Ecological Basis of Alpine Meadow Ecosystem Management in Tibet: Haibei Alpine Meadow Ecosystem Research Station
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Alpine meadow landscape in Northeast Tibet. Photo: Xing-Min Zhou.

Alpine meadow and shrub are the main pasture types on the Tibetan Plateau, and they cover about 35% of the total land area. In order to understand the structural and functional aspects of the alpine ecosystem and to promote a sustainable animal production system, the Haibei Alpine Meadow Research Station was established in 1976. A series of intensive studies on ecosystem structure and function, including the energy flow and nutrient cycling of the ecosystem, were the main tasks during the first 10 years. Meanwhile, studies with 5 different grazing intensities on both summer and winter pasture have been conducted. In the early years of the 1990s, the research station started to focus its research work on global warming, biodiversity and sustainable animal production systems in pastoral areas. Various methods for improving degraded pasturelands have been developed in the region.

INTRODUCTION

The Tibetan Plateau, a unique geographic unit, has a great impact on the Eurasian atmospheric circulation, and it has influenced the distribution of various ecosystems and their structure, function, adaptation, and evolutionary patterns since the plateau formed as the highest plateau in the world. The frosty, alpine shrub, alpine meadow, alpine steppe and alpine desert ecosystems are widely distributed in the area, which covers 2.5 mill. km^2. Alpine shrub and meadow cover about 35% of this land area. Due to the high-altitude climate, the ecosystems are very fragile and sensitive to global climate change. This area is therefore an ideal place to study ecosystem response to climatic change (1). On the other hand, grassland degradation, a major type of land desertification, has been described as a process of retrogressive succession of grassland ecosystems resulting from human activity (such as overgrazing) and the unfavorable environmental conditions on the Tibetan Plateau. Overgrazing has led to degradation of 30% of the pasturelands in the Haibei region. Obtaining a better understanding the ecological interactions and the processes necessary to sustain ecosystem composition, structure, and function of alpine ecosystem were among the main aims of the establishment of the Haibei Alpine Meadow Research Station in 1976. The dynamics of climate, grazing and its impacts and long term monitoring are also major concern at the research station. This paper will present a brief view of the research results from this station.

ENVIRONMENTAL CONDITIONS OF THE RESEARCH AREA

The Haibei Alpine Meadow Ecosystem Research Station is located in the northeast of Tibet, in a large valley oriented NW-SE surrounded on all sides by the Qilian mountains, at latitude 37°29'–37°45'N and longitude 101°12'–101°23'E. The average altitude of the mountain area is 4000 m a.s.l. and 2900–3500 m for the valley area. The Datong River passes through the south of the area. The landscape is characterized by large mountain ranges with steep valleys and gorges interspersed with relatively level and wide intermountain grassland basins. The climate at the Haibei Research Station is dominated by the southeast monsoon and high pressure from Siberia. It has a continental monsoon type climate, with severe and long winters and short cool summers. The average air temperature is –1.7°C with extremes of maximum 27.6°C and minimum –37.1°C. During winter months, the average temperature can drop to –15 or even –20°C in highland areas; during summer, the temperature in the warmest month (July) averages 14–22°C in the valleys and 4–10°C in the mountains. The average annual precipitation ranges from 426 to 860 mm, 80% of which falls in the short summer growing season from May to September. The annual average sunlight is 2462.7 hrs with 60.1% total available sunshine.

THE CHARACTERISTICS OF THE ALPINE MEADOW ECOSYSTEM

Over time scales of decades or centuries, many landscapes the Tibetan Plateau are altered by natural disturbances that lead to mosaics of successional patches of different ages. These patch dynamics are critical to the ecosystem structure and function. For a sound understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function, long-term monitoring and research are necessary. The dynamics of climate, grazing and its impacts are a major concern at the research station. Consequently, the research station has been formed based on CERN (Chinese Ecosystem Research Network, The Chinese Academy of Sciences) which was initiated to evaluate the effects of climatic change and human activity on the alpine meadow ecosystems of the Tibetan Plateau. The research station will address the fundamental relationships between climate, and aspects of the plateau environment such as ecology and vegetation dynamics over a range of time scales. Archives of past environments and biotic communities preserved in productivity, plant community structure, soil nutrients and major animal populations have being investigated since the research station was established in 1976. The experimental and analytical approaches will be used to unravel current climate effects on ecological processes. The basic understanding of the dynamics of climate and the alpine landscape and its ecology will be employed to assess the likely impacts on Tibet of predicted future climatic changes.

Abiotic Subsystems

The subsystem is composed of macroclimate, microclimate, and soil bank, it plays as important role in bio-communities as a driving force. Figure 1 (Li, unpubl. data) shows the annual average air temperatures at the research station from 1957 to 1997. There is insufficient evidence to suggest that air temperatures have increased during the last 40 years. However, from 1957 to 1967, the average air temperature was –2.3°C which is 0.4°C lower than the average for 40 years. After the first 11 years, from 1968 to 1975, the average air temperature was 0.4°C higher than the 40-year average. From 1976 to 1984, the yearly average air temperature varied greatly. In 1981, the average temperature was 0.8°C higher than the 40-year average. However, during these 9 years, there were only 3 years with an average air temperature of more than the year average of 40 year, so this period was colder than the 40-year average. The air temperature was relatively high during1985 to 1996. The highest annual average air temperature was –0.9°C for 1987. The average for 1985 to 1996 was 0.3°C higher than the 40-year average and 0.5°C higher than the preceding 10-year period.

The soil types of the Haibei research station are dominated by alpine shrub soil, alpine meadow soil, and bog soil, rich in nitrogen, phosphorus, and potassium. They are characterized by high organic content, underdevelopment and a thin soil layer. Nitrogen and phosphorus exist mostly in the organic state with a weak mineralization process. The ratio of available elements is low, especially due to a lack of available nitrogen and phosphorus. The soil nutritive conditions cannot meet the needs of plant growth. Nitrogen storage, mainly existing in the form of organic nitrogen, was 10.63 t ha^{-1} in the soil pool, and the nitrogen mineralization rate was very slow under natural conditions. The amount of accumulated mineralized nitrogen was only 1.59% of the total nitrogen. The soil nitrogen nutritive condition was characterized by abundant total nitrogen and a lack of available nitrogen. This could be a limiting factor for vegetation productivity (2).

Nitrous oxide emissions, caused by denitrification activities of soil microorganisms, in 3 types of vegetation soil, and different depths in the soil layers, were determined by gas chromatography on a GDX-102 column with ^{63}Ni Electroncapture detectors. The highest nitrous oxide emissions from dry soil were 155.69 ng N_2O g^{-1} d^{-1} (dry soil) and 180.17 ng N_2O g^{-1} d^{-1} for *Kobresia humilis* meadow and *Potentilla fruticosa* shrub, respectively. However, for reseeding degraded pasture, the figure can reach as much as 545.75 ng N_2O g^{-1} d^{-1} (3). The soil respiration of bare-ground and the dark respiration of plant-soil systems were not only influenced by temperature, but also related to soil water content and precipitation (3).

The activity of phosphorus transformation in the surface soil layer was higher than that in other soil layers. It is correlated with the soil temperature and organic matter. The activity of organic phosphorus transformation is higher than that of inorganic phosphorus transformation. The numbers of phosphate dissolving bacteria in the soils, and the phosphorus transformation show the following patterns:

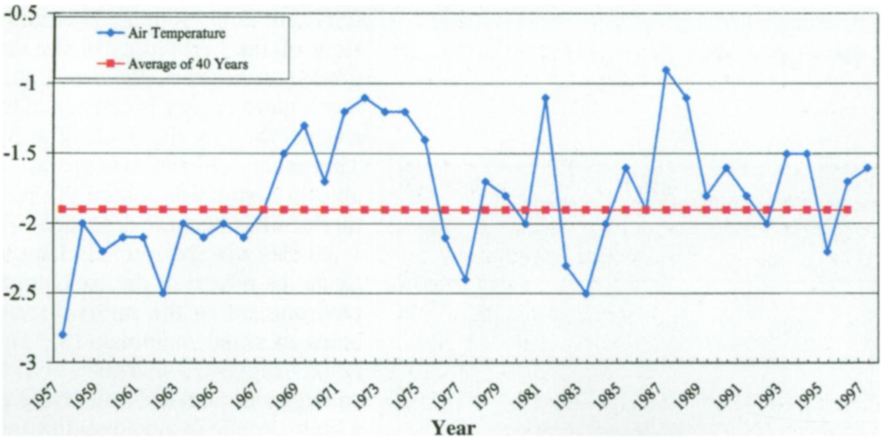
Potentilla fruticosa shrub > *Kobresia humilis* meadow > degraded meadow and 0–10 cm > 10–20 cm > 20–40 cm at different soil depths (4).

Producer Subsystems

With respect to the general biogeography of the region, the alpine meadow, dominated by *Kobresia humilis* and various grasses and forbs (depending on grazing density) are widely distributed along the valley floor. The shrub, *Potentilla fruticosa* joined by shrubby *Salix* species, are located on the northern slopes. The marsh vegetation consists primarily of *Kobresia tibetica* and *Pedicularis longiflora*. With respect to the overall land-use pattern in the region, the higher shrub lands on the mountains surrounding the valley are common summer grazing lands. The meadow vegetation is grazed in winter and is privately owned; ownership is generally demarcated by dirt and barbed-wire fences. The meadow can be grazed in winter because over 80% of the precipitation in the region occurs in the summer; less than 10% in the winter and, consequently, snow cover during the winter on the valley floor is quite sparse. Snow that does fall soon melts, except after occasional storms.

There is a substantial variation in herbage quality. The nutritive value deteriorates sharply in the autumn and winter following the normal growth cycles of flowering and senescence (Fig. 2). Herbage quality is considered adequate for animal growth and production in the summer, but only, at best, for subsistence, during the winter. Nutrient content is dependent on the plant species. The content of crude protein, crude fat and nitrogen-free extract of legumes and forbs is higher than in grasses and sedges whereas the crude-fiber contents give the opposite results. The monthly changes in nutrient content are not significantly different ($P > 0.05$) except for crude-protein and crude fiber. The crude-protein content can reach 13% at the beginning of the growing season. After the long winter season, the content of crude protein is only 5%, (dry

Figure 1. The annual average air temperature at the research station, 1957–1997.



matter) (5). The herbage nutritive value also varied with the altitude. Normally, the herbage distributed at higher altitudes has higher protein content and nonstructured carbohydrate (6). The main reason for this is the low temperatures at high altitudes. Low environmental temperatures result in decreased lignification of plant cell walls. Low temperatures also promote slower metabolic activity, which increases the pool of metabolites in the cellular content. This activity increases nitrates, proteins, and soluble carbohydrates, and decreases the structural cell-wall components.

The monthly patterns of biomass changes in the plants are significantly different ($P < 0.05$) for various plants. The annual biomass peak of unavailable forbs is from the end of July to mid-August. However, the annual biomass peaks of available forbs and grasses are at the end of August and mid-September, respectively.

With respect to the rather low photosynthesis area index and the strong solar radiation intensity, the photosynthesis of the plant community was characterized by a low light compensation point and a light saturation point of net photosynthesis, and a rather conspicuous light saturation point. All these photosynthesis characteristics are similar to the light response of a single leaf. Since the atmosphere is thinner and is more transparent in alpine regions, solar UV-B radiation intensity was higher in the Haibei alpine meadow region than in Xining and Nanjing. Consequently, alpine plants have high contents of UV-B-absorbing compounds. The compounds in methanolic extract of 21 species grown at Haibei showed that most plants had high absorbance at 265 nm and 320 nm. This may result from stronger solar radiation and UV-B radiation (7).

Consumer Subsystems

Sheep and yaks, the most important herbivorous animals in the region, live on herbage, which varies greatly with the season. The Tibetan sheep is one of earliest sheep breeds in China. Sheep are primarily used for the production of wool and mutton. In the research region, most sheep are of the Tibetan breed, although there are some crossbreeds orginating from crosses with breeds from other provinces in China. Nevertheless, due to their higher survival rates and better adaptability, the local breed have reasserted their importance in the region. However, the local sheep mature slowly and have a low productivity performance. About 25% maiden ewes lambing at 2-years of age, and the remaining 75% at 3 years of age. Lambing normally takes place in late winter, from December to January of the following year. When there is a shortage of forage, severe feed stress often occurs. Supplementary feeding is required to keep ewes lactating and lambs alive. The ewes breed only once a year and lambing rates range from 70–80% with twinning rare and not desired. The yield of wool is about 0.50–1.42 kg and the slaughter rate is less than 50% for adult sheep. Tibetan sheep wool (Xining clipped sheep wool) is very good for carpet production; however, the fleeces are not skirted or classed and, hence, the overall quality of the clip is extremely poor for textiles. The ratio of input and output of managing Tibetan sheep is 1:2.15 and the profit rate is 18.41%. From an economic view point, the population of Tibetan sheep should be increased in the future. The optimum ratio between sheep and yaks is 15:1, considering a combination of ecological, economic, and societal aspects.

The ratio of herbage intake and liveweight gain is very low due to the imbalance of herbage supply, both quantity and quality. Table 1 shows the ratio of herbage consumption per kilogram carcass production. As sheep age increases, the efficiency of herbage utilization decreases sharply.

Yak are a special kind of oxen living on the Tibetan Plateau at an altitude of 3000–6000 m and at very low temperatures, eating wild grass free from pesticides. The animal is characterized by a plump body, short legs and good health. Meat and milk are the major yak products. In addition, yak down is very useful in the textile industry. Sometimes, yak are used as pack animals. It is doubtful whether man could survive in Tibet without the yak. The herbage utilization of the yak is the largest, while Tibetan sheep take second place, and the pika utilizing the least herbage. However, the ratio of input to output of yak production is 1:0.71. The profit rate of managing a yak population is –4.88%. So, from an economic point of view, the yak population on alpine meadow pasture should be reduced.

Rodents, especially the plateau pika (*Ochotona curzoniae*) and zokor (*Myospalax baileyi*), are dominant rodents which compete for grass resources with sheep and yaks. The small carnivores, *Mustela altaica* and *M. eversmanni* are common but the large carnivores such as *Vulpes ferrilatus* and *Canis lupus* are rarely found. The energy flow of the herbivores in the degraded ecosystem indicated that much more energy is consumed by rodents than by livestock (Fig. 3). This energy utilization is unreasonable in a situation where the pastureland has become degraded.

Studies were performed to investigate the effects of the cold alpine environment on the survival strategies of small mammals (8). The results suggested that the survival strategies of pika and vole living at a high altitude in a cold region are:

Figure 2. Seasonal dynamics of standing crop biomass and crude protein content.

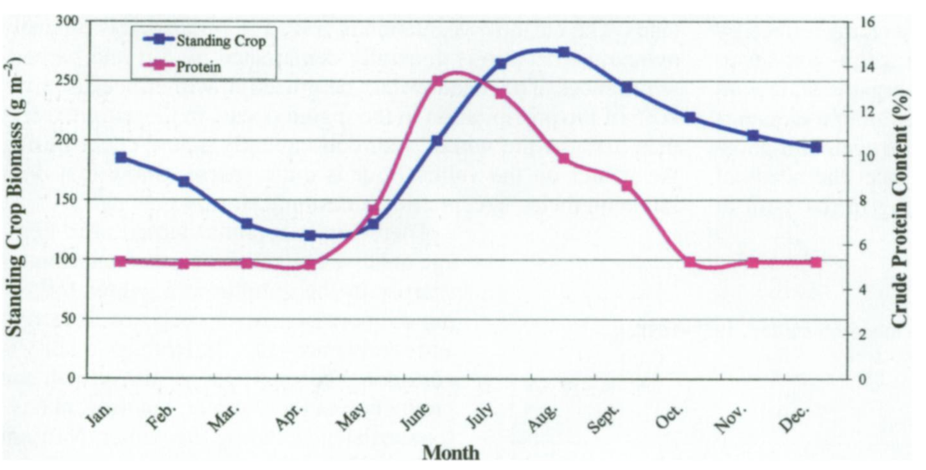


Table 1. The ratio herbage consumption (HC) to carcass (CW) at different ages in sheep.

Age (year)	1	2	3	4	5	6	7
Herbage consumption (HC, kg)	738	2700	4830	6060	7740	9420	11 110
Carcass weight (CW, kg)	7.66	15.41	21.33	27.15	29.16	30.74	28.38
HC/CW	96.3	175.21	226.44	223.20	265.43	306.44	391.47

Yak grazing on marsh meadow near the station. Photo: Xing-Min Zhou.

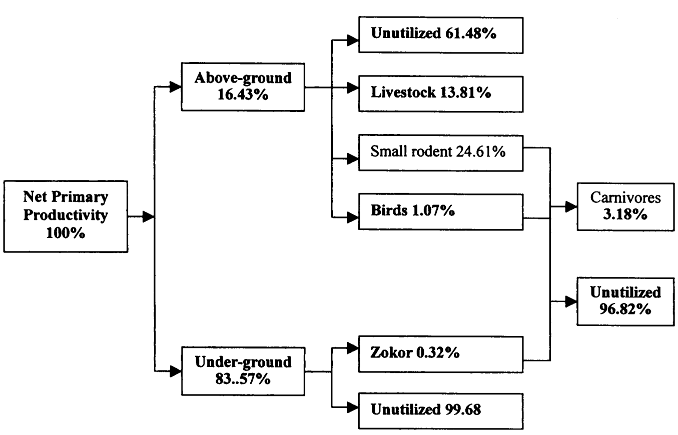
minimizing thermal conductance, energy expenditure, active time; reducing resting metabolic rate and cost of maintenance, increasing insulation, brown-fat tissue mass, and nonshivering thermogenesis capacity. Compared to the aboveground species such as pika and vole, zokor have a lower resting metabolic rate and nonshivering thermogenesis capacity (9). The resting metabolic rates of sheep and yaks were lower than those of the species living in low-altitude areas. It can be presumed that a cold environment causes the resting metabolic rate to decrease, and this is one the mechanisms animals use to acclimatize to cold and high-altitude environments (10).

Decomposer Subsystems

The characteristics of soil microorganisms in the decomposer sub-ecosystem of the alpine meadow are:

Numbers of bacteria, actinomycetes, and fungi were highest in the uppermost 0–10 cm of alpine meadow soil and decreased gradually with increasing depth in the soil. There were 24.7 x 10^6 to 85.2 x 10^6 bacteria g^{-1}, 8.7 x 10^4 to 20.1 x 10^4 actinomycetes g^{-1} and 1.1 x 104 to 7.9 x 104 fungi g^{-1} in 0–10 cm of soil depth, respectively. There were 0.8 x 10^6 to 25.7 x 10^6 bacteria g^{-1}, 0.8 x 10^4 to 13.6 x 10^4 actinomycetes $g^{-1}$and 0.1 x 10^4 to 1.6 x 10^4 fungi g^{-1}in 10–20, 20-40 and 40–60 cm of soil depth. The numbers of bacteria and actinomycetes peaked from mid-July to early September. The number of fungal spores in the warm season was lower than that in the cold season.

Figure 3. Diagram of energy flow of animal communities.



The cellulose decomposition rate exhibited a significant seasonal change. It was highest (58.39–74.19%) from July to August whereas only 1.89% was found during the cold season. The cellulose decomposition in alpine scrubby meadow soil was significantly higher than that in alpine meadow soil. It was correlated with the soil temperature. The decomposition rates of plant root, litter and animal feces were 26.55–29.84%, 20.34–22.95%, and 4.84–9.29% after 30 days buried, respectively. Dry matter loss correlated most often with temperature and relative humidity, rather than with other climatic factors.

Most of the nitrogen metabolic microorganisms are located in the surface layer and the numbers decrease sharply with depth. In the surface layer, denitrifying bacteria were usually dominant, followed by anaerobic nitrogen-fixing, ammoniazition, and nitrifying bacteria. Aerobic nitrogen fixing bacteria were not found in alpine meadow soil, and the nitrogen fixation in this soil is mainly accomplished by the anaerobic nitrogen-fixing bacteria. Denitrification and nitrogen fixation were higher at a depth of 20 cm in alpine meadow soil than in other soil horizons. Ammonification and nitrification were highest at a depth of 0–10 cm. Ammonification was greater than nitrification.

The numbers of inorganic phosphorus dissolving bacteria were 1.28 x 10^4 to 7.12 x 10^4 cells g^{-1} at 0–10 cm depth in alpine meadow soil, and the numbers of organic phosphorus dissolving bacteria were 4.27 x 10^4 to 14.81 x 10^4 cells g^{-1}. They decreased rapidly with increase in soil depth. The numbers of phosphorus dissolving bacteria were rather low in the degraded pasture.

Most of the enzyme activities of phosphatase, urease, protease, sucrase and catalase in alpine-meadow soil were concentrated in the uppermost 0–20 cm, where about 84% of the underground biomass and 86% of the microorganisms are concentrated (11).

ECOSYSTEM MANAGEMENT

Ecosystem management recognizes that in order to achieve a sustainable resource demand we must value ecosystems more highly than economically important goods and services (12). The production system in the region of the research station is semi-transhumant pastoralism where animals are free-range grazed. Herds usually consist of a mixture of yaks and sheep, with an average herd size of 250–300 head of sheep and 30–80 head of yaks. The grassland in the research region can be divided into 2 major types: winter-spring grazing, mostly in areas below 3000–3500 m, and summer-autumn grazing, in areas above about 3500 m. In general, winter and spring pasturelands are used from October to May while summer and autumn pasturelands are used from June to September. Summer-autumn pasture is generally a considerable distance away from the settlement and at the base of the high mountain. Winter-spring pasturelands are often fenced and a rotational grazing systems are employed by some households. Crop production is not practiced, or is occasionally practiced on a small scale, with the planting of some fodder crops for hay only. Herding households face problems with high mortality, especially of young stock, on account of the harsh winter climate, and general low productivity of their stock. The most serious threats are snowfall and snap cold spells during and shortly after the calving and lambing period in spring, which frequently cause heavy losses among newborn animals.

Sheep and yaks, the major farming animals in the region, live on herbage, which varies greatly with the seasons. In the warm season, May to September, when the pasture develops from phases of green growth and exuberance to the withering phase, feed is plentiful and of good quality with high protein, fat and nonstructure carbohydrate content. During the cold season, which lasts for more than 7 months, livestock live mainly on standing dead grasses, which suffer from great natural losses, even without being grazed on. In the cold season, livestock body-weight loss is 50% to 80% of the body weight gain during the warm season. Figure 4 shows the live-weight change of Tibetan wethers from 2 to 7 years old. Livestock production is characterized by a malignant cycle of full production in summer, strong in autumn, weak in winter, and dead in spring due to the herbage production seasonal imbalance (13).

A grazing experiment with 5 different stocking rates has been in progress at the research station since 1985. The results indicate that the grazing density has a great impact on the plant community structure and aboveground biomass. The proportion of aboveground biomass of grasses, sedges, shrubs and litter is significantly different for different grazing densities (Fig. 5) (14). At densities of 5.30 and 4.43 sheep ha^{-1}, the aboveground biomass decreased by 30.57% and 21.83%, respectively, after 3 years of experiments, whereas the aboveground biomass for densities of 2.68 and 1.80 sheep ha^{-1} increased by 20.66% and 34.52%. The proportion of grasses and litter decreased and forbs increased as the grazing density increased. The forbs, as indictor plants of grassland degradation, are mostly unavailable for sheep and yaks. There is sufficient evidence that the plant community composition change leads to changes in the rodent community. The dynamics of rodent populations mainly rely on the habitat pattern and feeding factors provided by plant species. The species diversity and number of rodent species, especially the zokor, showed a significantly positive correlation between the biomass of the zokor and grazing density. Moreover, the rodent species diversity is negatively correlated with the height of plants and the vegetative cover level, which is determined by different grazing densities (Fig. 6) (15). Zokor (*Myospalax baileyi*), the most harmful rodent in the area of the research station, live on forb roots which can extend as deep as 30 cm where zokor are most active (16). As a result, the zokor population will increase with a high proportion of forbs

Figure 4. The liveweight of Tibetan sheep at different ages.

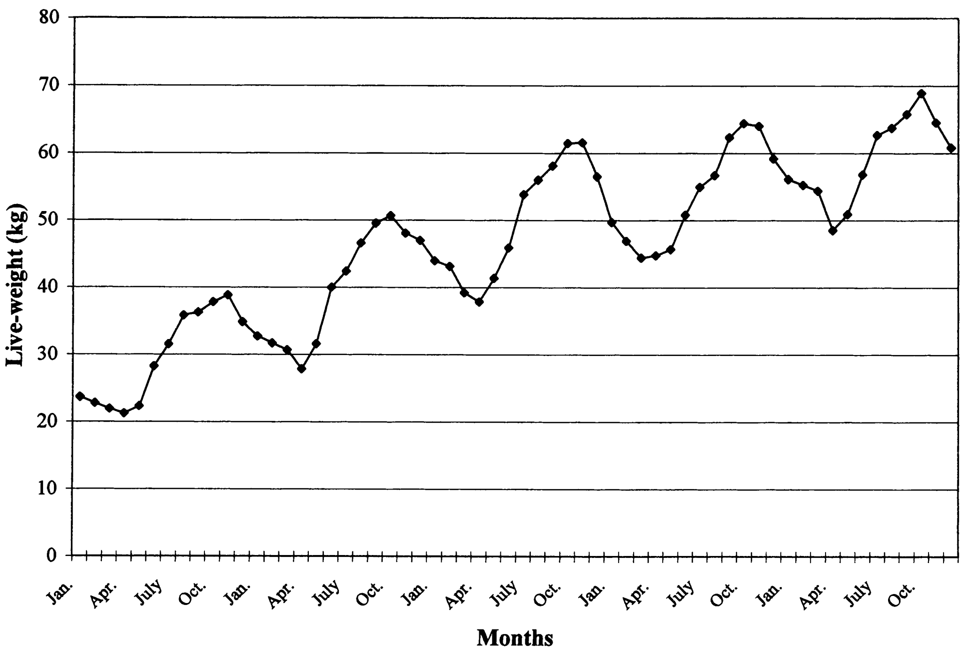


Figure 5. Biomass contents for alpine meadows under different grazing densities.

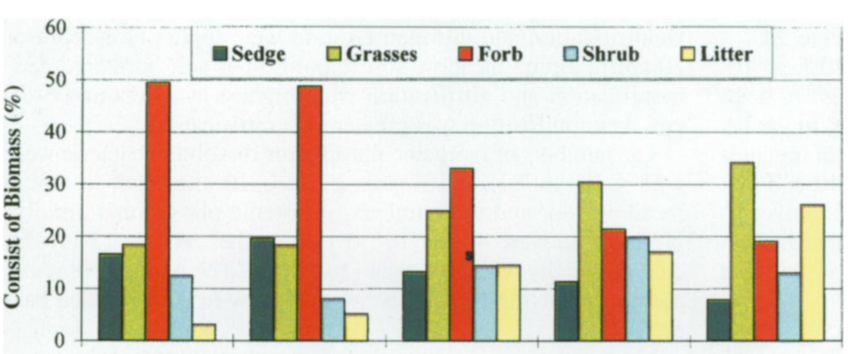


Figure 6. Zokor biomass at different grazing densities.

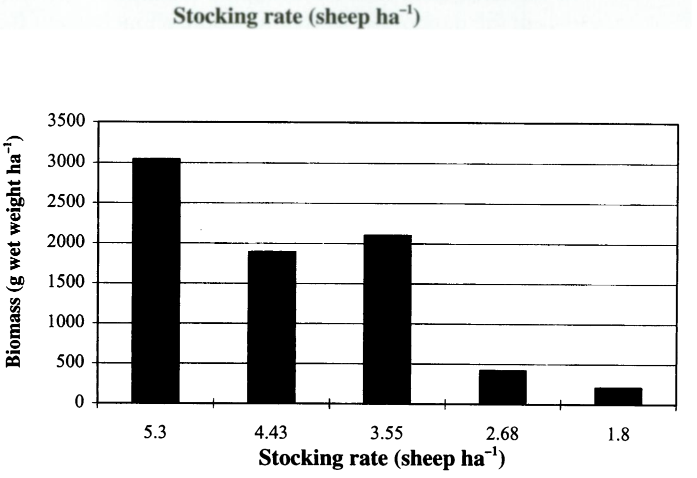


Table 3. Optimal population structure for Tibetan sheep (%).

Age (year)	0	1	2	3	4	5	6	7	Total
Before slaughter (in spring)									
Female	17.3	14.2	13.6	13.0	12.5	12.0	1.2	0	83.9
Male	16.1	0	0	0	0	0	0	0	16.1
Total	33.4	14.2	13.6	13.0	12.5	12.0	1.2	0	100.0
After slaughter (in early winter)									
Female	0	24.6	19.7	18.9	18.0	17.4	1.9	0	100
Male	0	0	0	0	0	0	0	0	0
Total	0	24.6	19.7	18.9	18.0	17.4	1.9	0	100

Table 2. The dynamics of aboveground net productivity at different treatments.

Year	Aboveground net productivity (kg ha^{-2})			
	SRAF	SRF	F	Control
1990	5482.0	4052.0	3208.0	3076.0
1991	4096.0	2850.0	2279.0	2243.0
1992	2890.0	2105.0	1760.0	1690.0
Average	4156.0	3002.3	2415.7	2336.3

in the plant community. These results, combined with evidence of enhanced forbs in the plant community under overgrazing conditions, suggest that overgrazing is probably the most important factor causing grassland degradation in the region.

Integrated management is the most effective approach for regenerating the productivity of degraded pasturelands (17). Fencing, reseeding, scarification and fertilizing are the most common methods for revival of vegetative cover for seriously degraded pastureland. The productivity increased 77.9%, 28.5% and 3.4% by treatment of scarification, reseeding, fertilizing, fencing (SRFF); scarification, reseeding, fertilizing (SRF); and fencing (F); compared to the control (Table 2). At the same time, the species diversity, richness and evenness also increase constantly. In this manner, land utilization is increased, soil erosion reduced, more food is produced, and the environment is regenerated through enhanced biological interaction, synergism and ecocycling.

Increased supply of fodder from the planting of oats and vetch (and/or other fast-growing species) allows the raising of sheep and yaks during the long winter, which in turn reduces the slaughter period and makes animal production more efficient. An experiment was performed to investigate the effect of a mixed community with oats and vetch, on the yield of fodder. The results indicated that the fodder yield of the mixed community was higher than in a monoculture. The optimum mixture proportion and density of oats and vetch are 3:1 (oats/vetch) and 800 plants m^{-2}, respectively.

The optimization which can be achieved harnessing ecological principles and biological processes, the grazing pattern, the grazing density, and the age structure of herd, sheep and yak fattening has been shown in a series of studies (18, 19). The studies on the optimal production structure, to maximize both the output of energy and the net income, gave similar results (Table 3). The results indicated that all of the 1-year-old wethers should be slaughtered before the winter in order to maximize the output of energy and net income from the ecosystem. If this is done, the efficiency of the system production will be improved and grazing pressure will be reduced. The main problem in achieving an optimal production structure is the smaller carcass weight of 1-year-old sheep, does not meet the market requirement when the sheep are slaughtered in first year. Various ways of increasing carcass weight have been developed in the region, including sunlight warming of animal sheds, animal fattening, foodstuff processing, fodder plantation and so on. Integrated environmental rehabilitation, sustainable utilization, moderate inputs of energy and materials system management plans have been developed and implementation in 6 pilot households near the research station.

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