Innovative grassland management systems for environmental and livelihood benefits

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Grasslands occupy 40% of the world's land surface (excluding Antarctica and Greenland) and support diverse groups, from traditional extensive nomadic to intense livestock-production systems. Population pressures mean that many of these grasslands are in a degraded state, particularly in less-productive areas of developing countries, affecting not only productivity but also vital environmental services such as hydrology, biodiversity, and carbon cycles; livestock condition is often poor and household incomes are at or below poverty levels. The challenge is to optimize management practices that result in "win-win" outcomes for grasslands, the environment, and households. A case study is discussed from northwestern China, where it has been possible to reduce animal numbers considerably by using an energy-balance/market-based approach while improving household incomes, providing conditions within which grassland recovery is possible. This bottom-up approach was supported by informing and working with the six layers of government in China to build appropriate policies. Further policy implications are considered. Additional gains in grassland rehabilitation could be fostered through targeted environmental payment schemes. Other aspects of the livestock production system that can be modified are discussed. This work built a strategy that has implications for many other grassland areas around the world where common problems apply.

degradation | herder

Grasslands occupy ~40% of the world's land area, excluding Antarctica and Greenland, supporting the livelihoods of ~1 billion people (1). Many of these grasslands suffer some degradation as a result of increased pressures from people and livestock populations and the political belief that they were an underused resource. Many grassland areas now produce much of the world's grain crops, but, in less productive parts, an extension of cropping has resulted in considerable degradation, exacerbated by the abandonment of nonviable cropping. New strategies are needed for the sustainability of these vast resources (2). Fortunately, many useful plant species are still present within these ecosystems, which means they could be managed to a healthier state.

The Eurasian grasslands, extending from eastern China to Europe, form the largest set of interconnected grassland ecosystems on Earth, containing several thousand plant and other species. China has 400 million ha of grasslands (3), of which 300 million ha are in the north and west, supporting 16 million people directly (4) plus many more indirectly. These are 40% of the poorest people in China earning <$2 per head per day. Rehabilitation of grasslands is critical for poverty alleviation.

The grasslands of China have been grazed by wild and then domesticated herbivores for millennia. During much of that time, the density of people and livestock was low, much grazing was in a transhumance system, grasslands had time to recover from grazing, and species adapted. More recently, grasslands were perceived as an underused resource. Today, grasslands are repeatedly grazed at higher stocking rates than were traditional, and the number of people dependent on them has dramatically increased. Across China, there are acknowledged problems on 90% of the grasslands (5). These include decreased ground cover, increased soil erosion, changes to less palatable species, and changes in associated fauna. The high density of livestock and people and reduced productivity of grasslands has reduced the sequestration of carbon and increased the net greenhouse gases released to the atmosphere (6). Some of these processes are longstanding; the Yellow River is so named because of the load of silt it commonly carries. Dust storms have always occurred, but the frequency of these effects and the annual quantity of material involved has increased (7), with great concern among urban populations across north Asia (5). The decline in productivity has led to low household incomes, compared with the overall dramatic increase in incomes across China. Increasing the quantity of herbage on grasslands is the common factor that improves the issues identified (8). As mentioned by several old herders in interviews, "when we were young, we had trouble seeing the cattle in the grassland; now we can see the mice." Local authorities do set "sustainable" stocking rates, but these are arguably based on the number of animals herders can manage to keep alive on the grasslands and are within the range herders would tolerate, rather than being rates designed to rehabilitate and sustain the grassland in good condition.

The primary problems in grasslands of northwest China requiring joint solutions can be broadly grouped into poverty alleviation and grassland rehabilitation (8, 9). Relocation of people and livestock may not be a viable solution for cultural reasons, and ultimately places extra pressures on other regions. The herders of northwestern China are often from minority groups, whose ancestors have managed livestock in these regions for millennia. Today, some in those groups wish to retain traditional lifestyles while increasing their incomes so they can benefit from the rapidly developing Chinese economy. Planting trees would displace people, and trees are not a natural part of much of these steppe landscapes. The grasslands can contribute to the supply of food, fiber, and some medicines for China's vast population. As China becomes more affluent, red meat consumption is increasing (10), and grasslands represent one of the more sustainable ways of producing that product.

Rehabilitating grasslands to increase the amount of standing herbage mass can improve livestock production, household income, and environmental services (2). When this project started, there were no clear directions identified that could be tested experimentally. Instead, a farm systems approach was adopted. Initial data collection and analyses at a farm level identified pathways for improvement in incomes and grasslands within national and local policies. China's rapidly developing market systems now pay for the quantity and quality of products. That means the yield of product is more important than maximizing the number of animals

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(8). Optimal solutions need to be found between the number of animals and animal product per hectare. This paper reviews the work done, using a case study on the desert steppe in the Inner Mongolian Autonomous Region of China, and initial success in alleviating these problems. Other villages were studied to the east and west of this site in Inner Mongolia and in Gansu (8) along a 1,500-km transect. All studies produced similar results. There are important global implications from the strategies used in this work.

Results

Desert Steppe Case Study. The study site [Bayin Village, Chaganbulige Township, Siziwang Banner (County), Inner Mongolia; ∼150 km north of the provincial capital, Hohhot] is on the Mongolian Plateau (1,000–1,500 m altitude), where there is a 3- to 4-mo growing season, with two thirds of the annual precipitation (250 mm compared with 100–300 mm for the desert steppe region) falling during summer. Average monthly air temperatures range from −15 °C in January to 20 °C in July. Any winter snow tends to sublimate and not increase soil moisture. There is often a dry period in spring/early summer when precipitation is most variable (coefficient of variation of 70%), with important consequences for grassland composition and summer growth. Winds are strongest and dust storms are frequent at that time.

The rapid increase in livestock since 1949 shows the increase in all main classes of livestock from 1949 to the early 1960s, then the dramatic decrease in cattle numbers from 1985 commensurate with a rapid increase in sheep and goats (Fig. 1) (11). Cattle numbers crashed when the grass became too short for them to effectively graze. The recent increase in cattle numbers is almost all dairy cattle that do not use the grasslands except for brief periods over summer or when not lactating. The full scale of these effects is hard to estimate, but would indicate that standardized stocking rates on grasslands have probably deceased in recent years.

Estimates of the standardized stocking rate [50 kg Sheep Equivalent (SE), which included horses, mules, and donkeys] based on estimated average live weights showed that, in 1949, this was ∼0.3 SE/ha, reaching ∼1 SE/ha in 1963 and remaining at that level to 2009, i.e., an increase of 3.3× in overall stocking rates since 1949; this may, in effect, be marginally lower at present if animal size has decreased over the years, which could not be determined. All large animals have decreased in number. Donkeys reached a peak of ∼11,000 in 1956 (500 in 2009), cattle ∼61,000 in 1965, horses ∼55,500 in 1976 (1,100 in 2009), and mules ∼7,800 in 1992 (600 in 2009). These declines have been occurring for decades. Only since 2000 can part of the decline be attributed to a change from draft animals to wider use of machinery on farms. Horses are a central part of Mongolian culture, but one that is proving very difficult to

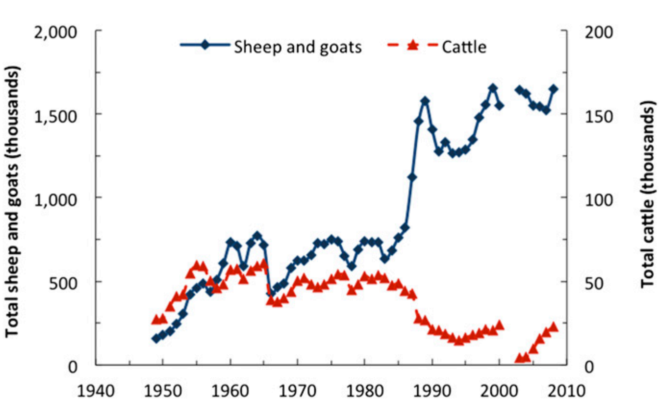

Fig. 1. Total number of sheep/goats and cattle in Siziwang Banner, Inner Mongolia autonomous region, 1949 to 2009. [Reproduced with permission from (24)].

sustain. Households now have very few horses in comparison with across the border in Mongolia.

Farms within the survey area had an average of 520 ha of grassland with ∼270 adult sheep and goats. When the variation in animal live weight and physiological state (e.g., pregnant, lactating) was considered, this resulted in an average stocking rate of ∼1.5 SE/ha (∼0.8 ewe equivalent/ha), which was greater than the average for the banner, as a result of the survey farms being in a wetter part of the region.

The grassland contains a range of C3 (e.g., *Stipa* spp.) and C4 (*Cleistogenes* spp.) grasses, other monocotyledons (*Allium* spp.), legumes (*Caragana* spp.), and forbs/small shrubs (*Artemisia* spp.). Good grasslands are dominated by perennial grasses, but, as they degrade, small shrubs become dominant. It was estimated that, in 2010, 30% of the biomass was desirable species and 70% was less desirable species. The less desirable species are those on which grazing livestock at best only maintain body weights over summer if given unlimited supply—an unlikely condition given the stocking rates. Total net annual primary production is now less than 1 ton dry matter/ha/y. No data are available to characterize earlier production levels, e.g., in 1950, to know how much grassland growth has changed. Ground cover at peak growth in summer is now ∼20%. Grassland degradation is characterized by a decrease in overall productivity (as mentioned by old herders) and/or a change in botanical composition. Strengths of these grassland ecosystems are that most of the species known to have been part of the ecosystem are still present and invasion by exotic species seems to be limited. This probably reflects the long history of grazing of the Eurasian grasslands. The exclusion of grazing can result in the recovery of species composition and an increase in productivity as shown for the typical steppe 500 km to the east of the study site (12, 13), although this did take years, depending on the degree of degradation.

The fundamental relationship regulating productivity from livestock is the relationship between feed (i.e., energy) supply and demand (14). This in turn affects many other processes, especially environmental services. Estimates of the relationship between feed supply and demand indicated that, for 9 mo of the year, feed intake is typically below maintenance requirements (Fig. 2), i.e., limited by energy supply. As a consequence, animals lose as much as 20% to 30% of their live weight (measured on farms) through autumn, winter, and spring (11). Losses can be considerable in harsh winters—described by Mongolians as Dzuds—which often follow summers with low early-summer rainfall that results in low annual grass production. Animals are stressed or recovering from stress throughout the year. Animals do gain weight through the summer, typical of a pattern of compensatory gain, in effect growing faster on the short grass than international standards (15) would normally predict. This high pressure on the grasslands means that ground cover is low for most of the year, soil erosion is a common problem, only plant species that are less desirable for livestock manage to survive (affecting biodiversity), and herders receive a lower price per animal sold as a result of the animals' poor condition.

A grazing experiment done in the district has established the general biological relationships between stocking rates and productivity (Fig. 3). The variability around the curve reflects year-to-year variation in feed supply, in terms of patterns and quantity. At stocking rates below ∼1.5 SE/ha, similar to the local average, production per head is relatively constant and, thus, as stocking rates increase, there is an increase in productivity per hectare to the biological optimal stocking rate of ∼2 SE/ha, well above the current rates. Data obtained on six neighboring farms for lamb growth over summer showed a very good agreement between the two data sets. Collectively, these data illustrate how herders focused on increasing production would continue to maintain a high stocking rate. Current stocking rates clearly aim for a biological maximum per head and per hectare.

The financially optimal stocking rate was estimated by using a model that assumed energy was the main constraint and animals

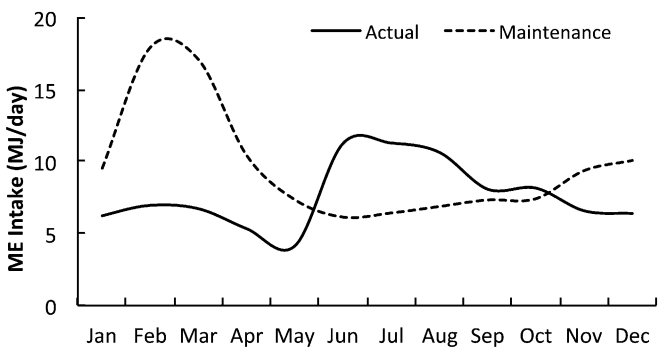

Fig. 2. Actual energy intake estimates for sheep on a typical desert steppe farm in an average year in comparison with the amount of energy required to maintain body weights. [Reproduced with permission from (24)].

were fed to at least a maintenance level, i.e., no weight loss. This showed that stocking rates could be reduced by ∼50% below current values (∼0.8 ewes per hectare) without any reduction in net household income; an increase was likely. The financial optimum stocking rate is around the range at which individual animal productivity is 60% to 75% of the maximum per-head production possible. As stocking rates increase, the marginal returns tend to zero and then become negative. This lower stocking rate has the added advantage of higher animal growth rates, especially in young livestock, which means they reach marketable size earlier and can be sold earlier, reducing overall grazing pressures. The economically optimal stocking rate (Fig. 4) (11) is considerably below the biological optimum (Fig. 3).

Pathways toward more financially efficient livestock production can vary, but a common strategy is to focus on quality assurance throughout the production cycle. That means optimizing the number and growth rate of progeny produced per breeding unit if meat production is the general goal. Within that strategy is the need to identify which animals to keep or cull. On six farms in the desert steppe study, every animal on each farm was weighed and inspected for condition three times per year. This information was then used to rank the productivity of all of the animals on a farm from the most to least profitable by using a simple model based on their condition (16). This work identified that many animals were old and arguably unproductive, the condition of teeth (sometimes there were none) and udders were often poor, and a significant part of each flock had animals that cost more to maintain than they generated in income. This reinforced other research findings that stocking rates can be effectively reduced and net incomes increased. A focus on only retaining the most productive animals producing higher-quality products would enable greater reductions in stocking rates to be achieved than modeled earlier; Fig. 4 is based on the assumption that all animals are of equal value.

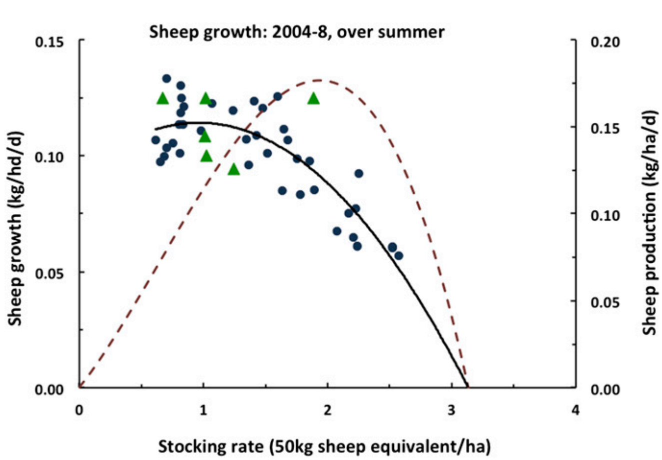

Fig. 3. Sheep growth rates per head (circles and solid fitted line; $y = 0.092 + 0.047x - 0.024x^2$; $R^2 = 0.74$) and derived values per hectare (dashed line) continuously grazing over 5 y. Data are only for summer, when grass was green. Data for lamb growth rates on neighboring farms over 2 y (2004 and 2005) is shown (triangles).

This research has shown that an emphasis on net financial returns justifies considerable reductions in stocking rates on these degraded grasslands. In the past, herders have clearly focused effort on maximizing biological production and total income from livestock. This increased the number of livestock, leading to grassland degradation. Reducing stocking rates without reducing net financial returns provides better conditions for grasslands to rehabilitate.

Siziwang Banner Response. Based on the results from the aforementioned work, the Siziwang Banner local government in western Inner Mongolia has implemented a program since 2009 aimed at reducing stocking rates while increasing household incomes. Some targeted subsidies support the 560 herders involved in the program. The farms involved in this program have increased their net income by approximately 50% compared with the control farms when the stocking rate was reduced by 45% to 65%. Although further work does need to be done to quantify net benefits, recent interviews with herders indicate they do believe the strategy is working and they have no wish to return to former practices. Herders say they are happy this strategy enables them to reduce stocking rates and they consider their grasslands condition to be improving.

The actual practices used in this program have now been developed from the principles identified in this research in collaboration with a commercial company and herder association who deliver training in nutrition, help source better-quality feed supplements, provide Dorper rams to mate with local sheep to produce a better lamb for meat, pay a 30% to 50% price premium per kilogram for lambs (if they meet the production targets of 30 kg at 12–16 wk), feedlot the lambs (to reach 50 kg live weight in 10 wk over summer), and then sell directly to the hot-pot restaurant market in Beijing. The local government subsidies support various steps used by the company, mainly training, ram purchases, and capital costs of feedlots. In 2011, the local authorities aimed to have 120,000 lambs produced through this new system. The program is expanding, and strategies are being developed for related issues.

This program means that there are no replacement ewes being bred in the target area. It is likely that nearby drier regions, where producing meat animals is more problematic, will focus on breeding replacements, thereby creating a new enterprise in the sheep production market chain. Other work is focusing on obtaining larger quantities of better-quality forages to feed animals.

Discussion

During the past century, overgrazing became a major problem not only in western China, but also through Central Asia, Africa, and other regions. Finding solutions takes time, but, as demonstrated here, the pace of progress can be hastened based on an analysis of the production system, as therein can lay the tactics and incentives to change. Such research needs to involve interdisciplinary and transdisciplinary studies to be successful. The team involved in this work included plant and animal scientists, social science input, farm and policy economists, modelers, and advisory staff. Each got to understand disciplines outside their own and contributed to the development of ideas based on their different perspectives. However, rather than trying to then model the whole system comprehensively, it was more effective to focus on key issues that obviously limited the system, i.e., the energy supplied in forages and feed, livestock demand, and cash flows. Adopting this strategy meant relatively simple models could be

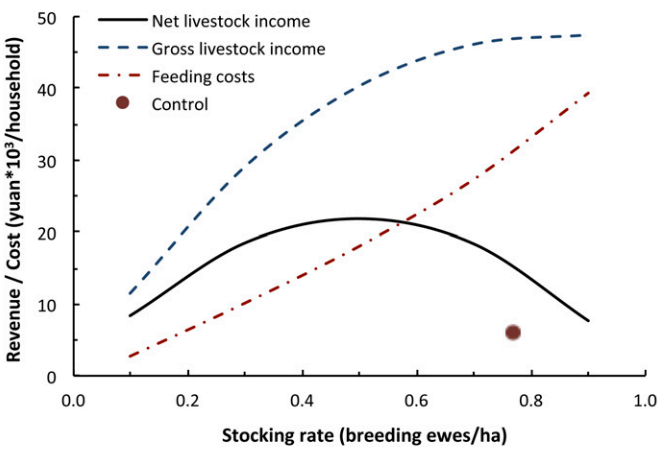

Fig. 4. Modeled estimates of net financial returns from livestock at different stocking rates for a typical farm on the Siziwang desert steppe. Model constraints were set to feed animals to a minimum of maintenance levels. Income from sale of lambs for meat plus wool. The "control" point is the surveyed village average stocking rate and net financial returns from livestock—in this case, animals are fed in a traditional way and gain weight only in summer. [Reproduced with permission from (24)].

built to identify the larger effects of changing practices and develop practical solutions in a short time frame. The models aim to estimate major trends, rather than exactly simulate an individual farm. Various components of the system can be changed to achieve grassland and household income improvements.

Farming System Style. The analysis described here has shown that herders have previously been more focused on maximizing biological output/animal number and thence gross income than on net financial returns. This reflects the knowledge and strategies on which herders base their management. Traditional knowledge tends to focus on how to survive in difficult environments, which the herders do very well, and on maximizing the number of animals as a measure of household wealth. This knowledge, however, has not provided the means of grassland rehabilitation, nor the tools for modern market systems whereby income relates more to the quantity and quality of meat, milk, fiber, and skins produced. The pathway of user to keeper to producer to breeder, first described for herders in East Africa (17), applies to the Chinese herders. They have considerable skills as "keepers," i.e., they raise adapted animals and know how to keep them alive, can sustain their households, and have a small surplus for trade. However, they need to learn new skills to progress to being "producers" and "breeders" whereby a higher proportion of their livestock production is sold and the farm is more a business rather than a subsistence way of life. Training programs can help that progression. Implicit in moving from keepers to producers is a major shift in goals from survival to maximizing net financial returns from livestock sales. What enables that shift among herders has not been well understood and would be an important area of future research. Previously, it had been thought that maximizing animal numbers was the main aim of herders as a measure of wealth and so that, when household goods were needed, there were animals available for sale. This study has shown that herders will respond more to improving net incomes than to maximizing animal numbers.

Livestock System Choices. This research has shown that reductions in stocking rates, especially when combined with keeping the more productive animals, can increase net financial returns from livestock and reduce grazing pressures on the grasslands. These are market-driven solutions to the problems of grassland management with inbuilt incentives for adoption. Various components of the system need to be modified to optimize benefits from changing practices. The following six sections represent the first steps in a phased program of landscape and farm improvement.

Select the better enterprise. The research presented here has focused on meat-producing systems. Other livestock products, especially wool and cashmere, could in some instances be more profitable, although this may be at stocking rates comparable to today (18), as fiber production does not require as high an energy intake as does meat. Such an outcome would not help grasslands to recover. Instead, the strategy could be to first reduce stocking rates to the point at which net financial returns are maximized with the existing enterprise, then change the enterprise, but keep that lower stocking rate. There would then be no penalty to the herder and the likelihood that their net household incomes would increase. To achieve this may require local policies that set "sustainable" stocking rates, which are policed, plus environmental services payments, so that grassland rehabilitation can occur. This especially applies in cases in which market signals are not sufficiently strong to cause farmers to reduce stocking rates. Communities have managed the utilization of their grasslands sustainably for centuries, as demonstrated in the High Atlas Mountains of Morocco (19).

Grassland management. The goal of improving grassland management needs to be clearly in mind as other changes are made. Understanding the processes that lead to degradation and govern rehabilitation, using local research sites, is essential to build confidence to change practices. Research is needed to clarify the patterns in grassland rehabilitation under different stocking rates. Preliminary work has shown that maintaining a higher level of herbage mass, which follows from lower grazing pressures, does optimize plant biodiversity on the desert steppe (20), in support of the strategy discussed here. These are typical slow variable responses (21), but ones that are critical for long-term system sustainability. The 50% reduction in stocking rate, shown in this case study to be financially viable, still leaves these rates higher than those in the early 1950s. Lower stocking rates may be necessary to restore grasslands to their longer-term desired states. The gap between financially optimal stocking rates driven by market based mechanisms vs. a long-term "ecological" and lower stocking rate is where there is a case for environmental services payments. Rather than through direct subsidies, this could be managed through a reverse auction scheme coupled to estimates of net cost: benefit to ensure that herders feel adequately compensated and there is good compliance. The need to link government ecosystem services schemes with market-based mechanisms has been identified as a valuable addition to current schemes such as Grain to Green (22).

Animal management. The focus needs to shift to livestock production efficiency rather than survival. The first step is to evaluate all the animals on a farm to decide which are the more productive to keep and to sell the rest to refine the general benefits of reducing stocking rates. Financial analyses indicate the proportion that needs to be culled to maintain or increase net returns. Emphasis and herder training needs to be focused on selecting those that maximize the financial returns per animal and for that to be part of normal farm management.

Animal nutrition. Income from animals does depend on how well they are fed. Often, animals are fed supplements that, at best, only slow the rate of weight loss. Restrictions in the study region limit the area that can be sown to forage crops such as maize. The amount grown is dependent on season, but typically inadequate to feed animals at the levels required for production. Research and extension are needed on low-cost tactics to improve the quality and quantity of feed.

Infrastructure. On many farms, there is limited infrastructure for the efficient management of livestock. In cold climates, "warm/greenhouse" sheds are needed to minimize weight loss through winter and maximize animal survival, especially where the feed supply is limited. Government funding is being provided to do this. Fencing is generally inadequate for livestock management, necessitating continuous herding of livestock around the one area. Often, there is only one watering point per farm, resulting in overuse of adjacent areas. With declining labor in rural areas, training is needed in regard to better ways of managing livestock.

Finance. Funding the changes required on a farm—e.g., better-quality animals and fodder, warm sheds—can often be an insurmountable constraint. The strategy discussed here of culling the least productive animals as a means of reducing stocking rates also provides a source of cash, part of which can be used to make changes in the livestock system rather than using banks, at which onerous terms typically apply. There is also a case for government payments to help farms reorganize, particularly if coupled to environmental services payments as noted earlier.

Chinese Government Policy. In efforts to improve household incomes, herders and officials at all levels of Government had, since 1950, sought to increase animal numbers, leading to dramatic increases in stocking rates, accentuating the pattern of degradation. Herders the world over often see increasing the number of animals as the pathway to greater wealth and income, especially in common grazing systems. In addition, the perceived productivity of grasslands in good condition resulted in transmigration programs that considerably increased the human population exploiting the meager resources available. It is now clear that too many people and livestock rely on systems that have inherent low productivity.

China has adopted a range of policies since passing the latest Grassland Law in 2002 (23). This aims to promote the ecologically sustainable use of grasslands, and the improvement of income and well-being of herders, many of whom are from ethnic minority groups. These changes in policy add to the "responsibility" system that was launched by Deng Xiaoping in 1979 and have been progressively implemented throughout China. The responsibility system, as applied to grassland farms, has meant that land is allocated to individual households. Some of this has been fenced to mark boundaries, although herders still stay with the livestock for all the time they graze. In other cases, a few families or whole villages still communally graze land. Individual allocations and management of land do provide the opportunities to better resolve sustainable stocking rates, but, in practice, herders had maximized livestock numbers. There is no tradition in many grassland regions of how to manage livestock within a fixed, defined farm boundary. Traditional practices were migratory around roughly defined routes.

More recent grassland policies focused on applying grazing bans. The most notable case has been in Inner Mongolia, where, during the past decade, the plan has been to progressively apply partial or complete grazing bans over 70 million ha in that large province. A subsidy is paid to herders during the ban. Total grazing bans are applied for 5 y, and this results in notable, visual improvements in grassland condition in some regions, although only limited monitoring has been done to record any gains. However, it is clear that compliance with the bans in some areas has been poor, as observations showed that the grasslands inside and outside the fences of "ban" areas were essentially the same. When the ban had ended, herders restocked at the same rates as previously, and any gains appear to have been transitory. Officials thought that the gains would be apparent and herders would then modify their practices to maintain some of those gains. No strategy was developed to identify the changes in practices that would be needed after the ban to sustain any gains in grassland condition achieved. The practices developed in this research provide a strategy to facilitate change and maintain farm practices in the desired direction with global implications.

During the course of this research, officials at all six layers of government in China (i.e., villages to national) were regularly informed on progress. That created a dialogue that helped interpret the outputs in context and provided information that had an impact on policy. The Communist Party of China Central Committee and the State Council released their 5-y plans for agriculture December 31, 2009, which included the statement that "the grass and livestock balance system shall be put into practice, the grazing prohibition, grazing land resting, and rotational grazing shall continue, indoor and pen raising shall be promoted, and the construction of artificial grazing land and water projects in pasturing areas shall be conducted properly." This indicates a significant shift from simply seeing the number of animals as the mechanism to improve herder incomes, to finding solutions based on how the system functions (i.e., "grass and livestock balance. . ."). China is now spending $2 billion/y on grassland management and allied poverty alleviation programs. Such a commitment is to be applauded, but much research needs to be done to ensure better tactics and strategies are identified and applied.

Methods

The primary data used in this research came from farm surveys (14, 24–26) involving repeat visits over a period of 2 to 3 y, during which farm practices did change, in part because of the knowledge imparted by the research group. The "control" and basic descriptors of farm states was then the starting condition, with the limitations inherent in that approach. It was not considered ethical to stop herders changing their practices. A small subsidy was paid to herders by local organizations to foster collaboration with the practices to be tested in the program and ensure more accurate data were collected. In return, participants were given training to help them improve their farm system. The farm data collected included monitoring the live weight and condition of every animal on a subset of the farms surveyed at key intervals during the year: start and end of summer and midwinter (near lambing times). Intensive interviews with herders were used to obtain qualitative information on patterns of change and outlooks.

Data on local conditions and general stocking rates were obtained from Banner Year Books. Although there can be some criticism of these data and how they have been collected since 1950, the general pattern agreed with the views of old herders who were interviewed. The order of effects was considered reasonable.

A series of models were used to analyze the data (15). These were as follows:

i) A spreadsheet feed balance analyzer for a "typical" farm in an average year, based on energy supply and demand for livestock. The typical farm was based on the averages for households surveyed in a village, but eliminating outliers, e.g., if one farm had cattle and all the others sheep, the cattle farm data were excluded. This model could be used to manually explore changes in the livestock system, before using model *ii*. Models *i* and *ii* used well established functions for livestock nutrition (27).

ii) A linear programing model to find optimal financial solutions for changing the livestock production system. The constraints that applied on the typical farm were used, particularly energy, opportunities to grow crops, labor, and finance. Solutions were sought for an average year.

iii) A precision livestock management model that used data from each of the animals on a farm to estimate the relative profitability of each animal so that those to keep or cull could be objectively determined.

Data were obtained from a grazing experiment (28) that used three stocking rate treatments, replicated three times. The livestock used were young animals. As animals varied in number and size over time, this resulted in variability in the standardized stocking rate.

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