

Land use change and carbon cycle in arid and semi-arid lands of East and Central Asia

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Abstract Dramatic changes in land use have occurred in arid and semi-arid lands of Asia during the 20th century. Grassland conversion into croplands and ecosystem degradation is widespread due to the high growth rate of human population and political reforms of pastoral systems. Rangeland degradation made many parts of this region vulnerable to environmental and political changes. The collapse of the livestock sector in some states of central Asia, expansion of livestock in China and intensive degradation of grasslands in China are examples of the responses of pastoral systems to these changes over the past decades. Carbon dynamics in this region is highly variable in space and time. Land use/cover changes with widespread reduction of forest and grasslands increased carbon emission from the region.

Keywords: land use change, carbon cycle, East and Central Asia.

The nomadic land use system has been an integral part of arid and semi-arid lands (ASAL) of Asia for the past several thousands years. Rangeland ecosystems and pastoral systems co-adapted and co-evolved to increase the land use efficiency and sustainability strategy. Short-term seasonal movements and long-term migrations in search of better pastures were the main land use strategies enabling people to cope with climate variability in this region. However, influence from settled societies of Russia and China began to impact the region since the 16th—17th centuries. The most dramatic changes in land use and land cover occurred in the 20th century due to political changes in the Soviet Union and China. Between 1700—1980, the total forests and grasslands area in Asia decreased by 313 million hectares, the largest decrease in any regions of the world^[1]. Croplands increased with a maximum during the last 30 years, but UNEP has estimated that 60%—70% of the grasslands in China, Mongolia and the Asian parts of the USSR are affected by desertification due to overgrazing and over-cropping^[2].

Soil organic matter (SOM) in temperate grassland averages 331 Mg/ha, and grasslands worldwide contain 12% of the earth's SOM^[3]. Soil carbon losses due to overgrazing and poor management of grasslands have been observed^[4]. Using three different land cover projections, changes in carbon levels in the grassland and dryland regions from 1800 to 1990 were estimated to be -13.2, -25.5 and -14.7 Pg, i.e. a net source of carbon due to cropland conversion^[5].

ASAL may be among the earliest ecosystems to exhibit the effects of climate change^[6]. In addition, vulnerability to climate variability and directional climate change in the ASAL is ele-

vated by human-induced land use changes^[7]. Modifications of land cover can also impact the climate system of ASAL^[8,9]. Thus land use/cover change, carbon cycle, and climate change within the region are coupled through complex non-linear interactions/feedbacks.

Objectives of this paper are: (i) To review land use changes in the ASAL of East and Central Asia; (ii) to review current knowledge and uncertainties in estimating carbon fluxes and stocks associated with climate and land use changes in this region.

1 Land use change

Land cover of arid East and Central Asia is dominated by rangelands including grasslands, steppe, and desert systems (Plate I and table 1). Changes in land use over the centuries have been defined by the physical climate and pastoral patterns of herding strategies. However recently, the increase in population pressures, political changes, and economic trends have modified the land use characteristics resulting in changes in carbon dynamics within the region.

The rangeland extends from the Mongolian Plateau of Mongolia and Inner Mongolia to the steppe of Central Asia. These systems are characterized by arid and semi-arid climate with a mean annual temperature of 4°C and a mean average precipitation of approximately 250 mm (table 1 and Plate II). The vegetation has moderate biomass with total biomass (aboveground and belowground) equaling about 3000 kg per ha (simulated values from Century ecosystem model). The total net primary production of the rangelands is about 1000 kg per ha. Despite these low levels of productivity, the soils tend to store large amounts of soil organic matter due to the higher proportion of root production (Plate III and table 1).

Table 1 Simulated values using the Century ecosystem model^[10,11]

	Land area /km ²	Mean annual temp./°C	Mean annual precip./mm	Veg C /g • m ⁻²	NPP /g • m ⁻² • a ⁻¹	Soil C (top 20 cm) /g • m ⁻²
Tundra	2455450	-3	402	470	107	4014
Desert	363649	10	84	45	27	2096
Grassland/steppe	7969480	4	250	300	100	2677
Forest	4792650	-1	522	6236	290	4576
	15581229					

The Mongolian steppe grasslands have strong continental climate characterized by rainfall (from 100 to 350 mm) occurring mostly during the warmer months of June, July and August (Plate II). The growing season is short, generally from 80 to 100 d. Snow cover is light, so soils are completely frozen in winter.

Analysis of climate relationship to soil carbon levels in the Mongolian steppe indicated that wind speed during growing season (negative) and June precipitation (positive) were the best predictors for soil carbon levels^[12]. Soil organic carbon levels were positively correlated with annual precipitation in Mongolia, but not in Inner Mongolia. The soil organic carbon levels were positively correlated with annual precipitation in Mongolia, but not in Inner Mongolia^[12]. The soil

organic carbon and nitrogen levels decreased along the precipitation (increasing) gradient in grazed plots in Inner Mongolia^[13]. These results suggest that different human and environmental factors in Mongolia and Inner Mongolia may have resulted in soil organic carbon pools of grassland ecosystems of the Mongolian Plateau.

Estimates of plant production derived from climate and remote sensing variables indicate that the Mongolian steppe ecosystems are very productive despite low levels of annual rainfall. The Century ecosystem model^[11] simulates this rapid response to rainfall inputs. The rain use efficiency of these ecosystems is very high. Simulation of ecosystem responses to climate change in the Mongolian steppe demonstrated sensitivity of soil carbon storage to changes in seasonal distribution of precipitation^[14,15]. The slight changes in rainfall during the critical months of May through July in this region resulted in large difference in aboveground NPP of the Mongolian Plateau. Comparative studies of different sites in Asia showed that the largest soil carbon losses due to climate change might occur in Tuva, Russia and Xilingole, China.

It has been found complex response of grasslands of the Mongolian steppe to global warming^[16], such as an earlier onset of green-up in large areas of eastern Mongolia and Inner Mongolia over the 1982—1991 period. Meadow steppe and relatively mesic areas of typical steppe dominate this region of advanced green-up. There are also large portions of desert steppe and dry areas of typical steppe both in Inner Mongolia and Mongolia, where there is a strong trend towards delayed green-up.

The grasslands of the Mongolian steppe have evolved under a long grazing history. Thus, a moderate grazing is likely to increased annual net primary production^[17] as shown by a comprehensive study of grazing impact on grassland ecosystems^[18]. Significantly higher CO₂ fluxes also were observed from areas with intermediate levels of grazing compared to no grazing or high grazing intensity when the carbon mineralization potential was evaluated (Pers. Comm., Wang & Barger). Land use distribution and major land use change events in ASAL of central and east Asia are summarized in table 2. More than 60% of the land in the five Central Asian countries (Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan and Tajikistan) is rangeland, accounting about 246 Mha^[19]. Arable lands are 43 Mha. Out of 400 Mha of the grasslands in China only 224 Mha are usable^[20]. Currently, Inner Mongolia has about 8 Mha of croplands and 63 Mha of usable rangelands^[21]. Over 80% of land in Mongolia is rangelands and arable lands occupy only about 1% of total agricultural lands^[22].

Table 2 Major land use change events in ASAL region of the East and Central Asia in the 20th century

	Rangelands/Mha	Croplands/Mha	Collectivization	Privatization
Mongolia	123	1.35	late 1950s	early 1990s
China (usable)	224		in 1950s	early 1980s
Inner Mongolia	63	8	in 1950s	early 1980s
Central Asia	246	43	in 1930s	mid 1990s

Major driving forces for land use change in the ASAL of East and Central Asia were population growth and policy.

Land use change in ASAL regions of China was intensified when large numbers of non-indigenous people moved into the area from other regions and greatly expanded the area of cultivation and more sedentary pastoral systems. By the Qing Dynasty (1644—1911), the greatest settlement and cultivation had occurred in the areas directly north of Beijing, in southern and central Manchuria, and on the adjacent steppe region^[23,24]. There was intensive migration of the Chinese people into Inner Mongolia since the early 19th century. The Chinese and Mongol populations in Inner Mongolia were about equal, with each being about 1 million in the early 19th century. In 1990 population of Inner Mongolia reached 21.5 million, with 17.5 million being Chinese, 3.3 million Mongols and 0.7 million others.

Similar patterns of politically induced changes in demography are found for the Asian region of former USSR. For example, as Russian dominance in this region increased during the 18th century, the Kazakh society was transformed from nomadic to more agrarian society. Total population of the central Asian countries increased from 23 million in 1959 to almost 54 million in 1996^[25].

Political changes of the past century have also impact on land use and its intensity in the region. The communist governments in China, Soviet Union and Mongolia forced conversion of some of the most productive grassland conversion into cropland and collectivization programs (table 2).

These policies not only reduced the amount of rangeland available for livestock production, but also increased grazing intensity, often on less fertile grazing lands. For example, two million ha of grasslands were converted into cropland in Inner Mongolia during 1958—1976^[21] and the total number of grazing animals tripled from 100 million to nearly 340 million in the 1949—1989 period^[20]. Land use practices with high mobility, diversity of coping mechanisms and traditional pastoral networks existed in Mongolia before collectivization. The countrywide collectivization of livestock occurred in Mongolia in the late 1950s.

During the 1930s the Soviet government introduced collective farming systems. A sedentarization of nomads was perceived as the main idea for rural development. Livestock mobility was reduced and dependence upon cultivated feed over the cold winters was increased with the collectivization of the pastoralists into state farms. Livestock populations increased steadily in the central Asian states during the collective period, and by the close of the Soviet period, they had over 63 million sheep or goats, 18 million cattle and 2 million horses as well as several hundred thousand camels and yaks^[26]. This increase in livestock numbers and the expansion of cultivation led to rangeland degradation and loss of soil fertility and carbon.

2 Impacts of land use change on carbon cycles

Conversion of grasslands into croplands and improper management of these croplands

caused large environmental damage, including carbon loss, in this part of the world. The most dramatic environmental change in the Central Asia is the drying up of the Aral Sea caused by withdrawal of water from the Amudarya and the Syrdaria rivers for irrigation. Salinization of soils due to the drop of the Aral Sea level occurred in an area of 4.9 Mha^[27]. A 30-year study of the carbon balance of the chernozem soils in northern Kazakhstan showed 25%—30% reduction of humus reserves due to cultivation^[28].

Overgrazing is also causing rangeland ecosystem degradation in this part of the world. For example, livestock population in Inner Mongolia was 9.2 million in 1947^[29] and reached 62 million by 1998^[30]. However, the total usable pasture decreased from 88 Mha in 1947 to 63 Mha at present^[29,21]. These 63 Mha of natural grassland can feed 44.2 million sheep units, and corn leaves and other fodder can support additional 10.5 million sheep units totaling 54.7 million sheep as maximum capacity. However, at present there are over 85 million sheep units. Grazing pressure has increased for the central and western regions of Mongolia during the recent decade, especially in Arhangai, Bayan-Olgii, Uvs and Hovd aimags by 50%—100%^[22].

Comparative study of culture and environment in Inner Asia show that pasture degradation was associated with loss of mobility in the pastoral systems^[31]. Rangeland degradation was the most severe at the research sites from Buyatia and Chita Oblast' (Russia), where sedentarisation level was the highest, compared to other research sites from Mongolia, Tuva (Russia), Inner Mongolia and Xinjiang (China). Our simulation studies using Century^[32] showed that year-long or summer heavy grazing for 50 years result in the largest loss of total soil carbon relative to other seasonal grazing scenarios. For example, summer heavy grazing resulted in a 15% soil carbon loss. A soil organic carbon level decreased by about 25% was observed at Xilingole heavy grazed site compared to the control site but no apparent impact was found in several heavy grazed sites in Mongolia.

Not all land use changes were negative for grassland ecosystem integrity and carbon storage. China started the new policy of sustainable management of rangelands with restoration of degraded or decertified lands. The crop sector collapsed in Mongolia during the transition to market economy. Sown areas decreased by half and crop production decreased about three times in 1995 compared to 1990. Livestock reduction in Central Asia and cropping industry failure in Mongolia could potentially contribute to natural restoration of degraded pastures and eroded arable lands. A higher rainfall use by typical steppe and shrub steppe vegetation communities than the last decade was found in southeastern Kazakhstan which indicate a recovery^[33]. This change coincided with a shift from intensive year-long grazing to very light or no grazing. Net CO₂ exchange between rangeland ecosystems and the atmosphere in three study sites from Kazakhstan, Uzbekistan and Turkmenistan also showed that the central Asian region may be acting as carbon sinks^[20].

3 Conclusion

Dramatic changes in land use have occurred in ASAL region of the Central and East Asia

during the past century, especially during the past decade. Grassland conversion into croplands and grassland degradation is largely due to the increasing of human population and political reforms of pastoral systems. This includes the collapse of the livestock sector in some states of Central Asia, expansion of livestock in China and Mongolia, intensive degradation of grasslands in China, multiple *zud* of 1999—2002 in Mongolia and recent intensive dust storms in north China and Mongolia. Identification of vulnerable regions and exploration of potential adaptation strategies to climate and land use changes are becoming critical issues for the sustainability of the region.

Carbon dynamics in this region show high temporal and spatial variability, some parts acting as carbon sources and others carbon sinks. Past land use/cover change, with the biggest reduction of forest and grasslands, increased carbon emissions to the atmosphere. Natural and human-induced recovery of grasslands shifts net C emission systems into net sinks.

Understanding the mechanisms that regulate carbon fluxes in and out of the ASAL ecosystems will contribute to our knowledge of complex carbon dynamics of the terrestrial biosphere. Coupling land use change, carbon cycling and climate change at local, regional and global scales are critical steps to undertake, which will require the integration of multiple, complimentary and independent methods that are used by different research communities^[34].

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