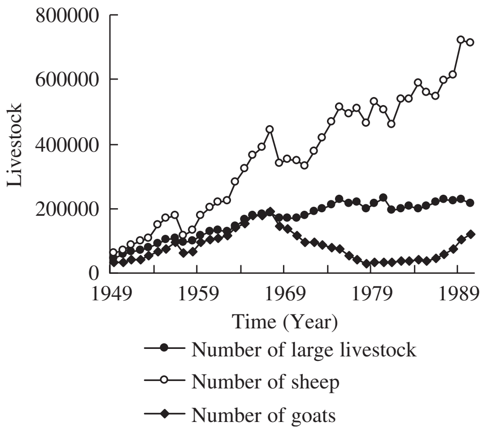

Fig. 8. Changes of livestock number from 1949 to 1990.

(Fig. 7). Total livestock increased about 350% from 143,012 in 1949 to 523,465 in 2000, and it even exceeded 1,000,000 in 1989 and 1990 (Fig. 8). The large increases in number of livestock and grazers imposed heavy pressure on the grassland and directly induced degradation. More seriously, cropland area also increased around 300% from 6617 ha in 1949 to 23,091 ha in 2000 (Fig. 9). The large increase of cropland area in the early 1960s can be attributed to the impact of land reclamation programs implemented during the early 1960s to alleviate starvation in the whole country. The cropland increment generally means loss of good grassland, which indirectly increases pressure on the remaining grassland. Further, the productivity of the newly reclaimed cropland is quickly lowered and they are subsequently exhausted and abandoned and more grassland is reclaimed. Therefore, a preliminary

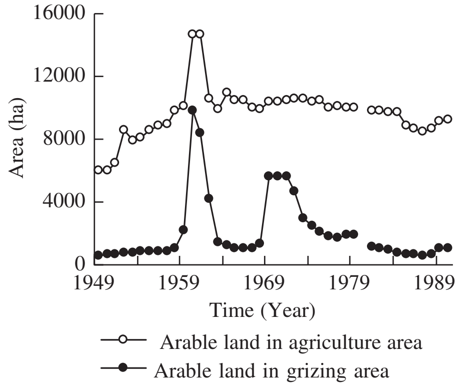

Fig. 9. Changes of arable land from 1949 to 1990.

conclusion can be drawn here, i.e. socio-economic development, rather than climate change, appear to be the main reasons for grassland degradation and desertification in Otindag sandy land over the past half-century. We will further investigate the impacts of socio-economic factors on desertification in this area when more data become available in the future.

These research findings have important implications for sustainable environmental management in Otindag area. First, local government should seek new solutions to deal with pressures from increasing population and associated demands for better livelihoods. To avoid falling into a circle of poverty, degradation of environment inducing more serious poverty, local government should adjust local socio-economic structures and enact more effective socio-economic development policies. One important aspect worthy of attention is livestock husbandry and agriculture operations. Currently, these activities depend entirely on natural conditions (Song, 2002). Typically agricultural practices proceed as follows: a farmer reclaims a patch of high quality grassland when productivity of old cropland is seriously lowered; however, the productivity of new cropland generally decreases significantly in 3–5 years and new cropland needs to be reclaimed again at that time (Zhu and Wang, 1993; Zhang, 1994). One possible approach to preventing this vicious circle is to maintain sustainability of cropland by establishing high yield cropland and grassland with sufficient energy inputs. Local governments should encourage adoption of water-saving irrigation technologies, high yield crop species and organic manure mixed with inorganic fertilizer (Zheng, 1998). Such agricultural practices would not only decrease reclamation for new cropland, but also help promote natural restoration of large amounts of previously abandoned croplands (Jin et al., 2001; Jiang, 2002). For grazing management, it is beneficial to extend the rotating grazing approach and apply manure to grasslands. These activities can reduce nutrient depletion and also facilitate grassland restoration.

The second implication is that government decision-makers should be very cautious in setting policies for corrective engineering projects. Some desertification control projects have been carried out in Otindag to rehabilitate the desertified land, supported by China Ministry of Sciences and Technologies and Chinese Academy of Sciences. The main activities include planting trees and shrubs in large patches in degraded grassland and sandy land, and shelter-forest along roads, via manual seeding or air-seeding. However, these projects did not fully take into consideration local environment characteristics to ensure ecological sustainability. Since the natural zonal vegetation in Otindag is prairie, it is difficult to maintain high-density planted trees and shrubs and their survival and sustaining rates are very low, as seriously reduces the effectiveness of such ecological engineering projects (Hui et al., 1996; Song, 2002). This study also found that the natural environment in Otindag sandy land could only support limited vegetation coverage, as indicated by the simulated FPC, which is only 46.7%. However, in most projects, artificial vegetation coverage is much higher than this number, and it should be adjusted when new restoration plantings take place in the future.

Another policy implication is with respect to grazing control. Simulated NPP supplies a relatively accurate estimation of annual production of grassland. Together with data on minimum food demands by different kinds of livestock, it is possible to estimate the maximum capacity of livestock that can be supported. This can serve as a reference point when setting grazing control policies for sustainable development of livestock husbandry, as well as rehabilitation of degraded ecosystems. However, consideration for the limitations of the model should be utilized. The simulated parameters are average values of land. Since the quality of pasture may be patchy and have seasonal variations, especially in desertified area that characterized by the mosaic of lower land and higher dunes, the suitable grazing ratio and vegetation coverage should be adjusted for different sites in practice. Based on observations over years in this area, one standard sheep consumes about 1.75 kg of dry forage daily. Since our NPP is 0.96 ton ha^{-1} yr^{-1}, a suitable grazing ratio in this area should be less than or equal to 1.5 standard sheep per hectare. That number should be reduced in practice, as sheep only use parts of plants. While rotating herds to a series of pastures from time to time would be ideal, it is impractical because of the large numbers of livestock now. The herds in the study area have to be fed in fixed pastures.

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