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The impact of human activities on natural capital and ecosystem services of natural pastures in North Xinjiang, China

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ABSTRACT

The implementation of systemic modeling methods to understand the variation of natural capital and ecosystem services in response to economic activities has huge significance for sound decision-making also at local scale. This paper reports the results of an investigation performed on the grassland ecosystem in North Xinjiang. The Emergy Synthesis method introduced by H.T. Odum in the 1980s was used to dynamically simulate the trend of grassland natural capital and its related ecosystem services. The simulation of natural capital was based on indexes of standing biomass, soil organic matter, soil nitrogen and soil water storages; ecosystem services were assessed by means of indexes of annual CO_2 uptake, O_2 release, forage supply as animal feed, food supply for human nutrition, and finally soil conservation. Results indicate that an upper limit of livestock carrying capacity in the region was reached in the year 1994; after that year the natural capital and main ecosystem services of the grassland ecosystem declined steadily. The emergy based currency equivalent value of the grassland ecosystem in terms of ecosystem services was higher than 87.3 billion Yuan RMB/yr in 1990. Such a value declined to 62.3 billion Yuan RMB/yr in 2010. Similarly, the total emergy based value of natural capital was about 331.7 billion Yuan RMB in 1990 and dropped to 155.6 billion Yuan RMB in 2010. According to the simulation model, the natural capital components such as biomass and soil stocks, the ecosystem services and the replacement value declined due to intensive herding and disturbance from human activities. Such trend is not sustainable because it exceeds the renewable carrying capacity of the area, but it is likely to continue until fundamental changes in human behavior and management of the grassland and animal husbandry occur or until the whole area is fully degraded. Social reasons prevent from simply decreasing the intensity of the livestock activities that provide living means to a large number of local farmers. As a consequence, the traditional low-productivity and environmental unfriendly grazing farming system should gradually be converted into a human-managed pasture based on farming higher productivity pasture crops in a small part of the local land, in order to decrease the grazing pressure on natural grassland of North Xinjiang.

1. Introduction

Ecological systems provide the essential natural capital and services (life support), which form the basis for sustainable development of economy and human society (Deutsch and Folke, 2003). Biosphere and societal sustainability rely on our collective capacity to protect the environment from the negative impacts of economic activities. The prosperity of next generations depends on the stock of integer productive assets that we are able to bequeath them (Ruggeri, 2009).

The essence of the concept of capital is that it is a stock capable to generate flows of goods and/or services (Ekins et al., 2003). Similar to the economic capital, the concept of natural capital identifies a stock of ecosystems (or their components) capable to provide goods and services to human societies and other species as well. It is rooted in relatively recent research about sustainable development (Costanza and Daly, 1992; Jansson et al., 1994), ecological integrity (Meffe and Carroll, 1994) and ecosystem health (Norton, 1991). The measurement of natural capital and its management during the economic development process are important aspects of the capital approach to sustainable development (Engelbrecht, 2009). Many ecologists pointed out the existence of a critical minimum level of

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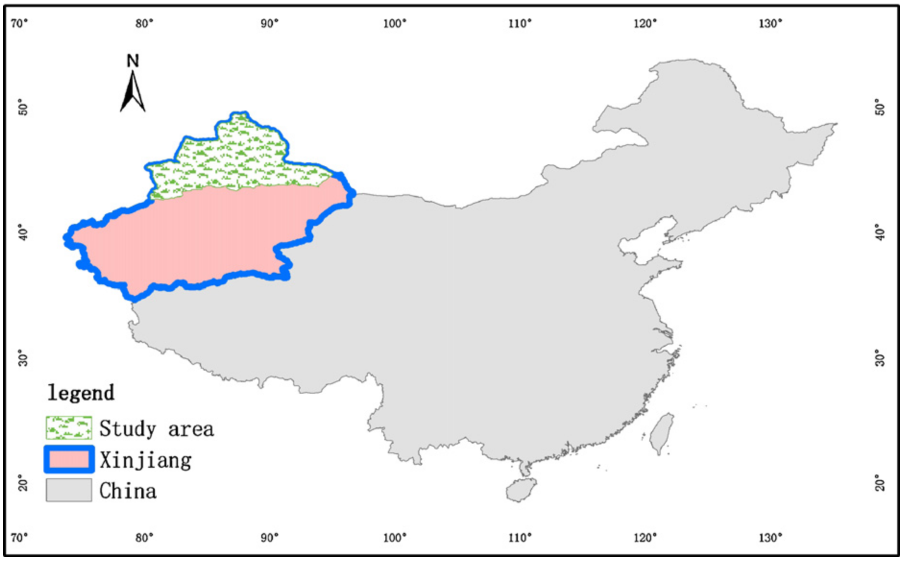

Fig. 1. Map of North Xinjiang area, northwestern border of China, with identification of the investigated area.

natural capital (ecosystems) below which humanity will not be able to benefit from the ecosystem services necessary for its survival (Richard, 2000). However, the real value of ecosystem services was not properly appreciated by human societies in the past, nor it is presently fully understood. Many short-term activities involving the extraction and processing of ecological resources have led to the destruction of natural capital worldwide, due to excess exploitation and lack of appropriate management.

A major step ahead towards the recognition of the importance of natural capital and the identification of different typologies of ecosystem services was made in the years 2000–2005 by the Millennium Ecosystem Assessment (MEA, 2005), an international survey leaded by the United Nations and other world Institutions, aimed at assessing the interplay of nature and economy. The study highlights the need for preserving the environment and its ability to provide life support to human societies. According to the MEA results, such goal should not be achieved by banning economic activities from environmental conservation areas, but instead by designing new ways to run economic processes in support to development and human well-being.

A more recent international survey was performed within the framework of TEEB – The Economics of Ecosystems and Biodiversity (TEEB, 2011), leaded by UNEP – United Nations Environmental Programme. The study draws “attention to the global economic benefits of biodiversity” and highlights “the growing costs of biodiversity loss and ecosystem degradation”. In its main report (Sukhdev, 2010; Chapter 5, The economics of valuing ecosystem services and biodiversity) the importance of coupling economic and biophysical methods such as energy, exergy and emergy accounting is highlighted, for more comprehensive understanding.

Haines-Young et al. (2006) modeled natural capital variations in terms of the range of functions supported by landscape. Ruggeri (2009) developed a new approach by using investment criteria for the measurement of natural capital in Canada. Petrosillo et al. (2010) assessed the impact of ‘conservation policies’ on the maintenance of natural capital in three natural parks of Apulia Region (Southern Italy) where natural capital variation was investigated by assessing the temporal dynamics of land-use/land-cover mosaics.

Grasslands worldwide and in China play a very important role in the regulation of atmospheric CO_2 increase and climate change. Unfortunately, the grassland natural capital and its functions are largely affected by livestock pasturing and other human activities. The latter had, in the last two decades, a strong impact on Chinese grasslands, which also affected the accuracy of carbon estimates based on grassland distribution (Ni, 2002). In fact, biomass production and use are closely associated with soil organic matter content, nutrient storage and biodiversity (Ming et al., 2004). Over-emphasizing the economic output of the grassland inevitably translates into disregarding its ecological functions and results into further degradation and depletion of natural resources.

Natural capital evaluation still requires an intense research effort (Azqueta and Sotelsek, 2007). Much is still to be done by both academic and administrative sectors on how to prudently utilize natural grassland in China. Human activities and natural resource exploitation must be monitored in order to develop suitable scenarios and policies for sustainable development. In our investigation, the biomass yield of the grassland plantation in North XinJiang was used as the main parameter in modeling the dynamics of CO_2 fixation, O_2 release, livestock biomass supply (hay production), as well as the main ecosystem services in support of soil organic matter formation and soil water cycles. This macro-scale simulation provides a scientific basis for protection, management and further development of the natural ecosystem at both regional and national levels.

2. Materials and methods

2.1. The investigated area

The desert and mountain pastures of North Xinjiang are located in the centre of the Eurasian continent. This is the northwestern border of China, adjacent to the Republics of Kazakhstan, Russia, and Mongolia on the western, northern, and eastern sides, respectively (Fig. 1). The area includes 40 administrative districts among which Yili, Tacheng, Alatai, Bogutala, Changji, Urumqi, Kalahari, Shihezi, and two counties in northern Hami. The site falls within the extremely arid continental climate region. Rain precipitation is heavier in western than eastern areas, as well as in the mountains than on the flat plains. The amount of precipitation in the mountains normally ranges within 400–600 mm/yr, the average annual temperature in the flat plain is normally at 5–7 °C, and the annual accumulated temperature (≥10 °C) is at 2500–3500 °C. The frost-free season lasts 140–195 days. The regional soil types include Brown pedocal, Sierozem, Gray-brown desert soil, Gray desert soil. As the latitude escalates, different types of soil appear alternatively in the mountains (Liao and Jia, 1996).

2.2. Components and use of grassland resources

The total grassland area of the Xinjiang region amounts to about 32.6 million ha, according to Liao and Jia (1996). The vegetation mainly includes small shrubs and semi-shrubs, typical of the temperate desert. According to the principles, systems and units for pasture classification adopted in China (Liao and Jia, 1996; Ren et al., 2008), the grasslands in North Xinjang are classified into seven types. The total area for each type of the pasture, its percentage of total grassland coverage, and the ecological functional parameters are presented in Table 1.

Due to the variation of topography, temperature, and precipitation, four main types of grassland have evolved, including the temperate grassland desert, temperate desert grassland, temperate grassland, and temperate meadow grassland, each accounting for 4.9%, 10.5%, 11.0% and 4.1% of the total grassland area (Table 1). Other temperate desert areas account for 16.7 million ha (51.2% of total area).

In the mountains, large patches of mountain meadows (about 7.6%), alpine meadows (accounting for 1.5%) and alpine grassland (3.6%) at higher latitude than alpine timberline are also observed.

The theoretical grazing capacity in this area is 16.3 million heads of sheep. The mountain meadow pasture has the highest grazing capacity which is approximately 27.8% of the total capacity. Although the desert pasture covers more than half of the total area, its grazing capacity only accounts for about 17%. Such estimates therefore suggest that mountain meadow pasture plays a key role in this region.

To meet the needs for seasonal rotational grazing of the livestock, the pastures are approximately divided into three season-based categories, namely Summer-Fall, Spring and Winter grazing areas. By the end of 1990, the number of livestock was 16.1 million heads, which is equivalent to 27.8 million units of sheep (Liao and Jia, 1996). All the pastures were heavily overloaded, especially during the spring and fall seasons. In areas that are also exploited for agriculture, livestock normally stays within the Spring pastures also during the Summer season, which places an additional grazing burden on those lands. Due to the bad weather conditions and shortage of hay in early Spring, a large number of the livestock would die each Spring, thus hindering the development of the livestock-related food manufacturing industry. Since in recent years, the Winter and Spring pastures have stored large quantity of dried grasses, the number of the overwintering livestock increased, which in turn created an additional pressure for feedstock demanding on the Summer pastures, and hence speeds up their degradation.

2.3. Pasture types, productivity, coverage areas and main eco-functional parameters

Strictly speaking, the desert plantation should not be classified under "pasture" from either livestock farming or ecological standpoints. Temperate desert plants have low productivity, their above ground tissues are composed of degenerated leaves, or prickly or highly keratinized shoots and branches with no leaves. The semi-shrubs as well as semi-trees have sour, fleshy but salty leaves, such as *Haloxylon ammodendron* (C.A. Mey.) Bunge, but even these trees grow very randomly and are unsuitable for grazing. Some desert plantations consist of perennial plants as spring layer and annual plants as summer layer; these plantations can provide short-term food for the livestock, but such resources are very limited and can only support a small number of animals, nor do they have much commercial potential. After grazing, these plantations degrade very severely, and the resulting ecological loss overweighs the economic benefit. For this reason, in developed countries the desert is never classified under the category of "pasture" or "livestock farm", and grazing is prohibited on these lands.

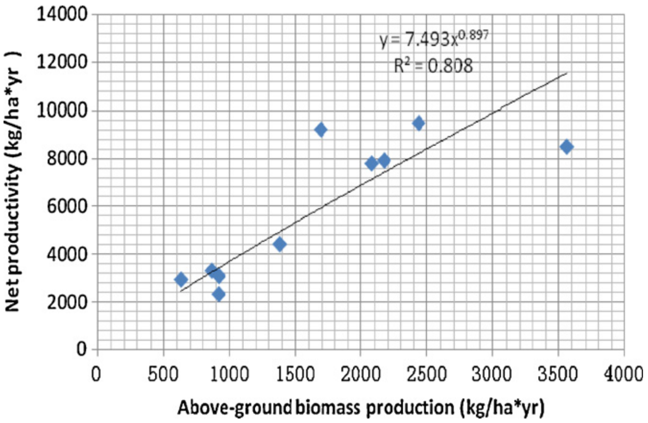

Fig. 2. Regression relationship between net productivity (vertical axis) and above-ground biomass production of the grassland (horizontal axis).

In Xinjiang, the winter pastures are mostly located near the desert zones of low mountains, along the mountain sides, or along the border of the oases. Traditionally, domestic animals are raised by allowing free grazing on these grasses, which is often referred to as "eating all up while treading through the land". Such old way of livestock farming is harmful to the ecosystem specially because of its low productivity. In order to restore the habitat for wild animals and maintain a relatively balanced ecosystem in the desert, such grazing practice should be regulated or limited.

The net productivity is one of the most important value components for an ecosystem. Fig. 2 relates the net productivity to the above ground standing biomass by means of a regression curve. This allows to evaluate the ecological capital and ecosystem services, by establishing a model that estimates the net productivity on the basis of above ground biomass. The data for the regression model were from records of long-term studies integrated by on field measurements in the current investigation campaign (Chen and Wang, 2000; Zhou and Zhang, 1995, 1996, 1997). Results show the correlation of net productivity with ground biomass that we then used as a reference in our simulation model. The calculated net productivity values of the pastures in North Xinjiang are reported in Table 1.

2.4. Dynamics of the natural capital and the main ecosystem services in response to human activity and livestock husbandry. The simulation procedure

Both the structure and functions of the pasture ecosystem change dynamically under the influence of human activities and animal husbandry. The whole dynamic process was simulated in this study in order to better understand the interplay of these activities and the surrounding environment. The basic aspects investigated for better understanding of the ecosystem dynamics included the biomass accumulation in the pasture ecosystem, the soil organic matter sequestration, the nitrogen and water accumulation in soil, the net primary productivity (NPP), the organic materials provided to humans, livestock and other users (food, seeds, grass, deciduous materials), and finally the services of CO_2 fixation and O_2 release. The modeling process was divided into two parts, namely the dynamic simulation of natural capital (amount and total value), and the related evaluation of the main ecosystem services associated to the annual process.

Table 1
Production area, grazing capacity and main biological characteristics of the grassland in North Xinjiang.

Grassland parameters	Grassland types										
	Temperate meadow steppe	Temperate typical steppe	Temperate desert steppe	Temperate steppe desert	Temperate desert	Alpine steppe	Alpine meadow	Mountain meadow	Low land meadow	Swamp	Total
Grassland coverage (ha) and % of total area	1,349,000 4.1%	3,581,000 11.0%	3,438,000 10.5%	1,588,000 4.9%	16,702,000 51.2%	1,189,000 3.6%	504,000 1.5%	2,471,000 7.6%	1,752,000 5.4%	50,000 0.2%	32,624,000 100.0%
Usable area (ha)and % of total area	1,225,000 4.8%	3,309,000 12.9%	3,093,000 12.0%	1,359,000 5.3%	11,406,000 44.3%	1,085,000 4.2%	459,000 1.8%	2,272,000 8.8%	1,487,000 5.8%	40,000 0.2%	25,735,000 100.0%
Average hay yield (kg/ha*yr)	1465	889	455	465	329	284	882	1648	1730	2183	–
Average above ground biomass yield (kg/ha*yr) (*)	2219.7	1347.0	689.4	704.5	498.5	430.3	1336.4	2497.0	2621.2	3307.6	–
Average net production capacity (kg/ha*yr)	7521.1	4805.0	2634.9	2686.8	1969.9	1726.4	4771.0	8358.6	8730.8	10,756.1	–
Grazing capacity (ha/sheep)	0.79	1.49	2.78	3.33	4.21	3.44	0.98	0.5	0.52	0.39	–
Theoretical grazing capacity (sheeps)	1,550,633	2,220,805	1,112,590	408,108	2,709,264	315,407	468,367	4,544,000	2,859,615	102,564	16,291,354
Total hay yield (t/yr)	1,794,625	2,941,701	1,407,315	631,935	3,752,574	308,140	404,838	3,744,256	2,572,510	87,320	17,645,214
Average dry weight of the above ground biomass (t/yr)(*)	2,719,129	4,457,123	2,132,295	957,477	5,685,718	466,879	613,391	5,673,115	3,897,742	132,303	26,735,173
Average dry weight of the below ground biomass (t/yr)(*)	13,595,644	22,285,614	10,661,477	4,787,386	28,428,591	2,334,394	3,066,955	28,365,576	19,488,712	661,515	133,675,864
Total biomass yield (t/yr)(*)	16,314,773	26,742,736	12,793,773	5,744,864	34,114,309	2,801,273	3,680,345	34,038,691	23,386,455	793,818	160,411,036
Total net primary production capacity (t/yr) (*)	9,213,343	15,899,610	8,149,688	3,651,317	22,468,957	1,873,187	2,189,893	18,990,822	12,982,644	430,245	69,317,669.5

The symbol (*) indicates that data were obtained from this experiment; data without (*) were taken from Grassland Resources of China (Liao and Jia, 1996). Land classification is according to Liao and Jia, 1996, Ren et al. (2008).

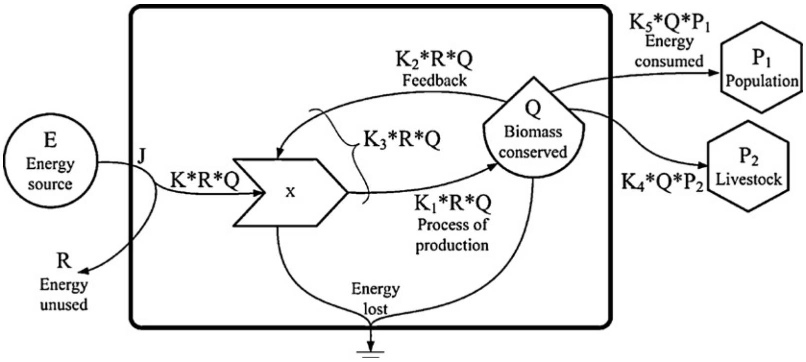

Fig. 3. System diagram of a plantation growth simulation model in North Xinjiang (GPP, gross primary production; PF, production feedback; NPP, net primary production). Modeling equations: $R = J/(1 + K \times Q)$; $GPP = K1 \times R \times Q$; $PF = K2 \times R \times Q$; $NPP = GPP - PF = K1 \times R \times Q - K2 \times R \times Q = K3 \times R \times Q$; $DQ/dt = K1 \times R \times Q - K2 \times R \times Q - K4 \times Q \times P2 - K5 \times Q \times P1$; $K3 = K1 - K2$.

The pasture ecosystem is supported by sustainable, local and outside energy resources such as solar energy, wind energy, rainfall and river flow. Those external factors contribute to the growth of pasture biomass. To design and run the simulation model, the environmental accounting method introduced by H.T. Odum (emergy synthesis; Odum, 1996) and its energy circuit language were used. Based on the model design and circuit language, equations were generated to describe the material and energy flow into and through the system itself (Fig. 3). The diagram schematizes the photosynthetic process by linking the available solar radiation to the biomasss growth, accumulation, and use by humans and livestock. Gross and Net Primary Production (GPP and NPP), biomass accumulation Q and feedback of higher to lower process levels are calculated and simulated by means of the following equations:

$$R = \frac{J}{1 + K \times Q} \tag{1}$$

$$\mathrm{GPP} = K1 \times R \times Q \tag{2}$$

$$\mathrm{PF} = K2 \times R \times Q \tag{3}$$

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{PF} = K1 \times R \times Q - K2 \times R \times Q = K3 \times R \times Q \tag{4}$$

$$\frac{\mathrm{DQ}}{\mathrm{dt}} = K1 \times R \times Q - K2 \times R \times Q - K4 \times Q \times P2 - K5 \times Q \times P1 \tag{5}$$

$$K3 = K1 - K2 \tag{6}$$

where GPP is the Gross Primary Production; PF is the Production Feedback; NPP is the Net Primary Production. *R* is the solar radiation that is not used in the process (albedo and other patterns) and indicates the still available potential for improvement of production. *Q* is the accumulated storage of biomass, PF is the feedback (the bigger the biomass *Q* the bigger is the solar energy uptake), DQ is the incremental variation of biomass.

All the simulation parameters were generated using the available and measured information on biomass yield, net primary productivity of the pasture ecosystem, as well as various factors that can affect the growth or decline of the biomass within the investigated system. Kinetic constants are obtained by means of standard simulation techniques, based on the initial values of the main parameters (Odum and Odum, 2000).

The pasture ecosystems were classified in 10 typologies (Table 1) according to (Liao and Jia, 1996). The solar light reflection ratio of the pasture is tightly linked with the density of the plantation. Some locations have very high plantation density, where the solar light reflection rate is very low. About 20% of the pastures have low biomass density, where the solar light reflection rate reached values as high as 50%. Few pastures experienced very severe degradation, and their solar reflection rate was even higher than 50%. The overall average of the solar reflection rate was between 20 and 50%. Consequently, our simulation used the parameters $J = 1$ and $R = 35\%$ for the average solar reflection rate (Ming et al., 2004). According to the statistical records, the total standing biomass (Q_o) was 1.6E+08 t at the beginning of the investigated period; NPP_o was 6.9E+07 t/yr; the organic matter consumption by humans was 5.1E+06 t/yr, and the biomass consumption by livestock was 5.1E+07 t/yr (Liao and Jia, 1996). These parameters and values are reported in Table 2 and can be considered the starting point to run the simulation and generate data for biomass (*Q*) and net primary productivity (NPP) variation over time (diagrammed in Fig. 4).

Table 2
Parameters and values of each modeling index used in the simulation (from Table 1).

Modeling index	Initial values for modeling
$k = 1.16\mathrm{E}{-08}$	$Q_o = 160{,}411{,}036$ t
$K3 = 1.234643755$	$J = 1$
$K4 = 6.75\mathrm{E}{-09}$	$R = 35\%$
$K5 = 6.23\mathrm{E}{-09}$	$\mathrm{NPP}_o = 69{,}317{,}669$ t/a
dt = 1	$J4 = 511{,}623{,}278$ t/a
$R = 0.35$	$J5 = 5{,}100{,}000$ t/a

Equations: $J = R + k \times R \times Q$ $(R = 0.35)$, $k = (J - R)/R \times Q$; $GPP = K1 \times R \times Q$; $PF = K2 \times R \times Q$; $NPP = GPP - PF = K1 \times R \times Q - K2 \times R \times Q = K3 \times R \times Q$, where $K3 = 1 - K2$; $J4 = K4 \times Q \times P2$, where $P2$ = total number of standard livestock units; $J4$ = consumption of pasture biomass by livestock = $K4 \times Q \times$ (number of livestock × 1.7 standard units/livestock) × 1.083 t/standard unit; $J5 = K5 \times Q \times P1$, where $P1$ is human population; $DQ/dt = K1 \times R \times Q - K2 \times R \times Q - K4 \times Q \times P2 - K5 \times Q \times P1$, where with reference to Fig. 3, GPP, gross primary production, PF, production feedback; NPP, net primary production.

2.5. *Assessment of the value of natural capital and ecosystem services*

In recent years, several methods for the estimation of the value of natural capital and ecosystem services have been developed. Traditional economic methods have been deeply questioned (and challenged) about their ability to account for ecosystemic values in terms of the currency system (Costanza et al., 1997; Daily, 1997). However, economic approaches, although innovative, keep their own limitations, in that they remain unable to evaluate systems for which a market value cannot be defined through willingness-to-pay and contingent evaluation methods (Brown & Ulgiati, 1999). Alternatively, the value of ecosystems can be assessed by means of the emergy synthesis approach (Odum, 1996). According to the emergy theory, value does not only rely on human preferences and willingness to pay, but instead it stems from the work of biosphere to develop and stabilize an ecosystem structure, growth, organization and diversity, measured in solar emergy joules (seJ). Emergy is the amount of available energy of one type (usually solar) that was

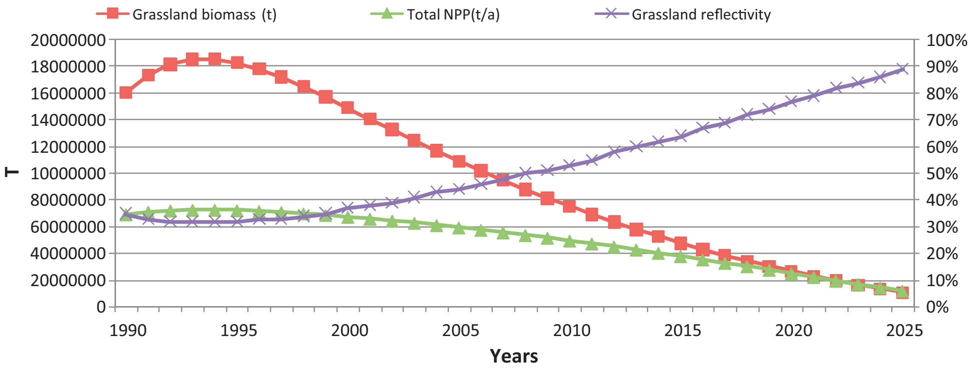

Fig. 4. Modeling of the impact of human activity and current extensive pasturing on total biomass and total net productivity, NPP (both curves referred to the vertical axis on the left, where T = tons). The grassland reflectivity is indicated by percentages on the vertical axis on the right (data from Table 4).

directly or indirectly required to provide a given flow or storage of energy or matter (Odum, 1996). The emergy invested (by nature or humans) to generate an energy or mass unit of product flow or service (J, g) is named respectively transformity or specific emergy (seJ/J, seJ/g). The emergy value is an important reference measure of the actual "size", the importance and the value of an ecosystem or its components at the scale of the biosphere; it indicates the environmental production cost of natural capital and ecosystem services as well as of goods and services in human-dominated systems. The ratio of emergy use to GDP (Gross Domestic Product) suggests a production cost (or the environmental support demand) for one unit of GDP generation within a national economy, in a given year. Such emergy-to-money ratio is measured as seJ/currency unit (for China, seJ/Yuan RMB).

For comparison purpose, the emergy value of a product or a resource can be converted into currency-equivalent units of a given country (em$, em€ or em¥), by dividing it by the emergy/GDP ratio of that country and year (previously calculated or from literature). When applied to the emergy value of an ecosystem or its components (forests, topsoil, ground-water, etc.), the resulting currency-equivalent is not an actual amount of money circulating into the market; instead it indicates a virtual economic value of the resource if the evaluation would take into account the biosphere work as a measure of production cost, instead of referring to market-dominated human preferences. Put in other words, the generation of wealth in a national economy is driven by direct and indirect biosphere support and the emergy based currency-equivalent is a way to acknowledge such contribution.

In our study, we have evaluated the emergy based currency-equivalents of the stocks of standing biomass (V_Q), soil organic matter (V_{OM}), total soil nitrogen (V_N), and retained soil water (V_W; from soil water holding capacity), as the main value indicators of natural capital, leading to a total grassland ecosystem value (V_{NC}) calculated as:

$$V_{NC} = V_E + V_{OM} + V_N + V_w \tag{7}$$

We have also evaluated the currency-equivalents of the annual ecosystem services flows (F), with focus on annual CO_2 sequestration (F_C), contribution to the atmospheric O_2 cycling (F_{O_2}), annual supply of organic materials to humans and livestock (F_{OM}), annual soil conservation (F_S), leading to a total ecosystem services value (E_{ES}) calculated as:

$$V_{ES} = F_C + F_{O_2} + F_{OM} + F_S \tag{8}$$

Table 3
Estimation of the value of main natural capital storages and ecosystem services in 1990 (reference year for the simulation over time).

Category	Calculation (see text)	Values ($\times 10^9$ Yuan RMB)
1. Natural capital value, V_{NC}	$V_{NC} = V_Q + V_{OM} + V_N + V_W$ (Eq. (7))	331.7
1.1. Standing Biomass, V_Q	Eq. (7.1), Appendix A	38.9
1.2. Soil organic matter, V_{OM}	Eq. (7.2), Appendix A	102.6
1.3. Soil total nitrogen, V_N	Eq. (7.3), Appendix A	188.8
1.4. Soil water holding capacity, V_W	Eq. (7.4), Appendix A	1.4
2. Ecosystem Service value	$V_{ES} = F_C + F_{O_2} + F_{OM} + F_S$ Eq. (8)	87.3
2.1 CO_2 fixation, F_C	Eq. (8.1), Appendix A	28.3
2.2 O_2 release, F_{O_2}	Eq. (8.2), Appendix A	41.2
2.3 Supply of organic matter to humans and livestock, F_{OM}	Eq. (8.3), Appendix A	16.8
2.4 Soil conservation, F_S	Eq. (8.4), Appendix A	1.0

The detailed equations used are listed and explained in Appendix A.[1]

3. Results

The emergy-based calculation of the grassland value shows (Table 3) that the main components of natural capital (standing biomass, soil organic matter, total soil nitrogen content, and soil water capacity) were worth 331.7 billion Yuan RMB in the year 1990. A total of 87.3 billion Yuan RMB worth ecosystem services was also provided by the grassland ecosystem in the same reference year.

The simulated biomass yields and selected ecosystem services (Table 4; Figure 4) were used to model the dynamic value changes of the grassland ecosystem by means of the equations provided in Appendix A and Eqs. (7) and (8). Results are listed in Table 5 and diagrammed in Figs. 5 and 6). According to the simulation results, the value of natural capital and ecosystem services increased slightly during the early 1990s of the last century, reaching a peak in 1994,

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[1] The emergy calculations in this paper were performed with reference to the biosphere baseline (i.e., the global emergy budget of the geobiosphere) of 9.44E+24 seJ/yr (Odum, 1996). In the most recent years, this value was updated to the value 15.83E+24 seJ/yr (Odum, 2000) and then refined to 15.2E+24 seJ/yr (Brown & Ulgiati, 2010). Another baseline of 9.26E+24 seJ/yr was reported by Campbell (2000). The appropriate value for the baseline is still in dispute by some emergy practitioners; however, what is important in our study is not the absolute values calculated, but how they change over time. In order to allow comparison with other studies, transformities calculated in this work can be updated by multiplying them by 1.68 (the ratio of 15.83/9.44) to obtain the updated value.

Table 4
Evolution of the main ecosystem's parameters in Xinjiang grassland.

Years	Total human population supportedby the pastures[a]	Total number of "standard sheep units"	Biomass consumption by human activities (ton/yr)	Biomass consumption by animals (ton/yr)	Storage of biomass on the pastures (ton)	Storage of organic matter in the pastures soil (0–20 cm) (ton)	Soil total nitrogen content (0–20 cm) (ton)[b]	Water capacity of the pasture soil (0–20 cm) (ton)[b]	Soil conservation in the pastures (ton)[b]	NPP total (ton/yr)	Solar reflection rate of the pastures[c]
1990	5.10E+06	2.78E+07	5.10E+06	5.12E+07	1.60E+08	1.49E+09	9.65E+07	1.63E+10	6.38E+08	6.93E+07	35%
1991	5.16E+06	2.89E+07	5.58E+06	5.75E+07	1.73E+08	1.61E+09	1.04E+08	1.76E+10	6.90E+08	7.12E+07	33%
1992	5.22E+06	3.01E+07	5.91E+06	6.26E+07	1.82E+08	1.69E+09	1.09E+08	1.84E+10	7.22E+08	7.23E+07	32%
1993	5.29E+06	3.13E+07	6.10E+06	6.65E+07	1.85E+08	1.72E+09	1.11E+08	1.88E+10	7.37E+08	7.27E+07	32%
1994	5.35E+06	3.25E+07	6.18E+06	6.92E+07	1.85E+08	1.72E+09	1.12E+08	1.88E+10	7.38E+08	7.28E+07	32%
1995	5.41E+06	3.38E+07	6.17E+06	7.09E+07	1.83E+08	1.70E+09	1.10E+08	1.85E+10	7.27E+08	7.24E+07	32%
1996	5.48E+06	3.52E+07	6.08E+06	7.19E+07	1.78E+08	1.66E+09	1.07E+08	1.81E+10	7.09E+08	7.18E+07	33%
1997	5.54E+06	3.66E+07	5.94E+06	7.22E+07	1.72E+08	1.60E+09	1.03E+08	1.74E+10	6.84E+08	7.10E+07	33%
1998	5.61E+06	3.80E+07	5.77E+06	7.20E+07	1.65E+08	1.53E+09	9.91E+07	1.67E+10	6.56E+08	7.00E+07	34%
1999	5.68E+06	3.96E+07	5.56E+06	7.13E+07	1.57E+08	1.46E+09	9.45E+07	1.59E+10	6.25E+08	6.88E+07	35%
2000	5.75E+06	4.11E+07	5.34E+06	7.04E+07	1.49E+08	1.39E+09	8.96E+07	1.51E+10	5.93E+08	6.75E+07	37%
2001	5.82E+06	4.28E+07	5.11E+06	6.92E+07	1.41E+08	1.31E+09	8.47E+07	1.43E+10	5.60E+08	6.61E+07	38%
2002	5.88E+06	4.45E+07	4.87E+06	6.78E+07	1.33E+08	1.23E+09	7.98E+07	1.35E+10	5.28E+08	6.46E+07	39%
2003	5.96E+06	4.63E+07	4.63E+06	6.62E+07	1.25E+08	1.16E+09	7.50E+07	1.26E+10	4.96E+08	6.30E+07	41%
2004	6.03E+06	4.81E+07	4.39E+06	6.45E+07	1.17E+08	1.09E+09	7.03E+07	1.18E+10	4.65E+08	6.13E+07	43%
2005	6.10E+06	5.00E+07	4.15E+06	6.27E+07	1.09E+08	1.02E+09	6.57E+07	1.11E+10	4.35E+08	5.95E+07	44%
2006	6.17E+06	5.20E+07	3.92E+06	6.09E+07	1.02E+08	9.48E+08	6.13E+07	1.03E+10	4.05E+08	5.77E+07	46%
2007	6.25E+06	5.41E+07	3.69E+06	5.89E+07	9.48E+07	8.82E+08	5.70E+07	9.61E+09	3.77E+08	5.58E+07	48%
2008	6.32E+06	5.63E+07	3.47E+06	5.69E+07	8.80E+07	8.19E+08	5.29E+07	8.92E+09	3.50E+08	5.38E+07	50%
2009	6.40E+06	5.85E+07	3.25E+06	5.48E+07	8.15E+07	7.58E+08	4.90E+07	8.26E+09	3.24E+08	5.18E+07	51%
2010	6.47E+06	6.09E+07	3.04E+06	5.26E+07	7.53E+07	7.00E+08	4.53E+07	7.63E+09	2.99E+08	4.97E+07	53%
2011	6.55E+06	6.33E+07	2.83E+06	5.04E+07	6.93E+07	6.44E+08	4.17E+07	7.02E+09	2.76E+08	4.75E+07	55%
2012	6.63E+06	6.59E+07	2.63E+06	4.80E+07	6.36E+07	5.91E+08	3.82E+07	6.44E+09	2.53E+08	4.52E+07	58%
2013	6.71E+06	6.85E+07	2.43E+06	4.57E+07	5.81E+07	5.40E+08	3.49E+07	5.89E+09	2.31E+08	4.29E+07	60%
2014	6.79E+06	7.12E+07	2.24E+06	4.32E+07	5.29E+07	4.92E+08	3.18E+07	5.36E+09	2.10E+08	4.05E+07	62%
2015	6.87E+06	7.41E+07	2.05E+06	4.07E+07	4.79E+07	4.46E+08	2.88E+07	4.86E+09	1.91E+08	3.80E+07	64%
2016	6.95E+06	7.70E+07	1.87E+06	3.82E+07	4.32E+07	4.02E+08	2.60E+07	4.38E+09	1.72E+08	3.55E+07	67%
2017	7.04E+06	8.01E+07	1.70E+06	3.56E+07	3.87E+07	3.60E+08	2.32E+07	3.92E+09	1.54E+08	3.30E+07	69%
2018	7.12E+06	8.33E+07	1.53E+06	3.29E+07	3.44E+07	3.20E+08	2.07E+07	3.49E+09	1.37E+08	3.04E+07	72%
2019	7.21E+06	8.67E+07	1.36E+06	3.02E+07	3.03E+07	2.82E+08	1.82E+07	3.08E+09	1.21E+08	2.77E+07	74%
2020	7.29E+06	9.01E+07	1.21E+06	2.74E+07	2.65E+07	2.47E+08	1.59E+07	2.69E+09	1.05E+08	2.50E+07	77%
2021	7.38E+06	9.37E+07	1.06E+06	2.47E+07	2.29E+07	2.13E+08	1.38E+07	2.32E+09	9.12E+07	2.24E+07	79%
2022	7.47E+06	9.75E+07	9.12E+05	2.19E+07	1.96E+07	1.82E+08	1.18E+07	1.98E+09	7.79E+07	1.97E+07	82%
2023	7.56E+06	1.01E+08	7.76E+05	1.92E+07	1.65E+07	1.53E+08	9.90E+06	1.67E+09	6.55E+07	1.71E+07	84%
2024	7.65E+06	1.05E+08	6.49E+05	1.65E+07	1.36E+07	1.27E+08	8.18E+06	1.38E+09	5.41E+07	1.45E+07	86%
2025	7.74E+06	1.10E+08	5.31E+05	1.38E+07	1.10E+07	1.02E+08	6.62E+06	1.12E+09	4.38E+07	1.20E+07	89%

[a] Assumed a population increase of 1.2% per year.

[b] Values calculated from biomass storage on the pasture, based on coefficients from Liao and Jia (1996) and Chen and Wang (2000).

[c] Average values from Ming et al. (2004).

Table 5
Modeled values of main ecological resources and service functions in North Xinjiang grassland ($\times 10^8$ Yuan RMB, 1990 value).

Year	A = B + C + D + E Total ecological resource value	B Biomass value	C Soil organic matter value (0–20 cm)	D Total nitrogen reserve value (0–20 cm)	E Moisture holding capacity value (0–20 cm)	F = G + H + I + L Total value of main service functions (per year)	G Value of CO_2 fixation (per year)	H Value of O_2 release (per year)	I Value of organic matter supply (per year)	L Soil conservation value (per year)
1990	3317	389	1026	1888	14	873	283	412	168	10
1991	3587	421	1109	2042	15	897	290	424	173	11
1992	3754	440	1161	2137	16	911	294	430	175	11
1993	3831	449	1184	2181	16	917	296	433	176	11
1994	3834	450	1185	2183	16	917	296	433	176	11
1995	3780	443	1169	2152	16	913	295	431	176	11
1996	3683	432	1139	2097	16	905	293	427	174	11
1997	3556	417	1099	2024	15	894	289	422	172	11
1998	3409	400	1054	1940	15	881	285	416	170	10
1999	3249	381	1004	1849	14	866	280	409	167	10
2000	3082	362	953	1754	13	850	275	402	164	9
2001	2913	342	900	1658	12	832	269	393	160	9
2002	2744	322	848	1562	12	812	263	384	157	8
2003	2578	302	797	1467	11	792	257	375	153	8
2004	2416	283	747	1375	10	771	250	365	149	7
2005	2259	265	698	1286	10	748	243	354	144	7
2006	2107	247	651	1199	9	725	235	343	140	6
2007	1961	230	606	1116	8	701	227	332	135	6
2008	1820	214	563	1036	8	676	219	320	131	5
2009	1685	198	521	959	7	650	211	308	126	5
2010	1556	183	481	886	7	623	202	295	120	5
2011	1433	168	443	816	6	595	193	282	115	4
2012	1314	154	406	748	6	567	184	269	110	4
2013	1201	141	371	684	5	538	175	255	104	4
2014	1094	128	338	623	5	507	165	241	98	3
2015	991	116	306	564	4	477	155	226	92	3
2016	893	105	276	508	4	445	145	211	86	3
2017	799	94	247	455	3	413	134	196	80	2
2018	711	83	220	405	3	380	124	181	74	2
2019	627	74	194	357	3	347	113	165	67	2
2020	548	64	170	312	2	314	102	149	61	2
2021	474	56	147	270	2	280	91	133	54	1
2022	405	47	125	230	2	247	80	117	48	1
2023	340	40	105	194	1	214	70	102	41	1
2024	281	33	87	160	1	182	59	86	35	1
2025	227	27	70	130	1	151	49	72	29	1

then declined steadily, mainly due to overgrazing of pastures by an excessive number of livestock. The growing number of livestock (*P*1), and the additional human activities (*P*2) implemented as consumers in the simulation model of Fig. 3 result into a negative net increase of biomass yield compared to the demand from human and animals. Results suggest soil organic matter and soil nitrogen content as the main value components of grassland natural capital, while CO_2 uptake and O_2 release are the largest value flows of annual ecosystem services provided (Table 5).

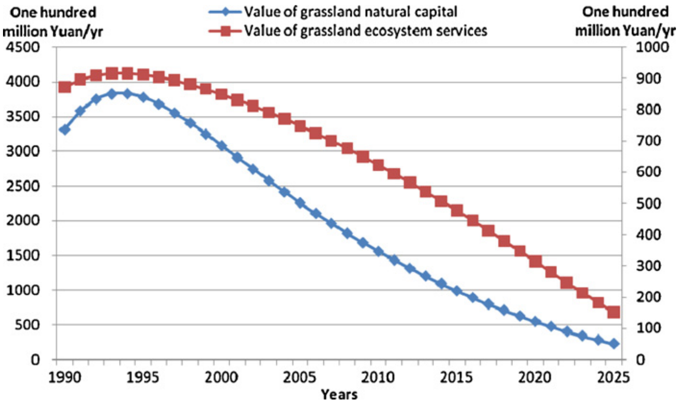

Fig. 5. Simulation of total values of grassland natural capital (left axis), and ecosystem services (right axis). Data from Table 5.

The slope of the solar reflection rate of the pasture dropped initially, as a consequence of biomass growth, followed by a sharp increase as a clear consequence of decreased biomass cover (Fig. 4). The overgrazing by increasing livestock population decreases the self-remediation ability of the pasture land and starts an irreversible degradation process in the pastoral ecosystem.

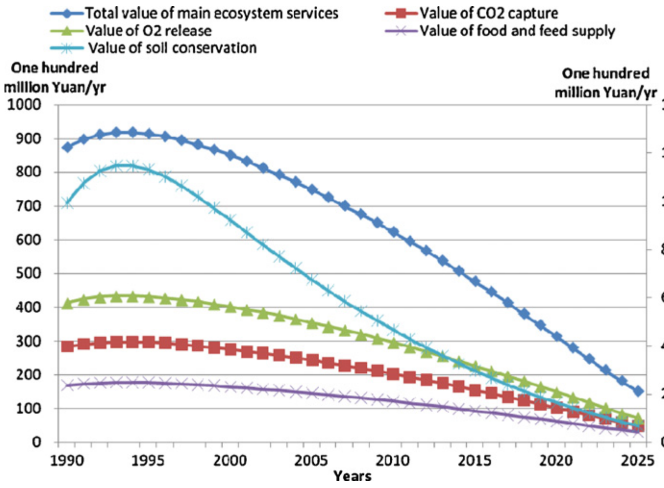

Fig. 6. Simulation of the value of selected grassland ecosystem services in North Xinjiang (data from Table 5). All values, except soil conservation, refer to the vertical axis on the left.

If the overexploitation continues, a severe degradation of the ecosystem of the grassland is the most likely consequence. The value of the grassland natural capital dropped from 331.7 billion Yuan RMB in 1990 to 155.6 billion Yuan RMB in 2010, and is expected to keep decreasing down to a low 22.7 billion Yuan RMB in 2025. The value of the main ecosystem services declined from 87.3 billion Yuan RMB in 1990 to 62.3 billion Yuan RMB in the year 2010, steadily decreasing to 15.1 billion Yuan RMB in 2025. In the year 2004, the agricultural and animal husbandry production value increased 3.7 fold (XUMSB, 2005) compared to 1990, while the value of grassland natural capital and ecosystem services dropped by 27% and 12%, respectively, during the same time period. This suggests that the fast economic growth was achieved at the expenses of a tremendous consumption of ecological resources and a consequent huge degradation of the ecological functions, which will inevitably cause severe impairment of the grassland ecosystems in North Xinjiang. The solar reflection rate increased from an average of 35% in 1990 to about 48% in 2007. If the situation remains unchanged, the degradation process will continue to worsen.

4. Discussion

The different stocks of natural capital and the different flows of ecosystem services are, from the point of view of the biosphere, all co-products of the same biosphere activity that supports the global cycles of energy and materials. The biosphere work of generating a resource may at the same time generate another different resource or service, at the same production "cost". Societies are less systemic than Nature and run processes separately, in so wasting large amounts of resources for lack of optimization. For this reason their costs should be calculated individually and added into a total, without any risk of double-counting.

The emergy method was therefore used to quantify the production costs afforded by Nature for each individual process (or, in some cases, the emergy cost of production in alternative industrial processes) and to generate a conservative estimate of potentially avoided monetary cost. The importance of applying the emergy method stems from the fact that within the market-based price system, many of these ecosystem values cannot be properly assessed, so that traditional estimation methods most often result in underpricing ecological properties.

As already pointed out, the emergy based currency-equivalents of environmental resources should not be considered as their real market price as if they could be actually traded. They should instead be considered as an indicator of the amount of economic activity that is supported or can be supported by natural capital and environmental services if they are not lost due to inaccurate management (similarly to the ability of fossil fuels to run an economic process when they are extracted and used). This means recognizing the importance of the environment in support of a country's economy: pasture supports livestock, which in turn supports the commerce, industry and the service sectors of the economy. A loss of these natural capital and services would imply a future loss of a fraction of the economic activity, or in other words the loss of a potential income to society. Furthermore, these virtual economic values could be regarded as a minimum "replacement value" of natural assets and services. If any of these natural assets and functions were lost due to environmental degradation, or if the whole pasture ecosystem is degraded, at least the same amount of investment would be needed to restore all or some of the above main functions through other patterns.

Results indicate that overgrazing and pasture activities have led and will likely lead to various degrees of degradation on the pastures in Xinjiang, over time. The productivity of the affected ecosystem also shows a fast decline. This is because the intensive livestock farming is much beyond the carrying capacity of the Xinjiang grasslands, and overgrazing only leads to environmental disruption and future environmental, social and economic unsustainability.

The 87.3 billion Yuan RMB/year worth of the main ecosystem services provided by the North Xinjiang grassland in the year 1990 is about 3.2 times the local market-based domestic product of 27.4 billion Yuan RMB in the same year (XUMSB, 2005). As a consequence, some compensation plan should be designed and implemented by the national or regional governments, in order to support and protect the local natural capital. A natural capital supporting investment is justified by the fact that the value of the related ecosystem services to society and local economy is larger than the investment itself.

It is necessary to re-design the current systems of production of both feedstock and animal husbandry. Improved, man-managed pasture patterns and a more environmentally friendly animal farming industry need to be implemented. Solutions are not easy, because they are strictly intertwined with the socio-economic performance of the local society and the needs of population involved. The "carrying capacity" solution, namely decreasing the intensity and size of livestock farms in order to meet the local biomass productivity, is not a feasible solution in the short run. Decreasing the activity of livestock farms would leave a large number of jobless farmers and would entail less support to local families (reconversion to other activities is not a short-run perspective, if any). As a consequence, short-run solutions must be found elsewhere, by reorganizing the agricultural activity in support of the livestock farming. Innovative biomass production patterns might be designed and implemented taking advantage of higher productivity crops and more efficient conservation and farming techniques. Since the value of the local natural capital and its related services is higher than its market value, a pasture related equity loan might be suggested. This financial mechanism should attract (and reward) investments aimed at the conservation of the ecosystem, while at the same time enhancing its development as human-managed pasture and modern livestock industry.

Both pasture and livestock industries need to shift gradually, systematically and strategically from a traditional, costly, low-productivity, environmental harmful conventional grazing production style to a human-managed, improved pasture, with higher productivity, and characterized by eco-friendly production systems, less dependent on grazing. The results of our value simulation confirm that the challenge is worth trying and may be capable to reward the efforts.

In order to protect the natural pasture and its important ecological functions, while at the same time developing a healthy and productive livestock industry, it was suggested (Wang et al., 2006) to grow 3.33 million ha of man-managed pasture in the area. Based on a projected yield at 9000 kg/ha (a very common yield in scientific literature for similar areas, as also pointed out in Table 1, as "average net production capacity"), the total hay production would reach 30 million ton, which is above the yield of 21.41 million ton provided by 32.6 million ha natural pasture in Xinjiang, in the present management state. If each sheep feeds on 1043 kg hay/year, the man-managed pasture can provide feedstock to 28.76 million sheep annually.

The hay produced by the improved, man-managed pasture plus the 20.32 million tons of crop straw and agricultural by-products that are currently available would add to a total of 50 million tons feedstock, which would be enough to feed the confined livestock population. As a consequence, the development of a suitable production chain between farming, processing and marketing industry would be based on sufficient pasture production and confined livestock feeding. The present low-productivity and low-efficiency style would be replaced by an energy-efficient, more environmental friendly and also more modern production system, which would be the key for the transition to an ecologically sustainable economy structure in North Xinjiang.

The proposal was not yet tested by means of a detailed emergy synthesis evaluation, so that it is not possible to highlight its global costs and sustainability. However, the fast degradation trend of the Xinjiang grassland does not leave many other alternatives in the short run. Intensive agricultural activities have already been proved to be energy and emergy intensive, and therefore not sustainable in the long run (Björklund et al., 1999; Ferreyra, 2006; Rotolo et al., 2007; Dong et al., 2008). However, the intensive management of a relatively small area (10% of total grassland area) would allow the regeneration of the degraded pasture and a potential transition to a different economic development, still to be designed, characterized by lower pressure on the local ecosystem. If sufficient time is allowed, the foreseen increase of renewable energy use worldwide and in the Chinese society as well as the adoption of more sustainable agricultural practices in highly intensive agriculture are expected to lower the environmental pressure on fragile ecosystems such as the Xinjiang area and lead to a more balanced interplay of economic production and environment. The accomplishment of this transition requires a huge research efforts and financial investments, but it is a much needed basis for creating a healthy ecosystem, strong economy and harmonious and stable future in the region.

5. Conclusion

The emergy method was used in this study in order to ascertain the environmental value of the main natural capital stocks and ecosystem services flows in the region of Xinjiang. In doing so, it was possible to express very diverse typologies of environmental resources in terms of their emergy units (seJ) and related currency-equivalents, and then run a 35 year simulation (from 1990 to 2025). Four typologies of natural capital stocks and four typologies of environmental services were simulated over time. The simulation model and equations were designed in order to also take excess pasture exploitation and related human activities into account. Results confirmed that intensive livestock farming in the region is much beyond the carrying capacity of the area. The same simulation has shown that the emergy based currency-equivalent value of annual ecosystem services was about 3.2 times the total domestic market-based productivity of 27.4 billion Yuan RMB in 1990, taken as the reference year. As a consequence, it can be inferred that investing in natural capital conservation is very rewarding (healthy natural capital provides ecosystem services in support of the economic processes and human welfare) and allows (or at least opens the way to) a sustainable development of the investigated area. Based on such result, projects for more intensive exploitation of only a relatively small fraction (∼10%) of the whole area by means of more appropriate crops and agricultural techniques as well as the use of agricultural residues and by-products for animal nutrition might prevent the excess grassland exploitation from overgrazing activities. These alternative solutions call for a more accurate emergy evaluation of the entire process in order to assess the overall sustainability of such innovative patterns.

The evaluation of natural capital and ecosystem services in terms of their emergy equivalents and then into currency-equivalents promises to be a powerful tool, not yet fully understood and implemented, to help environmental policy decision-making. It can be used to judge the worth of investments, projects and incentives for conservation, management and recovery of natural capital, beyond reliance on market dynamics and purely economic values.

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Appendix A.

A.1. *Calculation of the value of selected stocks of natural capital*

The following equation was used to calculate the total value of the main components of grassland natural capital, V_{NC}:

$$V_{\mathrm{NC}} = V_{\mathrm{Q}} + V_{\mathrm{OM}} + V_{\mathrm{N}} + V_{\mathrm{W}} \tag{7}$$

where $V_{\mathrm{Q},}$ $V_{\mathrm{OM},}$ V_{N} and V_{W} respectively represent the values of dry above-ground biomass, soil organic matter, total soil nitrogen content and retained soil water (soil water holding capacity indicates the integrity of soil structure, which also is to be considered natural capital), as follows.

I) Standing biomass

$$V_{\mathrm{Q}} = \frac{\text{Available energy stored in the biomass} \quad Q \times \text{transformity of the biomass}}{\text{emergy-to-money ratio} \quad R}$$

$$= \frac{(Q * 10^6 * E_1 * C * \mathrm{Tr})}{R} = \frac{(Q \times 10^6 \times 4 \times 4186 \times \mathrm{Tr})}{R} = 242.6 * Q \quad \text{(Yuan RMB)} \tag{7.1}$$

where V_{Q} indicates the emergy based currency equivalent value of the biomass; Q is the biomass dry weight (t) converted to g by multiplying by 10^6 g/t; E_1 is an average energy conversion factor for the above-ground biomass (=4 kcal/g) (Odum, 1996); C = 4186 J/kcal is the heat energy conversion standard from kcal to J; Tr is the transformity of the live biomass (34,044 seJ/J) (calculated in the present study); R is the emergy-to-money ratio of China in the reference year 1990 (2.35×10^{12} seJ/Yuan RMB) (Yan, 2001; Lan et al., 2002).

II) Soil organic matter

$$V_{\mathrm{OM}} = \frac{\text{Available energy in soil organic matter OM} \times \text{transformity of organic matter}}{\text{emergy-to-money ratio} \quad R}$$

$$= \frac{\mathrm{OM} \times 106 \times E_2 \times C \times \mathrm{Tr}}{R} = \frac{\mathrm{OM} \times 10^6 \times 5.4 \times 4186 \times \mathrm{Tr}}{R}$$

$$= 68.7 \times \mathrm{OM} \quad \text{(Yuan RMB)} \tag{7.2}$$

where V_{OM} indicates the emergy based value of organic matter; OM is the dry weight of soil organic matter (t) converted to g by multiplying by 10^6 g/t; E_2 is an average energy conversion factor for soil organic matter (5.4 kcal/g) (Odum, 1996); C and R as above-mentioned; Tr is the transformity of dry organic matter in soil (7145seJ/J) (calculated in the present study, according to 1.8% dry underground OM content, 213 year estimated topsoil replacement time, 2.64 g/cm^3 soil density).

III) Nitrogen storage in soil

$$V_{\mathrm{N}} = \frac{\text{Available energy of soil nitrogen N} \times \text{transformity of nitrogen in soil}}{\text{emergy-to-money ratio} \quad R}$$

$$= \frac{N \times 106 \times \mathrm{Tr}}{R} = 1957.4 \times Q_2 \quad \text{(Yuan RMB)} \tag{7.3}$$

where V_{N} indicates the emergy based value of soil nitrogen; N is the weight of soil nitrogen (t) converted to g by multiplying by 10^6 g/t; Tr is the transformity of the nitrogen (4.6×10^9 sej/g) (Odum, 1996); R as above.

IV) Storage of water retained in soil

$$V_{\mathrm{W}} = \frac{\text{soil retained water content} \quad W \times \text{transformity of soil water}}{\text{emergy-to-money ratio} \quad R}$$

$$= \frac{W \times 106 \times G \times Tr}{R} = 0.087 \times W \quad \text{(Yuan RMB)} \tag{7.4}$$

where V_W indicates the emergy-based value of soil water; W is the weight of soil water (t) converted to g by multiplying by 10^6 g/t; G is the water Gibbs free energy (4.94 J/g); Tr is the transformity of water in soil, estimated here from that of rainfall water (41,000 seJ/J)[2]; R as above.

All the measurements for soil organic matter, soil total nitrogen content and water capacity were taken from the top 0–20 cm soil layers, and the data are the average from these measurements (Liao and Jia, 1996; Chen and Wang, 2000).

A.2. Calculation of the value of selected annual ecosystem services

The total value of selected ecosystem services was evaluated using the following equation:

$$V_{ES} = F_C + F_{O_2} + F_{OM} + F_S \quad (8)$$

where V_{ES} is the total value of the main service functions of the ecosystem; F_C, F_{O_2}, F_{OM}, and F_S, respectively represent the values of CO_2 fixation, O_2 released, organic matters provided to human and livestock populations, and soil conservation and regeneration.

a) Annual sequestration of CO_2

This value was determined as

$$\begin{aligned} F_C &= 1.63 \times \text{NPP} \times P = 1.63 \times \text{NPP} \times 250\,(\text{Yuan RMB/t}) \\ &= 407.5 \times \text{NPP}\,(\text{Yuan RMB}) \end{aligned} \quad (8.1)$$

where 1.63 g of CO_2 are uptaken to generate 1 g of dry matter according to photosynthesis stoichiometry[3]; NPP is the net primary productivity (t); P is the avoided industrial cost for processing one ton of CO_2 which was taken as 250 Yuan RMB/t (Zhou and Yan, 2000).[4]

b) Annual contribution to the atmospheric O_2 cycle

This value was determined according to the equation:

$$\begin{aligned} F_{O_2} &= 1.2 \times \text{NPP} \times P_{O_2} = 1.2 \times 500 \times \text{NPP} \\ &= 600 \times \text{NPP}\,(\text{Yuan RMB}) \end{aligned} \quad (8.2)$$

where 1.2 g of O_2 are released to generate 1 g of dry matter according to photosynthesis stoichiometry; NPP is the net primary productivity (t); P_{O_2} is the unit price of industrial oxygen at 500 Yuan RMB/t (Xue et al., 1999).

c) Annual supply of organic materials to humans and livestock

This value was estimated according to the equation

$$\begin{aligned} F_{OM} &= \frac{(J_1 + J_2) \times 10^6 \times E_1 \times C \times \text{Tr}}{R} \\ &= 242.6 \times (J_1 + J_2)\,(\text{Yuan RMB}) \end{aligned} \quad (8.3)$$

where F_{OM} is the value of the organic materials including seeds, deciduous materials, biomass that is supplied into the production chain, and those consumed by livestock and humans. J_1 is the dry weight of the organic materials consumed by livestock; J_2 is the dry weight of the organic materials consumed by humans. Dry weight is expressed as ton and converted to grams by multiplying by 10^6 g/t. E_1 is an average available energy conversion factor for the biomass (4 kcal/g) (Odum, 1996); Tr is the transformity of the pasture biomass yield (34,044 seJ/J) calculated in the present work; C and R as above.

d) Annual soil integrity conservation (erosion prevention)

It is well known that soil erosion on the grassland of north China is due to deterioration of the natural environment result from overgrazing and dry weather. As a consequence, soil conservation due to better management of grazing should be considered a very important service for the sustainable development of this area, performed by the local ecosystems if its integrity is preserved.

The value of soil conservation was calculated by means of the following equation:

$$\begin{aligned} F_S &= \frac{Q_S \times 10^6 \times \text{OM\%} \times E_1 \times C \times Tr}{R} \\ &= 1.55 \times Q_S\,(\text{Yuan RMB}) \end{aligned} \quad (8.4)$$

where Q_S is the amount of soil conserved annually by the plantation (t) converted to g by multiplying by 10^6 g/t; OM% is the average soil organic matter content(3.0%); C, R and E_1 as above; Tr is the transformity of soil dry organic matter as above (7145seJ/J).

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[2] The transformity of rainfall water (chemical potential) is 18,199 seJ/J (Odum, 1996). We assume that water runoff is 55% and that only 45% of water is dynamically held in the soil for some time before being evapotranspired. The transformity of water storage in soil can therefore be estimated as proportionally higher than for rainfall, in the order of 41,000 seJ/J (old baseline).

[3] A more appropriate way of accounting for the amount of CO_2 sequestered would be to subtract J1 (biomass use by animals) and J2 (biomass use by humans) from NPP. Unfortunately, results based on data from Table 4, provide a positive net yield only from 1990 to 1994. In this year, the net yield becomes negative. The reason is twofold: NPP declines due to degradation, and consumption increases due to more intensive farming and better quality of life. Such results suggest that the additional demand from animals and humans after 1994 up-to-date was met, and will be met in the future, by importing feedstock and food items, if degradation continues at the simulated rate. Calculating the cost (and the value) of CO_2 fixation, no matter a fraction is returned to the atmosphere through the food chain without being stored, overestimates the actual storage benefit, but the reason is that the progress of the degradation prevents the benefit. In a way, we calculate how big the benefit would have been, or – in other words – we account for the extent of the potential benefit loss.

[4] The emergy cost of CO_2 sequestration could also be differently calculated, instead of relying on the economic cost of the technological process. One way would be to study the technological process of CO_2 re-injection into deep reservoirs. Unfortunately, at the best of our knowledge, nobody has performed an emergy evaluation of CO_2 sequestration through technology. This is because very few pilot cases have been implemented and they cannot be considered as a reliable benchmark for such an evaluation. A second way would be to assess how Nature sequestered CO_2 in the past. A very detailed emergy study of fossil fuel generation was recently published by Brown et al. (2011). Fossil fuels generation (coal, natural gas and oil) might be considered the most effective carbon sequestration mode and transformities per unit sequestered were calculated in the range 6.6E+04/1.7E+05 seJ/J, at least one order of magnitude higher than the transformity 7.1E+03 that we used for soil dry organic matter. This can be explained by the fact that fossil fuels are fully reduced organic carbon, while soil organic matter is still partially oxidized and the storage process is not completed. Therefore, the real value for the complete sequestration task would be much larger than our economically-based estimate, that should be considered as a conservative, lower bound.

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