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Review

Characterisation of locoweeds and their effect on livestock production in the western rangelands of China: a review

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Abstract. The rangelands of China are an important resource for livestock production, and play a strategic role in maintaining ecosystems and protecting the living environment of humans. Drought, overgrazing, infrastructure development, insufficient investment and poor management of rangelands have led to the invasion and spread of poisonous weeds in these rangelands in recent years. The rapid spread of poisonous weeds over the last few decades have caused a series of ecological problems, including a decrease in biological diversity and consequent desertification, and they are seriously affecting the ecological balance of rangelands, and the sustainable livestock production. Locoweeds, which belong to the genera *Oxytropis* and *Astragalus*, are an important species of poisonous legumes in the western rangelands of China, causing large economic losses. This review summarises the species and their ecological distribution, the toxic ingredients, the poisoning mechanism of locoweeds and damage control techniques for locoweeds. It attempts to highlight certain issues relating to research on locoweeds and how they are being tackled in order to understand the significance of locoweeds in preserving ecosystem diversity and the steps that require to be taken to control the spread of locoweeds in the western natural rangeland of China.

Additional keywords: biological diversity, damage control techniques, desertification, poisonous weeds, toxins.

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Introduction

Rangelands cover 393 million ha in China, equivalent to 41.7% of the country's total land area. About 85% of these rangelands are located in western China (Ministry of Agriculture of PRC 1996). Rangelands are an important resource for livestock production. They are also strategically important for China in preserving ecosystems, as well as protecting the living environment of herdsmen. In recent years, natural and human factors, such as climate change, drought, overgrazing, land reclamation and population growth, have led to a loss and degradation of the rangeland ecology. There has been a marked drop in plant community cover, a decrease in biological diversity, a decline in high-quality forage production, and an increase in the area of poisonous weeds. Currently, 90% of once natural rangelands have degenerated to varying degrees, 30% of them are already severely degraded, and this degradation is continuing at a rate of 2 million ha annually (Yao 2003; Zhang and Yan 2006). Invasive poisonous weeds of rangelands result in outbreaks of poisoning in livestock, which in turn causes serious economic losses to livestock production and restricts sustainable development. The poisonous weeds of the rangelands of western China have been reviewed recently by Lu *et al*. (2012) but this review focuses on one of the main groups of species, the so-called locoweeds.

Locoweeds are poisonous legumes that belong to the genera *Oxytropis* and *Astragalus*. After ingesting these toxic plants, livestock can develop diseases characterised by chronic dysfunction of the nervous system driving livestock crazy. Hence, these plants have acquired the name, 'locoweeds' (Zhao *et al*. 2008; Rong *et al*. 2010). In recent years the cover of locoweeds has been increasing continuously and locoweeds are becoming an increasing threat to livestock production in the western rangelands of China. Relevant data show that there are 46 species of locoweeds present in the western rangelands and they cover over 110 million ha, representing 3.3% of the western rangelands of China leading to a large economic loss (Lu *et al*. 2012). This review summarises the research history on the species and their distribution, the toxic ingredients, mechanism of toxicity of locoweeds, and finally the damage control techniques of locoweeds in the western rangelands of China. We also discuss some gaps in locoweed research while reviewing the significance and ecological functions of locoweeds in rangelands, and provide a theoretical basis for the rational development and utilisation of these plant resources.

Definition of locoweeds

'Locoweed' is not a scientific term in plant classification. The origin of the term, locoweed, can be traced back to the Spanish word '*loco*,' which was used to describe the apparent symptom of 'craziness' in livestock. Livestock fed on certain poisonous plants, suffered from a toxicosis characterised by chronic neurological dysfunction, making livestock act in a crazed manner. Thus, this type of poisonous plant was generally termed a 'locoweed,' and the poisonous disease was called 'locoism' or 'loco disease' (Marsh *et al*. 1919). Poisoning by an *Astragalus* plant was first reported in 1873. Subsequently, poisoning by an *Oxytropis* plant was reported in 1883. Poisonous plants of these two genera can cause loco disease (Crawford 1908; James *et al*. 1967). In the early 20th century, scientists put forth the idea that poisonous plants belonging to the genera, *Astragalus* and *Oxytropis* should be called 'locoweeds'. Most national and international scholars, until the late 20th century, supported this viewpoint (Marsh 1909; Mathews 1932; James *et al*. 1967).

Swainsonine was found to be the main toxic ingredient of locoweeds (Tulsiani *et al*. 1984). Further research, however, revealed that not all poisonous plants from the genera *Astragalus* and *Oxytropis* contained swainsonine. *Astragalus* and *Oxytropis* plants that did not have swainsonine could also cause poisoning in livestock, and these livestock did not show the characteristic symptoms of locoism (Burrows and Tyrl 2001). Swainsonine was also discovered in some non-leguminous plants, and livestock that ingested these plants presented with symptoms of locoism (Colodel *et al*. 2002; Dantas *et al*. 2007). Therefore, locoweeds are *Astragalus* and *Oxytropis* species that cause locoism as a result of the species containing swainsonine.

Research history of locoweed poisoning in China

The earliest report that locoweeds could cause poisoning of livestock in China was by Ren (1954), who reported that *Oxytropis hirta* and *Astragalus* species caused poisoning in the rangelands of north-west China. Since then, reports of poisoning of livestock by locoweeds have increased each year and have attracted extensive attention. Studies of locoweeds and poisoning of livestock by locoweeds may be divided into three stages: (1) research on locoweeds; (2) identification of toxins and mechanisms of toxicity; and (3) control and prevention of poisoning of livestock.

The first stage of research on locoweeds was from the 1950s to the late 1990s. Identification of species, distribution, and damage caused by locoweeds were identified during this stage. Many papers reported poisoning of livestock by different locoweeds in different provinces of China in quick succession. For example, Li and colleagues reported livestock poisoning by *O. glabra* in the Inner Mongolia Autonomous Region and Xinjiang Uygur Autonomous Region (Li and Liu 1978; Li *et al*. 1980). Zhang *et al*. (1981) reported poisoning by *O. kansuensis* in Qinghai province (Zhang *et al*. 1981). Lu and Wang (1982) reported poisoning by *Astragalus strictus* and *O. serioopetala* in the Tibet Autonomous Region. Xiao (1986) reported poisoning by *O. kansuensis* in Tianzhu county of Gansu province. Cao *et al*. (1986), reported poisoning by *O. glabra* and *O. ochrocephala* in Yulin city of Shaanxi province and Haiyuan county of Ningxia Hui Autonomous Region, while Huang *et al*. (1992), reported poisoning by *A. variabilis* in Gansu province. Chen and Sa (1992) reported livestock poisoning by *O. glabra* and *A. variabilis* in the Alasan League of Inner Mongolia Autonomous Region and Wang *et al*. (1998) reported poisoning by *O. glacialis* in Ali Prefecture of the Tibet Autonomous Region.

The second stage of research involved identifying toxins and poisonous mechanisms of locoweeds, which lasted for nearly 20 years from the 1980s to the early 21st century. Chinese scientists systemically analysed the toxic ingredients as aliphatic nitro compounds, selenium and alkaloids, and found that loco disease was caused by alkaloids rather than by aliphatic nitro compounds or selenium in China (Cao *et al*. 1988, Cao *et al*. 1989; Zhao *et al*. 1992; Shao *et al*. 2004).

Based on their structural features, alkaloids in locoweeds may be divided into three categories. The first category is indolizidine alkaloids, representative compounds being swainsonine and nitric oxide swainsonine. Cao *et al*. (1989, Cao *et al*. 1990) isolated swainsonine from *O. ochrocephala* and determined the concentration of swainsonine in *O. ochrocephala*, *O. kansuensis*, *O. deflexa*, *A. strictus* and *O. serioopetala*. Subsequently, swainsonine was isolated from *A. variabilis*, *O. kansuensis*, and *A. strictus* (Huang *et al*. 1992; Zhao *et al*. 1992). Swainsonine is considered the main toxic ingredient of locoweeds. The second category is quinolizidine alkaloids, which include anagyrine, thermopsine and lupanine. They were isolated from *O. glabra* and *O. ochrocephala* (Yang *et al*. 1989; Yu *et al*. 1989; Dong *et al*. 1993; Meng *et al*. 1994). However, a recent study could not detect these quinolizidine alkaloids in *O. glabra* and *O. ochrocephala* (Gao *et al*. 2012). The third category is piperidine alkaloids, its representative compound being 2,2,6,6-tetramethyl-4-piperidone. Tan *et al*. (1999) isolated piperidine alkaloids from *O. glacialis*, and considered them major toxic ingredients of *O. glacialis*. Although there are several views about the major toxic ingredients in locoweeds, the mechanism of poisoning by locoweeds is consistent in China and other countries. Swainsonine ingestion inhibits the activity of α-mannosidase, leading to an accumulation of oligosaccharides in cells causing vacuolar degeneration (James and Panter 1989).

The third stage of locoweed research has involved the study and promotion of integrated control and prevention techniques of poisoning of livestock by locoweeds. Research began in the 1980s and has continued until today. Major studies have integrated control techniques, such as the use of chemicals, drugs, ecological control and detoxification. In the early years, due to lack of awareness of the biology of locoweeds, the Chinese government attempted to eliminate locoweeds through manual and chemical methods. With improved understanding of the ecological role of locoweeds, these legumes are now regarded as an important part of rangeland vegetation rather than as poisonous weeds. As locoweeds are a plant resource, measures, such as ecosystem control engineering, dietary control, drug detoxification and biological fermentation, are being used to prevent and control poisoning of livestock by locoweeds.

Species and geographical distribution of locoweeds in China

The main species of locoweeds, *O. glabra*, *O. kansuensis*, *O. ochrocephala*, *O. glacialis*, *A. variabilis and A. strictus*, are shown in Fig. 1. They are distributed in Tibet, Inner Mongolia, Qinghai, Gansu, Xinjiang, Ningxia, Shaanxi, and Sichuan

Fig. 1. Six major locoweed species in the provincial rangelands of western China: (upper left) *O. glabra* observed in Inner Mongolia; (upper middle) *O. kansuensis* in Gansu; (upper right) *O. ochrocephala* in Qinghai; (lower left) *O. glacialis* in Tibet; (lower middle) *A. variabilis* in Inner Mongolia; (lower right) *A. strictus* in Tibet.

provinces of western China. There are over 11 million ha covered by locoweeds. *Oxytropis* and *Astragalus* species occupy ~2.8 and 3.3% of the total area in the western rangelands of China, respectively (Zhao *et al*. 2003, Zhao *et al*. 2008; Zhao 2008). The species of major locoweeds and their distribution in the western rangelands of China are given in Table 1.

Research on swainsonine and the toxicity mechanism of locoweeds

Determination of toxic ingredients in locoweeds

In 1929, Couch (1926) isolated the locoweed toxin from *O. lambertii* for the first time. He found that the toxin could induce loco disease in cats but he did not identify the chemical composition of the toxin. In 1936, a toxin was isolated from *A. mollissimus* and was named Locoin. Locoin and its derivatives, acetate, tartrate, and citrate, can induce locoweed poisoning. Locoin did not react with the general alkaloid reagents, and thus could not be identified as an alkaloid (Fraps 1936). Subsequently, swainsonine and nitric oxide swainsonine were isolated from *Swainsona canescens* and *A. lentiginosus*, respectively (Colegate *et al*. 1979; Molyneux and James 1982). A comparative toxicity test was carried out in pigs using *A. lentiginosus*, and the result showed that swainsonine was the main toxin in locoweed (Tulsiani *et al*. 1984). Later, James and Panter (1989) pointed out that swainsonine was the only toxin that could cause the characteristic clinical symptoms of loco disease.

In China, swainsonine was isolated from *O. ochrocephala* for the first time, and it was demonstrated that this alkaloid could strongly inhibit serum α-mannosidase activity in goats (Cao *et al*. 1989). Subsequently, researchers isolated swainsonine from *A. variabilis*, *O. kansuensis*, *O. glabra*, *O. glacialis*, *A. strictus*, *A. hamiensis*, and *O. falcate*. Data from these studies showed that swainsonine was the main toxin of locoweeds in China, which was consistent with the research data mentioned above (Huang *et al*. 1992; Ding *et al*. 1994; Ge *et al*. 2003; Li *et al*. 2005; Wang *et al*. 2005; Zhao *et al*. 2006).

Sources of swainsonine

So far, there are three sources of swainsonine. The first source is plants. It is known that plants containing swainsonine mainly include members of the genera *Astragalus* and *Oxytropis*, all of which are widely distributed in the western rangelands of China, where locoweed resources are very rich (Table 2). The second source is chemical synthesis. Mezher *et al*. (1984) synthesised swainsonine successfully for the first time through the six-step method in 1984. Due to the four chiral carbon atoms of swainsonine, all methods are required to synthesise a precursor. Swainsonine can be synthesised from intermediate derivatives by transformation in five to six steps. However, it is very difficult to synthesise swainsonine due to complicated procedures, harsh conditions, low yield, difficult separation, and the low activity of the product (Ye *et al*. 2009). The third source of swainsonine is biological fermentation. Fungi, such as *Rhizoctonia leguminicola* and *Metarhizium anisoplae* (Schneider *et al*. 1983; Patrick *et al*. 1993) and endophytic fungi of locoweeds, such as *Undifilum* spp., *Embellisia* spp., and *Fusarium proliferatum*, have been reported to produce swainsonine (Braun *et al*. 2003; Pryor *et al*. 2009; Zhou *et al*. 2012).

Toxicity mechanism of locoweeds

The structure of swainsonine cation is very similar to that of the mannose cation. This may explain its high affinity for

Table 1. Species, habitats, and distribution of locoweeds in the western rangelands of China

Genus	Species	Regional distribution of dominant species	Altitude (m)	Habitat
Oxytropis	*O. glabra*[A]	Alxa League, Erdos, Bayannaoer League, Wulanchabu League in Inner Mongolia; Jingtai, Minqin, Linze, Shandan, Gaotai in Gansu; Pingluo, Taole, Yanchi in Ningxia; Yili, Bortala, Bayingolin, Kizilsu, Aletai, Akesu, Kashi and cropland area in Xinjiang; Dingbian, Jingbian, Yulin, Shenmu in Shaanxi	400–3400	Arid desert grasslands, desert areas, bottomland meadows, valley terraces, alluvial plains and solonchak marsh, especially in sloping land at the edge of the dunes and alkaline calcareous sands
	O. ochrocephala[A]	Haiyuan, Guyuan, Xiji, Longde, Jingyuan in Ningxia; Huangzhong, Huangyuan, Minhe, Ledu, Huzhu, Xunhua, Hualong in Qinghai; Jingning, Huining, Jingyuan, Pingliang, Zhenyuan in Gansu	1900–5100	Field ridges, barren mountain, plain grasslands, alpine meadows, dry valley terraces, hillside gravel grasslands, glades; especially on black loessial soils
	O. kansuensis[A]	Haibei, Huangnan, Hainan, Haixi in Qinghai; Tianzhu, Yongdeng, Minle, Sunan, Shandan, Zhangye, Subei, Aksay, Linxia, Xiahe, Diebu, Luqu, Maqu in Gansu; Ruoergai, Aba, Hongyuan, Songpan in Sunan; Damxung, Linzhou, Medro Gongkar, Gongbo Gyamda in Tibet	2200–5300	Alpine meadows, alpine undergrowth, plain grassland riverside grassland, wetlands, forest gravel slopes; especially on alpine meadow soils
	O. glacialis[A]	Gar, Burang, Zanda, Rutog, Geji, Gerze, Cuoqin In Ali area of Tibet; High altitude unmanned area in North and central Tibet	4400–5300	High altitude grassland slopes, gravel slopes, beach gravel, sandy land; especially on alpine desert soils
	O. sericopetala[A]	Naidong, Sangri, Qusum, Giacha, Nang County in Tibet; Dazi, Linzhou, Qushui, Duilongdeqing in Lhasa; Nimu, Buren, Gyangze, Bainang, Lazi, Tingri, Dingjie in Xigaze	2900–4450	Floodplain sands, sand shale mountains, dune soils, grassland slopes, alluvial gravel sands, pebble beaches; especially on alkaline calcareous sand and desert soils
	O. falcata[A]	Yushu, Guoluo, Haibei, Haixi, Hainan in Qinghai; Linzhi, Changdu area in Tibet; Southern Gansu and Aba, Ganzi in Sichuan	2700–4300	Prairie regions, grassland slopes, shrubbery and meadows in meadow steppes, beaches, sand, valley gravel; especially on sandy soils
	O. defexa[A]	Qilian, Gangcha, Tianjun, Wulan, Dulan in Qinghai; Tianzhu, Sunan in Gansu; Aletai, Buerjin in Xinjiang	3300–5000	High altitude meadow steppes, valleys, steppe shrub gravel; especially on alpine meadow soils
	O. latibracteata[A]	Haixi, Haibei in Qinghai; Gannan, Hexi Corridor in Gansu; North-west Sichuan; North-western and central Tibet; Northern Xinjiang	1700–4200	Piedmont alluvial bottomland, floodplains, arid hillsides, shady slopes, sub-alpine shrub meadows, weedy meadows; especially on alpine meadow soils
	O. hirat[A]	Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shanxi, Shaanxi (North), Gansu (East)	800–2020	Arid grassland, slopes and roadsides, hilly slopes, grassland slopes, sand-rich slopes, rocky hills, sunny open forest; especially on brown soils
	O. glabravar	Shaanxi (North), Shanxi, Inner Mongolia, Ningxia, Gansu and Qinghai, etc.	800–2700	Salt grassland sand, hillside, river banks sand; especially on black loessial soil
Astragalus	*A. variabilis*[A]	Alxa League, Bayanjiner League, Erdos in Inner Mongolia; Baiyin, Jingtai, Wuwei, Minqin, Zhangye, Minle, Shandan, Gaotai, Linze, Jiuquan, Aksay, Dunhuang, Jinta in Gansu; Hami MaZongShan area, Changji Qitai in Xinjiang; Pingluo, Taole in Ningxia; Golmud in Qinghai	900–1900	Desert, semi-desert, dry riverbed alluvial sandy loess, semi-fixed dunes, Gobi desert; especially on alkaline calcareous sand or brown soils
	A. strictus[A]	South-east Gangdise Mountains in Tibet, distributed widely in Xigaze, Lhasa, Shannan, Nagqu, Changdu, Linzhi, etc.	2900–4800	River beaches, hillsides, lakeside lawns, river wetland, village side, roadside, cropland verges; especially in alpine meadow soils
	A. hamiensis[A]	Inner Mongolia Ejinaqi; Xinjiang Hami; Gansu Dunhuang	800–1500	Gobi desert, water sand land; especially in desert soils
	A. tibetanus	Pulan, Zhada in Tibet	3000–4000	Grassland slopes, riverside, swampland; especially on alpine meadow soils

(*continued next page*)

Table 1. (*continued*)

Genus	Species	Regional distribution of dominant species	Altitude (m)	Habitat
	A. confertus	Qinghai; Sichuan; Northern Tibet	4000–5300	Alpine meadows, riverside sandy places; especially in alpine meadow soils
	A. rigidulus	Baxoi, Nagqu, Lhasa, Yadong, Zhada in Tibet	3800–5000	Beach sands, grassland slopes; especially in alpine meadow soils
	A. leucocephalus	Lhasa, Milin, Zhada in Tibet	3000–3800	Grassland slopes, ditches and river banks; especially on alpine meadow soils
Sphaerophysa	*S. salsula*[A]	Jilin, Liaoning, Inner Mongolia, Hebei, Shanxi, Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang, etc.	960–3180	Hillsides, grassland, wasteland, sandy beaches, Gobi oasis, ditch sides and around salt ponds, strong drought tolerance; especially on saline-alkali soils of Gobi desert

[A]The main dominant species.

Table 2. Swainsonine content of aerial parts of plant species in the western rangelands of China

Plants	Location	Phenological stage	Swainsonine content (%)	Reference
O. glabra	Alasan Left Banner, Inner Mongolia	Full-bloom stage	0.0880	Zhao *et al*. (2005)
	Akqi, Xinjiang	Pod stage	0.0020	Wang *et al*. (2011)
	Hangjinqi, Inner Mongolia	Pod stage	0.0074	Bao *et al*. (2012)
O. kansuensis	Tianzhu, Gansu	Flowering and fruiting stage	0.0210	Cao *et al*. (1989)
	Zeku, Qinghai	Flowering and fruiting stage	0.0690	Wang *et al*. (2005)
	Zeku, Qinghai	Flowering and fruiting stage	0.0014	Tong *et al*. (2001)
	Hainan, Qinghai	Pod stage	0.0039	Duan *et al*. (2010)
O. ochrocephala	Haiyuan, Haiyuan	Flowering and fruiting stage	0.0120	Cao *et al*. (1989)
O. deflexa	Qilian, Qinghai	Flowering and fruiting stage	0.0250	Zhao and Cao (2000)
O. sericopetala	Qusum, Tibet	Flowering and fruiting stage	0.0060	Zhao and Cao (2000)
A. variabilis	Wuwei, Gansu	Pod stage	0.0290	Huang *et al*. (1992)
	Alasan Left Banner, Inner Mongolia	Flowering and fruiting stage	0.0116	Zhao *et al*. (2007)
	Alasan Left Banner, Inner Mongolia	Pod stage	0.0039	Cui *et al*. (2008)
	Minqin, Gansu	Pod stage	0.0103	Zhao *et al*. (2011)
A. strictus	Lhasa, Tibet	Pod stage	0.0050	Cao *et al*. (1989)
	Naidong, Tibet	Flowering and fruiting stage	0.0060	Zhao *et al*. (1992)
	Lhasa, Tibet	Flowering and fruiting stage	0.0043	Cui *et al*. (2008)

α-mannosidase and how swainsonine specifically inhibits α-mannosidase (Colegate *et al*. 1979). Swainsonine can specifically bond with the active binding sites of α-mannosidase, which are the 92nd, 95th, 204th, 206th, 228th, 341st, 471st, and 472nd amino acids in α-mannosidase, resulting in the loss of hydrolytic activity (van den Elsen *et al*. 2001).

Swainsonine induces disorders of the synthesis, process and transport of N-glycan, and the metabolism of oligosaccharides by inhibiting the activity of Golgi α-mannosidase II (MAN2A1), lysosomal acid α-mannosidase (MAN2B1), and cytoplasmic α-mannosidases (MAN2C1). These changes lead to abnormal function of cell membrane adhesion molecule and receptor, induces endocrine and immune function abnormality, extensive cell vacuolar degeneration in livestock, injury of central nervous system and other tissues, and cell dysfunction in nerve cells (Karasuno *et al*. 1992; Stegelmeier *et al*. 1995). Thus, poisoned livestock manifest a series of neurological symptoms. When vacuolar degeneration occurs in the reproductive organs, poisoned livestock also show reproductive dysfunction (Zhao 2001).

Relationship between endophytes and swainsonine in locoweeds

For a long time, swainsonine has been considered to be the product of secondary metabolites of locoweeds. In the 1930s, ryegrass (*Lolium perenne*) poisoning brought huge economic losses to sheep and cattle production. This poisonous disease was caused by alkaloid toxins, produced by endophytic fungal infections. A series of studies was carried out on the interaction between secondary metabolites and endophytic fungi of poisonous plants. Endophytic fungi were discovered from locoweeds, and toxin production was considered related to these fungi. In 1999, endophytic fungi were isolated from *O. sericea* for the first time, and it was identified as from the genus *Alternaria* (Braun 1999). Subsequently, some endophytic fungi were isolated from *A. mollissimus*, *O. sericea*, and *O. lambertii*. They were identified as *Embellisia* spp. by morphological methods and internal transcribed spacer sequence analysis, and were shown to produce swainsonine (Braun *et al*. 2003). High contents of swainsonine in plants were related to infection with endophytic fungi, while low contents of swainsonine were due to the deficiency of endophytic fungi through comparative tests between 16 populations of *O. lambertii* (Gardner *et al*. 2001). McLain-Romero *et al*. (2004) fed endophytic fungi, isolated from locoweeds, to rats and observed the typical symptoms of locoweed poisoning. This experimental result showed that endophytic fungi, isolated from locoweeds, contained swainsonine (McLain-Romero *et al*. 2004). Ralphs *et al*. (2008) conducted a survey of the major locoweeds from areas where locoweed poisoning has occurred to verify the presence of the endophyte and to relate endophyte infection with swainsonine concentrations. Species found to contain the fungal endophyte and produce substantial amounts of swainsonine were *A. wootoni*, *A. pubentissimus*, *A. mollissimus*, *A. lentiginosus*, and *O. sericea*. *Astragalus* species generally had higher concentrations of swainsonine than *Oxytropis* species. Swainsonine was not detected in *A. alpinus*, *A. cibarius*, *A. coltonii*, *A. filipes*, or *O. campestris*. The endophyte could not be cultured from *A. mollissimus* var. *thompsonii* or *A. amphioxys*, but was detected by polymerase chain reaction, and only 30% of these samples contained trace levels of swainsonine (Ralphs *et al*. 2008). Endophyte infection may enhance swainsonine production (Lu 2007). The endophytic fungal content of locoweeds containing swainsonine was at least 10 times more than those of locoweeds that did not contain swainsonine (Cook *et al*. 2009*a*, Cook *et al*. 2009*b*, Cook *et al*. 2011). Four swainsonine-producing endophytic fungi were isolated from three species of locoweeds, and they were named *Embellisia oxytropis*, based on the phylogenetic tree (Yu *et al*. 2009). *Undifilum* species are the main swainsonine-producing agent found in plants, and removing it completely eliminates swainsonine production (Oldrup *et al*. 2010). There are also different *Undifilum* species associated with different locoweed species (Grum *et al*. 2012). *Undifilum fulvum* and *U. cinereum* can also produce swainsonine (Baucom *et al*. 2012). The above experimental results demonstrate that there is a close relationship between endophytic fungi and swainsonine production.

Damage caused by locoweeds

Poisoning and death of livestock

Locoweeds contain contents of crude protein of 130–200 g kg^{-1} DM. Hence, liveweight of livestock may increase during initial ingestion but liveweight is lost at a later stage (Yang 2002; Huang *et al*. 2003). Livestock reveal toxic symptoms (characterised by dyskinesia) after ingesting locoweeds continuously for

Table 3. Regional distribution of locoweeds in the western rangelands of China

Province	Area ($\times 10^4$ hm^2)	Main locoweed	Severely affected areas
Tibet	282.1	*A. strictus*	Lhasa (Dazi, Linzhou, Dangxiong), Xigaze (Zhongba, Saga, Gyangze), Shannan (Naidong, Qusum, Giacha), Linzhi (Milin, Linzhi, Bomi)
		O. glacialis	Ali (Cuoqin, Gerze, Geji), Nagqu(Xainza, baingoin, Shuanghu)
		O. sericopetale	Lhasa (Qushui, Dazi, Nyemo), Shannan (Naidong, Qusum, Giacha), Xigaze (Sa'gya, Bainang)
		O. falcata	Linzhi, Changdu
Inner Mongolia	239.8	*O. glabra*	Alxa League, Erdos, Bayannaoer League, Wulanchabu League
		A. variabilis	Alxa League, Erdos, Bayannaoer League
		A. hamiensis	Alxa League (Ejin Banner)
Qinghai	206.1	*O. kansuensis*	Xining(Huangyuan, Huangzhong), Haibei (Qilian, Gangcha, Haiyan), Haixi (Tianjun, Wulan, Dulan), Hainan (Gonghe, Guide, Xinghai), Huangnan (Zeku, Henan)
		O. ochrocephala	Xining (Huangyuan, Huangzhong), Haidong (Huzhu, Hualong, Gaomiao)
		O. falcata	Haibei, Haixi, Guoluo, Yushu
		O. deflexa	Haibei (Qilian, Menyuan, Gangcha, Haiyan), Haixi (Tianjun, Wulan, Dulan)
		O. latibracteata	Haixi (Tianjun, Dulan, Wulan)
		A. variabilis	Haixi (Golmud)
Sichuan (North-west)	82.5	*O. kansuensis*	Aba (Hongyuan, Zoige, Aba, Songpan), Ganzi (Yajiang, Ganzi, Litang, Kowloon)
		O. ochrocephala	Aba (Hongyuan, Zoige, Aba, Songpan), Ganzi (Yajiang, Ganzi, Litang, Kowloon)
		O. falcata	Ganzi (Ganzi, Batang)
Xinjiang	70.9	*O. glabra*	Altay, Aksu, Kashgar,(Shufu, Shule), Bayingolin State (Yuli), Kezilesu State (Aheqi)
		A. variabilis	Hami, Balikun, Yiwu, Qitai
Gansu	34.3	*O. kansuensis*	Tianzhu, Yongdeng, Sunan and Subei, Axel, Gannan (Xiahe, Luqu, Diebu, Maqu)
		O. ochrocephala	Jingning, Huining, Jingyuan, Pingliang, Zhenyuan
		O. glabra	Minqin, Jingtai, Jinchang, Linze, Gaotai
		A. variabili	Minle, Minqin, Jinchang, Linze, Gaotai
		O. falcata	Southern Gansu (Gannan Tibetan Autonomous Prefecture)
Ningxia	8.0	*O. ochrocephala*	Guyuan (Xiji, Haiyuan, Guyuan, Pengyang, Lund, Jingyuan)
		A. variabilis	Shizuishan (Pingluo, Taole)
		O. glabra	Shizuishan (Pingluo), Wuzhong (Wuzhong, Lingwu, Yanchi)
Shaanxi	No details	*O.glabra*	Yulin (Dingbian, Jingbian, Yulin, Shenmu)

30–40 days. The livestock most sensitive to locoweeds are horses, followed by goats, sheep and cattle, while rodents are quite resistant (Liu 2006).

Due to the spread of locoweeds in rangelands, the incidence of locoweed poisoning has increased in the western region of China in recent years. About 100 000 head of livestock were poisoned by *A. strictus* and 47 000 livestock died, which accounted for 39.9% of the total incidence in the 28 counties of the Tibet Autonomous Region in 1980 (Lu 1986). Some livestock ingested *O. kansuensis* and were poisoned in Tianzhu county, the morbidity, mortality and abortion rates were 89.1, 21.9, and 29.0%, respectively, in some villages of Tianzhu county in Gansu province in 1987 (Li *et al*. 1987). More than 100 000 sheep were poisoned by *O. kansuensis* and 4000 of these died, leading to economic losses of more than 10 million RMB in Qinghai province in 1993 (Wang 1993). The incidence of locoweed poisoning was 58% in the rangeland of the Alashan League of Inner Mongolia Autonomous Region from 2000 to 2004. However, the morbidity reached 60% and the mortality was 30% in the Alashan League in 2010 (Lu *et al*. 2011). The economic losses caused by locoweed poisoning have increased in the western rangelands of China in recent years (Lu *et al.* 2012).

Spread of poisonous weeds and destruction of the ecological balance of rangelands

Locoweeds have some characteristics, such as thick roots, green colour, and strong resistance to environmental changes. Therefore, they thrive better than other forage under harsh environmental conditions. This leads to a decrease in biological diversity of rangelands, resulting in the rangeland being dominated by a single species of vegetation. For example, *O. glabra* accounted for 30–50% of local rangeland in Ordos city of Inner Mongolia Autonomous Region, and it become the dominant poisonous weed in this area (Li and Liu 1978). The area, in which *O. kansuensis* was found, had reached 130 000 ha in Tianzhu county of Gansu province, and the extent was thousands of hectares (Li *et al*. 1987; Li 1990). *Oxytropis ochrocephala* has already accounted for 42.7–51.7% of local grassland in the southern mountains of Ningxia Hui Autonomous Region (Cao *et al*. 1986). On the other hand, the area in which locoweeds was found has exceeded 1.91 million ha in 28 pastoral areas of Tibet Autonomous Region. The average cover of locoweeds is ~45%, but the severe areas in Rikazesaga and Zhongba counties can reach 70–80% (Wang *et al*. 2009), while the distribution area of locoweeds exceeds 2 million ha in Qinghai province (Shen *et al*. 2009). The

Table 4. Prevention and control measures for locoweeds used in China and elsewhere

Measures		Method of implementation	Effect	Advantages and disadvantages	Reference
Traditional	Burn	Locoweeds burned in concentrated places	Obvious short-term effects	Saving time and effort; no selection, cannot destroy the roots	Fan *et al*. (2006)
	Cultivation	Small area, high density, and sowing forage seeds after digging locoweed roots up	Incomplete removal, locoweed can grow in next year	Low cost; less efficient, seed spreads easily and destroys pasture vegetation	Ralphs and Ueckert (1988); Zhou *et al*. (2004)
	Chemical weed control	Using chemical weed killings such as clopyralid, Dichloro-methoxy benzene acid, 2,4-D butyl, Starane, Glyphosate	Obvious effects, kills 100% plants at seeding stage, 84.4% at vegetative period, 87% at full flowering stage	Simple, quick effect; not selective, kills other plants, contaminates environment, continuous medication	Ralphs *et al*. (1988); Li *et al*. (1988); McDaniel *et al*. (2007); Davis *et al*. (2009)
Modern	Inoculating pathogens	Inoculating specific pathogens in contaminated areas of locoweeds	Causes specific diseases in locoweeds, inhibits the spread of locoweeds	High specificity, easy to do; slow effect, hard to control	Ma *et al*. (1994); A *et al*. (1996); Tang *et al*. (2007)
	Phytophagous insects	Mass release of insects, such as weevils, that consume locoweeds	Leading to death of locoweeds, inhibits spread	High specificity; prevents biological invasion	Thompson *et al*. (1995); Pomerinke *et al*. (1995)
	Competitive forage	Planting cold-season forage in areas of locoweeds	Inhibits spread of locoweeds, even kills seedlings	No damage to eco-system; slow effect, limited by climate, not suitable for large-scale promotion	Ralphs *et al*. (2007)
	Training livestock to avoid eating locoweeds	Mixing forage with compounds such as LiCl, resulting in aversion by livestock	Livestock no longer eat locoweed, no side effects	Easy to do, obvious effects; need to avoid group-promoting effects	Ralphs (1992); Pfister and Stegelmeier (2002)
	Eco-system control project	Making grazing plans according to the eco characters and density of locoweeds	Avoid chronic toxicity caused by long-term feeding of locoweeds	Easy to do, can make full use of locoweeds; cannot use in disaster areas	Ralphs *et al*. (1987); Ma *et al*. (2000); Li (2000); Obeidat *et al*. (2004)

provincial distribution of locoweeds in western China is shown in Table 3.

Prevention and control of locoweeds

Locoweeds not only have an adverse impact on the rangeland ecosystem but also cause poisoning of livestock and death. It thus exerts a great influence on livestock production and the income of herdsmen in western China. Large amounts of human, material and financial resources have been invested in the prevention and control of locoweeds and have resulted in remarkable achievements. Prevention and control techniques for locoweeds, both locally and abroad, are shown in Table 4.

Locoweeds have many advantages and disadvantages. According to recent studies, locoweeds are resistant to drought and cold temperatures, as well as poor and saline soil conditions. As a result, locoweeds are capable of regenerating rangelands and can adapt to the harsh environment of western China. Thus, locoweeds can be effective in preventing windstorms, fixing sand, conserving soil and moisture, enhancing soil fertility and promoting sustainable development in western regions of China (Lu 2007; Ma 2008; Lei and Bei 2009). Along with perfecting the pasture management system, some economic and effective control techniques need to be adopted, for example, inoculation of locoweed pathogenic bacteria (Li *et al*. 2007; Li and Nan 2009), raised locoweeds-eating insects, and planting improved pasture species.

Conclusion

The damage caused by locoweeds is more serious than that of snowstorms and contagious diseases, and has become the biggest obstacle restricting the sustainable development of livestock production in the rangelands of western China (Liu 2006). However, locoweed is also an important part of natural rangelands, and it plays an important role in preventing sandstorms and promoting regeneration of rangeland vegetation. Therefore, it is argued that there should be a change from the traditional concept of prevention and control of locoweeds. From an ecological perspective, close attention should be paid to ecological protection of rangelands as well as rational exploitation and utilisation of locoweeds by using comprehensive prevention and control techniques. Further research, however, needs to be carried out before such techniques can be used.

Some of the factors that need to be researched are: first, the toxin-producing mechanism, currently considered to be produced by endophytic fungi in locoweeds (*Undifilium* spp.). The molecular mechanism of toxin production from endophytic fungi is unclear. Therefore, the toxin-producing gene should be clarified in the endophytic fungi of locoweeds. The toxin-producing gene could be knocked out to produce non-toxic locoweeds that play an important role as excellent forage for livestock (Mukherjee *et al*. 2012). Second is the mechanism of poisoning by locoweeds. It is considered that swainsonine inhibits the activity of intracellular α-mannosidase, and causes metabolic disorders of intracellular proteins with the accumulation of oligosaccharides. This eventually leads to poisoning of livestock, but the molecular mechanism of this process remains unclear. Therefore, the influence of swainsonine on α-mannosidase gene expression and regulation needs to be clarified, swainsonine-induced apoptosis signalling pathways need to be characterised, the relationship between sensitivity of livestock to locoweed poisoning and differences in expression of α-mannosidase, needs to be understood, finally revealing the molecular mechanism of locoweed poisoning.

Third, based on the locoweed species and their ecological distribution, remote sensing technology can be combined with field investigation to clarify changes in the cover of locoweeds to provide an early warning of the outbreak of locoweeds. At the same time, studies need to be performed on the use of integrated prevention and control measures, including ecological, biological, drug and chemical techniques. Control and prevention techniques for locoweeds need to be designed. This system will have important significance for controlling the occurrence and transmission of locoweeds.

Finally, recent research revealed no signs of a pathogenic interaction between the locoweed plant and the *Undifilum* fungus and supports the hypothesis of a mutualistic or commensal relationship. The *Undifilum* endophytes of locoweeds appear to act more like commensals than mutualists, offering few benefits to their hosts under certain environmental conditions. Any benefits that the locoweed endophytes may confer on their hosts are as yet unknown (Reyna *et al*. 2012; Creamer and Baucom 2013).

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