Forum: The History and Development of Small Mammal Control on China's Grasslands and Potential Implications for Conservation

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Abstract

Grasslands make up 40% of China's territory and are important ecological and economic areas. The native small mammals that inhabit these grasslands are often seen as pests competing with livestock and are subjected to population control. At the same time, several species are functionally important ecosystem engineers, and their removal can have far-reaching consequences for grassland health. We review the history and development of attempts to control populations of small burrowing mammals on China's grasslands from ancient times to the present day, and the relevance of these programmes to grassland conservation. We describe the different methods of control in use today, and attempt to assess their prevalence and their possible effects on grassland ecosystems from a conservation perspective. Non-chemical methods are used, including manual trapping and biological control with native predators. Four rodenticides are currently registered for use on China's grasslands. Most chemical control is carried out with botulinum toxins type- C and D. We identify 40 species, across two orders (Rodentia and Lagomorpha) and seven families, which are targets of pest control. Two of these species, *Marmota sibirica* and *Ochotona koslowi*, are classed as Endangered by the IUCN. Several others are important ecosystem engineers. Case studies on the potential ecological impacts of control programmes against two ecosystem engineers, the Chinese zokor (*Eospalax fontanierii*) and marmots (*Marmota* spp.), are described. Finally, we give recommendations for researchers on how to approach this issue.

Keywords: grassland conservation; mammal control; ecosystem engineer; marmot; zokor

Introduction

China's grasslands account for 40% of the country's territory, and total approximately 186 million ha, depending on the classification (Kang et al., 2007; Squires et al., 2009, see Fig. 1). Concentrated in the western provinces (and autonomous regions) of Gansu, Qinghai, Sichuan, Ningxia, Tibet and Xinjiang, and the north-eastern provinces including Inner Mongolia, they are the site of economic activity that provides the livelihoods for much of China's ethnic minority pastoralist populations (Kang et al., 2007). Grassland degradation has increased in extent and severity over the past 50 years (Squires et al., 2009), and while estimates of the exact amount of degraded grassland vary and are difficult to measure (Harris, 2010), some estimates put the amount of degraded pastoral grasslands at 1.05

million km^2 (Squires et al., 2009), or as high as 90% of the total grassland area (Fan et al., 1999).

FIGURE 1

Grassland degradation is a complex process, and many causative factors are involved. However, local pastoralists and officials have often placed part of the blame for grassland degradation on the burrowing activity of native small mammals (Harris, 2010; Smith et al., 2006). Burrowing mammals are considered pests which compete with livestock for forage (Wang et al., 2020), exacerbate soil erosion (Fan *et al*. 1999), and reduce plant biomass and diversity (Delibes-Mateos et al., 2011). However, outbreaks of small mammals (such as plateau pika) are more likely a result of grassland degradation caused by climate change and overgrazing, which then further triggers more severe degradation (Niu et al. 2019). The literature includes many large estimates for the total area of grassland specifically damaged by small mammals each year. For example, Kang *et al*. (2007) claim that 10-20% of China's grasslands are "heavily infested by rodents", while Chinese zokor *Eospalax fontanierii* and plateau pika *Ochotona curzoniae* specifically are thought to cause severe degradation over an area of 40,000 km^2 of the Qinghai-Tibetan Plateau (Kang et al., 2007). Official statistics list over 7% of grasslands as degraded specifically by mammals (see Table 1), while Liu et al. (2020) claim that small mammals are responsible for the loss of 13.884 billion kg of forage grass a year, resulting in annual losses of CNY 2.85 billion. Such estimates are often based on unclear or biased survey methodologies which do not account for the complex nature of interactions between grasslands and mammals, and vague definitions of what constitutes degradation (Harris, 2010). However, these claims may have influenced the government's decision to implement large-scale small mammals control. Population control of small mammals on the country's grasslands has long been a priority issue for both central and local government, with large sums of money being dedicated towards eradication and control programs in successive five year plans (Singleton et al., 1999b). For example, the annual cost of control of Brandt's vole *Lasiopodomys brandtii* can reach up to USD 100,000,000 (Smith et al., 2006), while from 2006 to 2011, USD 120,000,000 was earmarked for use in controlling plateau pika in Qinghai province's Sanjiangyuan National Nature Reserve alone (Wu and Wang, 2017) (not adjusted for inflation). Since large scale rodent control began in the 1960s, over ten different rodenticides have been applied to the grasslands of the Qinghai-Tibetan Plateau (Fan et al., 1999). According to the Chinese Ministry of Agriculture, 38,000 tons of rodenticide was used every year from 2003-2005 (van den Brink et al., 2018). This is likely an underestimate of the total amount used, as it does not include those rodenticides used for the control of zoonoses such as plague, which at the time of writing were administered by a different government department (van den Brink et al., 2018). Specific details on the scale, efficacy and side effects of current grassland pest control programmes are not widely available in the literature (Badingqiuying, 2016; Dixon et al., 2017).

TABLE 1

More recent studies have shown that rather than causing degradation, increases in small burrowing mammal densities can be facilitated by changes to habitat structure caused by changes in grazing management strategies and climate (e.g. Li et al., 2011; Wang et al., 2020; Zhong et al., 1999; Shi et al., 1998, 2001). High densities are therefore thought to be a symptom of grassland degradation rather than the primary cause. In such cases, these animals can indeed reduce biomass and compete with livestock for forage (e.g. Wang et al., 2020; Li et al., 2011). However, they also provide irreplaceable ecosystem services (Smith et al., 2019; Davidson et al., 2012), and their effects on ecosystem processes vary with density and habitat (Root-Bernstein and Ebensperger 2013). Small burrowing herbivores in grasslands are an important functional group of ecosystem engineers (Delibes-Mateos et al., 2011), meaning that their burrowing and foraging activities modulate the availability of resources to other species, inducing changes in community structure and ecosystem processes (Jones et al., 1994; Shi, 2007). Burrowing mammal presence is often associated with increases in soil organic matter and water filtration (Platt et al., 2016), increased productivity (Mallen-Cooper et al., 2019), increased habitat heterogeneity at local and landscape scales (Davidson et al., 2012), and an increase in the diversity and species richness of many associated taxa including plants, arthropods, and vertebrates (Mallen-Cooper et al., 2019; Romero et al., 2015).

Deliberate attempts to remove such functionally important native species around the world have been called “a classic example” of the divide between science and policy (Smith et al., 2006) and a “paradox” (Delibes-Mateos et al., 2011). To try to clarify the situation in China, we conducted a semi-structured narrative literature review in which we 1) produce a time-line of historical and current methods used to control small mammal densities; 2) outline the efficacy and potential side-effects of each method; 3) identify the native grassland species targeted for pest control, and 4) describe the ecosystem engineering effects of targeted species and possible ecological consequences of their removal.

Methods

Control Methods

To compile a list of the pest control methods used in China, we performed a systematic search of the China National Knowledge Infrastructure (CNKI, www.cnki.net) using the Chinese language search terms “grassland” (*caoyuan*, 草原), “rodent damage” (*shuhai*, 鼠害), and “control” (*fangkong*, 防控). Information was extracted from several recent reviews of grassland pest control (Liu et al., 2020; Liu 2018; Liu 2019). We also consulted two Chinese handbooks on mammalian pest control (Guo et al., 2012; Yang et al., 2016b), and a book on global rodenticide use (van dem Brink et al., 2018). Once we had arrived at a list of methods, we conducted literature searches in Google Scholar for the name of the method, both alone and paired with the word “China”. We also searched Chinese language equivalents of each term in CNKI.

Target Species

We compiled data from several sources to create a list of small mammal species currently targeted for pest control in China. These sources were two reviews of rodent pest management research priorities: a systematic review of the English language literature from a global perspective (Capizzi et al., 2014), and one narrative review from China (Liu, 2019). We also consulted a review of the literature on Chinese pika species (Lambert et al., 2023), and three Chinese handbooks on grassland pest management (Guo et al., 2012; Sun et al., 2019; Yang et al., 2016b). The scientific names of each species given in these sources was altered to match the current taxonomy given in Wilson and Reeder (2005). Species mentioned which do not occur on grasslands (according to habitat descriptions given by the IUCN) were removed from the list.

Engineer Case Studies

To give an overview of the ecosystem engineering effects of burrowing mammals on China’s grasslands, we describe case studies of two relatively well studied mammals: the Chinese zokor and marmots *Marmota* spp.. Information on each was compiled from papers resulting from a search of ISI Web of Science using the terms (Zokor OR *Eospalax* OR *Myospalax*) and (Marmota) respectively.

Results and Discussion

We identified several different methods used for controlling small mammals on China's grasslands. Methods currently in use include traditional plant-based poisons, manual trapping, biological control with native predators, chemical rodenticides (including anticoagulants and botulinum toxins), and fertility control. In previous decades, acute rodenticides were also used. Liu *et al*. (2020) give a breakdown of the area of grassland controlled by each method in 2012, which we reproduce here (see Fig. 2). A time-line of changes in control methods against the backdrop of environmental and political change in China is given in figure. 3.

FIGURE 2

FIGURE 3

Historical review of control methods

The attempts of people in China to deal with the presence of small mammals as pests of rangelands and farmland can be traced back to 350 BCE, during the Spring and Autumn (春秋) period (770-476 BCE), where rodent pests and their eradication are mentioned in the *Book of Song* (Wang, 1984; Yang and Tang, 1988). Until the early 20th Century, small mammal control in all countries consisted mainly of physical traps, building rodent-proof structures and the use of herbal remedies (van den Brink et al., 2018). Before the founding of the People's Republic in 1949, control of mammals in China was conducted at a small scale and limited to the use of locally produced traps (Deng and Wang, 1984) and plant components, usually derived from Traditional Chinese Medicine (Wang, 1984). Such strategies are still in use today on a smaller scale, and the introduction of the principles of ecologically based pest management (Singleton et al., 1999a) mean that alternatives to chemical rodenticides, such as biological control with native predators, are also used. We discuss these non-chemical methods first.

Traditional Chinese medicine

China has a long history of using plant parts to control pests, many of which are derived from the classics of Traditional Chinese Medicine (Yang and Tang, 1988). Wang (1984) gives a list of 12 plants whose toxic parts have been used to control rodents in China, including seeds of the strychnine plant and *Rhododendron* leaves. They will not be discussed in detail here, as information on their use is scarce, and their effects on both target and non-target species are limited and unlikely to raise issues related to conservation (Wang 1984).

Physical trapping

Physical traps, such as arrow traps (Yang et al., 2016a), were once widespread and used to control ground squirrels, gerbils, zokors, and others (Deng and Wang, 1984). The main drawback of trapping is that it is labour intensive and inefficient. Only one individual can be caught per trap, and so the traps need constant supervision in areas where a large population of mammals is present. Traps are only usually effective when used against small populations of mammals in a clearly defined and limited space (Smith and Meyer, 2015). Despite this, they are still commonly used on the grasslands for small scale projects and privately by local people (Liu, 2019). They are often used for controlling zokors (Yang et al., 2016a), which easily become averse to baits poisoned with chemical rodenticides (Singleton et al., 1999). Liu *et al*. (2020) report that of the total area of grassland subjected to small mammal control in 2012, 9.59% was treated with manual trapping methods (see Fig. 2).

Control with native predators

Artificial perches have been constructed across the grasslands of Xinjiang, Inner Mongolia, Qinghai, Tibet, and Gansu over the past 30 years (Liu, 2019). 34.62% of the area of total controlled grassland is subject to this form of rodent control (Liu et al., 2020, see Fig. 4).

These perches are commonly used around the world as a component of ecologically based rodent management (EBRM) (Labuschagne et al., 2016; Sara et al., 2016), and in China they aim to attract raptors to areas of high rodent or pika density (See Fig. 3). Birds are a popular choice as agents of biological control as they can respond in space and time to changes in densities of prey (Smith and Meyer, 2015). Evidence is inconclusive as to whether artificial perches are a reliable alternative to rodenticide use. Their effects are rarely quantified (Kross et al., 2018), and so far no studies of their efficacy have been conducted in China (Hygnstrom et al., 1994; Labuschagne et al., 2016). The most recent review of their efficacy (Labuschagne et al., 2016) focused only on their use in croplands, rather than on grasslands. Some authors have reported a significant decrease in rodent populations following installation of perches to attract raptors (e.g. Kay et al., 1994; Munoz and Murua, 1990), but many of these studies are based on indices of rodent abundance, are conducted only over a short term, and lack statistical rigour in the form of replication or controls (Labuschagne et al., 2016). Other authors have reported no significant differences (Askham, 1990; Howard et al., 1985). The effectiveness of predators at controlling small mammal populations depends on the population dynamics of the target mammal, and the degree to which a given predator is involved in limiting prey populations (Salo et al., 2010). Native small mammals have evolved alongside their avian predators, and their populations often change in synchrony (Hygnstrom et al., 1994). Rodents with cyclical populations may reproduce too quickly for predators alone to seriously reduce their numbers (Singleton et al., 1999), while Salo *et al*. (2010) showed that the effects of top-down predator control on small mammal populations may be limited at the cycle’s peak. For this reason, perches are almost always used in conjunction with other methods, such as chemical control (Hygnstrom et al., 1994). The use of non-avian predators to control small mammals, such as mustelids, cats, foxes, and snakes, is sometimes recommended in China (e.g. Guo et al., 2012). Liu *et al*. (2020) estimate that non-avian biological control occurs on 4.45% of the total area of controlled grassland, at small scales with little mammal-attributed degradation (see Fig. 2). We found no reports or surveys detailing this type of control.

FIGURE 4

Chemical Control

In 1942 China began the industrial development and manufacture of acute chemical rodenticides and engaged in large-scale organised mammal control campaigns (Deng and Wang, 1984; Yang et al., 2016b). From the founding of the People's Republic in 1949 until the present day, chemical control has been the most popular method of mammal control in China, as it is in most countries (van den Brink et al., 2018), although use of acute rodenticides is now banned. As of 2019, 134 chemical rodenticide products were registered for use in China (Liu et al., 2020, see Table 2). Around 90% of these are first or second generation anticoagulants. Others are bacterial products (Botulinum type D and C), or sterilising compounds such as α-chlorhyodrin, quinestrol, and levonorgestrel (Qu et al., 2015). Of the 13 active ingredients registered for use in China, only seven are registered for use on the grasslands. These include botulinum toxins type- C and D, triptolide, and four types of curcumol. Anitcoagulants are no longer officially registered for use on grasslands (Liu et al., 2020). However, recent small scale studies indicate that they are still tested on mammals there (e.g. Tan et al., 2019 tested the effects of bromadiolone on zokors) and are still used privately by local households.

TABLE 2

Acute Rodenticides

The earliest chemical rodenticides to be developed and used were acute rodenticides. These chemicals are fast acting, inorganic poisons. They are highly toxic to multiple species, and lack an antidote (van den Brink et al., 2018). As such their use is currently prohibited in China (Liu et al., 2020). We give here an overview of historical campaigns using acute rodenticides.

China began to develop acute rodenticides during the 1950s. The first widely used rodenticides in China were zinc phosphide (Fan et al., 1999), arsenic(III) oxide, and yellow phosphorus (Wang, 1984). 18 different acute rodenticides were produced between 1950 and 1984, and the most frequently used were zinc phosphide, 1080 (AKA Fussol, Fluorakil), 1081, and gliftor. Annual large-scale poisoning campaigns using these acute rodenticides began in 1956 (Deng and Wang, 1984), and the first application of zinc phosphide on the grasslands of the Qinghai Tibetan Plateau occurred in 1958 (Fan et al., 1999). Between 1964-65, more than 26,667 km2 across 20 counties of Qinghai was treated with both zinc phosphide and 1080 in order to poison plateau pika, Chinese zokor, Himalayan marmot *Marmota himalayana*, and Qinghai scrub vole *Neodon irene* (Fan et al., 1999). By the 1990s, more than 208,000km^2 of grassland had been treated with acute rodenticides (Fan et al., 1999). These campaigns presented substantial problems in terms of both effectiveness at removing target species and the poisoning of non-target species. Acute rodenticides in general have been completely superseded by anticoagulants both in terms of efficacy and safety (Fan et al., 1999; Wang, 1984). As such, they are no longer permitted for use on the grasslands.

First Generation Anticoagulants

The discovery of anticoagulant rodenticides (ARs) in the late 1940s and early 1950s caused a steep decline in the use of acute rodenticides worldwide (Bentley, 1972; van den Brink et al., 2018) and in China (Fan et al., 1999; Wang, 1984). In terms of poisoning target mammals, ARs have several notable advantages over acute rodenticides. Their physiological effects are delayed, and so animals that consume a sub-lethal dose are unlikely to develop bait shyness as they will not associate the effects with the consumption of bait. In fact, the FGARs are all chronically toxic, meaning they are more potent when taken in several small doses over time (Hadler and Buckle, 1992). However, these properties can also lead to ecological and conservation-related problems.

The first anticoagulant to be widely used in China was sodium diphacinone, which was first manufactured there in 1967 and is still used to this day (see Table 2). Thereafter, use of acute rodenticides declined, and they were all but replaced by ARs within a decade (Deng and Wang, 1984). The most common first generation anticoagulant rodenticides (FGARs) currently used in China include diphacinone, sodium diphacinone, warfarin, and coumatetralyl (Guo et al., 2012). None of these are currently registered for use on China's grasslands.

Second generation Anticoagulants

FGARs were the dominant means of small mammal control worldwide between 1950-1965 (Hadler and Buckle 1992). Second generation anticoagulants (SGARs) were developed in the 1970s after resistance to FGARs became widespread (van den Brink et al., 2018). SGARs are more acutely toxic than FGARs, sometimes by up to 100-fold, and can kill after a single dose (Hadler and Buckle, 1992). They have a greater capacity for bioaccumulation in both target and non-target prey species, generally remain within tissues for a longer period (Lohr and Davis 2018), and have a longer half-life in the liver due to their high affinity for binding sites (Elliott et al., 2014). This makes them more likely to be involved in secondary poisonings than FGARs. The top three most commonly identified and most abundant rodenticides in prey species are all SGARs.

Most chemical rodenticides registered for use in China contain SGAR compounds as their active ingredient (see Table 2), though none of these are officially registered for use on the grasslands (Liu et al., 2020). They may still be used privately.

Ecological side-effects of ARs

ARs are toxic to many vertebrates (van den Brink et al., 2018). Accidental consumption of poisoned baits by non-target species is known as primary poisoning (Quinn, 2019). While this is most common in granivorous mammals, it also occurs in reptiles, birds, and invertebrates that actively feed on baits (Elliott et al., 2014). ARs also accumulate in the liver tissue of target mammals, and can persist for many months. Secondary poisoning occurs when a predator or scavenger consumes prey that has been poisoned with ARs, and can be fatal (Quinn, 2019). It can also occur via other pathways (Elliott et al., 2014), such as when insectivorous mammals consume invertebrates that have been accidentally poisoned (Dowding et al., 2010). ARs can have effects on the behaviour of target species making them more susceptible to predation, thus increasing the chances of secondary poisoning via this pathway. For example, they can delay escape responses and change activity patterns in small mammals (Lohr and Davis, 2018). Recent studies around the world have demonstrated the widespread exposure of predators and other non-target species to ARs (van dem Brink et al., 2018).

While both primary and secondary exposure of non-target species to rodenticides is common and widespread across many taxa and environments, there is still limited information on the effects such exposure has at the population or ecosystem level due to the difficulty of obtaining unbiased and representative samples (Quinn, 2019). There are no published data on the prevalence of either secondary poisoning or accidental poisoning of non-target animals on China’s grasslands, although unpublished anecdotal reports from local governments and herders state that birds have died after consuming poisoned pikas in Qinghai Province (Wang et al., 2020) and the Tibetan and Inner Mongolian Autonomous Regions (Liu, 2019). However, it is unclear whether there is any causal link in these incidents.

EBRM

Concern about environmental damage due to secondary poisonings has lead to a growing acceptance of Integrated Pest Management (IPM) and Ecologically Based Rodent Management (EBRM) as frameworks for controlling rodent numbers (Shi et al., 2020). These strategies emphasise using knowledge about a target species' ecology and biology to sustainably manage them in a way that limits toxic residues (Shi et al., 2020). In China, alongside traditional methods, these methods include application of botulinum toxins and contraceptives.

Botulinum toxins

The species *Clostridium botulinum* comprises many genetically heterogeneous strains of soil-dwelling bacterium responsible for causing the disease botulism. All strains produce botulinum toxin, a potent neurotoxin which is categorised into one of eight subtypes designated A-H. Botulinum toxin types A, B, E, and F are known to be toxic to humans (Emmeluth 2006). Types C and D are used to control burrowing mammals in China, especially zokors and plateau pikas (Li et al., 2021a; Badingqiuying, 2016). Together, they were used in the majority of control operations across China's grasslands for the year 2012 (see Fig. 2). They work by blocking acetylcholine release in motor neurones, resulting in paralysis. Death occurs by circulatory paralysis or respiratory failure (Emmeluth 2006).

Botulinum type C has been tested on and used to control Mongolian gerbil, Great gerbil *Rhombomys opimus*, Daurian ground squirrel (Zhang et al., 2003), Daurian pika *Ochotona* *dauurica*, among others. It is currently the most commonly used poison in the control of plateau pika (Smith et al., 2019). Bolutinum type D is also used to control Chinese zokors (e.g. Li et al., 2019), Qinghai scrub voles (Li et al., 2021), plateau pikas and Daurian pikas, among others.

There has been little research conducted into the possible side effects of application of botulinum C toxin, and most research on toxicity and outbreaks in wildlife are conducted in areas where the bacterium itself is responsible for transmission. Many authors have argued that botulinum toxin is environmentally safe as it does not damage predators or pollute the environment (e.g. Li et al., 2021b). However, this does not account for the effects of removing or reducing populations of important ecosystem engineers from the grasslands (see below). There is currently little information available on the possibility of accidental primary poisoning of non-target mammals by botulinum toxin. Badingqiuying (2016) reports anecdotal evidence that local people observed deaths of some unidentified raptors after feeding on pikas poisoned with botulinum toxin in Nangchen County, Qinghai, in 2010. Li *et al* (2021b) carried out experiments on toxicity in livestock as well as several common predator species on the grassland i.e. bearded vulture *Gypaetus barbatus*, cinereous vulture *Aegypius monachus*, steppe eagle *Aquila nipalensis*, and golden eagle *A. chyrsaetos*. They concluded that doses high enough to control small mammals were not enough to kill these species through accumulation. However, this does not rule out other potential pathways of accumulation in predators, such as through consumption of non-target small mammals, or through invertebrates.

Fertility-based approaches

Sterilisation was first proposed as a means to control pest species by Knipling (1959). Fertility control is a popular choice in China, as it is assumed to control mammals in a more humane way that does not completely eradicate populations and does not reduce the positive effects of burrowing mammals on the environment (Shi et al., 2020). China is one of the few countries where sterilisation is a registered and approved method of mammal control (van der Brink et al., 2018), and research into its effects is a fruitful and ongoing area of research (Liu, 2019). Both chemical and plant-based sterilants are used, although large scale campaigns are not yet possible due to the lack of understanding of species-specific doses or potential side effects (Shi et al., 2020). The aim is to interfere with reproduction at the beginning of the breeding season, without causing death or inhibiting other biological functions or development (Shi et al., 2020). Sterilisation using baited foods has been tested in the control of plateau pikas, Brandt's voles, reed vole *Microtus fortis*, striped field mouse *Apodemus agrarius*, Chinese striped hamster *Cricetulus barabensis*, grey hamster *Cricetulus migratorius,* Midday gerbil *Meriones meridianus,* Djungar hamster *Phodopus songorus*, Mongolian gerbil, and greater long-tailed hamster (Liu 2019, Zhang et al., 2003, Kang et al., 2007). It is a particular focus of research intended to control Brandt's vole (e.g. Zhao et al., 2007; Shi et al., 2020) and plateau pika (Qu et al., 2015). Products containing the sterilising compounds α-chlorohydrin, curcumol, and triptolide are registered for use in China, with curcumol and triptolide being frequently used on the grasslands (Liu et al., 2020). α-chlorohydrin is a gametocide used to sterilise males. It is not widely used around the world, and is toxic in large doses. Male sterilisation is also problematic in polygynous species, or species with variable mating systems (Smith and Meyer, 2015). Most trials on grassland mammals use either quinesterol, a synthetic estradiol analogue, or levongesterol, a synthetic progestrogen, or 1:1 mixture of the two known as EP-1 (Zhang et al., 2003; Qu et al., 2015; Shi et al., 2020). These compounds reduce population densities, but results vary between species (Qu et al., 2015), and infertility is only temporary. They are also toxic in large doses (Shi et al., 2020), and toxicity varies between species, necessitating extensive trials before large scale application can begin. Qu *et al.* (2015) observed significantly fewer individuals of white-rumped snowfinch *Onychostruthus taczanowskii* on colonies treated with quinestrol than control colonies, and significantly more individuals of rufous-necked snowfinch *Montifringilla ruficollis* on treated colonies than control colonies, one year after application of quinestrol. They attribute this to a reduction in active pika burrows, as *M. ruficollis* breeds in abandoned burrows, while *O. taczanowskii* breeds in active burrows (Zeng and Lu, 2009). However, this study did not measure baseline bird or pika abundances at sites before fertility control was applied. The effects of large-scale use of infertility compounds on both target or non-target wildlife are currently unknown.

While the move away from chemical rodenticides is welcome and has reduced environmental damage in China, the removal or reduction of small mammal populations by any means can still have significant effects on the community.

1. Targeted species

In total, 49 species across two orders and seven families were mentioned as targets for pest control. When only considering species found on grasslands in China, this number totalled 40. The full list can be found in the supplementary materials (Table S1, available online). A document published by the Chinese government identifies 13 of these species as important pests (http://www.gov.cn/xinwen/2019-12/18/content_5462013.htm. accessed on 25/03/2023). The extent and scale of the campaigns against each species is in most cases unknown, and likely varies a great deal. Some listings (e.g. Thomas's pika *Ochotona thomasi*) may be the result of misidentification in the field (Lambert et al., 2023). Others, such as the relict ground squirrel *Spermophilus relictus* or striped desert hamster *Phodopus sungorus,* do not occur in China and are likely artefacts of changing taxonomy or of misidentification. Two other species of note are Koslov's pika *Ochotona koslowi* and Siberian marmot *Marmota* *sibirica*, both of which are classed as Endangered by the IUCN Redlist (IUCN, 2020) and may function as keystone species in their range (e.g. Suuri et al., 2021; Murdoch et al., 2009). It should be noted that this list is not the result of an exhaustive review of the Chinese literature and should not be regarded as complete.

2. *Case studies of ecosystem engineers*

The ecosystem engineering effects of zokors and marmots have been studied in enough detail that they can be given here as case studies, illustrating the potential impacts of the removal of grassland mammals. The case of the plateau pika is more well known and will not be repeated here. Interested readers are referred to Smith et al.'s (2019) review of that species' ecosystem engineering effects and the impacts of its control.

Zokors

Zokors (Family Myospalacidae) are subterranean rodents, spending the majority of their life underground. Of the five species of zokor in China (Smith and Xie, 2010), three are considered targets for pest control (see Table S1, available online). The most frequently targeted and most well studied species is the Chinese zokor, *Eospalax fontanierii*. This species is endemic to China (Smith and Xie, 2010) and occurs widely across the alpine and steppe meadows of Qinghai, Gansu and Sichuan Provinces, where it is the sole subterranean herbivore (Zhang, 2007). Much like other small mammalian herbivores on the plateau, zokors are considered to compete with livestock for forage, to cause soil erosion through their burrowing, and to decrease productivity by foraging and covering vegetation with their mounds (Niu et al., 2019; Zhang et al., 2003).

As with plateau pika (Smith et al., 2019), an observed increase in zokor numbers associated with degraded grasslands is often interpreted as a cause-and-effect relationship, where an increase in zokor density leads directly to degradation. Li *et al*. (2011) showed that an increase in zokors preferred foodstuffs (in this case the silverweed *Potentilla anserina* L.) can lead to a bottom-up regulated increase in zokor population density, which in turn leads to significant loss of biomass compared to control plots when they forage. The increase in silverweed was induced by experimental warming, implying that warming of plateau grasslands under climate change could lead to increased zokor densities (Su et al., 2015). Heavy grazing can also lead to such increases. Wang et al. (2020) found that continuous grazing under heavy stocking rates and rotational grazing during the cold season lead to decreased cover of sedges, facilitating invasion by *P. anserina* and *Potentilla fruticosa* L., two preferred zokor feed species, increasing their density. It is likely that increased zokor densities are the result of degradation caused by over-grazing and possibly climate change (Li et al., 2011), rather than the cause.

Zokors are controlled through the application of rodenticides (Niu et al., 2019), especially botulinum toxins (Li et al., 2019). More common is the use of physical bow-and-arrow traps (Yang et al., 2016a), and artificial perches have been constructed to attract natural predators (Yang et al., 2016a). Chemical and physical control of zokors has been widespread since the 1970s (Niu et al., 2019). Chemical control has proved problematic for the control of zokors. Their almost entirely subterranean existence means that baiting can be difficult. Baiting techniques with anticoagulant rodenticides have been shown to eliminate fewer than 70% of zokors in the targeted area (Singleton et al., 1999). Zokors have a rapid learning ability, and may display social learning of food preferences. This means they can easily become bait-shy when exposed to sub-lethal doses and are cautious around baits. For this reason, chemical control can be very intense (Niu et al., 2019, see Fig. 4) and is often combined with or replaced by physical traps. Recent publications have advocated the increased use of botulinum toxins in the control of zokor (Li et al., 2019).

FIGURE 5

While detailed data on zokor population trends and control programmes are unavailable, Zhang et al. (2003) claim that between 1990 and 2000, large scale poisoning campaigns reduced zokor populations by 31.6% on the QTP. In 2014, 31,151km^2 of alpine grassland was poisoned in order to reduce zokor numbers (Niu et al., 2019). The combination of poisoning and harvesting for traditional medicine has resulted in the apparent near extirpation of zokor in some areas of the plateau according to Zhang et al. (2003); complete eradication is specifically stated as a goal by some local governments (Niu et al., 2019). However, there are not enough reliable data available to confirm this.

Engineering effects of zokor

Zokor burrowing creates patches of fertile soil richer in total organic carbon, total and available nitrogen, phosphorus and potassium than the surrounding grassland (Bao et al., 2016; Su et al., 2020). These patches are then quickly colonised (Wang et al., 2008). Soil moisture has been found to increase significantly with increased zokor disturbance, while soil temperature decreases (Chu et al., 2020; Niu et al., 2019). Diversified microenvironment induced by zokor disturbance lead to an increase in soil macroinvertebrate richness (Ye et al. 2023), fungal and prokaryotic diversity and richness, which in turn increases rates of organic matter turnover and nutrient cycling (Su et al., 2020).

Most research into the ecological role of zokors has focused on their ability to change plant community structure and biomass. Zokors alter vegetation structure through two major pathways: through their selective foraging and caching behaviour and by creating bare mounds of soil which become the starting point for succession (Chu et al., 2020). Xie *et al.* (2014) found that zokors selectively cached typically unpalatable (to livestock) and poisonous forbs such as *Polygonum viviparum* L., *Stellera. Chamaejasme* L., and *Oxytropis* *kansuensis* Bunge*.,* and rarely selected for grasses and sedges. The zokor's summer diet is also dominated by forbs such as *Potentilla* spp., *Saussurea likiangensis* Franch., and *Oxytropis coerulea* (Pall.) DC. (Wang et al., 2000), but can shift in response to vegetational change (Xie et al., 2014). Grassland degradation can cause them to compete with livestock for usually negatively selected grasses and sedges (Hu et al., 2017; Wang et al., 2020), as well as increasing the density of preferred forbs (Wang et al., 2020).

The bare patches of soil left by zokor mounds become the sites of succession by plants and so they form an important part in maintaining community diversity (Niu et al., 2020). Niu *et al* (2020) observed that in plots with the highest mound density, 29.5% of total rangeland was occupied by mounds of differing ages. New mounds are colonised relatively rapidly, and succession usually arrives at a climax community resembling the inter-mound grassland in 4-8 years (Niu et al., 2019; Hu et al., 2017). Niu *et al*. (2019; 2020) found that on alpine meadow, overall species richness, biomass, and diversity (Shannon's and Simpson's indices) in mound-free areas all increased with increasing zokor burrow density. This trend was reversed on alpine steppe. Despite the complex relationships between zokors and plant communities, a general trend seems to be an increase in dominance of forbs during early to middle stages of succession on mounds, culminating in a climax community similar to the background community within 4-8 years (Niu et al., 2020). While increasing plant diversity and richness at a local scale (Niu et al., 2019), these forbs are often unpalatable to livestock (Zhang et al., 2003). This could contribute to the perception of zokors as pests and competitors with livestock. At broader scales, cyclic succession can cause a mosaic of communities which overall increases plant species diversity, and edge effects can lead to an increase in overall biomass at moderate densities (Wang et al., 2008).

There are no studies examining the relationship between zokor densities and animal communities. However, they are an important prey species and their burrows are used by other species as shelter and breeding sites. Most predators on the plateau rely on the high densities of plateau pika as a prey source (Smith et al., 2019). In times when pika densities are low, zokors are a valuable prey source for raptor species (e.g. Upland buzzard *Buteo hemilasius*, saker falcon, and little owls *Athene noctua*) and carnivores such as steppe polecat (*Mustela eversmanii*), lynx (*Lynx lynx*), Chinese mountain cat (*Felis bieti*), and Pallas's cat (Zhang, 2007). Zhang (2007) claimed that abandoned zokor burrows are sometimes colonised by root voles (*Microtus oeconomus*) and Gansu pika (*Ochotona cansus*), and that their burrows are used by several bird species, though there are no other records of this in the literature. There are currently no studies directly investigating the long-term effects of zokor removal from grasslands.

Marmots

Marmots are large diurnal burrowing ground-squirrels in the genus *Marmota*. All four species of marmot in China (*M. sibirica*, *M. himalayana*, *M. caudata*, and *M. baibacina;* (Smith and Xie, 2010)) are listed as targets for control (see Table 2.). As the main source of plague in China (Ge et al., 2015), they are controlled largely as part of public health programmes rather than as agents of grassland degradation (Qu et al., 2016; Smith and Xie, 2010). The large-scale defoliation they cause, along with their preference for livestock grazing sites (Nikol'skii et al., 2019; Nikol'skii and Ulak, 2006), means conflict with herders does occur (e.g. Zaman et al., 2019; Nikolskii and Vanisova, 2020). Details on the extent and efficacy of marmot control programmes in China are unknown, although unsuccessful past attempts to control plague by eradicating marmot hosts mean that more targeted prophylactic methods are now preferred (He et al., 2021).

While many authors assume that marmots are important ecosystem engineers (Armitage, 2000), experimental and species-specific evidence for their importance has only recently begun to be collected (Ballová et al., 2019; Suuri et al., 2021; Valkó et al., 2021). Marmots generally are important prey species for a variety of predators, including gray wolf *Canis lupus*, snow leopard *Panthera uncia*, red fox *Vulpes vulpes*, and brown bear *Ursus arctos* (Aryal et al., 2012; Karimov et al., 2018; Wang et al., 2014)*,* and their burrows increase local diversity of arthropods, hosting a variety of Diptera and Coleoptera (Armitage, 2000; Sorokina and Pont, 2011). The most frequently studied species appears to be the Endangered *M. sibirica,* found in Mongolia and the neighbouring regions of China's Inner Mongolia Autonomous Region and Heilongjiang province (Smith and Xie, 2010). They are classed as Endangered by the IUCN due to overharvesting for fur, meat, and components of traditional medicine (Kolesnikov et al., 2009), and populations are declining (Clayton, 2016).

Their burrowing behaviour and excretion patterns alter soil nutrient content by increasing the amount of nitrogen and phosphorus on burrow patches (Valkó et al., 2021; van Staalduinen and Werger, 2007), especially in clustered colonies (Yoshihara et al., 2010b). The mounds they create become sites for succession, creating a mosaic of communities and increasing species diversity and richness at a local scale (Yoshihara et al., 2009; Yoshihara et al., 2010a). Forbs often dominate these patches compared to graminoids at undisturbed sites (Yoshihara et al., 2010c), and the resulting increased abundance of flowers leads to increased richness of pollinating arthropods (Yoshihara et al., 2010a).

Mammal communities were found to be significantly more abundant and diverse on colonies than off across three sites in Mongolia (Suuri et al., 2021). The burrows of this species provide nesting sites for Vulnerable Pallas's cat (Ross et al., 2010), corsac foxes *Vulpes corsac* (Murdoch et al., 2009), hedgehogs, rodents, and badgers (Townsend and Zahler, 2006). Other small mammals which share their burrows include tolai hare *Lepus tolai*, ground squirrels, Brandt's vole, and steppe polecats *Mustela eversmannii* (Suuri et al., 2021). Birds were also found to be significantly more abundant on colonies than off (Suuri et al., 2021). Mongolian racerunners *Eremias argus* were found to occur exclusively on marmot mounds (Suuri et al., 2017). Communities of insects and spiders are significantly more diverse on mounds than off (Buyandelger et al., 2021), and beetles of the Tenebredae (*Blaps* spp.) are found in greater numbers in marmot burrows (Suuri et al., 2021). In general, Siberian marmot burrows create distinct habitat patches different from the surrounding uninhabited vegetation (Townsend, 2009).

The Himalayan marmot, despite being the most widespread and common *Marmota* species in China, is perhaps one of the least studied (Aryal et al., 2015). It is often considered an important ecosystem engineer, and although direct evidence for this has yet to be established experimentally, it seems likely given the ecological similarities with *M. sibirica*. Himalayan marmot burrows provide dens for the Endangered Chinese mountain cat (Han et al., 2020) and red foxes. They also increase plant diversity and cover of palatable plants at local scales when foraging alongside plateau pika (Qu et al., 2016). Authors have reported an apparent preference in livestock for grazing on Himalayan marmot colonies (Aryal et al., 2015; Nikol'skii and Ulak, 2006), possibly due to the changes they cause in biomass and nutritional value of forage (Yoshihara et al., 2010b). Despite their control, Himalayan marmot numbers have apparently increased in some areas due to an effective hunting ban (Qu et al., 2016). There are currently no specific studies analysing the effect of Himalayan marmots on the surrounding ecosystem in China.

Implications

Scale of campaigns

Details on the operations against many of the targeted species were unavailable in the literature. While estimates of the scale of historical campaigns are available, more accurate data is needed on the scale and intensity of current poisoning campaigns to fully evaluate the potential threat to biodiversity. Detailed information of the policies themselves is needed, but it should be noted that actions of local people do not always correspond with the law. Badingqiuying (2016) reports significant distress caused by the ethical and religious ramifications of large-scale poisoning campaigns among Tibetan Buddhist practitioners in China, and in some instances local people refuse to comply (e.g. Yeh and Gaerrang, 2021).

Population trends

While there are claims by authors that populations of some targeted species, such as zokors (Zhang et al., 2003) and Himalayan marmots (Aryal et al., 2015), are declining in China, there is in fact little direct evidence to suggest this, and population trends for most species are unknown. A priority for conservationists interested in this topic would be to obtain good quality estimates of population densities and trends for the two Endangered species listed above (*M. sibirica* and *O. koslowi*), and of the threats facing them. Detailed estimates are available for populations of *M. sibirica* in Mongolia (e.g. Townsend 2009), and hunting for fur and meat are thought to be the main drivers of population declines there (Kolesnikov et al., 2009). However, despite populations being routinely monitored in the course of plague prevention strategies (e.g. He et al., 2021) little if any work has been done on the ecology of this species in its range in China and only rudimentary estimates of density are available. Almost no new data have been published on *O. koslowi* since its rediscovery in 1984 (Li et al., 2006). Populations are fragmented and appear to be decreasing at a rapid rate (Li *et al*. 2006; Lorenzo et al., 2015). Smith and Foggin (1999) hypothesised that pest control could be directly implicated as one cause of this decline, though this has never been demonstrated experimentally. Climate change has also been cited as a potential threat (Leach et al., 2015), however, as with most research on this species, data are scarce, and inference must be cautious. Despite being Endangered species, both *O. koslowi* and *M. sibirica* are absent from China’s recently updated National Protected Species List.

Ecosystem function of targeted species

Though authors promote the use of botulinum toxins as an environmentally friendly means of control due to its apparent lack of accumulation in the food chain, successful botulinum control campaigns still can have significant effects on the ecosystem. Li *et al*. (2019) showed that botulinum type-D toxin was effective at reducing zokor populations by up to 90% in controlled plot experiments. Large-scale and permanent removal of locally abundant ecosystem engineers are likely to have far-reaching consequences for the ecosystem. For some species, such as plateau pika and Mongolian marmot, these effects are well documented. Others, such as Chinese zokor, have recently become the subject of similar studies (e.g. Niu et al., 2019). Engineering effects of other species that are known to be targets of control programmes, such as Brandt's vole and Himalayan marmot, are less well studied. One potentially fruitful area of study should be determining the ecosystem engineering effects of these animals and the response of the ecosystem to their control. Researchers must also recognize that the engineering effects of burrowing mammals can vary across different habitat types (e.g. Niu et al., 2019; Suuri et al., 2021; Yoshihara et al., 2010a); densities (Wang et al., 2020, 2019), and depending on interactions with other species (e.g. Bagchi et al., 2006; Qu et al., 2016).

Environmental impact of new methods

Currently, research on small mammal control in China is focused on designing safe protocols for the large-scale application of fertility treatments (Liu, 2019). The potential for accidental ingestion by other species, species-specific toxicity levels, and the effects of long-term population reduction on associated species should continue to be investigated.

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Tables

				Area (km^2)			
Category				% of total grassland area			
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2017**
Grassland	**392832.66**	**392832.66**	**392832.66**	**392832.66**	**392832.66**	**392832.66**	**392832.66**
	100	100	100	100	100	100	100
Damaged by mammals	**38678**	**38724**	**36914.88**	**36776**	**29084.17**	**28069.95**	**28446**
	9.85	9.86	9.40	9.36	7.40	7.15	7.24
Mammal control present	**6415.65**	**7020.67**	**7223.33**	**7585.27**	**6154.27**	**6173.13**	**7464.67**
	1.63	1.79	1.84	1.93	1.57	1.57	1.90

Table 1: Official estimates of the amount of grassland degraded specifically by native small mammals, and the area of grassland where pest control operations are undertaken, for the years 2010-2017. Figures taken from China's National Bureau of Statistics: https://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0C0A&sj=2020: accessed 1/3/2020

Active ingredient	**Type**	**Registered products containing**	**Registered on grasslands**
Bromadiolone	SGAR	61	No
Brodifacuom bromide	SGAR	36	No
Coumatetralyl	FGAR	10	No
Diphacinone (-Na)	FGAR	6	No
Warfarin	FGAR	4	No
Clostridium botulinum toxin type-C	Bacterial derivative	3	Yes
Clostridium botulinum toxin type-D	Bacterial derivative	3	Yes

Triptolide	Anti-fertility	2	Yes
Flocuomafen	SGAR	2	No
Curcumol	Anti-fertility	2	Yes
Cholecalciferol	Vitamin D	2	No
alpha-chlorohydrin	Anti-fertility	2	No
Diphenyl-barium sulphate		1	No

Table 2 - A list of active ingredients in currently registered rodenticides in China. Compiled from Liu et al (2020)

Figures and Captions

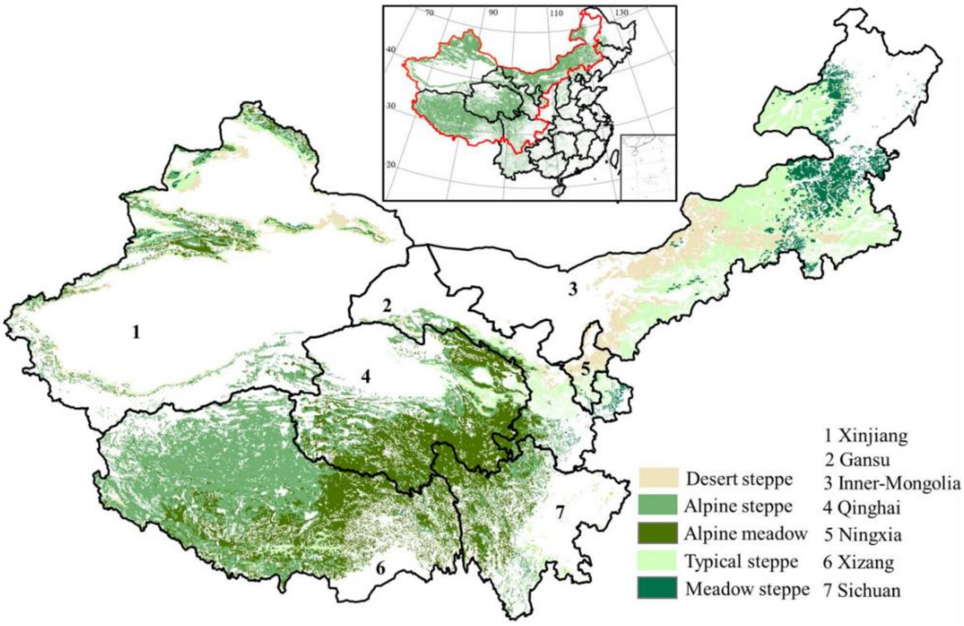

Figure 1: Map showing the extent of grassland in China and the major contiguous grassland types. The grassland in China is mainly located in the north and west, administratively distributed among seven provinces.

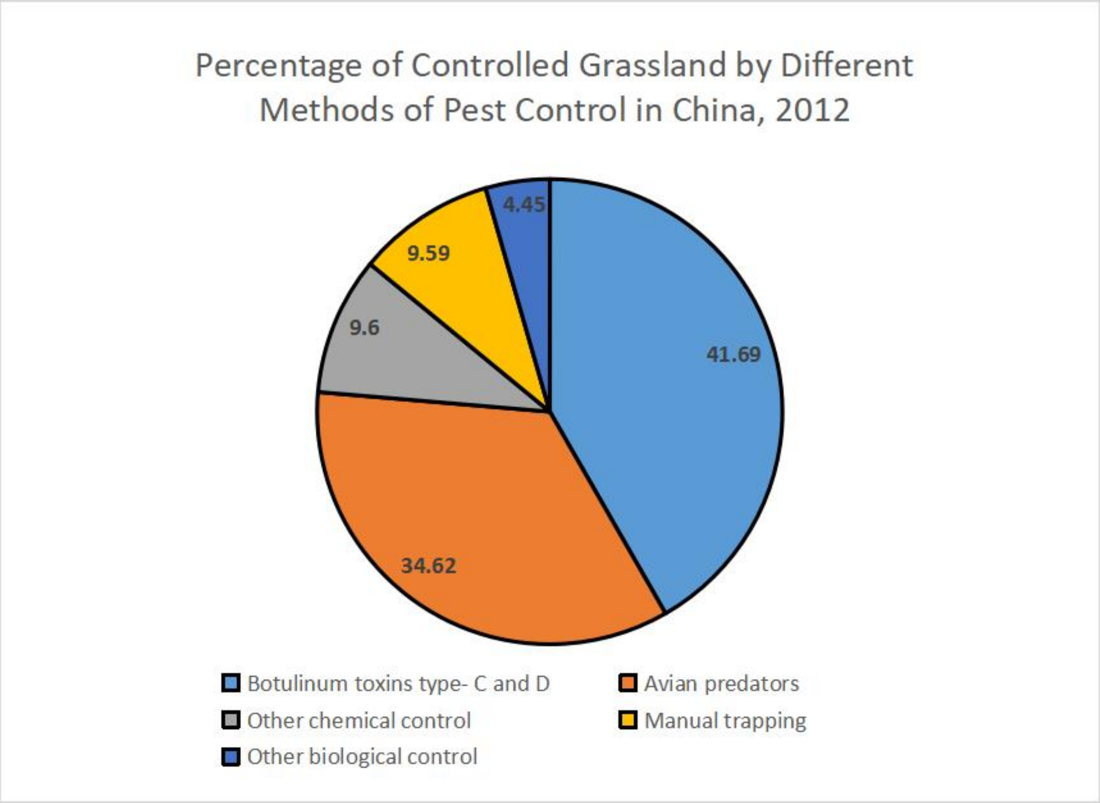

Figure 2: Chart of percentage area of total controlled grassland subjected to five different methods of pest control in 2012. Data taken from Liu et al., (2020). Note that percentages do not equate to 100 due to overlap in the distribution of control methods.

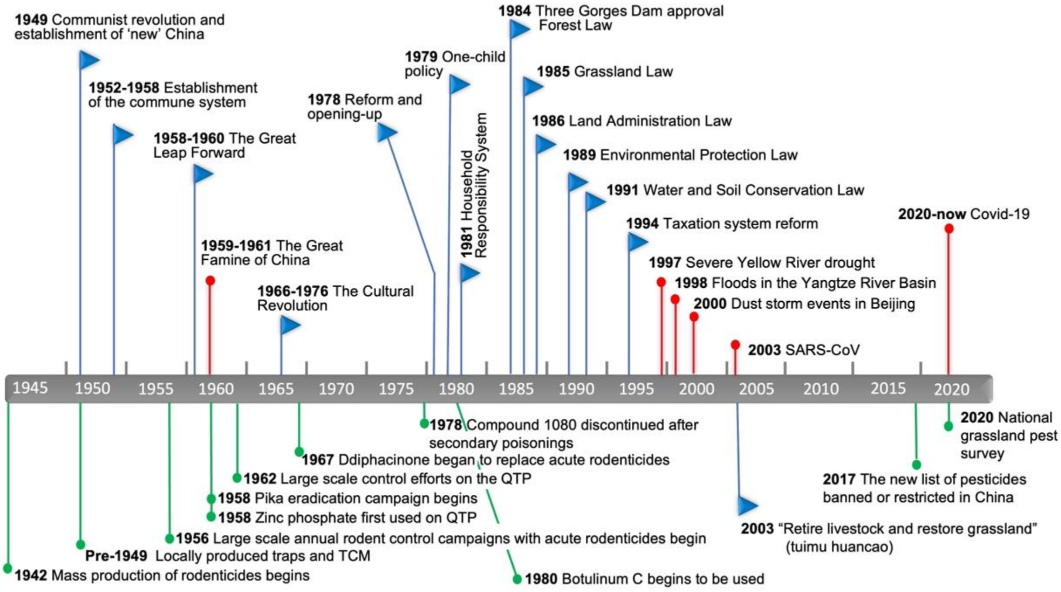

Figure 3: Timeline of development of small mammal control methods and relevant political change in China. Key political or policy events (blue markers), human-environmental

disasters (red markers), and the events regarding small mammal control (green markers) in China from 1940s to 2020.

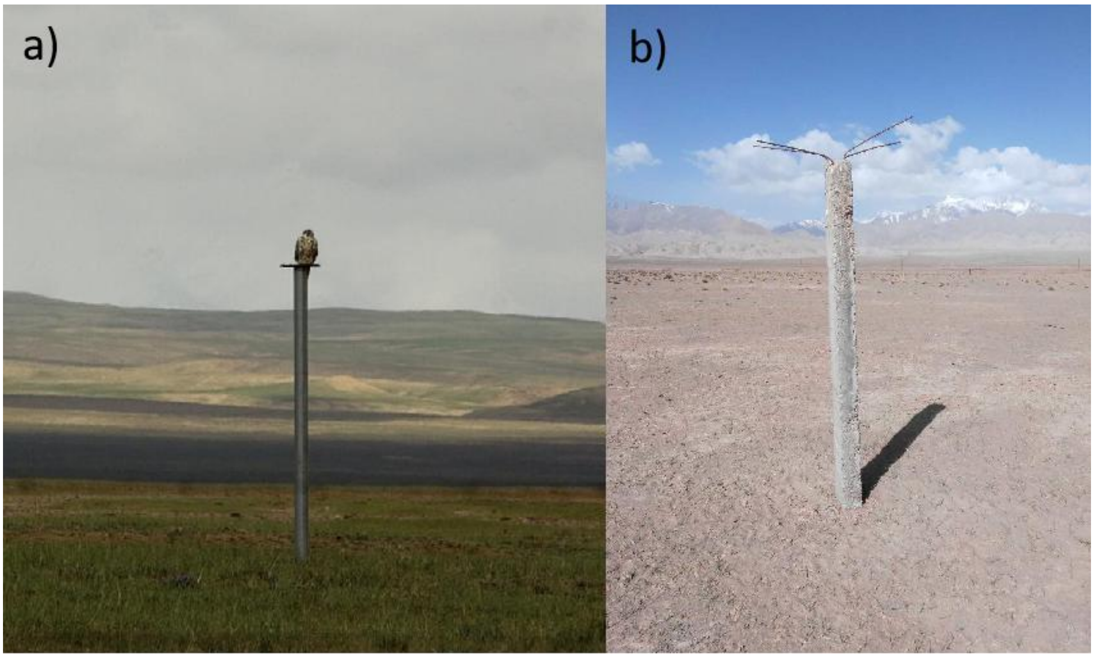

Figure 4: Two examples of artificial perch in Gansu Yanchiwan National Nature Reserve, one of which (a)) is in use by a saker falcon (*Falco cherrug*). Photo credit: Sydney Greenfield and Joseph Lambert

Figure 5: (A) A pika and zokor poisoning campaign under way and (B) remains of zokors collected after control, likely with botulinum toxin. Figure reproduced with permission from Niu et al., 2019. Photo credit: Yujie Niu