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Review

The sustainable development of grassland-livestock systems on the Tibetan plateau: problems, strategies and prospects

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Abstract. The Tibetan plateau is the source of most of the major rivers of Asia and has a huge impact on the livelihoods of the population, who have for centuries engaged in traditional herding practices. Sustainable management of the plateau is of critical importance not only for maintaining livelihoods but also because of its vital ecological function. The major problem of sustainable development in these grassland-livestock systems is the conflict between forage and livestock production. Despite considerable investment of manpower, material resources and capital over many years, attempts to resolve the problem have not been successful. The magnitude of conflict between forage and livestock is addressed by presenting 19 resolution strategies based on numerous research data. Each of these strategies is evaluated in terms of how it can be implemented, its potential benefits for livestock production, current progress and the requirement for further research. The 19 strategies have been divided into four topic categories, namely; grassland-forage, livestock, economy and market, society-culture, which cover the basic elements of sustainable development in this pastoral region. It is argued that improved planning and implementation of the proposed strategies must be based on the background investigation of natural and social status of the pastoral region. Particular attention needs to be given to genetic resources and technology in order to ensure the successful implementation of these proposals. In addition to expanding the use of 18 currently practiced strategies, the authors propose a further novel strategy of replacing the current intensive form of ecological migration with a model incorporating two semi-permanent settlements. The objective of this novel strategy is to retain the nomadic element of pastoral husbandry while increasing the temporal and spatial scale of rotational stocking to reduce pasture degradation on the Tibetan plateau. It is argued that these proposals should be urgently incorporated into two national plans for the pastoral livestock industry, and the construction of an ecologically safe shelter zone on the Tibetan plateau, while ensuring a sustainable livelihood of its pastoral residents. Ensuring a successful implementation of these strategies in resolving the conflict between grassland and livestock, and promoting sustainable development on the Tibetan plateau, requires willing support at the level of national investment and policy commitment and from the herdsmen.

Additional keywords: conflict, grassland, ecology and livelihood, livestock, nomadic system, resolution strategies, sustainable development.

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Introduction

The Tibetan plateau covering $2.57 \times 10^6\,km^2$, is a unique geographic zone due to its average altitude of over 4000 m, annual mean temperature below 0°C, sparse human population and predominantly pastoral agriculture, and is recognised as the third pole of the earth (Fig. 1) (Zhang *et al*. 2002). The grassland-livestock systems serve an important function by maintaining both the natural environment and the livelihoods of local residents, which together support the unique cultural heritage of the Tibetan plateau (Miller 1999; Richard 2002). The total area of grassland (steppe and meadow) on the Tibetan plateau is ~8.7 million ha, representing 51.3% of the area of the Tibetan plateau (Piao *et al*. 2006). The ecological functions of the grasslands include the retention of water, soil, and carbon (C), maintaining biodiversity and ensuring the stability of seasonally frozen soil (Wang *et al*. 2002; Xie *et al*. 2003; Xu *et al*. 2004;

Fig. 1. Map showing the subject area of the Tibetan plateau in Asia.

Miller 2005). The huge quantity of C stored in the soil (33.5×10^9 t C) represents 2.4% of total global soil C (Wang *et al*. 2002) and is easily vulnerable to gaseous emission if the vegetation and soil are allowed to deteriorate. The grassland supports nearly 41 million Tibetan sheep and 13 million yaks (*Bos grunniens*) (Long *et al*. 2009) and just in excess of 1.3 million cattle (*Bos taurus*) and cattle-yak hybrids, which provide the livelihood of more than 9.8 million people on the Tibetan plateau (Long 2003), comprising the largest nomadic human population in the world.

Grassland-livestock husbandry has been practised on the Tibetan plateau for almost three millennia (Long 2003). Thus, the association between soil, grassland, livestock and herders has proved a very stable system within this environment, with its long periods of low temperatures, low atmospheric oxygen content, high organic C accumulation and low turnover rate of mineral elements, and has contributed to the social-economic structure of the Tibetan plateau region (Shang and Long 2007). The alpine native forages have characteristically high protein, fat and sugar contents, and relatively low fibre contents compared with lowland plants. The high quality of alpine forages allows grazing yak and sheep to recover the liveweight lost over winter through compensatory growth in a short growing season of 90–120 days (Long 2003). In this ecosystem, Tibetan nomadic herdsmen have acquired intricate knowledge enabling the utilisation and management of the grassland and livestock supporting an environmentally sustainable system (Long 2003). Any change to the grassland-livestock system will impact the environment, livelihoods, and even social structure of the Tibetan plateau (Cheng and Shen 2000). Thus, maintaining the health of the grassland-livestock system is the key task for sustainable development on the Tibetan plateau.

Sustainable development includes the successful adaptation to global change (Swart *et al*. 2003). The ecosystem of the Tibetan plateau is vulnerable due to energy flow and element cycling occurring in a very harsh environment (cold temperatures, high altitude and low atmospheric oxygen content) (Shang and Long 2007). Because these nomadic herdsmen depend heavily on their livestock, which in turn depend on grasslands, any strategies for enhanced sustainable development on the Tibetan plateau must ultimately depend on the two basic elements of grassland and livestock (Cheng and Shen 2000; Brown *et al*. 2009). The interface between grassland and livestock was at the core of previous sustainable development of eco-socio-cultural systems (Dong *et al*. 2009). The remarkable growth and focus of scientific and technical developments within the Tibetan plateau, especially during the past 30 years, have been in the management of grassland and livestock systems (Du 2006). Additional investment of private capital in the grassland and livestock industry has been encouraged (Li 2011*a*). Better genetic resources of yak and sheep have been selected or introduced into the pastoral area (Yu 2009; Zhang and Zhang 2009). The government and herders have increased forage storage capacity to be able to supply more feed in the cold season (Ji *et al*. 2010) and improved forage processing technologies have been implemented in pastoral areas (Ma *et al*. 2008*a*; Li 2011*b*).

Grassland degradation has been increasingly regarded as the primary cause of ecological, economic and social problems on the Tibetan plateau (Long *et al*. 2009; Harris 2010; Zhou *et al*. 2011), and even across the entire pastoral region of China (Squires *et al*. 2009). This urgent problem confronting grassland-livestock systems has become increasingly severe and widespread, and the impact of grassland degradation has become more widely recognised (Kang *et al*. 2007; Squires *et al*. 2010). Grassland degradation causes a wide variety of problems, such as soil erosion, landslides and flooding leading to population displacement, water loss, decline in biodiversity and economic recession, all of which threaten the basic stability of the ecology and society on the Tibetan plateau (Dong *et al*. 2007*b*; Gao *et al*. 2011; Zhou *et al*. 2011). Over the past 30 years, the large increase in livestock numbers has been considered by many to be the major cause of degradation of the grassland vegetation leading to problems in the grassland-livestock sector and the widespread deterioration of the grassland ecosystem (Tao and Gao 1992; Nelson 2006; Song *et al*. 2009; Lu *et al*. 2009*a*; Ho and Azadi 2010; Kemp *et al*. 2011*b*). For example, from 1959 to 1999, the grassland area available per head of cattle (almost as Yak) declined from 13.7 ha to 2.9 ha in the Naqu region (Min and Cheng 2001). Such a dramatic change in the relation between grassland resources and livestock, is a key factor contributing to the problems and conflicts between grassland health and the livestock industry (Huang *et al*. 2007; Wang *et al*. 2010*a*; Kemp *et al*. 2011*a*, 2011*b*), which, since the 1990s, has become a major concern of local people, government and scientists in China, but which, until now, have remained unsolved (Yeh 2005; Kemp and Michalk 2011). Although the frequently abundant populations of pikas (*Ochotona curzoniae*) have often been blamed for exerting additional grazing pressure leading to grassland degradation, studies have shown that overgrazing by livestock, rather than grazing by pikas, is more likely to convert a grassland to forb-dominance (Hogan 2010) and their exclusion from grassland areas has shown little, if any, impact on the herbage mass (Pech *et al*. 2007). Of greater significance is the physical damage caused by their burrowing activities and its impact upon soil properties (Sun *et al*. 2010) and net ecosystem CO_2 exchange (Liu *et al*. 2013).

Problems in the grassland-livestock production system have arisen due to a range of other factors as well, such as: climate change, lack of marketing expertise, poor grassland and livestock management, a fluctuating economy, a lack of clear, objective-driven policy for the livestock industry and a lack of investment (Hou 2009; Lu *et al*. 2009*a*). Thus, successful resolution of the crisis in natural resources, especially in those remote regions, will depend upon a multi-disciplinary strategy (Hardin 1968; Zhao 2000; Dong *et al*. 2011), incorporating a variety of approaches, revised husbandry methods, innovative technologies and marketing throughout the pastoral livestock industry, and not only by government and herdsmen (Wen 2000; Lu *et al*. 2009*a*). In this paper, we discussed the problems facing the grassland-livestock system and in view of the results of recent studies conducted on the Tibetan plateau, proposed a multi-pathway strategy, with discussion of the functions and prospects of such an approach in providing a resolution.

Problems of grassland-livestock systems on the Tibetan plateau

Socioeconomic and cultural developments on the Tibetan plateau are closely related to the fluctuating prosperity of the grassland-livestock industry (Zhang 2001; Cheng and Min 2002; Ping *et al*. 2011), an industry which is prone to catastrophic losses of livestock due to natural disasters (Zhou 2004; Gesang *et al*. 2009; Shang *et al*. 2012). Records show that in the Qinghai-an plateau grasslands, animal husbandry has suffered various natural disasters over the past 200 years (Gao and Qiu 2011), resulting in repeated losses of livestock, and even human populations, and damage to the economy and infrastructure (Sun 1999; Zhang *et al*. 2001; Lu 2006; Ni and Xie 2007). Instability of the livestock industry, caused by natural disasters, has resulted in population migration, demographic changes, social-economic collapse, and even changes in the fortunes of Buddhist temples (Min and Cheng 2001; Mao 2006). However, over the past half century, due to improved infrastructure and market demand, there has been a steady increase in the development and prosperity of the grassland-livestock industry, supporting socioeconomic development in the region (Zhao *et al*. 2000), but resulting in rapid growth of the total livestock population and the resulting conflict with pasture maintenance and stability of the ecosystem. Evidence of growth in the human population is reflected in the steadily increasing demand for the importation of food into the Tibetan plateau from other regions of China, from 20 tonnes in the 1970s, 45 tonnes in the 1980s and to 70 tonnes in the 1990s (Nyima 2000). The total human population of Tibet is, at present, three times that of 60 years ago, and could reach four to five times that number by 2050 (Guo and Cao 2006). Although there has been a slight decline in the percentage of the population engaged in agriculture over the past 20 years, it still represents >75% of the total population of the region (Cheng and Min 2002; Liu and Shen 2007), and is likely to remain so for a long time. Comparable figures for Qinghai and Tibet showed a 19% and 24% increase in population engaged in agriculture over the past 20 years, respectively (Fig. 2) (QPBS 2010; TARBS 2010). In addition to the increasing resident population, increasing external demand for livestock products (meat, milk, fur and wool) from the plateau imposed further pressure on the livestock industry to continue increasing production and efficiency (Chen and Suolang 2002; Li 2007). While the imbalance between supply and demand within the grassland-livestock industry has sustained socioeconomic development over the past 60 years, it has been at the expense of almost unlimited consumption by livestock of what have become increasingly limited grassland resources (Bauer 2005; Long 2007).

While some authors suggest that global warming, rather than overgrazing, is the primary cause of degradation of grasslands (Klein *et al*. 2007; Wang *et al*. 2012), the current consensus is that livestock numbers on grasslands on the Tibetan plateau are beyond their natural carrying capacity (Harris 2010; Squires *et al*. 2010). This has resulted in the widespread degradation or deterioration of pasture, within which livestock can only be supported by utilising surplus products from non-pastoral agricultural areas (Wang *et al*. 2008*b*). Grazing by livestock during winter in northern Tibet has been estimated to be 42% in excess of what the grassland can support, and estimates as high as 139% in excess of carrying capacity have been calculated for some areas (Wang *et al*. 2004). Within the Tibetan plateau, the worst area for grassland degradation is Tibet, followed by the provinces of Gansu and Qinghai (Hao *et al*. 2008). Investigation by satellite remote sensing has shown that in northern Tibet 76.7% of the change in grassland area has been within the range of natural variation, while only 23.3% of grassland has been significantly degraded during the 23-year period between 1981 and 2004 (Yang *et al*. 2007). However, there are large areas of

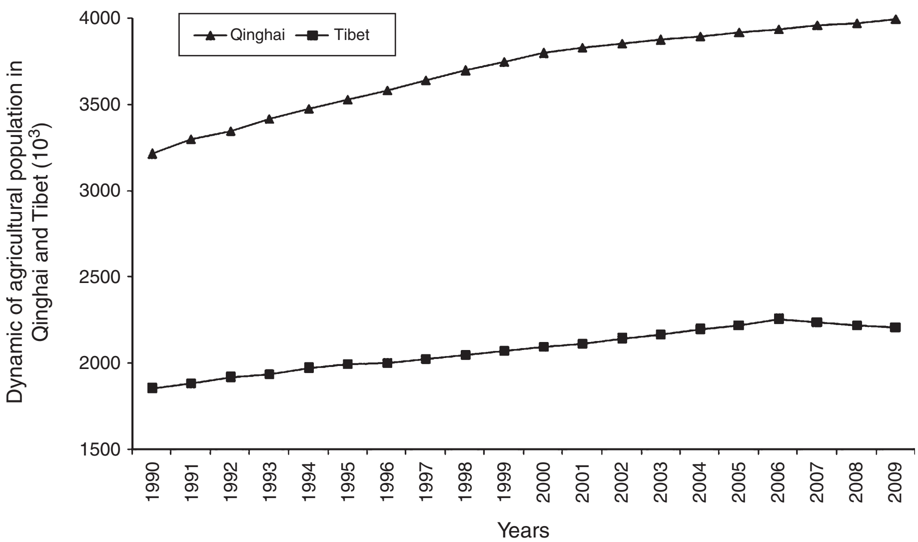

Fig. 2. Changes in the agricultural population of Qinghai and Tibet in the past 20 years (data from QPBS 2010).

degraded grassland which are dominated by poisonous weeds, with high vegetation cover, and which cannot be detected by remote-sensing technology at present (Long *et al*. 2009). Analyses conducted by Qian *et al*. (2007) showed that although Qinghai and Tibet have the highest theoretical livestock carrying capacities (28.7×10^6 and 26.84×10^6 sheep units, respectively), they are, nevertheless, overstocked by 27% and 89%, respectively. In their paper, Qian *et al*. (2007) described what they considered to be the maximum carrying capacity of some pastures, even when herbage utilisation rates were in excess of 50% of herbage production. However, Dong *et al*. (2006) argued that utilisation rate in excess of 50% were inappropriate for alpine meadows and that, therefore, maximum carrying capacities should be constrained to an upper limit of herbage utilisation of 50%. Thus, according to the criterion of Dong *et al*. (2006) it would appear that Qian *et al*. (2007) considerably underestimated the true extent to which these pastures are overstocked. Based on research conducted in the Nagqu prefecture in northern Tibet, Wang *et al*. (2005*b*) stated that the true severity of meadow degradation was greater than that suggested in an earlier study by Yang and Yang (2000). The rate of degradation was greatest during the period from 1980 to 2000, as reported for Shenzha County where the area of degraded grassland in 1986, 1996 and 2000 were 620.7×10^3 ha (31.6%), 1395.3×10^3 ha (71.10%), and 1482.0×10^3 ha (75.07%), respectively (Liu *et al*. 2002*b*). In the headwater region of the Yangtze and Yellow rivers, the area of bare-land degraded grassland was reported also to have increased considerably between 1986 and 2006 in Qinghai province, as reported by Ma (2007) (Fig. 3). Similarly, in Tibet, the area of degraded grassland was reported by Shao and Cai (2008) to have increased significantly in the previous 15 years. Grassland degradation and desertification on the Tibet plateau are closely connected to the livestock numbers (Zhang *et al*. 2004). As a result of grassland degradation, livestock have been forced to graze in marshland areas for longer periods than was the case previously, and the height of vegetation in these areas in the 1960s and 1970s was ~67% lower than in the previous century (Liu *et al*. 2002*b*). In addition to the greater number of livestock, changes in their seasonal breeding pattern have led to increased pressure on the available forage, which, coupled with forage shortage during the winter period, has increased their dependence of marshlands, resulting in a net loss of wetland area and their value in providing ecological services (Pan *et al*. 2007). Indeed the degradation of these swamps and wetlands has reached disastrous levels and has been recognised by the Chinese government as being likely to cause a range of severe ecological problems on the Tibetan plateau, such as loss of biological diversity and hydrological buffering capacity (Li 2006; Wang *et al*. 2007; Zhang *et al*. 2011).

Over the past 30 years, the number of livestock and level of production has increased in the alpine grassland regions, but forage production on grasslands has failed to increase sufficiently to avoid shortages of forage on the Tibetan plateau (Fig. 4) (GMSC 2006, 2007, 2008, 2009, 2010*a*). Thus, there is an urgent need to address what has become a perennial imbalance of forage supply and requirement in the grassland-livestock system. Data from 2010 show that total cattle numbers (90% comprising yak) in Qinghai were $5–5.5 \times 10^6$, with total sheep and goats numbering $12.7–14.8 \times 10^6$ (QPBS 2010), while in Tibet the total number of cattle (95% comprising yak) were estimated at $4.7–6.5 \times 10^6$, and the number of sheep and goats was $15–18 \times 10^6$ (TARBS 2010). With such numbers of livestock on the Tibetan plateau, assessment needs to be made of the scale by which the problem varies from year to year. Using the formulae proposed by Qian *et al*. (2007), the minimum annual shortfalls in forage supply in Qinghai and Tibet are equivalent to 3.7 and 16.3 million tonnes of hay, respectively. The total annual shortfall of the whole Tibetan plateau may be somewhat greater, but only slightly because deficiencies in the regions of Sichuan, Gansu, Yunnan and Xinjiang are less (Long *et al*. 2009). The total annual shortage of forage on the Tibetan plateau, at present is equivalent to 2 mega tonnes of hay, which can be interpreted as meaning that 2.7 million sheep units receive insufficient feed every year

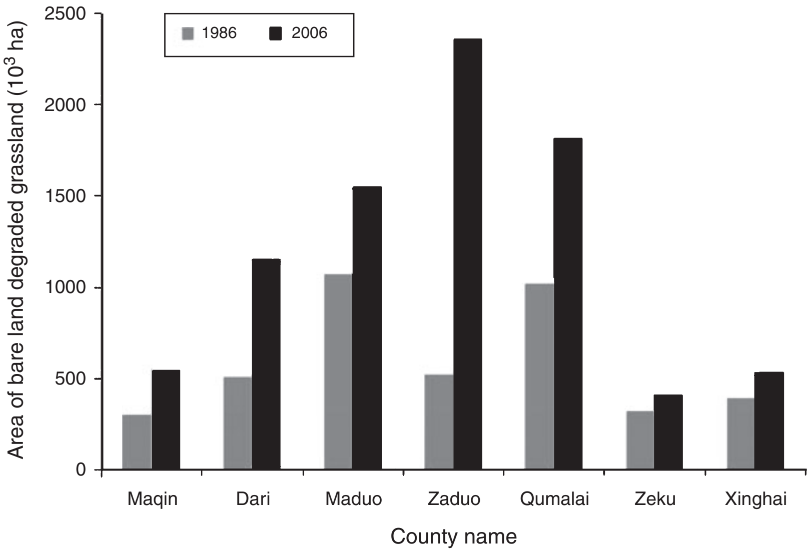

Fig. 3. Changes in the area of bare-land degraded grassland between 1986 and 2006 in seven counties within the Qinghai province (Main, Zeku, Xinghai, Dari, Zaduo, Qumalai and Maduo) in the headwater area of Yangtze and Yellow rivers (data from Ma 2007).

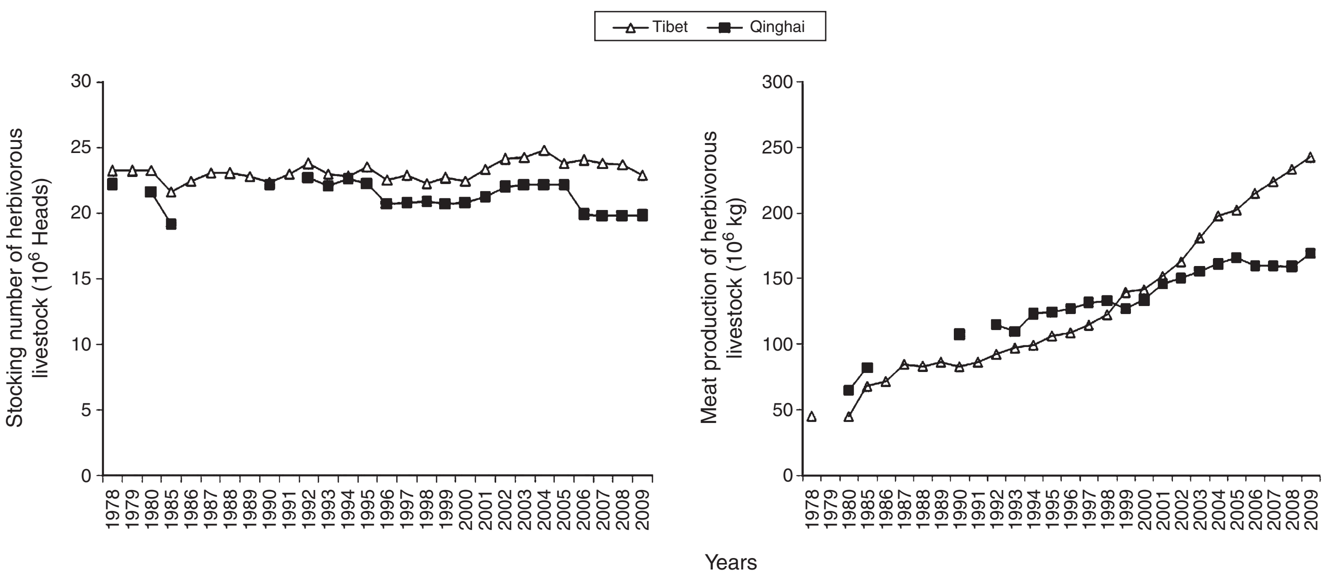

Fig. 4. Changes in total livestock numbers (left) and production (right) in the Tibet and Qinghai prefectures on the Tibetan plateau during the period 1978–2009 (data from QPBS 2010; TARBS 2010). The total number of herbivorous livestock is the sum of those for yak, horses, sheep and goats.

resulting in liveweight loss. Thus there is an urgent need to resolve the problem of forage shortage, primarily by reducing the numbers of livestock in order to ensure the sustainability of the grassland-livestock production system on the Tibetan plateau.

In addition to socioeconomic development over more than 50 years, there are other factors that may have contributed to the imbalance between forage and livestock in grassland-livestock systems on the Tibetan plateau. Harris (2010) stated that the problem was caused by a combination of factors, such as climatic change, agricultural policy, economic markets, population growth and human activity. Generally, there is an absence from the scientific literature of any suggestion that the traditional nomadic pastoralism has contributed to grassland degeneration, which is not surprising, considering that such deterioration has only taken hold over the past five or six decades, as discussed by Harris (2010). Even the occasional suggestion (Miller 2005; Bai *et al.* 2008) that herdsmen have traditionally considered the size of their herds as reflecting their wealth, and that this may contribute to the problem of overstocking to the detriment of pastures and soils, does not withstand scrutiny, for the same reason that pasture degeneration was not a problem until the latter half of the 20th century. Thus the imbalance between grassland and livestock, although undoubtedly a result of overstocking, is not seen as attributable to the traditional nomadic system *per se*. Squires *et al*. (2010), Kemp and Michalk (2011) suggested that it was a failure of marketing mechanisms and policies to keep pace with increased livestock production that had resulted in the accumulation of surplus livestock on grassland and subsequent damage to pasture ecosystems. Certainly, the increases in human population over recent decades would suggest that there was no lack of demand for livestock products. While, a substantial amount of research has gone into quantifying the extent and nature of damage to grassland and ways of repairing that damage, attention has also to be focussed on ways of reducing or eliminating conflict within the grassland-livestock sector. The objective of this paper is to summarise the contribution to be made by different technologies, and to propose potential remedial strategies to promote sustainable development of grassland-livestock systems on the Tibetan plateau.

Elements for a multi-strategy resolution

In a previous paper (Shang *et al*. 2012), we considered strategies to combat the damage resulting from snow disasters in this region of China's grasslands, and proposed an integrated model for a sustainable grassland-livestock system, in which the concept of a multiple-strategy approach was advanced. Within the wider context of this present review, we suggest that in addition to changes in socioeconomic policies and advances in grassland and livestock management, the introduction of innovative strategies and methodologies can contribute to the development of a sustainable grassland-livestock system. Based on a systemic review of technologies and models of grassland and livestock husbandry developed over the last several decades in China, we discuss the content, value and potential benefits of the following 19 pathways. Evaluation of these pathways is based upon experience gained from scientific and technological advances in the grassland-livestock industry, primarily in Tibet, Qinghai, Gansu and Sichuan, but also in other grassland areas of China. The outcome of this exercise is intended to provide an overview of approaches currently utilised or that could be potentially used for solving the problems within the grassland-livestock systems of the Tibetan plateau and to promote the adoption of the constituent pathways.

Restoration of degraded grassland (A)

There are three possible outcomes of grassland degradation on the Tibetan plateau, namely desert, bare-land and poisonous-weed ecotypes, although desertification and bare-land are frequently accompanied by the transient establishment of poisonous-weed communities (Zhao *et al*. 2004; Li *et al*. 2006, 2013*a*; Shang and Long 2007; Yang *et al*. 2007; Shao and Cai 2008; Long *et al*. 2009). Frequently, researchers have described pastures according to the extent to which they have become degraded, such as slightly, moderately, severely, or extremely degraded (Liu *et al*. 2004*b*; Yuan and Zhou 2004; Zhou *et al*. 2005; Li *et al*. 2006; Ma 2007; Liu and Dong 2008), in order to ascribe restorative programs appropriate to the degree of degradation (Gao *et al*. 2009). Such studies have shown that, as the severity of degradation increases, there is a decline in vegetation cover and soil quality, with loss of the usually dominant species of grasses (*Stipa aliena*, *Elymus nutans* and *Poa crymophila*) and sedges (*Kobresia humilis*, *K. pygmaea* and *K. capilifolia*), increased occurrence of weed species with little or no feed value, such as *Artemisia gmelimii*, *Ligularia virgaurea*, *Ajania tenuifolia* and *Aconitum pendulum* (Shang *et al*. 2013), and an overall reduction in herbage mass and feeding value of herbage (Shang and Long 2007; Shang *et al*. 2008, 2013; Gao *et al*. 2009, 2010; Li *et al*. 2013*a*, 2013*b*; Wen *et al*. 2013). With changes in species composition, sward structure deteriorates and areas of bare soil increase, leading eventually to loss of soil structure and the possibility of soil erosion, all of which creates considerable challenges for grassland restoration (Shang *et al*. 2008). Such detailed vegetation studies have proved of great value in providing guidance for restoring degraded grassland on the Tibetan plateau (Xue *et al*. 2009). Nevertheless, further investigations into the damage caused to the plant communities, seed banks and soils of degraded pastures and their capacity for recovery are still required.

Much research into the state of grasslands on the Tibetan plateau has utilised data collected by remote-sensing technology but this research has not been used to provide guidance as to methods for restoration of degraded grasslands (Zou *et al*. 2002; Liu *et al*. 2004*b*, 2008; Shao *et al*. 2008; Liu and Dong 2008). Similar, but more detailed, research has been conducted to identify and evaluate the extent to which grasslands have become degraded within the headwater areas of the Yangtze and Yellow rivers, particularly bare-land areas, sometimes referred to as 'black soil' areas (Liu 2007; Liu *et al*. 2008, 2009; Shao *et al*. 2008, 2009; Lu *et al*. 2009*b*). The results of this work have proved useful in identifying areas requiring restoration, although the process is likely to be gradual. Research conducted using remote-sensing techniques (Zhang *et al*. 2006*a*; Liu and Dong 2008), augmented by field studies (Dong 2001; Li *et al*. 2006), and has proved useful in studying the processes of desertification within the Tibetan plateau. However, research in this area is incomplete and, because of the considerable consequences of desertification, further survey of degradation gradients and their distribution is urgently required. There are, however, certain limitations to remote-sensing technology. While desertified and bare-land degraded grasslands can be readily distinguished from undamaged grasslands, the technology cannot readily detect poisonous-weed areas. Thus, further refinement of remote-sensing technology is required (Li and Liu 2003, 2007), possibly incorporating phenological data on different plant species.

Slightly and moderately degraded grassland has a high capacity for self-recovery, so that for restoration of such degraded grasslands, the common and accepted method for regeneration is to prevent further interference, by enclosure with fencing (Ma *et al*. 2002; Shang *et al*. 2006; Yan *et al*. 2006; Li *et al*. 2013*a*). In general, slightly and moderately degraded grasslands can achieve good recovery by enclosure within 3–5 years, especially in terms of vegetation cover, the rate of recovery being more rapid in wetter and warmer regions where both vegetation and soil structure can be gradually restored (Zhou *et al*. 2003). The aboveground herbage of restored grassland can be up to 10 times greater than that present before fencing, and the vegetation coverage can be returned to between 90 and 100%. However, the rate and the extent of restoration will differ, depending on ecological zones and vegetation types (Yang *et al*. 2003). Recent studies have focussed on the time required to restore slightly and moderately degraded grassland, but further research is needed with greater emphasis, not only on how to restore grassland on the Tibetan plateau, but how to sustainably manage these fragile grasslands following restoration (Ma *et al*. 2002).

Severely or extremely degraded grasslands, which include desert, bare-land and poisonous-weed areas, are generally considered to present much greater problems for restoration. In the past 30 years, Chinese scientific and technical research has led to the testing of various techniques for restoring these three extreme forms of degraded grassland (Ma *et al*. 2007*a*; Shen *et al*. 2009). These have included methods for controlling the processes of desertification and techniques for restoring desertified, bare-land and poisonous-weed areas to productive grasslands (Dong 1999; Ma *et al*. 2007*a*; Zhao and Long 2008). The need for urgent action to allow restoration of degraded grassland has been supported by implementation of the various state-sponsored projects, namely 'Turning pastureland into grassland', 'Ecological re-settlement' and 'Nomadic resettlement', which have overseen, to varying degrees, the fencing of pastures, the banning of grazing livestock and relocation of pastoral households (Ptackova 2012).

However, such attempts at restoration have frequently proved unsatisfactory due either to the failure to regenerate grassland or reversion after regeneration (Zhou *et al*. 2007; Li *et al*. 2013*a*). The main problems have been: (1) failure to restore vegetation in desert areas, or subsequent rapid desertification, due to the poor soils, wide-blown sand and lack of water (Shen *et al*. 2009); (2) rapid degradation of re-established plant communities on bare-land due to poor management or poor soil structure and composition (Wang *et al*. 2006*c*; Ma *et al*. 2007*b*; Cao and Long 2009); and (3) re-emergence of poisonous weeds after their initial control (Shang *et al*. 2008). These problems are exacerbated by climate change and rapid increases in rodent populations (rodent disasters). Therefore, important subjects for future research should include: (1) rodent population control, combined with grassland restoration modelling (Wang *et al*. 2006*c*; Ma *et al*. 2007*a*); (2) identification of local grass species suitable for ecological stabilisation with which to create new vegetation cover in desert areas (Shen *et al*. 2009); (3) modelling and identification of climate factors responsible for weed outbreaks in order to predict weed population dynamics for the strategic application of herbicides (Ning *et al*. 2004; Ma *et al*. 2006). In addition, in the cases of desertified and bare-land areas, it is imperative that techniques be developed to re-build the soil systems (Dong 1999; Wang *et al*. 2006*c*; Yang *et al*. 2006), taking into account the propagative bank of vegetation and nutrient status of the soil as key factors (Shang *et al*. 2006; Han *et al*. 2007).

Establishing large areas for production of sown forage (B)

At present, large areas of sown pasture are grown to produce forage supplements for livestock in the cold season and, in the event of snow disasters, as a rescue forage resource (Xu 2005; Cao *et al*. 2007). Across the Tibetan plateau, local herders and government agencies support the planting and cultivation of large areas of sown forage crops (Xu 2005). Most sowing of forage crops is conducted on flat areas at altitudes above 3000 m, including some valley areas, although occasionally crops are sown on slopes not exceeding 15° in order to allow cultivation and soil/water conservation. Most sown crops do not receive irrigation, relying solely on rain, although in some cold desert areas, limited irrigation may be available from local rivers (Ma *et al*. 2007*b*; Shi *et al*. 2007*a*). However, it is difficult to cultivate new and larger areas of land for growing sown forage because pasture-protection policy prohibits tillage of natural pastures in rangeland regions (Hu 2004). In northern Tibet, most pastoral villages have an area of 10–20 ha of land used for cultivated forage production, and in each county larger areas (>2000 ha) are farmed for forage production under the supervision of rangeland management departments. The forage from these sown pastures is conserved as hay for winter supplementation. Investigation has shown that, while the land area suitable for cultivated forage production is ~7×10^6 ha, at present only 80×10^3 ha is actually used for this purpose, representing 0.14% of the whole grassland area of Tibet. Nevertheless, this area is insufficient to supply enough supplementary winter forage for current livestock numbers (Cao *et al*. 2007).

In the Qaidam region (altitude >2600 m), the total yield of cultivated forage is 52 times that of the natural grassland (Qi 2007). Oat forage production can be as much as 10.7 tonnes dry matter (DM) ha^{-1} on the Tibetan plateau (Hu 2000) and yields of alfalfa can be up to 8.4 tonnes DM ha^{-1} in northern Tibet (Long 2011). Forage DM yields from cultivated pastures (*Elymus nutans*) at altitudes of 4000 m (rainfall 500–650 mm per year) in Qinghai province have been as high as 8.6–10 tonnes ha^{-1}, although the average seasonal yield is ~5.7 tonnes DM ha^{-1} (Shi *et al*. 2007*b*). The main method of conserving sown forages on the Tibetan plateau is as hay rather than silage because of the low temperatures and lack of adequate facilities. Mixed pastures of clover and ryegrass have been reported as yielding up to 14.7 tonnes of DM of forage ha^{-1} in the alpine regions of Sichuan province (Qin and Wu 2005). Much effort has gone into the investigation of yield and persistency of cultivated forage meadows on the Tibetan plateau. This has included research into the most suitable native species for long-term leys, such as *Poa pratensis*, *Elymus nutans*, *Elymus sibiricus*, *Festuca sinensis* and *Puccinellia tenuiflora*, as well as oats (*Avena sativa*), barley (*Hordeum vulgare*), perennial ryegrass (*Lolium perenne*), alfalfa (*Medicago sativa*), peas (*Pisum sativum*) and arrow's tongue bean (*Vicia sativa*), grown as monocultures or in mixtures (Ma *et al*. 2007*b*; Shi *et al*. 2007*a*; Li 2011*b*). We suggest that appropriate programs for cultivation of land for forage production should be explored to support the grassland-livestock industry, within the current numbers of livestock, while protecting the condition of natural grasslands (Hu 2000).

The main problem facing forage production from sown pastures on the Tibetan plateau is lack of persistence, requiring effective management methods (Zhang *et al*. 2003). Sown pastures with a single plant species start to deteriorate by their fourth year (Wang *et al*. 2005*a*), whereas in mixed-species pastures degradation can be delayed to 5–6 years under normal conditions (Shi *et al*. 2005). Weed invasion is the primary cause of degradation of sown pastures in alpine areas in the short-term (Zhang *et al*. 2003), the secondary cause usually being damage by rodents (Zhang *et al*. 2003). The early control of weed and rodent populations are therefore two key factors for ensuring the long-term utilisation of sown pastures (Zhou *et al*. 2007). In addition to weed and rodent control, management practices, such as fertiliser use and irrigation, can further enhance the long-term production of sown pastures (Ma 2006). Annual sown pasture is very important in northern Tibet for the production of winter forage supplements during the short growing season, from June to September (Long 2011). Further investigations are, therefore, required to determine which annual species, as well as perennial species, are best suited to the regional climatic conditions, soil type, soil nutrient status and water content in order to establish sown pastures.

Species and varieties indigenous to the high plateau should be grown to test their suitability for expansion into additional wider areas (Wei and Zheng 2006), although appropriate research is required to develop the necessary grassland management skills to maximise production and longevity of these species, and to examine the possible environmental consequence of conversion from native to cultivated grassland in order to challenge present restrictions on cultivated grassland. Further research is required to examine the possible incorporation of forage legume species, either into mixed all-legume or grass-legume forage crops on the Tibetan plateau (Zhang *et al*. 2006*b*; Li *et al*. 2010), especially at altitudes above 4000 m. Thus, a practicable approach of combining restoration of degraded grassland with establishment of cultivated pastures to improve management techniques for sustaining large areas for conservation and grazing is required. Already, in other alpine regions of the world, high quality forages are being successfully harvested from permanent grasslands (Marini *et al*. 2008; Jayanegara *et al*. 2011), as a result of careful management by controlling mowing frequencies and stocking density.

Forage production within livestock sheds or greenhouses (C)

Frequently, herders produce forage within their livestock sheds (without roofs) or greenhouses in the warm season when livestock have moved onto summer pastures and the sheds would otherwise be empty for ~3 months (Jin *et al*. 2001). Forage production by this system has been named, 'Winter-Shed and Summer-Forage' (WSSF; from the Chinese, 'DongjuanXiacao'). It has become a well established method of forage production on the Tibetan plateau for making hay to supplement animals during the cold season and as a safe-guard against starvation during natural disasters (Sun *et al*. 2007). It is possible to produce large quantities of forage biomass during a relatively short growing season due to: (1) the organic- and nitrogen-rich fertiliser left in the sheds after the winter, (2) shed walls retaining heat and admitting enough sunlight to maintain an equitable microclimate, thereby promoting plant growth, and (3) reduction of damage by rodents (Wang 2009). In addition to local grassland species, forage crops, such as barley, oats, peas, alfalfa, annual ryegrass, turnip, and radish, can be used for WSSF on the Tibetan plateau. Mixed plantings of barley and oats can yield up to 14 tonnes of DM of forage ha^{-1}, although, in general, forage yield is ~5.7 tonnes DM ha^{-1} in animal corrals of the Naqu region of northern Tibet, at altitudes of ~4500 m, and with an annual rainfall of ~400 mm (Sun *et al*. 2007). Frequently, the yield of forage grown in corrals is greater than on unenclosed land (Wang 2009) although most corral areas are small (<0.5 ha) and the technology employed in planting and managing WSSF differs between herders so that forage production can vary significantly.

Forage yield in individual holdings demonstrates a wide variability across the Tibetan plateau, depending on species, planting technology and post-harvest management. The maximum forage yield from a greenhouse is ~8.6 tonnes DM ha^{-1} (altitude is ~4500 m, and rainfall is ~400 mm per year) (Long 2011). While this method of forage production has attracted the interest of herders and benefited them, many would like to grow yet more feed, not only to reduce livestock losses, but to improve livestock production and product quality in order to increase their income by commanding high prices at the point of sale. Many of the annual or perennial forage species grown in greenhouses or livestock houses can be harvested twice during the growing season and, in livestock houses, can be grazed by the livestock returned from summer pasture for housing. Thus, by providing more than one harvest, production from such forages is two to three times greater than on open land on the Tibetan plateau.

As mentioned previously, WSSF cannot only provide an important source of forage for winter feeding of livestock, but a life-saving source of food for livestock during snow disasters. For example, 1 tonne of hay produced from WSSF will be sufficient to feed ~50 Tibetan sheep for 10–20 days during a snow disaster (Wang 2009). Thus, herdsmen and local government agencies should recognise the benefits provided by WSSF. However, although WSSF is popular on the Tibetan plateau, especially in areas adjacent to grassland farming practices, there are still some problems associated with WSSF and further studies are required to determine the best time and methods for planting forage seed, soil tillage and harvesting, and investigation of more productive species, especially for crops such as turnips. In addition, the technology of WSSF needs to be extended to remote pastoral areas where local herdsmen lack experience in planting and management practices necessary to benefit from WSSF.

Mowing forage in alpine wetland (D)

Alpine wetlands provide an important source of grazing pasture for livestock in the colder seasons on the Tibetan plateau, especially in spring when there is a of lack of forage elsewhere (Zhao 1982; Zheng *et al*. 2009). The total wetland area of Tibet is ~6.5×10^6 ha, and is ~8.16×10^6 ha in Qinghai province. Overall, in recent years there has been a decline in the total area of alpine wetland on the Tibetan plateau, with some wetland converting to drier alpine pasture (Bai *et al*. 2008). The forage mass and nutritional content of wetland vegetation are high, and provide a suitable source of forage for livestock (Wu *et al*. 2009). The higher feeding value of alpine wetland herbage, compared with that of other grassland, is thought to be a result of adaptation of metabolic processes to physiological stresses imposed by the cold temperatures and higher altitude of the wetlands (Guo *et al*. 2014). The herbage mass of *Kobresia tibetica* (the dominant species of alpine wetland) is high, and may reach 768 kg DM ha^{-1} in August, sufficient to support 2.9 sheep units ha^{-1} for 1 year (Zhao *et al*. 2003). In addition to using alpine wetland for grazing livestock, these pastures can also be mown, and the harvested forage used to supply supplementary feed in the cold season (Zheng *et al*. 2009). It is, however, extremely important to plan the utilisation of these areas for grazing and mowing in order to avoid wetland degeneration. It is now commonly accepted that wetland degradation is the result of excessive livestock grazing, as well as excessive drainage by humans during the past 60 years (Yang and Wang 2001).

The best time for mowing is during July or August. Experiments in Dangxiong county have shown that mowing swards to leave a stubble height of no less than one-third of their pre-cutting height in July can yield 0.3 tonne of DM of forage ha^{-1} for conservation, and sufficient aftermath, together with any subsequent regrowth by the end of the growing season, to provide pasture for grazing in the following winter and spring (Long 2011). Thus, it is recommended that mowing height should not be shorter than one-third of the mean pre-harvest pasture height. Nevertheless, under the current situation of over-stocking, it is not possible to keep the utilisation rate of wetland below 50%, and in most years it exceeds 70% (Chen and Liu 2002). The implementation of grazing and conservation managements in alternate years and tighter control over the utilisation of pasture for conservation and grazing may provide a more efficient and sustainable means of using wetland vegetation (Wu *et al*. 2009). Although the mowed vegetation from marshland may be conserved either as hay or silage (using suitable methods to compress and cover the silage to prevent aerobic deterioration), ensilage provides the opportunity for incorporating additional sources of energy and protein to improve the feeding value of the conserved diet (Li 2011*b*).

A 10-year investigation of three traditional grazing practices on a wetland pasture, namely, whole-year, winter-spring and winter-only grazing, has demonstrated that the grazing method did have a significant effect on vegetation, such as herbage mass and height and species diversity (Zhao *et al*. 2010*a*). Such results clearly demonstrate how strict control of access by grazing livestock can promote high levels of forage production. Enclosure of degraded wetland by fencing can allow rapid recovery and allow up to a 3.5-fold increase in herbage mass, compared with degraded swamp, illustrating a high capacity for self-recovery and sustainable production under careful grazing management.

Recent studies, using satellite remote-sensing data, have provided accurate identification of the distribution of wetlands on the Tibetan plateau (Zhang *et al*. 2011), showing the extent of their fragmentation and isolation, but not their forage production potential, either for grazing or conservation. Increasingly, pastoral activity has encroached onto the alpine wetlands of Tibet (Zhao 1982; Zheng *et al*. 2009), so that urgent investigation is required to determine the impact of such activities on these fragmented areas and the extent to which the damage can be reversed. In addition to a more efficient utilisation of wetland vegetation by stricter control of grazing and mowing for conservation, the development of improved technology for cutting and processing forage in order to obtain feed with a high nutritional value is required. Such increases in efficiency, together with strict control of livestock numbers, may well provide much of the reduction in grazing pressure required to allow the recovery of these valuable alpine wetlands.

Forage production in cold desert areas (E)

In spite of the high altitude and harsh climate of the cold desert regions, on suitable soils, supplied with irrigation and the inherently good light quality during the growing season, there is abundant evidence of successful forage production in cold desert areas, especially in the Ali region of Tibet. On the plateau, the altitude of the cold desert area is at least 4000 m, with annual rainfall of only 100–200 mm, although ample river-irrigation is available in some areas. There are increasingly large areas in which alfalfa is being grown successfully, as well as other forages (Ma *et al*. 2008*b*; Yan and Lin 2009). In the Ger county of the Ali region, alfalfa and other forages grow well at an altitude of 4500 m, and have become the main sources of feed for livestock, yielding ~1.8 tonnes DM of hay (alfalfa) annually, well in excess of the natural grassland, and providing an oasis for livestock production (Ma *et al*. 2008*b*; Wang 2011). Nevertheless, crucial to the growth of forages in these areas is the availability of adequate water supplies.

Although there are many rivers in the cold desert regions, water is frequently not sufficiently well retained by soils to be available for forage production. Thus, the utilisation of the plentiful local water resources for forage production is one of the key technologies required for the forage industry in cold desert regions (Yang 2002). A further problem concerns the over-wintering of plants, when, in addition to plant tissues becoming frozen or encased in ice, any soil water present is likely to be unavailable due to freezing. In addition to supplying water, the availability of a sufficient depth of soil to offer protection to geophytic plants over winter may be important to survival. The use of synthetic covering material or gravel technology, which is very popular in low altitude desert areas, and the application of mulches to conserve soil warmth and moisture could provide beneficial protection (Gan *et al*. 2013).

A further important area of research must be the investigation of novel species and varieties of plants suitable for establishment and production of high yields in the cold desert regions. Meanwhile, we suggest there is an urgent need for further evaluation of the availability and distribution of water on the Tibetan plateau to provide guidance for its strategic use for irrigation and the promotion of forage crop production in the cold desert regions (Li *et al*. 2005).

Forage production from forage-crop rotation systems (F)

Forage production in farming areas and the adoption of forage-crop rotation techniques have been important in increasing crop yields and improving livestock husbandry; especially in the ecotone of pastoral-agricultural areas or their mosaic zone (Wang 1988*b*). In lowland arable farming areas of China, there is a long history and accumulated experience of forage-crop rotation, which may well prove valuable for developing rotational forage-crop systems on the Tibetan plateau, and provide a means of incorporating forage production along with livestock production in traditionally pastoral areas (Xing *et al*. 2011). On the Tibetan plateau, there are large areas of farmland, which provide food for local residents and some forage for their livestock. In particular, the Three Rivers (Yarlung Tsangpo river, Tibetan river and Nyang Qu river) basin of southern Tibet is an important grain-producing area on the Tibetan plateau (Shang *et al*. 2009). The rotational forage-crop system is not only an efficient way of producing forages and increasing grain production, but provides a means of protecting and improving soil condition, thereby increasing productivity (Jin 2005; Paltridge *et al*. 2009). Not only are forage-crop rotations an efficient way of increasing agricultural diversity and production on large-scale farms, but they can equally well be adapted for smaller areas of farmland (Bieba 2006; Sun *et al*. 2006). At present, rotational systems of forage-crop production are being widely adopted on the Tibetan plateau, and have demonstrated benefits for both the ecology of the area, by improving soil structure, water retention and resistance to desertification, and the economy, by increasing income from a diversified and more productive agriculture and livestock production industry (Bieba 2006). However, further development of technologies for the protection, cultivation and processing of specific forage species will require additional research to be undertaken in order to boost the adoption of rotational systems, especially in areas of small-scale farming (Bieba 2006; Xing *et al*. 2011). To promote further adoption of the practice, high quality demonstration models of rotational forage-crop practice should be implemented on the Tibetan plateau, along with some policy and market adjustments from local government to support the integration of supplementary forage production and livestock husbandry (Bieba 2006; Xing *et al*. 2011).

The earliest documented evidence of forage production in China was during the Western Han dynasty (2000 years ago), when the envoy Zhang Qian introduced alfalfa from central Asia into China, for use as a feed for livestock (Wang 1989). The subsequent growth of forage crops in rotations has been implemented over different time scales, with longer-term models generally being used for perennial forage species, and shorter-term models for annual forages, depending upon the local seasonal patterns of temperature and precipitation. In the basin of the Three Rivers Region of Tibet, there are ~65 700 km^2 of farmland, where the system of cultivation provides two crops per year or three crops in 2 years (Jin 2005; Bieba 2006), and may include the planting of forage crops. However, in the basin of Yellow river, the usual system is to produce only one crop per year, but with forages being incorporated into the arable rotation every 2 or 3 years.

During the last decade of the 20th century and early part of the 21st century, forage production in Tibet has developed rapidly, and the proportion of the total farming area planted to forages has increased from less than 1% to ~20%, which has contributed to the increase in livestock numbers over this time, and promoted the economic development of Tibet (Li *et al*. 2007). From research conducted over 10 years, Jin (2005) proposed a double-cropping rotation model, which incorporated cereal as well as forage species and different rotation sequences. Although this double-cropping model was suggested for use in southern Qinghai, the model could, where appropriate, be adapted for use in Tibet. Where double-cropping has been adopted, the production of two crops per year is popular with producers due to the heavy total crop yields that can be achieved. For example, following the harvesting of barley in July or August, there are 2 or 3 months when ~70% of the annual rainfall occurs and it is still warm enough to produce fodder crops of annual legumes or *Brassica* species (Jin 2005). However, in southern Tibet, a simple annual rotation system comprising 4 years of cropping with 1 year of forage production is more appropriate to local climatic conditions and soil environment (Wei *et al*. 2007). In addition to increasing forage yields and improving soil fertility by introducing forage-crop rotations into otherwise barren land, the cultivation of alternating species can reduce the risk of damage by pests and diseases (Yue 1987), and reverse land degradation by improving soil structure and fertility (Bieba 2006).

Straw processing for forage (G)

Efficient straw processing provides an important contribution to the livestock industry, although straw alone cannot satisfy animal requirements for maintenance let alone production (Li *et al*. 1991). While the direct feeding of straw to livestock has been practised in farming areas for a long time, there is insufficient straw produced on the Tibetan plateau to make a significant contribution to livestock nutrition, and transport of straw from arable areas is expensive making it difficult to extend the practice very far. In addition, without the availability of suitable processing technology, it is difficult to improve the nutritional value of straw (Han *et al*. 1997). Nevertheless, there is scope for development of the straw-feeding industry in the pastoral areas of the Tibetan plateau. However, for these remote areas, it is necessary not only to increase investment for transport and infrastructure, but to provide equipment and technology to process large quantities of straw for high quality winter feed (Jin *et al*. 2009). The introduction of processing plants should initially be focussed on straw-producing areas close to or surrounded by pastoral enterprises although currently the rate of uptake of the technology in such districts is low (Wang *et al*. 2008*a*). There is, nevertheless, a need for further integrated development of cereal and forage crop production, as well as intensive grassland farming, to provide straw and other feeds to support the livestock industry (Li *et al*. 2007). There is a variety of farms, differing in size and type, within the wider pastoral farming area of the Tibetan plateau which could readily adapt to growing crops yielding straw as a valuable by-product for the straw-feed industry, such as in the Three Rivers region of Tibet and the Haidong and Hainan regions of Qinghai province (Ma *et al*. 2008*a*; Qin *et al*. 2010). In addition, the straw-feed industry should focus on supplying products for the intensive livestock finishing centres, to which livestock from many local pastoral livestock-rearing areas are sold. In this way, the time livestock spend on grassland can be reduced, so increasing turn-over rate and numbers, and the income of the herders.

Straw-feed processing technology is now very well developed and efficient and processed straw can provide a considerable contribution to the livestock industry (Jiao 2007; Xie *et al*. 2010). For example, during the period from 2000 to 2002, under the 'Straw-feed industry development' initiative, in 12 industrialised areas of Gansu province alone, 7.73 million tonnes of straw were processed, producing 5.87 million tonnes of silage and 1.69 million tonnes of ammoniated feed, accounting for 44.5% of straw production, and contributing an additional 696 million Chinese Yuan to the value of animal production (Wang *et al*. 2006*b*). During the processing of straw, the addition of high protein forage materials, such as alfalfa, can improve the digestibility of straw and voluntary intake, as well as reduce feed energy losses and greenhouse gas emissions (Yang *et al*. 2008). At present, various simple straw-feed processing techniques, such as chopping, incorporating mixed grains (or straws) are being used, but some technologies, involving ensilage, microbial and biochemical treatment, require further investigation and development. Nevertheless, the current simple practice of feeding wheat and maize straw, mixed with beans, grains and trace elements, is proving successful in increasing the liveweight gains by Tibetan livestock during the cold season (Liu *et al*. 2002*a*). As well as the direct benefits for livestock production, the feeding of straw to livestock avoids atmospheric pollution caused by burning, and contributes to a more comprehensive utilisation of straw, which, with its expanding use in other industries, drastically reduces straw wastage (Cao and Wei 1999; Li *et al*. 2009).

Transporting forage from arable regions (H)

With the current livestock population and availability of fodder on the Tibetan plateau, the sustainability of the livestock industry is dependent upon input of forage from outside the area, particularly in the event of snow disasters (Shang *et al*. 2012). The efficient operation of existing transport and logistical systems in order to ensure the large-scale haulage of forage into the Tibetan plateau from regions outside requires continued planning and coordination at the national level, not least because of high cost of transport and lack of effective large-scale haulage facilities by local farmers and herdsmen. Thus, it is both important and appropriate that external aid should be supplied for the transport of seasonal supplies and disaster relief (Zhang and Li 2009). In recent decades, the organisation of forage transportation by the civil administration departments has contributed considerably to reducing livestock losses on the Tibetan plateau during snow disasters. Nevertheless, the reliable provision of the large amounts of forage that are needed for livestock requires careful year-round planning. The availability of more accurate, long-range weather forecasting to predict snow disasters on the Tibetan plateau should allow strategic transport of feed supplies in advance. In addition to road transport, the Qinghai-Tibetan railway provides major transport and logistical capabilities, enabling the easy movement of large consignments of livestock feed. Although transportation of forage to the marginal areas of Tibetan plateau is relatively easy due to their proximity to arable farming areas and a good road network, there remains the problem of access to remote areas, away from the main transport routes, which necessitates careful planning of operation.

Up until now, the lack of a centralised authority to identify demand, and coordinate the supply and transport of forage has impeded the development of an efficient, integrated system across the Tibetan plateau. Foremost, there is a requirement to identify demand. The various regions across the whole plateau area need to be classified according to their forage requirements for livestock during average years and in the event of climatic disasters. This should be accompanied by an investigation of the available resources in the surrounding agricultural areas, to identify the number and size of locations, and quantities and types of forages available annually. From these data, an integrated plan to deliver forage resources to where they are needed must be formulated to minimise transport distances, time and costs, and identify regional sites where appropriate stockpiles of forage should be located for strategic dispersal in the event of emergencies. The Tibetan plateau is extremely vulnerable to catastrophic climatic events, such as snow disasters, and a proactive, rather than reactive approach to disaster relief is required (Wang *et al*. 2006*a*). The establishment of numerous large forage-reserve centres, well in advance of winter, will provide hubs from which livestock feeds can be distributed more effectively and efficiently by road transport (Shang *et al*. 2012).

Feed blocks (I)

Feed blocks have been shown to increase the utilisation of forages by livestock (Zhang 1998) and provide a means of improving the nutritional value of conserved forages provided to domestic animals on the Tibetan plateau (Wang *et al*. 2011). Nevertheless, use of feed blocks has not been widely adopted in all areas of the Tibetan plateau, especially in remote pastoral areas, where further promotion is required. Although formulations vary, the three primary functional ingredients of feed blocks are usually urea, molasses and minerals. The inclusion of urea provides a source of nitrogen, to compensate for the generally low crude protein content of winter pasture and cereal straw supplements. Addition of molasses serves as a binder and an attractant and provides a source of readily fermentable carbohydrate to ruminants.

Additional minerals usually include calcium, phosphorus and sodium, as well as micro-elements, such as iron, copper, zinc, manganese, iodine, selenium and cobalt, which may be otherwise deficient in the diet. In addition to non-feed materials, such as clay or bentonite, which may be incorporated as fillers or solidifiers to facilitate block formation, sources of energy and protein, particularly rumen undegradable protein, may be added to further supplement the diet. A wide variety of feed block formulations have been developed. A typical formulation, by weight, for blocks provided to yaks is: maize flour (13.5%), wheat bran (10%), colza cake (13.5%), molasses (46%), urea (10%), salt (2%), minerals (1%) and bonding agent (4%, e.g. bentonite) (De 2004), whereas that for sheep is urea (13%), molasses (26%), salt (10%), wheat bran (30%), minerals (16%) and bentonite (5%) (Zhang *et al*. 1999).

The resulting improved nutrition has been shown to increase liveweight gain of Tibetan lambs during fattening (Yu *et al*. 1998; Yu 2009), reduce winter liveweight loss by yak and cattle, thereby improving their value at sale (De 2004), improve milk yield and reproductive performance of yaks (Zhang 1998), and assist rapid recovery of livestock with the emergence of fresh herbage growth in the spring (Xu 2002). In a comprehensive study to examine the effect of feed blocks on the performance of yak, Dong and Zhao (2007) demonstrated an improvement in liveweight gain, reproductive performance (reduced calving interval, increased calving rate and increased calf birthweight and survival), milk yield and calf liveweight performance.

Although feed blocks can be manufactured by a simple moulding process, the use of more sophisticated pressure-moulding machineries can produce harder blocks, more resilient to adverse weather conditions. Such machinery, as well as the raw ingredients, is unlikely to be readily available in more remote areas. However, feed blocks manufactured using more specialised machinery available in industrial areas can be as easily transported to the pastoral regions of the plateau, as could the raw ingredients. Moreover, feed blocks can be readily transported along with forages to the regional stockpiles to await wider distribution.

The beneficial effects of providing feed blocks, long recognised by other sectors of the livestock industry, need to be extended to increase livestock performance in the high altitude pastoral areas of the Tibetan plateau. In addition to the improved livestock, there are benefits to pastures. With animals being in better body condition at the emergence of new plant growth, there may be a reduction in the grazing pressure exerted on alpine swards. The provision of feed blocks should be routinely incorporated into the system to provide a supplementary source of energy and minerals during the winter in order to alleviate shortages of forage (De 2004).

Establishment of regional and local forage reserves (J)

The building of regional and local forage reserve stations can fulfil an important role in safeguarding the sustainable development of grassland livestock in China (Liu *et al*. 2004*a*). In attempts to facilitate disaster relief projects, the building of a system of forage reserves has begun on the Tibetan plateau although stores have been designed more for grain storage rather than forage, and only at the level of county or regional depots. A similar scheme was established in Xinjiang by the building of 133 regional storage depots (Liu *et al*. 2004*a*). However, what is required is the integrated involvement of the straw processing, transport and feeding industries in the establishment of a forage reserve system (Jin *et al*. 2009). In addition to providing vital relief during disaster emergencies, the local and regional forage reserve centres should be drawn upon routinely to resolve conflicts of forage supply and livestock demand. If regular and guaranteed provision of forage supplements can be used to ensure better reproductive rates, survival and liveweight performance of livestock, then with the same number of breeding females, the annual output of finished livestock can be increased, thereby raising herders' incomes. The increased pressure on pastures, due to the greater numbers of young stock produced, will be offset to some extent by the shortened period required for finishing the animals for slaughter. On pastures threatened by overstocking, similarly, a guaranteed supply of forage supplements and improved overall livestock performance can provide herdsmen with the confidence to reduce breeding stocks, secure in the knowledge that livestock output and family income can be maintained (La 2006; Du and Li 2007). In the event of snow disasters, the considerable costs incurred by the requirement for immediate and large-scale transportation of forage to rescue livestock can be lessened by the provision of local forage reserves and further investment in an adequate road network. Such a model could ensure the long-term sustainability of the livestock production industry on the Tibetan plateau. On the Tibetan plateau, in Qinghai province a program had already been implemented to create forage reserve centres. For example, five counties in the Haibei region established hay reserves of ~184 000 tonnes in 2009. In 2010, the national forage industrial technology system conducted an investigation of forage reserve systems in Inner Mongolia, Gansu, Qinghai, Hebei and Sichuan (SFITS 2010).

Overall, on the Tibetan plateau, although some forage reserve bases have been built, there is as yet no integrated system of forage supply, and plans still fall short of the guiding ideology of, 'prevention in disaster seasons, increasing benefit in non-disaster seasons'. We suggest that the work of building regional and local forage reserves should be extended down to the level of individual households. There should not simply be a reliance on investment at the level of national government but involvement by households in accumulating forage reserves to permanently raise livestock production levels, as well as avert catastrophic losses in the event of climatic disasters. The entire organisation of forage reserves should be linked at all levels, through a multi-tier model, down from ecosystem through province, district and county to household, to produce a unified system of forage reserves. The regional authorities would be required to provide a management role in the operation of the reserve system by assessing the pattern and size of reserve bases required, overseeing the assignment and distribution of fodder, and enabling households to increase their forage reserve capacity. In addition, encouragement, and possibly financial assistance, should be given to herders to create and maintain forage reserves at the household level, in order to provide readily accessible feed resources for livestock in case of catastrophic events, such as snow disasters, for use until large-scale relief measures can be put into effect. The establishment of such a widespread and comprehensive system of forage reserves would undoubtedly require considerable investment from national government in the infrastructure of the Tibetan plateau. However, such expenditure would have a pivotal role in promoting the long-term sustainable development of the grassland-livestock industry. The provision of forage reserve stations and establishment of additional large areas for forage production locally could, with improvements to the road infrastructure, where required, provide an integrated feed support model to serve the grassland livestock industry well into the future.

Reducing stocking rate (K)

Current livestock numbers on the Tibetan plateau are in excess of its long-term sustainable carrying capacity (GMSC 2010*b*). What is required is an immediate evaluation of current stock numbers and a halt to any further increases. Where there is evidence of light or moderate degradation of pastures, herders should be encouraged to reduce grazing pressure, and where there is severe degradation, to totally exclude animals from the area. Simultaneously, documentary evidence should be gathered in order to provide a foundation for reliable advice to herdsmen on pasture and animal management. Although, many studies have been conducted to determine the livestock carrying capacity of grasslands across the Tibetan plateau, they cannot provide the level of detail required for each county, in order to provide accurate guidelines to implement the necessary reductions in livestock (Yang and Yang 2000; Qian *et al*. 2007; Fan *et al*. 2011). We suggest that the basic administrative area for the technical implementation of a livestock reduction policy should be the county. However, to retain the goodwill and cooperation of herdsmen, measures must be taken to avoid a reduction in their income. Perhaps understandably, the number of livestock owned by a household is seen as the basis to guaranteeing its wealth, and large herds may be considered as insurance against severe winters and other natural disasters. What are considered as adequate herd sizes should be studied and confirmed for different ages, regional and cultural backgrounds, and even different families, in order to implement reductions in livestock numbers, with minimal impact on householders' incomes. Only by assuring herders of stable, if not immediately increased incomes, are they likely to comply readily with any recommendation to reduce livestock numbers on grasslands (Ji *et al*. 2010). In addition to the current advice from national and local government agencies concerning reduction of herd sizes, efforts should focus on encouraging consumer demand and establishing reliable market outlets for animal products from grassland in order to increase the per unit price received by herders. By guaranteeing their income in this way, herders may have the confidence to reduce the pressure of livestock on grassland, which in the longer term should assure them of a better livelihood and the sustainable development of their industry (Kemp *et al*. 2011*a*, 2011*b*). A further benefit might be improved product (meat) quality on better quality grasslands (Willems *et al*. 2013), which can be achieved by destocking. In addition, by reducing labour requirements for livestock management, family members would be able to seek other sources of income, either within or around the home, or further afield, and children would be able to spend more time in education.

At present, in the pastoral areas of the Tibetan plateau, a reduction in livestock numbers is difficult to achieve, not least because of variations in the estimated extent of overgrazing by livestock. The various studies that have been undertaken on this subject have often produced conflicting results. Using data collected at grassland monitoring stations across all the counties, the conclusions published by GMSC (2010*a*) were that the numbers of sheep units (sheep unit = 50 kg sheep) was 38% and 25% in excess of grassland carrying capacity in Tibet and Qinghai, respectively. These values were lower than those reported by Qian *et al*. (2007) but higher than those of Yang and Yang (2000). According to Fan *et al*. (2011), in the Three Rivers headwater region, livestock numbers have risen over a period of 18 years to exceed the carrying capacity of the grassland by 50%. Based on a study of the livestock numbers and herbage production on similar pastures in Gannan prefecture, within Gansu province, Liu *et al*. (2010) recommended that livestock numbers should be reduced, but within an overall plan taking into account the theoretical net herbage production of the grasslands, and the potential for developing alternative sources of forage production, both locally produced and imported. A similar proposal to reduce livestock numbers has been offered by Long (2011) based on current livestock numbers, theoretical carrying capacity of pastures and potential forage supplement production, in which the cultivated forage as a proportion of all forage supplements is the key measure to determining the required reduction. On this basis, if the area of cultivated forages is increased to 10 times that of the current area (i.e. increased to 115 000 ha) this would be sufficient to maintain a viable livestock breeding population in Tibet (Long 2011). Nevertheless, we emphasise that only by a reduction in livestock numbers, together with other approaches to reducing the pressure on grasslands, can the integrated development of the livestock industry be achieved.

Increasing annual livestock offtake (L)

Reducing the period that livestock are present on grasslands will not necessarily lead to a reduction in the number of livestock sold annually but will lead to a reduction in the grazing pressure on grassland over the year. It does, however, require good livestock management, including the judicious use of alternative forage resources, to ensure high prices for the livestock sold and an acceptable level of income for the herdsmen (La 2006). Focusing on improving the individual performance of animals can result in an increasing awareness by herders of the need to balance the resources of native grassland, cultivated pasture and forage supplements, and imported forage and roughage necessary to improve provide a high level of the grassland-livestock output and income (Kemp *et al*. 2011*a*). Low levels of individual animal performance simply result in the accumulation of livestock, increased total maintenance requirement over their lifetime and, thus, increased grazing pressure on the grasslands.

Furthermore, in addition to simply improving growth rates, aiming to provide animals for slaughter in prime condition at times when consumer demand and, therefore, prices are highest can have a profound effect on income (Lei *et al*. 2004). In general, yaks and sheep of the Tibetan plateau exhibit high rates of liveweight gain and improvement in body condition with their return to spring pasture, so the most profitable time for slaughter is when they provide prime carcasses, usually during the late summer or early autumn, i.e. from September to October (Liu *et al*. 2005). This advantage, however, is lost if non-productive male animals are not slaughtered in the autumn, and subsequently lose body mass during winter, which they have to recover during the next summer, thus again requiring pasture resources. This is a strong reason for slaughtering animals at a young age, rather than after 2 years. Although there are substantial differences between regions and classes of livestock, there has been a substantial increase in the percentage of livestock offtake annually over recent decades (Fig. 5) (QPBS 2010; TARBS 2010; Long 2011; Sun *et al*. 2011). Of course, in order for any increased supply of animals to the market not to impact negatively on prices, it is important that government organisations work to incentivise the livestock market and promote consumer demand. Inevitably, however, there will be fluctuations in supply and demand, and on the Tibetan plateau where livestock products are in short supply during the winter cold season, there is a need which has to be met from other areas. Bearing in mind the cost of transport, what is required from the livestock industry is flexibility in order to balance supply and demand across large areas, and to source, buy, promote and market livestock products when they are at the peak of condition for the consumer, and provide high prices for the producers.

Lu and Deng (2011) proposed a government-funded monetary solution to the problems created by the seasonal fluctuations in the supply of livestock products to consumers. At the conclusion of their work, they suggested the adoption of a farm-produce subsidy, which they entitled, 'Subsidy to circulation link if price high, and subsidy to production link if low price'. By providing subsidies to those engaged in processing, marketing and consuming agricultural products when prices are too high and financial assistance to farmers when prices are low, such a system could stabilise final prices of products to the consumer and safeguard producers' incomes. Seasonality of supply is inevitable but short- and long-term financial security is vital to the survival of livestock producers and maintenance of the grassland ecosystem.

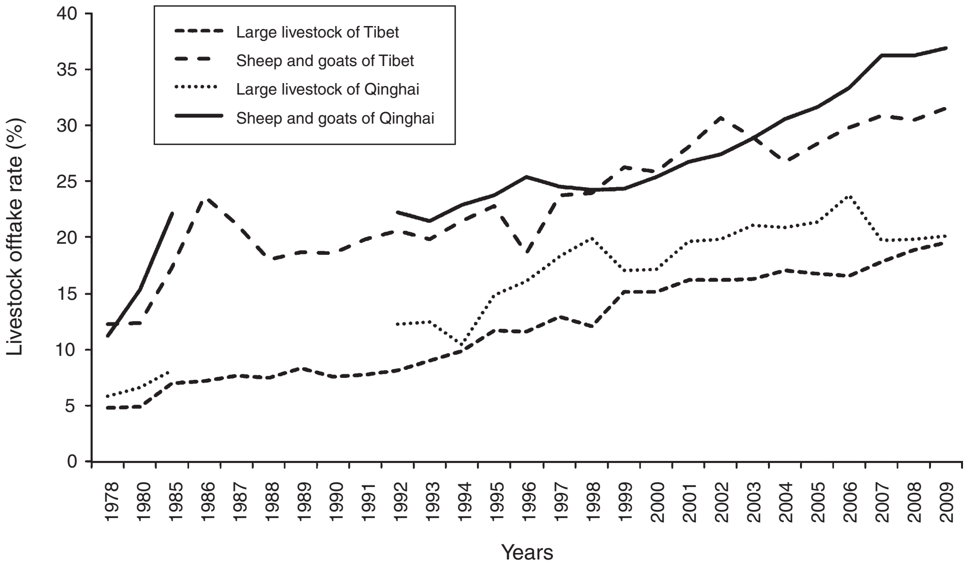

Fig. 5. Changes in annual livestock offtake rate over the period from 1978 to 2009 from Tibet and Qinghai (original offtake rate data from QPBS 2010; TARBS 2010). Large livestock comprise yak, cattle and horses.

Increasing turnover of livestock is a problem for herdsmen rearing livestock on the grasslands due to the longer period taken to reach acceptable slaughter weight and condition, compared with intensively reared animals. The slower and more variable growth rates imposed by the fluctuating nutritional value and seasonality of food supply make planned marketing difficult. While the current turnover rate is higher than it was 20 years ago (Cai *et al*. 1986; Zhao 1987), it is still very much lower than that achieved by the intensive livestock industry (Wu 2005). Such problems are exacerbated due to the difficulty in transporting animals to the livestock markets at various times of the year, due to weather conditions or the remoteness of herds from transport loading points. Although some herdsmen are reluctant to sell more animals, seeing their retention as insurance against winter losses, many are unwilling or unable to do so due to what they see as failings by the transport industry to supply cheap, flexible and reliable loading and delivery of their animals, as and when needed (Sun *et al*. 2011). Such problems lie not with the primary producers but with the transport service, and impose a severe constraint upon the ability of herders to sell their livestock at the most suitable time regarding quality and market demand (Li 2008). Thus, increasing the turnover rate of livestock can only proceed with the simultaneous improvement of transport facilities (Da 2006). Without a marked improvement in the service provided by transporters across the Tibetan plateau, including the more remote areas, the required large-scale improvement in livestock turnover rates will not be forthcoming.

Modifying the reproductive season of livestock (M)

Oestrus, breeding, lactation and rapid growth by young livestock require a higher than maintenance level of nutrition, which, due to the seasonal fluctuations in forage supply on the Tibetan plateau, may be constrained because of the variations in grazing pressure (Luo *et al*. 2010). Livestock (yaks, sheep and goats) on the Tibetan plateau are generally in oestrus from March to November, when adequate nutrition and energy are available from grazed pasture. If they are required to give birth during the winter, then during the previous spring they require an ample supply of forage to ensure a rising plane of nutrition for ovulation and successful implantation. Unfortunately, during the early spring, forage will often be in short supply and there will be increasing competition for these limited resources, from lactating females and young stock (Zi 1995, 2003). During the winter, shortages in forage supply can frequently cause the liveweight of yak and sheep to decline by 25–35%, with even greater losses or death ensuing in more severe cases (Liu 1983) and, in the case of pregnant females, the possible of fetal reabsorption or abortion. For animals required to give birth in spring, the period of feed demand for ovulating females will be in summer, when there is a peak in forage growth to provide ample, high quality forage. Although, after parturition, milk yields will benefit from plentiful supplies of fresh vegetation, if offspring are born later, they may not gain sufficient liveweight to survive the oncoming winter. To reduce forage demand from pastures and facilitate high intakes, it would be prudent to exert some control over livestock breeding in order to avoid forage shortages at vulnerable periods of the animals' breeding and rearing seasons (Liu 1983). On the Tibetan plateau, for most livestock, mating is concentrated towards the end of the season of plentiful forage supply, during the months of August–October (Zi and Zhong 2007). Although it is more difficult to regulate the breeding season of the large animals (yaks) than the smaller ones (sheep and goats), studies of yak reproductive characteristics, hormonal regulation and the effects of seasonal forage dynamics suggest that there is scope for some adjustment to the breeding season by manipulation of forage supplements (Zhang and Yu 2005; Zhang and Zhang 2009). In addition, techniques, including oestrus control and synchronisation and artificial insemination, provide further means of adjusting the reproductive cycle to coincide better with the seasons of peak forage availability.

Further investigation of the interactions between the herbage growing season and the livestock species reared in different areas of the Tibetan plateau should be conducted to provide additional guidance for improving performance of livestock husbandry.

Modifying the structure of livestock groups (N)

The species of livestock, breed and age structure of the herd or flock have a bearing upon the best use of the quantity, quality, and seasonal availability of grazing and supplementary feeds, in order to maximise the production efficiency and turnover of livestock to the markets. Different animal species and herd or flock structures require differing and appropriate management, depending on their reproductive capacity, growth rates and age at which they reach maturity. Similarly, different breeds of the same species may make different use of the same grassland resources with consequences for pasture ecology, product quality and herdsmen's economy (Willems *et al*. 2013). The age structure of the herd or flock is of paramount importance in maintaining the highest possible reproductive capacity and production level for the livestock industry. Commonly, older yak and sheep comprise a large percentage of the number of animals in a herd or flock because the optimum age for marketing animals to maximise turnover and economic returns is 1.5–2.5 years (Lei *et al*. 2004). In fine-wool sheep, reproductive performance at 4.5 years of age provides a reliable indication of whether individuals should be retained for future breeding and improvement of the flock (Li *et al*. 2008). Non-productive, weak and old animals should be culled in order to reduce wasteful use of herbage and forage supplements, and to maximise yield and efficiency of utilisation of feeds (Zhao 1987). However, depending upon the type of animal and desired offtake rate, the ratio of males to females, proportion of castrated males, number of births annually, and number of male and female animals finished for market need to be considered in creating the herd or flock (Lei *et al*. 2004). For example, the optimal ratio of breeding ewes in Qinghai fine-wool sheep flocks is considered to be 60–62% (Wang 1988*a*). The ratio of male yak to female yak is generally below 1 : 15, but a better ratio would be 1 : 18. In the Gannan autonomous prefecture (eastern Tibetan plateau), the current ratio of the number of yak and sheep per household is ~1.15 : 2.02, which appears about optimum for the current condition of grassland and availability of forage supplements (Ji *et al*. 2010). Nevertheless, based on grassland conditions, herders may need to reassess and adjust their animal group structure and adapt their use of forage supplement to maximise economic benefits, utilising the available precision technology for pasture management at different levels (Yang 2012). Careful management of group structure and animal husbandry are the best guarantee of sustainability for grassland-based livestock production (Qin and Zhou 2005).

At present, there is a lack of rational analysis of the whole livestock industry and a cohesive model for dealing with the different animal species and group sizes in the pastoral area of the Tibetan plateau. The use of mixed grazing groups of yak, sheep and other livestock within the different grassland areas needs to be studied, in order to develop models to determine the optimal composition of such groups, because at the level of the individual herd, most consist of mixed animal species (Yang 2012). In addition to producing recommendations for a sustainable livestock group structure and breeding and rearing policies across the livestock industry, there is a requirement for market regulation to service the industry and promote the sale of livestock and animal products (Yue and Hui 2004). Restructuring of the livestock industry on the Tibetan plateau should proceed at three levels: the regional level, equivalent to specific ecological zones; the intensive level, including any livestock fattening centres; and the pastoral herd level. Reorganisation at the regional level should proceed, taking into account the different species and their geographical distributions, local climatic conditions, seasonality and availability of forage, the condition of animals when sold, and the proximity and capacity of marketing centres, in order to develop a comprehensive plan for the livestock industry in that area (Lei *et al*. 2004; Ji *et al*. 2010).

As described in the previous paragraph, at the level of the individual herd or flock, careful consideration needs to be given to the species, age and reproductive structure of the livestock. Such restructuring of the livestock sector is not only important for improving the efficiency of supply of animal products to the consumer but also is vital to regulation of the carrying capacity of the grasslands, maintenance of their ecological hydrological functions, and the economy of the plateau region (Du *et al*. 2000).

Improving the quality of livestock products (O)

Persuading herders to accept the need to reduce livestock numbers depends, to a great extent, upon increasing the value of livestock products in order to maintain their income (Wang *et al*. 2010*b*). While a reduction in supply might otherwise increase per unit price due to scarcity, long-term security of income must be founded upon the production, promotion and marketing of high quality products, for which the consumer is prepared to pay a premium price. Over the previous 10 000 years, the indigenous animals (yak and Tibetan sheep) have evolved to survive the challenges imposed by the high altitude and cold environment of the Tibetan plateau regions, and are better able to digest the fibre contents of the native grasses and sedges compared with other exotic livestock breeds (Richmond *et al*. 1977; Guo *et al*. 2014). The yak is the most representative of livestock from these regions, and the unique features of its many products need to be publicised to develop a vibrant market (Ji 2001). Three main local populations of yak in Tibet produce very high quality meat, milk and wool (Ji *et al*. 2000*a*, 2000*b*, 2001). The protein content of yak meat is ~21–22%, which is proportionately 59% higher than in cattle (*B. taurus*) (Xiong 1999). The fat content of yak meat, however, is only 2–3%, equivalent to ~70% of that found in cattle (Xiong 1999). Yak meat is also rich in vitamin B_1 and B_2, calcium, phosphorus, magnesium, iron, manganese and other mineral elements (Xiong 1999). Essential and non-essential amino acid levels are higher in yak meat than in beef; in particular histidine, glutamic acid, arginine, alanine, aspartic acid and glycine (Jiao *et al*. 2005). Functional fatty acid content of yak milk is between 5.5 and 8.6%, which is higher than in cows' milk (3%). In addition to linoleic acid, other functional fatty acids are more than twice those in cows' milk, including eicosapentaenoic acid and docosapentaenoic acid (Yu *et al*. 2006). It well may be that the forage of the alpine pastures contributes to a particularly high fatty acid quality in yak milk and meat, as is the case for sheep and cows in the European alps (Leiber *et al*. 2005; Richter *et al*. 2012). This gives the extensively produced mountain products a clear advantage over products from industrialised intensive livestock agriculture. Yak hides are generally of inferior quality compared with those of other cattle (*B. taurus*), and the coarse hair fibres are little used outside the local area because of their poor textile quality. Nevertheless, the down fibre of the yaks' coat has become increasingly valued worldwide over recent decades because of its inherent characteristics of softness, lustre and thermal properties (Wiener *et al*. 2003). While the yield of this down fibre is generally low and variable, and represents only a small proportion of the herders' income, there may be opportunities for improvement by utilising breeds selected for their higher fibre yields, such as the Juilong yak (Cai *et al*. 1980). Yak bone has plenty of minerals, which is beneficial for growth in children, and the prevention of osteoporosis in elders (Li and Suo 2002). For the nutritional and therapeutic significance of yak production, there are opportunities for more and in-depth research (Luo *et al*. 2009).

Marketing of the special and unique attributes of animals produced on the Tibetan plateau is essential to improving its livestock industry. This requires not only improved marketing, but also increased investment in research and technology to improve the output and the quality of animals produced in the alpine areas. However, the present overstocking and degradation of grassland is not conducive to improving either quality or output of livestock production. Over the past 50 years, the output of yak and Tibetan sheep products per animal has declined by ~50% due to overstocking and poorer nutrition from the degraded pastures resulting in a reduction in livestock size. A reduction in the number of livestock is crucial to improving the quality of livestock and their products (Long 2003). In addition, the special and unique attributes of animal products from these regions require quality certification. The use of brand marketing should be developed more which can increase the income from and demand for high quality products on the Tibetan plateau.

Intensive livestock industry (P)

The provision of local intensively managed pastures for livestock is important to enable herders to provide sufficiently high intakes, including supplementary feeds, for finishing their livestock and as holding areas before transport, depending upon market demands on the Tibetan plateau (Wu 2005). Previously, the distribution of such pastures was irregular, reflecting the fragmented dispersal of marketing centres. What is required is an orderly provision of such facilities, integrated with the development of regional markets to serve the grassland-livestock industry (Dong *et al*. 2007*a*). Three decades ago, it was suggested that the provision of intensive livestock production facilities is of major importance to the development of the livestock industry on the Tibetan plateau (Wang 1984). The further development of intensive rearing centres to improve the commercial value of livestock should continue to be concentrated in the traditional areas between the pastoral and arable regions, such as those around Qinghai Lake (Zhang *et al*. 2000). The establishment of nationally subsidised, intensive livestock production centres in key grassland-livestock rearing areas, such as the Hainan prefecture in Qinghai province, the Gannan prefecture in Gansu province, and the Lhasa valley of Tibet, will provide useful demonstration centres within major livestock rearing areas. In addition to promoting the intensive livestock industry, the local government should encourage the establishment of dedicated livestock haulage businesses in the townships, and encourage individuals to invest in a variety of additional livestock-orientated businesses, and facilitate the integration of farming and livestock-rearing enterprises (Wen 2000). While it is important that the intensive livestock industry continues to be supplied by animals from the pastoral herds, thereby supporting the extensive rural economies, further development of husbandry methods, feed technology and equipment, and continued exploration and expansion of marketing outlets is needed (Wang *et al*. 2010*b*).

The development of the livestock industry, based on concerns for the ecology and long-term sustainability of the Tibetan plateau ecosystems, provides ample reason and opportunity for the expansion of the intensive livestock-rearing sector as an integral part of it (Xie *et al*. 2005). Rather than considering the pastoral and intensive livestock sectors as being separate, or even in competition with each other, they should be seen as complementary parts of the same system, which, along with their research and development resources, should provide a strong stimulus for sustainable development of the grassland-livestock system. The investment of capital, technology and talent in these enterprises should be seen as an appropriate means of support by the nation and encouragement for the farming industry (Li 2009). Growth of the intensive livestock industry should be encouraged to take place around existing towns with good transport networks, providing ready access for herders and livestock from the grassland herding areas. The proximity of intensive livestock-rearing centres to townships will also provide a flexible source of labour necessary to meet the seasonal fluctuations in demand, depending on the throughput of animals. With national support, investment and facilities should be provided, extending from the herdsmen's level, through intensive livestock-rearing units, to the slaughtering and marketing facilities, in order promote animal trading to increase the turnover of livestock from grassland to market (An *et al*. 2002; Li 2011*a*).

Ecological-economic win-win model for household pasture (Q)

Within the overall grassland-based livestock rearing system, at the level of the individual herd, the household pasture provides the basic integrated unit of production (Li and Ding 2006). On the Tibetan plateau, household pastures are important in that they provide a combination of both natural grassland and cultivated grassland, in which the proportion of cultivated grassland is high. Although, large areas of cultivated grassland are difficult to establish, they can be achieved by reclamation of degraded grassland, following the practice of sowing various forages according to the procedure originally developed for restoration of 'bare-land' degraded grassland in Qinghai province (Ma and Lang 1998; Ma *et al*. 2002; Yang 2007). Success depends upon the initial important steps of securing funding for support and management of cultivated grassland and the cooperation of the herdsmen. The key incentive towards this end is that restoration of degraded grassland can provide a direct economic benefit to those involved (Ma and Lang 1998; Li 2001). The final goal of this model of household pasture improvement is increased production of forage from the cultivated grassland and reduction of the grazing pressure on the natural grassland (Ma *et al*. 2007*a*). Thus, the cultivated grassland has two economic functions, to provide forage for mowing and conservation in the summer, and provide grazing in the cold season. While the conserved forage provides feed for use during the winter, the availability of cultivated pastures for winter grazing can delay the movement of livestock onto the summer pasture and allow their earlier return. Implementation of this model can achieve the aims of providing both ecological and economic benefits to herdsmen, in a win-win situation (Ma and Lang 1998; Shang *et al*. 2006).

There are four crucial concerns which have to be resolved in order to achieve the success of the win-win model for establishing household pastures on the Tibetan plateau. First, significant investment is required for the initial facility, cultivation and sowing of pastures. Second, households that has a proven record of good grazing management and animal husbandry need to be recruited to the scheme. Third, herders need to have a positive attitude towards collaboration with others herders and local managers. Finally, a long-term and professional research team is required to provide technical support. The research team of Qinghai Academy of Animal and Veterinary Science has successfully established this model over the past 10 years and has encouraged many local herders to adopt this model of production in Maqin County. While the initial establishment and growth of pastures may present difficulties, once established, they can very soon provide benefits for the livestock and herders. Another benefit has been that herders have not had to reduce their livestock numbers and have actually increased their income. Thus, by using investment from central government and a combined model of 'top-down' approach to ecological restoration and 'bottom-up' approach to livelihood improvement, together with advice from local research teams, herders have been rewarded and incentivised by their increased incomes (Kemp *et al*. 2013). The success of this model has brought encouragement and confidence for development of a sustainable grassland-livestock industry. Further work is required to encourage more herders to participate in long-term establishment of cultivated grassland.

Development of alternative enterprises to supplement herdsmen's income (R)

The development of alternative industries to livestock rearing provides opportunities for herder's families to supplement their income from other sources, thereby reducing their reliance on the grassland-livestock industry (SDTG 2003). There is a variety of unique industries available which can provide alternative means of income (Bao and Zhang 2005; Sun *et al*. 2012, 2013). On the basis of ecological and economic characteristics, Zhong (2003) divided Tibet into nine zones, each possessing unique resources for the development of local industries to support the economy of the country. For many years on the Tibetan plateau, herder's incomes have been almost entirely dependent upon the livestock industry, with livestock-derived income representing more than 80% of the economy in pastoral areas. However, a major and increasing source of additional income has been generated from the collection of natural organic resources, especially of the Chinese caterpillar fungus (*Ophiocordyceps sinensis*). Although the caterpillar fungus has been used in Tibetan medicine for many centuries, the dramatic increase in its market value over the past 15 years has contributed considerably to the income of herders' families. Between 1997 and 2004, the price paid to pickers increased by 350%, making it the major source of income for many households and accounting for an average of 40% of rural cash income in the Tibetan Autonomous Region (Winkler 2008).

As Winkler (2008) points out, the benefits of this alternative grassland resource to rural families are that they have the intimate knowledge of where it is likely to be found, they have access to the grasslands where it occurs, and there is no need for capital investment. As well as providing household incomes, both livestock rearing and the collection of the caterpillar fungus are reliant upon grassland conditions (Chen *et al*. 2001; Li *et al*. 2004). Thus, their management for the long-term survival of both enterprises is of paramount importance (Wang and Wang 2011). While it is in the interests of herdsmen's families to protect the grasslands from over-exploitation, the sale of permits to local pickers, while generating income for the licensing authorities, has done little to restrain collection due to illicit harvesting by non-herding families.

The unique environment and climate of the Tibetan plateau has created an unequalled natural resource, within which there is great potential for further development (Du and Zheng 2008; Sun *et al*. 2012, 2013). With sound development and utilisation of these resources, the rural households of the Tibetan plateau can contribute significantly to the economy of the area and improve the welfare of the indigenous population (Ding 2008). Exploitation of specialised local products, such as the caterpillar fungus used in traditional Tibetan medicine, requires stringent planning and control for their sustainable management. Recently, because of the high market prices paid for the fungus, over-exploitation has caused considerable damage to grasslands due to digging, even exceeding that caused by overgrazing in some areas. Without adequate controls, the increasing demand and prices paid for this commodity will result in further extensive damage to its native grasslands. What is required is an integrated plan, based on data obtained from rigorous investigations similar to that conducted in the Naqu region on the distribution of the caterpillar fungus (Jin *et al*. 2010). In addition to the contribution made by the fungus to Tibetan medicine, research should be conducted into the efficacy of other natural resources used in traditional remedies to allow further development as a source of income. Recent decades have witnessed a growing interest and demand for Tibetan ethnic products, not only from within China, but worldwide. Products including paper, textiles, jewellery, metalwork, bone and Tibetan hardwood items provide an opportunity for manufacture on a range of scales.

The development of a speciality, ethnic and cultural industry for Tibetan products, may play a key role in the sustainable development of the economy and culture on the Tibetan plateau (An 2005). However, while adoption of an increasingly sedentary lifestyle would seem to favour small-scale handicraft manufacture, the problems of starting up such enterprises are many. Among many pastoral households illiteracy and the lack of knowledge of market demand, production techniques, business and merchandising practices, and poor access to investment capital and markets, present insuperable barriers. As a result, such opportunities as present themselves are frequently taken up by economic migrants from densely populated areas, rather than benefiting the indigenous rural household members (Bauer 2005). The unique ecology and culture of the Tibetan plateau will undoubtedly continue to attract visitors to the area. However, even with the investment that a growing tourism industry may attract, the benefits of this income are unlikely to reach far into the pastoral communities of the Tibetan plateau.

Redesigning the nomadic model of pastoral industry (S)

Nomadic pastoralism has provided a sustainable, albeit at times precarious, livelihood for the occupants of the Tibetan plateau for centuries without causing degradation of the grassland ecosystem (Bao 2005; Harris 2010). The degradation of pastures, prevalent in recent decades, is frequently and erroneously interpreted as a consequence of 'backward' practices of nomadic herdsmen (Fig. 6*i*). An investigation into the impact of different state-sponsored policies on grasslands across inland areas of Asia concluded that areas, such as Inner Mongolia, which had retained nomadic pastoralism, reported much lower levels of pasture degradation than those that had promoted more sedentary models of livestock farming (Sneath 1998). Rather than being due to any fault of the nomadic model of pastoral livestock husbandry itself, the increased grazing pressure on grasslands has been a consequence of the increased pressure of population growth. With the reduction in infant mortality, many more children are reaching adulthood and establishing their own flocks and herds. Between 1951 and 2005 the livestock population of Tibet alone has risen 10-fold, to 50 million (Bauer 2005). Thus, the recent problems of overgrazing lie not with nomadic pastoralism *per se* (Gao and Wang 2009). The nomadic model has a long history and proven output of animal production from these high altitude pastures, and should be retained, along with the accumulated wisdom of herding families, in order to solve the current problems of the grassland-livestock system.

The predominant current model of nomadic herding is one of 'half-settlement', in which there is a seasonal transfer of humans and livestock between permanent winter and temporary spring, summer and autumn settlements (Fig. 6*ii*). Such a pattern is more popular with the younger generation, who prefer to live in towns, rather than adopt a purely nomadic existence, and provides easier access to alternative employment and education (Fig. 6*iii*). Nevertheless, due to increased pressures on livelihoods caused by environmental degradation, economic migration has led to a decline in the numbers of herders in recent decades (Gai *et al.* 2005). Ultimately, of course, if economic migration was to continue to increase it could lead to a reduction in the number of young experienced and innovative herdsmen on the grasslands, and problems regarding the sustainability of the

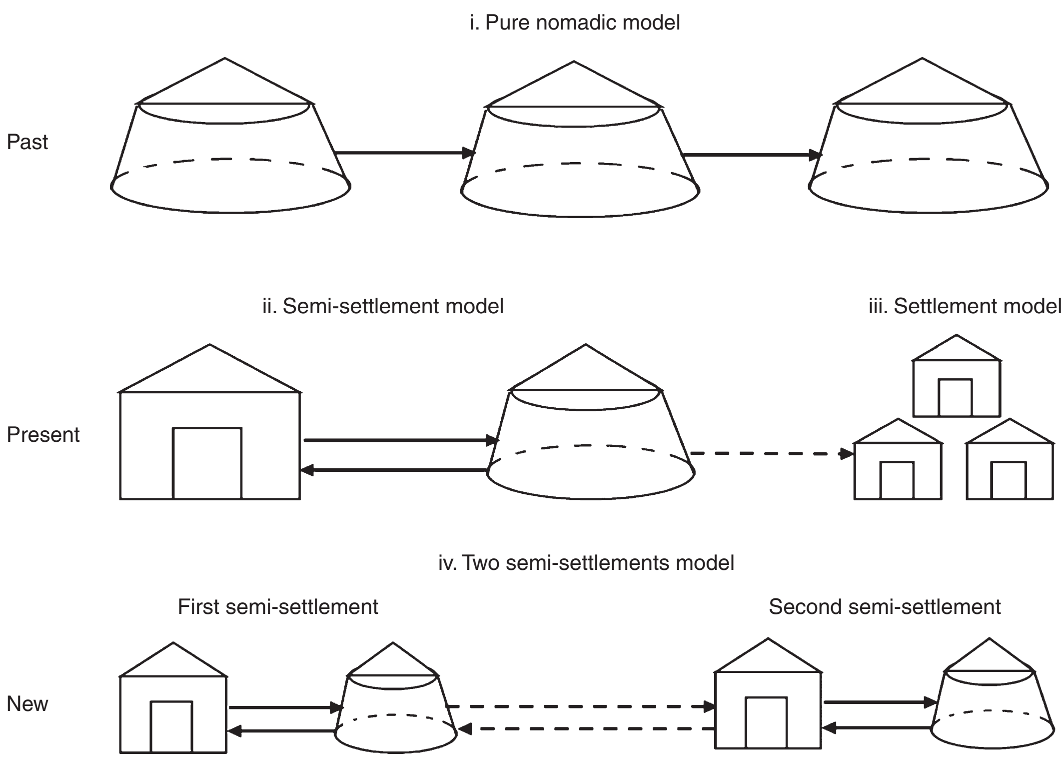

Fig. 6. The historic, present and proposed 'new model' of nomadic grassland-livestock herders' settlements. Notes: in the pure nomadic model (i) the frequency of movement and duration of encampments depends upon grassland conditions. In the semi-settlement model (ii) having spent the winter in permanent accommodation, herders and their livestock move to higher pastures for several months of the year, with some family members travel to find alternative incomes in urban areas. The proposed two semi-settlement model involves households moving between two permanent and semi-permanent sites for periods of 3–5 years depending on grassland conditions.

grassland-livestock industry would be the consequence. Nevertheless, the present trend for more pastoral households with smaller herds and land areas available to them is exacerbating the problem of grassland degradation (Gai *et al*. 2005) and leading frequently to problems of inbreeding within herds (Zi 2003). As an investigation into the effects of earlier government policies promoting household enclosures as a means of increasing pastoral productivity in Inner Mongolia concluded, contrary to expectations, such policies had in fact contributed to land degradation (Williams 1996).

Grazing management needs to operate over larger spatial and temporal scales in order to allow greater movement of animals and utilisation of more distant spring and summer pastures, thereby reducing grazing pressure on grasslands closer to centres of habitation (Fig. 6*ii*). We recommend, therefore, a reversal of the trend towards more division and fencing of the grassland, and the removal of fences, and the merging of small areas of grazed grassland held by individual households to create larger pastures for rearing livestock on a more extensive scale. With larger combined herds, the labour required to move animals long distances to alternative grazing pastures could be reduced by economies of scale. Moreover, the removal of the physical constraints imposed by fencing and small area ownership will increase the seasonal mobility of herdsmen and their animals. Transhumance has for centuries allowed the nomadic herdsmen of these regions to withstand annual and seasonal fluctuations in climate and plant growth. We think, also, that the model of livestock enterprise-herdsmen should be encouraged in order to increase the turnover of livestock from grassland to market.

Nevertheless, the present trend for more households (with smaller herds and land areas), making livestock management slightly easier is seriously exacerbating the problem of grassland degradation by long-term settlement in single, relatively confined areas (Gai *et al*. 2005). With such large increases in the overall numbers of livestock grazing many of the grasslands at present, the opportunities for pastures to recover from overgrazing are few (Wang *et al*. 2005*a*, 2010*a*). Lu and Deng (2011), in their consideration of China's 'Western Development Strategy', concluded that the most effective solution to increasing farmers' profits is to further reform the system of dual-ownership of land in rural areas. By allowing land to be used for investment and/or operation in various patterns, they suggest that farmers will be able to obtain additional profits from intensive and large-scale operation of land. To limit degradation and allow recovery of degraded pastures, in addition to enlarging the spatial scale of livestock rotation, we need to increase the temporal scale. We suggest that rather than operating a simple seasonal rotation every year from a semi-permanent settlement (Fig. 6*ii*), herders should operate a long-period rotation of 3–5 years in first semi-settlement, then move to a second semi-permanent settlement area to operate a second long-period rotation, again for 3–5 years, before moving back to the first settlement (Fig. 6*iv*). The problem, understandably, is how to operate such a radical change in grassland management and to gain the support of herding families to implement it. For herdsmen to have to move between two semi-permanent settlements every 3–5 years, in addition to their seasonal transhumance, is not an easy option (Zhao 2007). Considerable investment would be required to build second semi-permanent settlement villages with sufficient amenities to attract pastoral herdsmen and their families to facilitate such ecological migration.

Discussion

Two national plans ('Ecological livestock industry' and 'Construction of ecological safe shelter zone') have been proposed and implemented in order to establish an ecologically sound livestock industry and an ecologically safe shelter zone on the Tibetan plateau. The plan to develop the livestock industry is aimed at solving the problems of grassland degradation and improving the livelihoods of herdsmen, with support from national investment. This is to be achieved through systems engineering, quality enhancement and development of unique products in order to reduce reliance on the 'quantity' model of livestock breeding by herdsmen, and through improvement to the infrastructure and marketing mechanisms to drive the economic development of the pastoral regions and gradually reduce the pressure on grasslands (Hou 2010). The establishment and maintenance of the ecologically safe shelter zone on the Tibetan plateau will focus on grassland restoration and improvement of the area's ecological functions, continued provision of suitable habitats and environments for maintenance of the biodiversity particular to the Tibetan plateau (Zhong *et al*. 2006; NDRC 2009). By promoting the livestock industry to improve the livelihood of herdsmen and safeguard the ecological function of the grasslands, respectively, the national project should contribute considerably towards the development of a sustainable grassland-livestock system. Incorporation and implementation of the 19 pathways within national projects will provide the technologies for their execution.

The development of a sustainable grassland-livestock system is dependent upon the application of numerous technologies targeted at safeguarding and improving three basic functions, i.e. ecological, livelihood and social-cultural functions (Long 2007). The 19 pathways, by which we propose the future of the grassland-livestock industry should be secured, target these three functions. With the exception of the final pathway proposing redesign of the nomadic model of the pastoral industry, numerous research studies and demonstrations of the other 18 pathways have been conducted on the Tibetan plateau. The results of these exercises have already established the benefits to be derived from their application, thereby justifying their implementation. The final pathway, requiring the establishment of two semi-permanent settlements, is aimed at reducing the detrimental impact of over-stocking on grassland degradation, but will also impact upon the nomadic way of life and ecological migration. However, such a revolutionary approach requires research in order to examine, not only its impact on the grassland ecosystems, but its effect on livestock enterprises and marketing, household income, ecological migration and its acceptability and implementation by pastoral farming families (Komarek *et al*. 2012).

In the preceding sections we have summarised 19 pathways (A–S), reviewing their present status and suggesting further investigations which need to be undertaken. Figure 7 provides a schematic representation of the 19 pathways to illustrate their relationship within four target areas (namely: grassland-forage, livestock, economy and market, society and culture), and the order of priority in which they should be implemented by herders

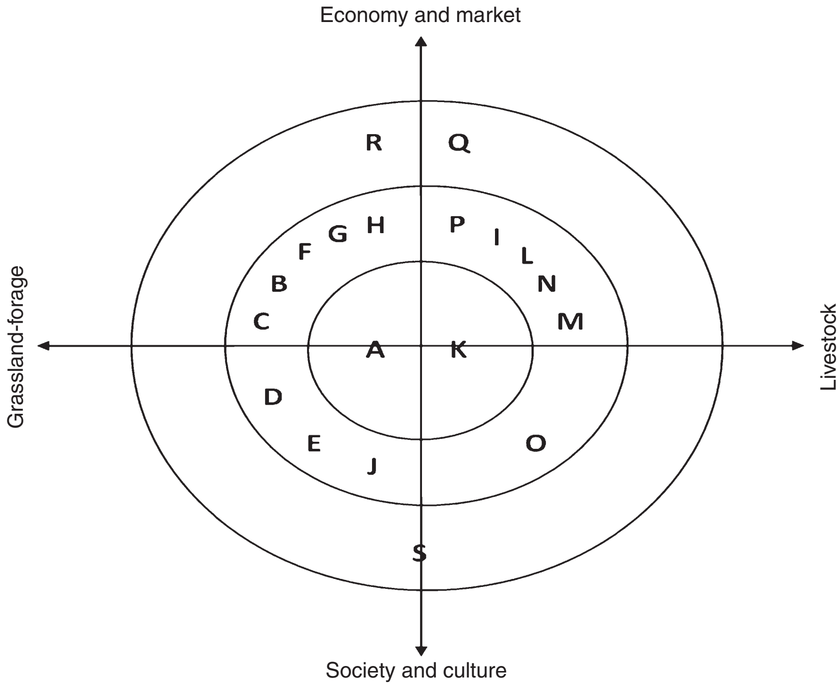

Fig. 7. Schematic representation of proposed pathways (A–S), their relation with four target areas (grassland-forage, livestock, economy and market, society and culture).The inclusions of the 19 pathways (A–S) in small, medium and large circles indicates the order in which they should be implemented by herders and governments; first, second and third, respectively. Meaning of abbreviation from A to S in the model: A – restoration of degraded grassland; B – establishing large areas for production of sown forage; C – forage production within animal sheds or greenhouses; D – mowing forage in alpine wetland; E – forage production in cold desert areas; F – forage production from forage-crop rotation systems; G – straw processing for forage; H – transporting forage from arable regions; I – feed blocks; J – establishment of regional and local forage reserves; K – reducing stocking rate; L – increasing annual livestock offtake; M – modifying the reproductive season of livestock; N – modifying the structure of livestock groups; O – improving the quality of livestock products; P – intensive livestock industry; Q – ecological-economic win-win model for household pasture; R – development of alternative enterprises to supplement herdsmen's income; S – redesigning the nomadic model of pastoral industry. A full description of A–S is given in the text.

and governments. The relative distance between the letters (A–S) and their proximity to the axes represent the closeness of their relationships with each other, within the overall context of the grassland-livestock economy of the Tibetan plateau. Clearly, none of the pathways acts in isolation and all are interrelated to varying extents, thereby benefitting to varying degrees both grassland-forage and livestock production. For example, the establishment of regional and local forage reserve systems will directly impact upon both grassland forage and animal production. For each of the pathways to provide maximum benefit towards the development of a sustainable grassland-livestock industry, and long-term security for the ecological, livelihood, and social-culture function of the all-important Tibetan plateau ecosystems, a full and integrated implementation of some the pathways is required.

Increases in livestock numbers and over-grazing on pastures in recent decades have inevitably contributed to increased greenhouse gas emissions, the most potent of which is methane (Bolan *et al*. 2004; Bilotta *et al*. 2007). In addition to the enteric methane emitted by ruminants, overstocking leads to loss of vegetation, soil degradation and desertification of grasslands, all of which release amounts of methane and CO_2 into the atmosphere. Thus, reductions in livestock numbers and the damage caused to pastures are required in order to reduce their contribution to atmospheric methane and global warming (Rui *et al*. 2011), which are already contributing to shrinkage of the Himalayan glaciers and a reduction in the hydrological function of the Tibetan plateau.

Implementation of each of the suggested pathways will contribute directly or indirectly to a reduction of greenhouse gas emissions. Most notably, reduction of livestock numbers and increased offtake rate will immediately reduce enteric gas emissions and, by reducing grazing pressure, help prevent degradation of grassland vegetation and soils, even allowing the relatively rapid regeneration of slightly- and moderately degraded grassland. Research conducted on the Tibetan plateau, has shown that much of the grassland degradation can be reversed by reducing the pressure from grazing livestock. Further demonstrations have confirmed that early intervention and the reduction of such interference provides the cheapest and most effective way of restoring grassland systems (Gao *et al*. 2010). Nevertheless, to maintain the integrity of grassland ecosystem function, there needs to be a wider focus than simply on reducing grazing in order to reduce disturbance from human activity.

For centuries humans have sustained a nomadic livelihood following their herds between the different alpine pastures during the course of each year, with little impact on the ecological functions of the grassland ecosystems of the Tibetan plateau. However, in recent decades, in their quest to achieve a higher standard of living, they have started to damage those functions, with the likelihood of an accelerating incidence of ecological disasters and emergencies in the future (Bain 2010). The development of alternative sources of income, together with access to the necessary technology and marketing outlets, is required in order reduce householders' reliance on their livestock as the sole means of income, and thereby reduce herd sizes and overgrazing of grasslands (Gao *et al*. 2009; Dong *et al*. 2011). The provision of transient labour by family members has long been an alternative source of income for pastoral households. However, it is reliant upon the continued requirement for such labour. The expansion of townships and increasingly sedentary lifestyle of farming households may provide sources of temporary employment but is does lead to increased competition for such labour once development reaches completion. It is important that any reduction in livestock-derived income does not result in a fiscal vacuum leading to economic migration, depopulation of the grasslands and the loss of husbandry skills accumulated by generations of pastoral herders. Responsible management of the grasslands with grazing herds is essential not only for continued livelihood of a large proportion of the rural community but to the sustainability of the ecological functions of the Tibetan plateau. Without the presence of future generations of herdsmen to manage livestock numbers at levels sufficient to maintain the grasslands, the possible consequences to the environment could be as equally catastrophic as overgrazing.

The resilience of these grass- and sedge-rich grasslands is very much dependent upon the presence of grazing livestock, albeit in lower numbers than at present. As already pointed out, temporary withdrawal of livestock from slightly- and moderately degraded pastures will in many instances be sufficient to allow recovery, whereas greater intervention in the form of weed eradication, reseeding and rest from grazing will be required where pastures have become seriously degraded and weed-infested. Revegetation of bare soils (black soils), while not irreversible, requires greater and more long-term intervention (Ma *et al*. 2007*a*). Nevertheless, after the vegetation cover and species composition of damaged pastures have been restored, moderate grazing pressures are required to maintain them.

For the successful implementation of the 19 pathways and the development of a sustainable grassland-livestock system, support is required by the creation of national policies and legislation incorporated into the government's long-term plans of operation (Wang *et al*. 2010*a*). However, government investment in long-term, top-down approaches is invariably expensive and less effective in tackling the problems facing pastoral livestock producers in grassland areas (Dong *et al*. 2011). Little can be achieved on the grasslands without the active support and co-operation by the plateau herdsmen. What the herdsmen need is the provision of sound, research-based advice on the implementation, risks and benefits of adopting new practices, and financial aid in the form of low-interest loans or grants, and the willing adoption of techniques and demonstration of the benefits by pioneering herdsmen within their localities (Cao *et al*. 2011). For example, researches, followed by demonstrations of the technology and benefits to be derived from the win-win model for household pasture production, have resulted in its enthusiastic adoption by herdsmen in several areas. While the government has provided subsidies to meet some of the costs of planting forages and for processing feeds in pastoral areas, an additional indirect incentive for local herders to adopt some of the aforementioned pathways has been the relatively lower cost of home-produced conserved forages compared with the cost of buying hay from market in the cold season, which in recent years has been ~2–3 RMB per kg fresh hay (Zhao *et al*. 2010*b*; Liu *et al*. 2012). On the Tibetan plateau, as so often in farming communities elsewhere, the benefits derived by pastoral households implementing new technology, provide powerful displays for others to follow suit.

It is important that the experiences and values of traditional cultures are not overlooked in the adoption of new management practices; not least because of their important role historically in the enduring development of the nomadic grassland-livestock industry on the Tibetan plateau (Long *et al*. 2008). The traditional concepts of husbandry industry on Tibetan plateau focussed on two main aspects. First, livestock played an integral part in the life of the Tibetan people living in desolate grasslands, providing both the sustenance and fabric of their daily lives. Second, the numbers of livestock provide a symbolic measure of a family's wealth, even though they may never be converted into hard currency. However, with the development of the local economy and society within the context of the national and global economy, the grassland-livestock system of Tibetan plateau faces increasing challenges and the need to update production and marketing strategies. Under the influences of climate change and growth in of human population, the requirement to update the grassland and livestock production and the choices available provide considerable dilemmas (Fang *et al*. 2011; Haynes *et al*. 2014). The distribution of the various livestock species across the plateau differs depending upon to their preference for and availability of different grassland types across the terrain. For example, the yak is more suited to living in the high meadows, whereas sheep are better suited to living in lower grassland areas and goats prefer the dry area (desert). Nevertheless, for much of the time in many areas, yak and sheep graze together in mixed herds. Problematically, however, due to increased temperatures on the plateau, some herders are ceasing to breed yaks, which prefer the alpine (*Kobresia*) meadows and colder areas, and replacing them with sheep or goats.

An important reason why herders keep large numbers of animals, even to the detriment of their pastures, is as an insurance against the devastating losses of animals which can occur during snow disasters. Herders hope that with large numbers of livestock, at least a sufficient number will survive the severest of winters to provide a breeding nucleus from which to rebuild their herds or flocks (Shang *et al*. 2012). However, for several decades, with improvements in pasture management and feed supply, the animal industry has been more resilient to seasonal shortages in feed availability, reducing the need for excessive herd sizes (Kemp *et al*. 2013). A joint-industry model of several or more households in a locality pooling their resources has also proven an effective means by which to tackle the variation of market, climate, and grassland production, and implement sustainable management protocols in many areas of the plateau, but requires good organisation and economic management (Kemp and Michalk 2011).

While the win-win model has proved successful in some areas, the implementation of this and other pathways, requires continuing coordinated support from researchers, professionals, practitioners and policy makers (Dong *et al*. 2011). To maintain the greatest possible cost-effectiveness for government investment in the grassland economy of the Tibetan plateau, the emphasis has to be on co-ordination between these different strata. While researchers need to conduct investigations into the impact of husbandry practices on the grassland ecosystems, they need to consider the experiences and concerns of the grassland communities. Similarly, policy makers need to consider not only the needs and impact of changes on individual pastoral families, but safeguard the economy and social structure of the entire population of Tibetan plateau. Thus, what might be considered a more 'bottom-up' approach to implementing these pathways is required to demonstrate to herdsmen the need for mutual co-operation to achieve the desired long-term benefits (Kemp *et al*. 2011*a*, 2011*b*; Shang *et al*. 2012).

From the summaries of current status and future requirements of the 19 pathways, it can be seen that attention should focus on the investigation of natural and social issues in the grassland-livestock system. A further important requirement is the establishment and conservation of genetic collections representative of as many plant and animal populations from grasslands of the Tibetan plateau as possible. Continued development of the technologies required to implement the various pathways should be of continuing concern. Poor implementation of previous strategies to rectify the problems of the grassland-livestock industry has, in the past, frequently been a cause of failure of projects. Therefore, ongoing monitoring and evaluation of the suitability of technology should be pursued, with follow-up and feedback from livestock practitioners given due recognition in order to improve the variety of techniques, their strengths and resource requirements, and their adaptation to local problems within the system.

Which, when and how many pathways should be implemented by herders, managers, and governments depends on many factors, such as their willingness, social and economic conditions, and policy and marketing, but must follow two overriding basic principles: (1) to be adapted according to local conditions and not simply applied without consideration of such conditions; (2) implementation should be sensitive to previous practices and be conducted on the basis of voluntary implementation by the herders (Wang *et al*. 2010*a*). While further research and technological innovation are needed for successful implementation and integration of the 19 pathways into an overall strategy for resolving the problems of the grassland-livestock system on the Tibetan plateau, it should not be assumed that any rigid formula will provide a definitive solution for a sustainable livestock sector on the grasslands. Flexibility in implementation across the region and the continued requirement for rigorous scientific research will be required to underpin adaptations needed to safeguard the livestock industry, ecological functions and social structure on the plateau against a background of climate change. Research is required to tackle not only the presently perceived problems of grassland and soil degradation, but future perturbation to the delicate balances between livestock, vegetation, soil structure and socioeconomic stability of the region. As evidenced by recent research (Dong *et al*. 2011; Rui *et al*. 2011), it would be naive to neglect the effects of global warming on even the most basic of livestock-vegetation-soil relationships.

Finally, we have to acknowledge that, while human activity on the plateau grasslands is part of the problem of their sustainability, their presence is also vital to the implementation if any solutions. While some economic migration may be necessary to alleviate the economic and social pressure on rural communities, the provision of sustainable livelihoods for the remaining pastoral households is essential to guaranteeing the development of a sustainable grassland-livestock system (Zhang *et al*. 2008). The guarantee of adequate household incomes should always be seen as a priority for maintenance of the productive and ecological capacity of the rural grassland communities and the surrounding urban conurbations.

Conclusions

The overriding problem of the grassland-livestock system is the conflict between grassland and livestock, which has multiplied in recent decades and has become a huge threat to ecological security and livelihood of the indigenous population, increasing the critical challenges of sustainable development on Tibetan plateau. Based on the experience of Chinese researchers in grassland-livestock systems over many years, we propose a solution incorporating a range of 19 strategies, involving grassland, forage and livestock management, the agricultural by-product industry, marketing and social culture, all of which require some projects or plans combined with more pathways in order to provide a gradual, but more effective integrated solution to the problem. From government to herdsmen, we should strive towards sustainable development at grassland, forage, livestock, industrial, economic and social-culture levels through the adoption of appropriate changes and technologies.

The implementation of these pathways is crucial to the success of two existing plans for the establishment of an ecologically sound livestock industry and the construction of an ecological safe shelter zone on the Tibetan plateau. In addition to further scientific investigation, where the required knowledge is absent, a continual monitoring and review of the progress of these reforms in grassland, forage, livestock, industry-economy and socio-cultural aspects will be required throughout their implementation. Attention should also be paid to the conservation and improvement of genetic resources and their deployment throughout the pastoral livestock sector. These various pathways should be recognised and incorporated in policy development by government. For successful adoption of these pathways across the pastoral livestock industry, a primary goal should be to ensure the livelihood of herdsmen and their families in order to encourage their active participation and endorsement.

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