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Source: Mountain Research and Development, 26(2) : 153-162

Published By: International Mountain Society

URL: https://doi.org/10.1659/0276-4741(2006)26[153:LCCAII]2.0.CO;2

Mountain Research and Development Vol 26 No 2 May 2006: 153–162

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The responses of the ecosystems along the 0°C mean annual isotherm to global climate change are intense and involve significant changes in land cover at the watershed scale. This paper evaluates changes in land cover in the center of Qinghai-Tibet, the headwater region of the Yangtze and Yellow Rivers, on the basis of two sets of remote sensing data (1986 and 2000) and field investigations. Over a period of 15 years, 23% and 34% of alpine cold swamp were recently turned into alpine cold meadow or alpine cold steppe, and decreased in area by 25.9% and 42.7% in the headwater areas of the Yellow and Yangtze Rivers, respectively. Moreover, more than 20% of high-coverage alpine cold meadow and alpine cold steppe were converted to lower-coverage alpine cold meadow (vegetation coverage > 80%) and alpine cold steppe (vegetation coverage > 50%). Desertified land increased by 18.4% (bare rocks and sparse land) and 31.1% (sandy land) in the headwater area of the Yellow River and by 17.8%–18.5% in the headwater area of the Yangtze River. Land cover change in this region involves a complex transition between land cover types, which have a great influence on soil nutrients and the soil organic carbon (SOC) pool. Land cover changes in the study area over the 15-year study period led to the loss of 336.6 Gg of SOC, of which 61.6% were lost by alpine cold swamp transformation, and a total nitrogen (N) loss of 26.9 Gg, of which 81.9% occurred in the headwater area of the Yangtze River. The changes in the carbon and nitrogen cycles have serious implications for greenhouse gas emissions due to land cover change caused by climate warming in the Qinghai-Tibetan Plateau.

Keywords: *Land cover change; alpine cold swamp degradation; grassland cover type transition; soil nutrients; soil organic carbon pool; China.*

Peer-reviewed: *February 2006* ***Accepted:*** *March 2006*

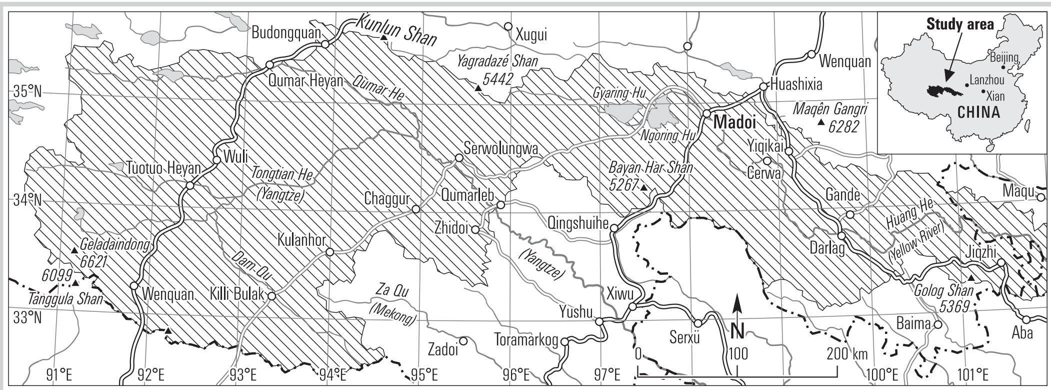
Introduction

Land cover changes affect the spatial patterns of ecological landscapes, and evolving landscape patterns inevitably cause an evolution in ecosystem functioning. Various ecological landscape variables, such as biological productivity (plant biomass and stock capacity), soil nutrients (soil organic matter and nitrogen [N] content), and water conservation capacity, have been identified as landscape function characteristics (Turner et al 2003; Hietel et al 2004). The effects of land use and land cover changes on resources, environment, and sustainable development have become a major scientific issue (Potter 1991; Vörösmarty et al 2000). Globally, land use and land cover changes impact on biogeochemical cycling, which may be complicated by land cover types, geographical conditions, and differences in historical land cover patterns (Compton and Boone 2000; Parfitt et al 2003). Land cover change in permafrost regions—which are sensitive to global climate change—involves complex interactions among vegetation distribution, carbon (C) dynamics, and nutritional status of soil conditions (McGuire et al 2002; Christensen et al 2004). Therefore, a better understanding of the impacts of land use and land cover changes on watershed soil C and N and on ecological processes will become critical for planning, management, and sustainable development of watersheds, and will have major implications for the global greenhouse gas budget (Potter 1991; Vörösmarty et al 2000; DeFries and Eshleman 2004).

The Yangtze and Yellow Rivers, the two largest rivers in China and Asia, spring from the center of the Qinghai-Tibetan Plateau; their source areas are jointly called the headwaters region (Figure 1). This region has a unique natural environment: a specific ecological function for water conservation of the large headwaters and abundant natural resources, high species diversity, and genetic resources that have a profound influence on the environment of the catchment. However, some primary research results show that the ecological systems in the headwaters region have been seriously degraded (Cheng and Wang 1998; Wang et al 2000). Therefore, the region has become the focus of public concern and received considerable attention from scientists (Wang et al 2001; Chen and Gou 2002; Dong et al 2002). The headwaters region has one of the densest river networks in the world, with numerous large and small rivers, and is commonly known as "China's water tower." It is also the world's largest and highest-altitude alpine cold meadow and wetland region, and possesses rich biodiversity (Chen and Gou 2002; Dong et al 2002). However, the natural environment in the region is very harsh, and the ecosystem is very fragile.

With growing awareness of global climate change and the impact of human activities, many scholars have recently studied eco-environmental issues in the region as well as trends in development. However, no general agreement has been achieved so far concerning the direction of environmental evolution and the probable sequence of future changes (Wang et al 2001; Chen and Gou 2002). The specific objectives of this paper were 1) to characterize the major spatio-temporal processes of land cover change in the headwaters region in the

FIGURE 1 Location of the study area: the headwaters region of the Yangtze and Yellow Rivers. (Map by Andreas Brodbeck)



center of the Qinghai-Tibetan Plateau; 2) to evaluate the relative impacts of land cover variation on soil C and N in the headwaters region, along with its environmental implications; and 3) to analyze the causes that drive alpine cold ecosystem change in the headwaters region.

Material and methods

Study area and land cover types

The Yangtze River source area selected for our eco-environmental research (90°30′–95°35′E / 32°30′–35°40′N) extends over an area of 12.12×10^4 km^2, whereas the Yellow River source area (33°00′–35°35′N / 96°00′–99°45′E) has a catchment area of 6.56×10^4 km^2 (Figure 1; Wang et al 2001). The headwaters region has a typical continental, alpine cold and dry climate with an annual mean air temperature of –4.3°C. Annual mean precipitation is 350–540 mm, mostly falling as snow and heavy rain, and annual evaporation amounts to 1204–1327 mm (Wang et al 2001). High altitude, coldness, and dryness are the basic climatic features of the region (Wang et al 2001; Chen and Gou 2002).

According to land cover and land use classification principles (Xiao et al 1997; Jorgenson et al 1999), the land cover types in the headwaters region may be classified as follows: grassland, including alpine cold meadow, alpine cold steppe, alpine cold shrub, and alpine cold swamp; forest, including forest land (dominated by *Picea crassifolia*) and sparse forest land (dominated by *Sabina przewalskii*), mainly occurring in a small area at the southern end of the Yellow River source area (Peng 1987); a water body system, including glaciers, lakes, and rivers; and a barren land system, including sandy land, shoaly land, bare rock, and sparsely vegetated land. Among these, the most important natural resources and environmental features are found in the grassland ecosystem occupying 54.04% of the whole headwaters region. As structure and functioning of the grassland ecosystem form the environmental basis for the economic development of the region, grassland ecology is the main topic of our study (Wang et al 2001).

Land cover analysis method and data

Supported by ERDAS IMAGE and Arc/Info software, 2 sets of remote sensing data from 1986 and 2000 collected by the Thematic Map (TM) satellite were processed, on the basis of 1:100,000 topographic maps. To reveal the characteristics of land cover changes, 2 major grassland types—alpine cold steppe and alpine cold meadow—were further divided into 3 subtypes each according to coverage: high-cover (HC) alpine cold steppe (>50% coverage), medium-cover (MC) alpine cold steppe (30–50% coverage), and low-cover (LC) alpine cold steppe (<30% coverage), as well as HC alpine cold meadow (>80% coverage), MC alpine cold meadow (50–80% coverage), and LC alpine cold meadow (<50% coverage). The indices of land use/cover variation ratio and land cover transformation ratio were used to reveal the basic characteristics and spatial patterns of land cover variation. The analytical methods used were as follows:

(1) Land use and land cover variation ratios: the mathematical expression of P_i, the relative variation extent of a single land type, is:

$$P_i = (LU_{it_1} - LU_{it_0}) / LU_{it_0} \times 100 \qquad (1)$$

where LU_{it_0}, LU_{it_1} represent the area of the i type of land cover at the beginning and end of observation in this study; and

(2) Land cover transformation ratio: the transformation probability matrix of land cover types in different periods was established. The matrix corresponding to the elements of land type was directly used to analyze the ratio of transformation of a land cover type into other land cover types in a certain period.

Soil sampling investigation and data analysis

Based on the rate of change, 4–7 sampling sites were selected within each of the 5 different land cover types: alpine cold meadow, alpine cold steppe, alpine cold swamp, sandy land (SD land), and bare rocks and sparsely covered land (BR&S land). The sampling points within each site were chosen based on different land cover types, landform, and the sub-division of land cover types (for example, alpine cold meadow was divided into 3 subtypes according to coverage, as mentioned above). Soil moisture and vegetation coverage were tested and quantified for each sampling point. Two to three replicated soil samples were collected from each sampling point. Based on the soil layer depth believed to be affected by land cover changes, soil samples were taken from 0–0.5 m, separated into two layers: 0–0.2 m and 0.2–0.5 m. All soil samples were analyzed for bulk density, organic matter content, and total available soil nutrient (N) content, with mean values being calculated for each site. The Walkey-Black chromic acid digestion method was used to measure soil organic matter (SOM), and the salicylate-hypochlorite Kjeldahl digestion method to establish total N (Nanjing Agricultural University 1992).

Determining the thickness of active layer in permafrost and vegetation coverage

The EKKO100 geologic radar detector and direct current electrode depth gauge techniques were used to determine permafrost thawing depth, or the thickness of active layer at each t-sampling point. In addition, bore hole data were used to obtain the thickness of both active layer and permafrost, and to correct the data from EKKO100 geologic radar detection. Vegetation coverage was determined via satellite image classification and reference table including the interpretation mark database.

Estimating soil C and N changes

The topmost 0–0.5 m, ie the soil layer most susceptible to land use and land cover changes, was examined for C and N changes. Development in soil nutrient content (ΔY) from before (t_0) to some time after (t_1) a given land use change can be represented as:

For the whole region:

$$Y = \sum\sum \nabla_{ij} (\rho_j Y_{jt_1} - \rho_i Y_{it_0}) F_i a_{ij} h \tag{2}$$

For the i type land use classes:

$$\Delta Y_i = \sum_{j=1}^{n} \nabla_{ij} (\rho_i Y_{it_1} - \rho_j Y_{jt_0}) h F_i a_{ij} \tag{3}$$

where Y_{it_0} is the soil nutrient content (g/kg) before land use change in land use type i; Y_{jt_1} is the soil nutrient content (g/kg) some time after land use change to land use type j; ρ_i is the soil bulk density before land use change (kg/m^3); ρ_j is the soil bulk density some time after land use change (kg/m^3); h is the mean soil thickness (m), in this case 1.5 m; F_i is the area of land use type i (m^2); and a_{ij} is the transfer probability element of different periods (unitless). The Nabla operator ∇_{ij} expresses that if $i = j$, then there was no change.

Land cover changes and—more specifically—land use changes have been shown to be significant contributing factors to changes in global soil organic carbon pools (Keller et al 1990; King et al 1995). Accordingly, soil organic matter contents and bulk densities were determined, and mean values were used to calculate the mass of soil organic carbon per unit area: SOC_A (Fang et al 1996; Duan et al 1997):

$$SOC_A = \rho h SOM \alpha \tag{4}$$

where SOM is the mean organic matter in the soil (% by mass); ρ is the soil bulk density; h is the depth of soil; and α is the Bemmelen Index, 0.58 (unitless), which allows conversion of soil organic matter (SOM) content to soil organic carbon (SOC) content (Fang et al 1996; Duan et al 1997).

Soil carbon loss is mainly attributable to 2 pathways: (i) soil respiration, including root respiration, decomposition by microorganisms, and mycorrhizal respiration; and (ii) organic matter decomposition precipitated by changes in land use. Assuming negligible soil carbon losses through wind or runoff erosion, based on changes in soil carbon content, a mass equivalent of gaseous carbon lost to/from the atmosphere from/to the soil can be estimated, for a given period of time (from t_0 to t_1) and for a given area (F), as:

$$E_c = F(SOC_{A,t_1} - SOC_{A,t_0}) \tag{5}$$

Results and discussion

Land use and land cover change

Grassland cover change in the study area was determined during the 15-year period from 1986 to 2000 (Table 1). In the headwater area of the Yangtze River, alpine cold swamp and alpine cold meadow decreased by 42.7% and 12.1%, respectively, while alpine cold steppe increased by 7.4%. In the headwater area of the Yellow River, alpine cold swamp and alpine cold meadow decreased by 25.9% and 8.2%, respectively, and alpine cold steppe decreased by 1.1%. The 2 watersheds shared some similar trends: the alpine cold swamp, alpine cold meadow, and alpine cold shrub areas decreased, and the decrease in alpine cold swamp was the largest. However, the magnitude of change differed notably.

Land cover type transformation matrices were developed to enable a comprehensive analysis of the

TABLE 1 Index of grassland cover change in the headwaters region of the Yangtze and Yellow Rivers from 1986 to 2000; BR&S = bare rocks and sparsely covered land.

Land cover type	Area in 1986 (km^2)		P_i (%) Yangtze catchment	P_i (%) Yellow catchment
	Yangtze	Yellow		
Alpine cold meadow	39,981.0	28,280.2	–12.1	–8.2
Alpine cold steppe	38,786.5	15,223.8	+7.4	–1.1
Alpine cold swamp	5529.1	2489.0	–42.7	–25.9
Alpine cold shrub	15.2	568.0	–9.8	–1.5
Sandy land	3275.5	2080.2	+17.8	+31.1
BR&S land	26,997.8	13,097.6	+18.5	+18.4
River area	4142.0	1808.3	–0.8	+18.7
Lake area	983.3	1499.3	–1	–2.8
Glacier land	1330.8	92.8	–13.5	–21.9

magnitude and direction of land cover changes (Tables 2 and 3), each element representing the transition ratio from the i^{th} land cover type in 1986 to the j^{th} land cover type in 2000. In the headwater area of the Yangtze River (Table 2), 8% of the original LC (low-cover) alpine cold meadow turned to alpine cold steppe and 14% turned to bare rock and sparse land, with the remaining 76% unchanged. Of the MC (medium-cover) alpine cold meadow, 69% remained unchanged, with 16% and 8% turning into alpine cold steppe and LC alpine cold meadow, respectively, and 7% turning into bare rock and sparse land. Of the HC (high-cover) alpine cold meadow, 71% remained unchanged, with 15% turning into LC and MC alpine cold meadow, 7% turning into alpine cold steppe and another 7% into bare rock and sparse land, respectively. MC and HC alpine cold steppe showed a similar change to that of MC and HC alpine cold meadow, with 68% and 72% remaining unchanged, respectively, while 24% turned into LC alpine cold steppe.

In the headwater area of the Yellow River (Table 3), HC and MC alpine cold steppe changed more significantly, with 23% of HC steppe turning into MC and LC steppe and 29% of MC steppe turning into LC steppe due to degradation. An additional 2% and 3% degraded into bare rock and sparse land, and the remaining

TABLE 2 Matrix of transformation from grassland cover types to other grassland and non-grassland cover types in the headwater area of the Yangtze River from 1986 to 2000; HC = high-cover, MC = medium-cover, LC = low-cover; BR&S = bare rocks and sparsely covered land.

1986	2000								
	LC alpine cold meadow	LC alpine cold steppe	MC alpine cold meadow	MC alpine cold steppe	HC alpine cold meadow	HC alpine cold steppe	Alpine cold swamp	BR&S land	Sandy land
LC alpine cold meadow	**0.76**	0.06	0	0.03	0	0	0	0.14	0
LC alpine cold steppe	0	**0.83**	0	0.04	0	0.01	0	0.08	0.03
MC alpine cold meadow	0.08	0.04	**0.69**	0.11	0	0.01	0	0.07	0
MC alpine cold steppe	0	0.24	0	**0.68**	0	0.03	0	0.04	0.01
HC alpine cold meadow	0.04	0.02	0.09	0.02	**0.71**	0.05	0	0.07	0
HC alpine cold steppe	0	0.11	0	0.13	0	**0.72**	0	0.02	0.01
Alpine cold swamp	0.03	0.03	0.05	0.01	0.21	0.01	**0.57**	0.07	0

TABLE 3 Matrix of transformation from grassland cover types to other grassland and non-grassland cover types in the headwater area of the Yangtze River from 1986 to 2000; HC = high-cover, MC = medium-cover, LC = low-cover; BR&S = bare rocks and sparsely covered land.

1986	2000								
	HC alpine cold steppe	HC alpine cold meadow	MC alpine cold steppe	MC alpine cold meadow	LC alpine cold steppe	LC alpine cold meadow	Alpine cold swamp	BR&S land	Sandy land
HC alpine cold steppe	**0.72**	0.06	0.08	0	0.15	0	0	0.02	0.01
HC alpine cold meadow	0.01	**0.78**	0.01	0.09	0	0.06	0.01	0.04	0
MC alpine cold steppe	0.02	0	**0.62**	0	0.29	0	0.02	0.03	0.02
MC alpine cold meadow	0	0	0.01	**0.8**	0.01	0.11	0	0.06	0
LC alpine cold steppe	0	0	0.08	0	**0.78**	0	0	0.06	0.08
LC alpine cold meadow	0	0	0	0	0.05	**0.86**	0	0.09	0
Alpine cold swamp	0.01	0.11	0.02	0.03	0.04	0.03	**0.74**	0	0.01

72% and 62% remained unchanged, respectively. As for HC and MC alpine cold meadow, 15% and 11% turned into LC meadow, respectively, and 4% and 6% degraded into bare rock and sparse land, with the remaining 78% and 80% unchanged, respectively. Only 57% of total alpine cold swamp remained unchanged in the headwater area of the Yangtze River, whereas 29% turned into alpine cold meadow and 7% degraded into bare rock and sparse land. In the headwater area of the Yellow River, 16% of alpine cold swamp turned into alpine cold meadow, 7% into alpine cold steppe, and 3% into lake and sandy land, with 74% remaining unchanged. The most significant transformation processes included (i) the transformation of alpine cold swamp meadow into alpine cold meadow and alpine cold steppe, and (ii) the transformation of HC and MC alpine cold meadow and steppe into LC meadow and steppe, and of LC alpine cold meadow and steppe into bare rock and sparse land as well as sandy land, which indicated that the grassland ecotypes were severely degraded.

The bare rock and sparsely covered land area increased by almost the same percentage, 18.4%, in the headwater areas of the Yangtze and Yellow Rivers from 1986 to 2000. This was mostly due to grassland degradation, with 6.3%, 5.3%, and 7.1% of alpine cold meadow, alpine cold steppe, and alpine cold swamp, respectively, turning into bare rock and sparse land in the headwater area of the Yangtze River, and with 5.8% of alpine cold meadow and 3.8% of alpine cold steppe turning into bare rock and sparse land in the headwater area of the Yellow River (Table 4).

TABLE 4 Changes from grassland cover types to other land cover types in the headwaters region of the Yangtze and Yellow Rivers from 1986 to 2000, in percent; BR&S = bare rocks and sparsely covered land.

1986	2000							
	Headwater area of Yangtze River				Headwater area of Yellow River			
	Cultivated land	Water body	Sandy land	BR&S land	Cultivated land	Water body	Sandy land	BR&S land
Alpine cold meadow	0	0.51	0.08	6.33	0.07	0.92	0.04	5.82
Alpine cold steppe	0	0.73	2.36	5.34	0.06	0.63	3.81	3.77
Alpine cold swamp	0	0.81	0.34	7.13	0	0.89	0.75	0.16
Alpine cold shrub	0	3.08	0.17	0.80	0.01	1.92	0	0.10

FIGURE 2 Soil organic matter (SOM) and total soil nutrient (N) content in the main grassland types in 0–0.2-m and 0.2–0.5-m soil layer for both catchments together.

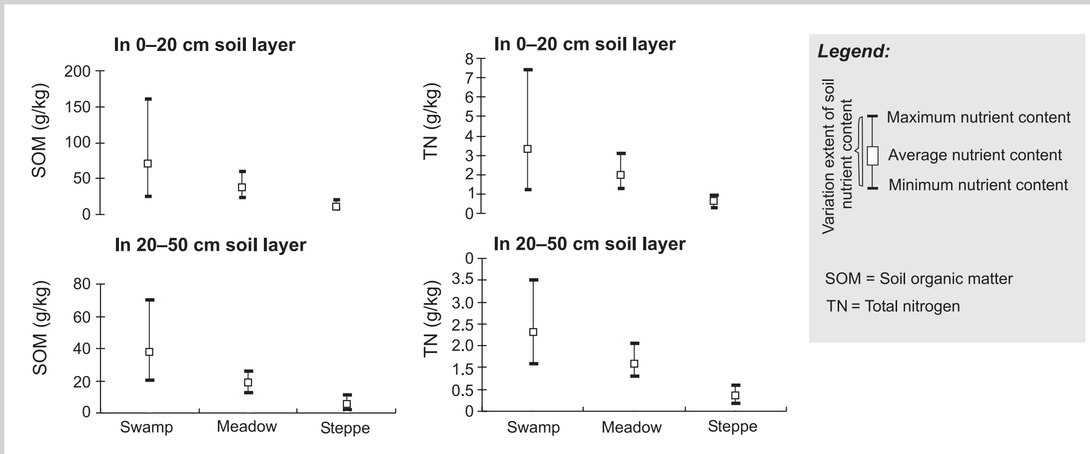
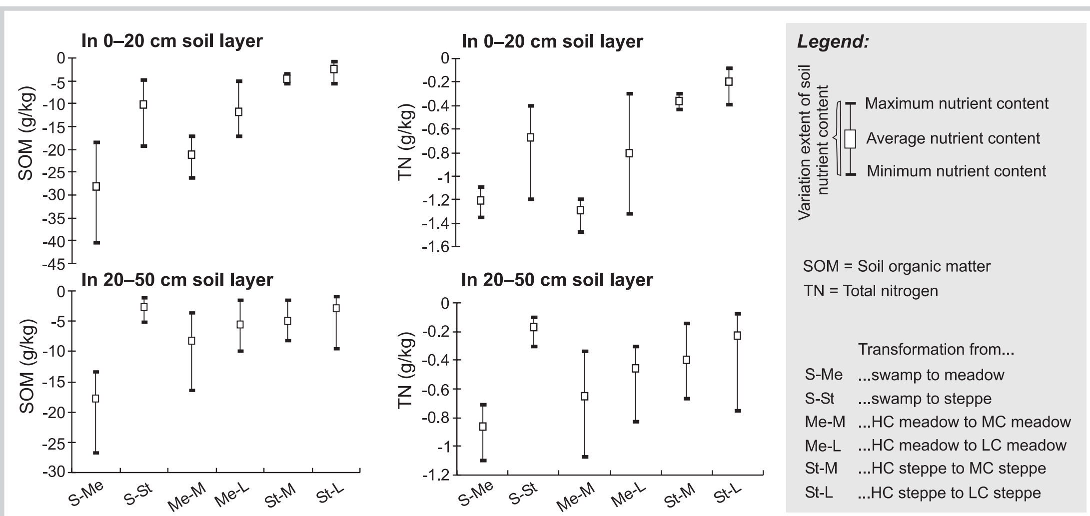


FIGURE 3 Changes in soil organic matter (SOM) and total soil nutrient (N) content caused by 15 years of land cover change for both catchments together; HC = high-cover, MC = medium-cover, LC = low-cover.



Sandy land (Table 4) increased significantly by 31.1% and 17.8% in the headwater areas of the Yellow and Yangtze Rivers, respectively. The increase in sandy land was mainly attributable to alpine cold steppe transformation in the headwater areas of the Yangtze and Yellow Rivers (2.4% and 3.8%, respectively). In the water body category, the glacier and lake areas decreased significantly in the two watersheds, by 21.9% and 2.8%, respectively, in the headwater area of the Yellow River, and by 13.5% and 10%, respectively, in the headwater area of the Yangtze River. There was little cultivated land in 2000, only 0.1% in the headwater area of the Yellow River.

Impacts of land cover change on soil organic matter and N content

Total soil N and SOM in original soils for different land cover types are presented in Figure 2. Alpine cold swamp soil has the largest content and variance of SOM and total N both in the 0–0.2-m and 0.2–0.5-m soil layers. Generally, average SOM and total N content in alpine cold swamp soil were twice those in alpine cold meadow soil, and more than 3 times those in alpine cold steppe soil.

The changes in SOM and total N content in each type of grassland soil after 15 years of land cover change are shown in Figure 3. SOM and total N in the 0–0.2-m layer of alpine cold swamp soil had greatly decreased in the case of the swampland having been transformed into alpine cold meadow and alpine cold steppe, with SOM decreased by 60.3% and 85.6%, respectively, and total N decreased by 63.8% and 79.9%, respectively; the decreases in the 0.2–0.5-m layer amounted to 53.2% and 92.8% for SOM and 52.7% and 90.7% for total N, respectively. In the case of HC alpine cold meadow having degraded to MC and LC alpine cold meadow, average SOM had decreased by 43.1% and 68.1% in the 0–0.2-m layer and by 55.83% and 70.7% in the 0.2–0.5-m layer, respectively, whereas total N had decreased by 34.8% and 69.6% in the 0–0.2-m layer and by 40.4% and 57.8% in the 0.2–0.5-m layer. There was a similar decrease in magnitude of SOM and total N content in alpine cold steppe land in the case of HC steppe having degraded to MC and LC steppe, with 59.9% and 78.7% for SOM and 43.7% and 69.7% for total N in the 0–0.2-m layer. Average SOM and total N content in alpine cold meadow formed by alpine cold swamp transition were generally lower than those in original alpine cold meadow soil, and a similar trend was observed with regard to alpine cold steppe soil. After the alpine cold grassland had turned into bare rock and sparse land, a significant decrease in SOM and total N had occurred in soil types in alpine cold swamp and alpine cold meadow areas; generally, average SOM over the entire 0–0.5-m layer had decreased by 91.1% and 88.4%, respectively, and average total N had decreased by 85.3% and 81.6%, respectively.

Soil organic carbon and soil N losses due to land cover change

The majority of land cover transformation pairings resulted in soil N loss; for example, all alpine cold meadow turned to alpine cold steppe, alpine cold swamp degraded and turned into alpine cold meadow or steppe, and all grassland types turned into desert land as sandy and BR&S lands. In the headwater area of the Yangtze River from 1986 to 2000, soil N loss due to transformation of alpine cold swamp into alpine cold steppe, alpine cold meadow, and BR&S land was, on average, 2.9 Gg or 196.7 Mg/yr, 6.7 Gg or 448.6 Mg/yr, and 4.8 Gg or 320.6 Mg/yr, respectively (Table 5). Soil N loss due to transformation of alpine cold meadow into alpine cold steppe and BR&S land was 2.9 Gg or 194.7 Mg/yr and 2.5 Gg or 164.7 Mg/yr, respectively. Over the same 15-year period, some HC alpine cold meadow land was degraded and turned into MC and LC meadow, resulting in a total soil N loss of 1.2 Gg or 77.3 Mg/yr (Table 5). In the headwater area of the Yellow River, similar soil N losses occurred as a result of land cover changes.

Some changes, such as LC alpine cold steppe turning into MC and HC alpine cold steppe, MC alpine cold steppe turning into HC alpine cold steppe, and SD and BR&S lands turning into alpine cold steppe, resulted in soil N gains. These gains were due to processes of ecological restoration, leading to an increase in soil N by 0.3 Gg in the headwaters region of the Yangtze and Yellow Rivers.

SOC loss caused by land cover changes in the headwater area of the Yangtze River was calculated according to equations (4) and (5), assuming a 15-year period after the land cover change, a 0–0.5-m soil layer, and excluding SOC changes associated with root respiration, decomposition by microorganisms, or mycorrhizal respiration (Table 6). Fifteen years after transformation of alpine cold swamp into alpine cold meadow and alpine cold steppe, mean SOC losses were 95.5 Gg of C and 37.6 Gg of C, respectively (Table 6). Fifteen years

TABLE 5 Total N loss (–) or gain (+) caused by land cover change in the headwater area of the Yangtze River from 1986 to 2000 (Gg N); BR&S = bare rocks and sparsely covered land; HC = high-cover, MC = medium-cover, LC = low-cover.

1986	2000							
	LC alpine cold meadow	LC alpine cold steppe	MC alpine cold meadow	MC alpine cold steppe	HC alpine cold meadow	HC alpine cold steppe	Alpine cold swamp	BR&S land
LC alpine cold meadow	0	–0.04	0	–0.01	0	0	0	–0.07
LC alpine cold steppe	0	0	0	+0.06	0	+0.03	0	–0.09
MC alpine cold meadow	–0.35	–0.42	0	–0.87	0	–0.05	0	–0.73
MC alpine cold steppe	0	–0.37	0	0	0	+0.07	0	–0.11
HC alpine cold meadow	–0.56	–0.46	–0.60	–0.37	0	–0.70	0	–1.67
HC alpine cold steppe	0	–0.29	0	–0.19	0	0	0	–0.07
Alpine cold swamp	–1.46	–1.95	–1.59	–0.55	–3.68	–0.45	0	–4.81

TABLE 6 Soil organic content (SOC) loss (–) or deposition (+) caused by land cover change in the headwater area of the Yangtze River from 1986 to 2000 (Gg C); BR&S = bare rocks and sparsely covered land; HC = high-cover, MC = medium-cover, LC = low-cover.

	2000							
1986	LC alpine cold meadow	LC alpine cold steppe	MC alpine cold meadow	MC alpine cold steppe	HC alpine cold meadow	HC alpine cold steppe	Alpine cold swamp	BR&S land
LC alpine cold meadow	0	–0.33	0	–0.08	0	0	0	–0.75
LC alpine cold steppe	0	0	0	+0.42	0	+0.40	0	–0.85
MC alpine cold meadow	–3.86	–4.21	0	–9.08	0	–0.45	0	–7.71
MC alpine cold steppe	0	–2.83	0	0	0	+0.91	0	–0.96
HC alpine cold meadow	–6.95	–5.16	–8.00	–4.28	0	–7.79	0	–19.62
HC alpine cold steppe	0	–3.34	0	–2.66	0	0	0	–0.82
Alpine cold swamp	–19.77	–24.75	–22.48	–7.07	–53.27	–5.83	0	–62.62

after transformation of alpine cold meadow into alpine cold steppe, mean SOC loss was 31.4 Gg of C in the headwater area of the Yangtze River (Table 6). Similar soil N losses occurred as a result of land cover changes in the headwater area of the Yellow River.

Based on these data, land cover changes in the study area led to the loss of 336.6 Gg of SOC from 1986 to 2000. While 83.2% of this SOC loss occurred in the headwater area of the Yangtze River, 61.7% were due to degradation of alpine cold swamp into alpine cold meadow and alpine cold steppe. In the same period, land cover changes within the study area also resulted in a total N loss of 26.9 Gg, with 81.9% of total N loss occurring in the headwater area of the Yangtze River, while 65.7% of total N loss were due to degradation of alpine cold swamp into alpine cold meadow and alpine cold steppe.

General discussion

The relationships between alpine cold ecosystems, permafrost, and biogeochemistry

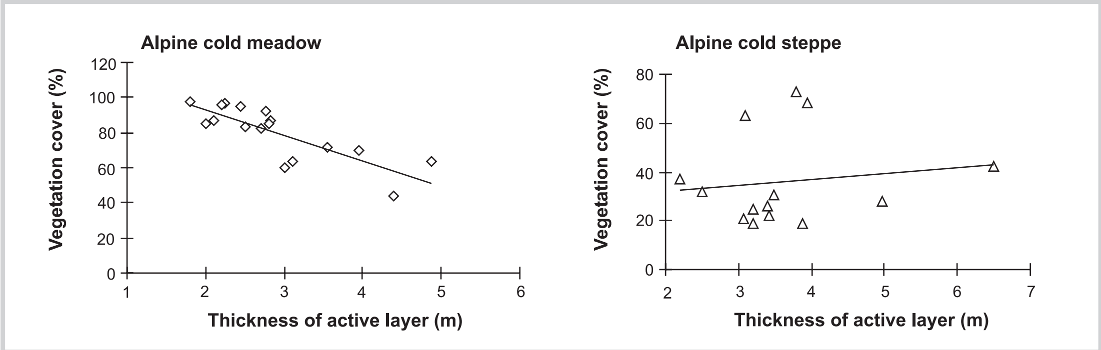
Continuous permafrost in the Qinghai-Tibetan Plateau mainly occurs in the center of the plateau, between the Kunlun mountains and Mt Tanggula, where the headwater area of the Yangtze River is located. In the headwater area of the Yellow River, some island permafrost can be found locally (Zhao et al 2000; Wu et al 2001). The presence of a permafrost layer has a great influence on the growth and development of alpine cold swamp and alpine cold meadow ecosystems. On the one hand, the permafrost layer can effectively prevent surface water and soil water from downward seepage and enable the root zone to have a higher water content. On the other hand, nutrients leached from an active layer can be concentrated in the permafrost layer and thus become unavailable to plants. In addition, lower soil temperatures contribute to the accumulation of organic matter and soil N (Ji 1996; Zhao 1996). Accordingly, the lowlands and valleys with permafrost in the headwaters region of the Yangtze and Yellow Rivers have well-developed alpine cold meadow ecosystems and alpine cold swamp ecosystems, with 70.3% of alpine cold swamp and 63.5% of alpine cold meadow being located in the headwater area of the Yangtze River; moreover, there are high contents of organic matter and total N in the alpine cold meadow and alpine cold swamp soils.

Numerous observations and studies (Zhao 1996; Zhao et al 2000) have shown that there is a significant statistical correlation between vegetation cover and thickness of active layer in alpine cold meadow and alpine cold swamp ecosystems: as the thickness of the active layer increases, the vegetation cover of alpine cold meadow (including alpine cold swamp) decreases (Figure 4). However, there is no significant trend of alpine cold steppe coverage changing with the thickness of the active layer (Figure 4). Alpine cold meadow and alpine cold swamp were thus more sensitive to permafrost changes, while alpine cold steppe may remain relatively stable.

The impacts of permafrost change on land cover

In the last 30 years, as a result of climate warming, ground temperatures in the upper layer (0–40 m) of the permafrost soil on the Qinghai-Tibetan Plateau have obviously risen (by 0.2°C to 0.3°C on average; Cheng et al 1997). The rise in ground temperatures has expanded the thawed soil area, thickened the seasonal thawing layer, or even led to complete disappearance of

FIGURE 4 Relationship between vegetation cover and thickness of active layer.



permafrost (Wang 1998; Zhao et al 2000). Permafrost degradation has resulted in soil moisture decrease in the rooting zone, surface soil desiccation, swamp drying up, and changes in soil structure and composition (Ji 1996; Zhao 1996). Furthermore, it has led to degradation of alpine cold meadow and alpine cold swamp vegetation, and triggered succession of dominant plant species (Cheng and Wang 1998; Wang 1998).

Conclusion

The headwater areas of the Yangtze and Yellow Rivers, located in the center of the Qinghai-Tibetan Plateau, show intense responses to global climate change. This permafrost environment has undergone pronounced land cover and biogeochemical changes. Its alpine cold meadows and alpine cold swamps are intimately related with permafrost conditions. Climate warming, primarily observed in permafrost degradation, has resulted in land cover changes characterized by transformation of alpine cold meadow and alpine cold swamp into steppified meadow or alpine cold steppe and desertified landscape such as sandy and BR&S lands. Such land cover changes indicate that the environment of the headwaters region of the Yangtze and Yellow Rivers tends towards degradation that reduces both soil fertility and carrying capacity. This, in turn, has major implications for the sustainability of land use practices and development in the near future. Land cover changes in the study area from 1986 to 2000 resulted in a SOC loss of 266.9 Gg of C and a total soil N loss of 19.5 Gg. These huge SOC and total N losses inevitably also have serious implications for gaseous losses of C and N in chemical forms that can act as greenhouse gases, and thus could further amplify climate change. As various grassland ecosystems occupy more than 60% of the plateau (Wang et al 2002), further studies are needed to clarify the potential of greenhouse gases being emitted in grassland ecosystems due to land cover change in the whole Qinghai-Tibetan Plateau.

ACKNOWLEDGMENTS

This study was funded by the “Hundred People” Project of the Chinese Academy of Sciences, the Natural Science Foundation of China (Nos 90511003 and 30270255), and the national key scientific plan (973) (No 2003CB415201).

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