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Identifying priority protection areas of key food resources of the giant panda

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ABSTRACT

Animals that live in seasonal environments adjust their reproduction cycle to optimize seasonal forage quality. Giant pandas (*Ailuropoda melanoleuca*) are seasonal altitudinal migrants that feed on bamboo shoots and leaves with different nutritional quality. However, the importance of bamboo shoots to giant pandas, especially small and isolated populations, is not fully appreciated. Here, we explored whether mating time of giant pandas is shaped by bamboo shoot phenology. We also assessed the intensity of ongoing bamboo shoot harvesting by local communities in 42 giant panda reserves based on questionnaire surveys. Varying intensity and protection levels of bamboo shoot harvesting were found. From these data, we developed a priority ranking scheme of protection areas for this key food resource. Our study showed that pandas time their mating behavior to coincide with bamboo shoot phenology due to the high nutritional demands associated with mating and pregnancy. We also found that bamboo shoots were not well protected in many places. Liangshan, Daxiangling, and Xiaoxiangling, containing the most isolated panda populations, were identified as the areas with the most urgent need of protection. Furthermore, equal attention should be paid to the QiongL-B population, as this region holds considerable potential to serve as a corridor between the Minshan and Qionglai populations. To address the challenges posed by bamboo shoot harvesting, we recommend establishing more practical bamboo shoot management policies, increasing public awareness of bamboo shoot protection, and providing alternative sources of income for local communities.

Keywords: Giant panda; Forage quality; Bamboo shoot harvesting; Reproduction timing; Conservation management

INTRODUCTION

Nutritional forage is essential for many migrating herbivores that respond to seasonal variations in the availability and quality of resources (Aikens et al., 2017; Fryxell & Sinclair, 1988; Mysterud et al., 2001). High-quality forage significantly contributes to the reproductive success, survival, and growth of animal populations (Barboza & Parker, 2008; Middleton et al., 2018; Monteith et al., 2014; White, 1993). As such, many species have evolved to synchronize their reproductive timing with the phenology of vegetation, maximizing the availability of high-quality forage (Ben-David, 1997; Lewis & Kappeler, 2005; Plard et al., 2014). Thus, the availability of crucial food resources during the key periods of mating and birthing can greatly impact reproductive success and population growth of seasonal breeders. Ensuring the protection of key food resources, which are vital for the successful reproduction of endangered animals, is an essential conservation measure for their survival.

The giant panda (*Ailuropoda melanoleuca*) experienced an evolutionary dietary shift, transitioning from omnivory to obligate herbivory with bamboo dietary specialization (Han et al., 2019; Ma et al., 2021). As seasonal altitudinal migrants, giant pandas rely on bamboo shoots and leaves with different nutritional quality (Nie et al., 2015; Wang et al., 2023). Bamboo shoots that occur during specific seasons serve as crucial food resources for panda reproduction, as they are abundant in essential nutrients, particularly protein, required to support embryonic development and subsequent lactation

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(Nie et al., 2015). To optimize nutrient acquisition during mating and pregnancy, giant pandas shift from a diet of leaves to shoots at around the time of mating, typically lasting from March to May each year (Nie et al., 2015).

As a flagship species of biodiversity conservation, the giant panda benefits from comprehensive protection within 67 nature reserves across China (Wei et al., 2015). Notably, the recent downgrading of its conservation status from endangered to vulnerable (Swaisgood et al., 2016), coupled with the establishment of the Giant Panda National Park, represents both a significant milestone and a new era in the conservation of this species (Huang et al., 2020). At present, the giant panda population is estimated to comprise 1 864 individuals, contained within 33 local populations based on geographic isolation and the level of disturbance in their respective habitats (State Forestry and Grassland Administration, 2021). However, various panda populations, particularly those that are isolated and scattered, still face human interference, including local community harvesting of bamboo shoots, which serve as an important source of food and income (State Forestry and Grassland Administration, 2021; Wei et al., 1996). For instance, in regions such as Liangshan Mountains, the large-based bamboo shoots of *Yushania* and *Qiongzhuea* species are not only preferred by pandas but also by local people (Bai et al., 2019; Wei et al., 1996), with harvesting now a substantial source of anthropogenic disturbance, leading to local panda population decline (Bai et al., 2019).

In the present study, we amalgamated existing data on the timing of mating behavior and bamboo shoot consumption in giant pandas residing in the Qinling and Qionglai Mountains. We also collected data on reproductive activities to ascertain whether the timing of mating in giant pandas is related to bamboo shoot phenology. We further conducted questionnaire surveys to assess the extent of bamboo shoot harvesting by local communities residing near panda reserves across six mountain ranges. Finally, we also aimed to identify those local panda populations experiencing high bamboo shoot harvesting and determine the level of priority for the protection of this key food resource. Our findings should help inform future conservation actions, including the allocation of efforts and resources across panda populations.

MATERIALS AND METHODS

Data collection and questionnaire survey

The giant panda is distributed across six mountain ranges in China (Figure 1A), including the Qinling, Minshan, Qionglai, Daxiangling, Xiaoxiangling, and Liangshan Mountains (Wei et al., 2018). Here, we complied reproductive and foraging data for giant pandas from the Qinling and Qionglai Mountains based on previous literature (Supplementary Table S1), as well as our ongoing field observations on the reproductive activities of giant pandas in Foping Reserve in the Qinling Mountains (Nie et al., 2015; Zhou et al., 2022). We also incorporated data on giant panda mating times reported by the

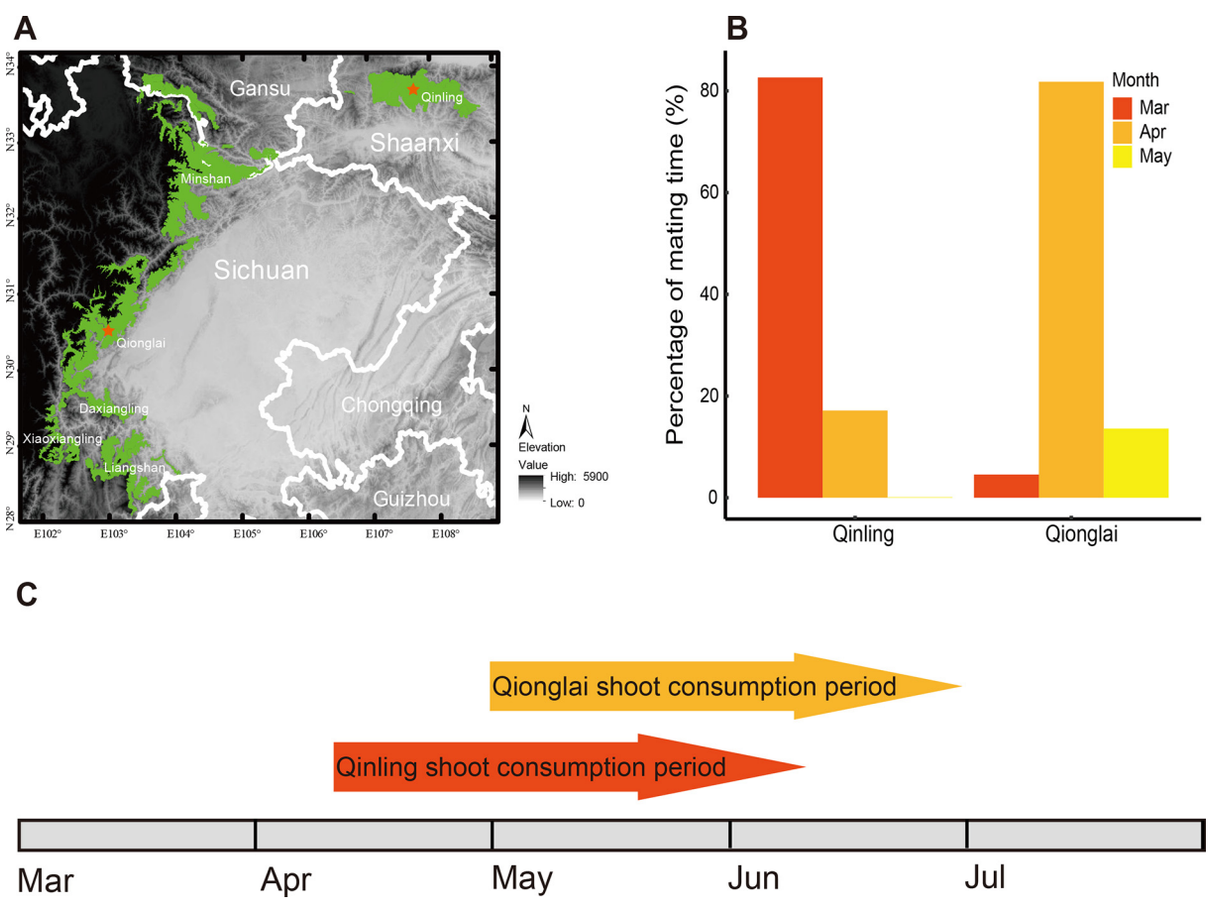

Figure 1 Different mating times and periods of bamboo shoot consumption of giant pandas from the Qinling and Qionglai Mountains (determined by published and current study data)

A–C: Geographic distribution area according to IUCN data (http://www.iucnr edlist.org) (A), mating time (B), and period of bamboo shoot consumption of giant pandas (C).

Qinling and Qionglai Mountain reserves (Supplementary Table S1). To assess the intensity of bamboo shoot harvesting by local communities residing near giant panda reserves (Supplementary Table S2), we conducted a questionnaire survey regarding bamboo shoot harvesting status, bamboo shoot management policies, and awareness of giant panda protection among local people. The questionnaire contained both open and closed questions (Supplementary Table S3). Reserve managers from each reserve provided responses through collaborative discussion. In total, we obtained 45 questionnaires from 42 nature reserves across the six mountain ranges.

We used the questionnaire to collect information about each reserve, including name, status (national, provincial, or municipal reserve), reserve area, panda population size within the reserve, human population size of the county, and human population size living in the reserve. We also collected information regarding the bamboo species harvested by people in each reserve, including bamboo species, bamboo elevation range, and bamboo shoot growth duration and timing. According to previous study and field observations of feeding behavior (Hu, 1981), we classified giant panda preference for bamboo species into three categories: prefer (staple food), normal (alternative food), and avoid. Furthermore, based on long-term observations by the local preserve managers, we used the purpose of bamboo harvesting by local people to gauge harvesting intensity, categorizing the quantity of bamboo shoots to be harvested into different levels: i.e., high (intended for sale), medium (intended for food consumption), low (intended for occasional food use), and none. Notably, we found a highly significant correlation between the intensity of bamboo shoot harvesting and specific bamboo species, as people exhibited a preference for species with larger base diameters. We further included the annual duration of bamboo shoot harvesting, assessed using bamboo phenology data and direct field observations by local preserve managers (Hu, 1981). We also noted the presence or absence of bamboo shoot harvesting policies (yes/no) and assessed bamboo management policies as being strict (complete ban with daily patrols during shooting period), moderate (not strictly banned but with regular patrols), and absent. To assess local awareness of giant panda conservation, we evaluated the knowledge of preserve managers based on three aspects: (1) Awareness of the protected species status of the giant panda (yes/no); (2) Awareness of the importance of bamboo shoots to giant pandas (yes/no); and (3) Support of local people for restricting bamboo shoot harvesting (yes/no). Finally, we determined the purpose of bamboo shoot harvesting among the local people.

Data analysis

The local population size of giant pandas was obtained from the fourth national survey conducted during 2011–2014 (State Forestry and Grassland Administration, 2021). The "ggplot2" package in R was used to map the intensity, duration, and management of bamboo shoot harvesting across the six mountains. We assigned values to categorical variables following Huang et al. (2022). Specifically, the intensity of bamboo shoot harvesting was coded from 0–3 (0=none, 1=low, 2=medium, 3=high), bamboo preference of giant pandas was coded from 0–2 (0=avoid, 1=normal, 2=prefer), and management of bamboo shoot harvesting was coded from 0–2 (0=none, 1=moderate, 2=strict). We then estimated the bamboo shoot harvesting index (BSHI=Intensity of bamboo shoot harvesting×Duration in days of bamboo shoot harvesting, ranging between 1 and 180) to determine the current protection status of the panda population using the natural breaks method and "classInt" package in R (Bivand, 2020). The natural breaks method aims to determine the optimal arrangement of values into different classes based on natural groupings inherent within the data. The method identifies class breaks that create groups with similar values, while maximizing differences between classes. Specifically, the boundaries for these classes are established at points where there are substantial variations in the data values (Chen et al., 2013; Zhang et al., 2022). Both intensity and duration of bamboo shoot harvesting were considered as crucial factors limiting the availability of this key food resource for giant pandas. We then ranked the index into conservation importance levels (from A to E) to determine the priority level for key food resource protection areas, with level A areas representing those with the highest priority for future protection initiatives. The area-perimeter ratio was used to represent the degree of habitat fragmentation of the local population area (McGarigal, 2012). A general linear regression model was used to examine the relationship between the intensity of bamboo shoot harvesting and bamboo preference of giant pandas, as well as the management practices related to bamboo shoot harvesting. We also employed general linear regression to test the relationship between BSHI and the area-perimeter ratio of local populations, as well as the relationship between BSHI and giant panda population density. These analyses aimed to assess whether local panda populations with relatively fragmented geographical distribution and high population density were subjected to greater disturbance through bamboo shoot harvesting. All statistical analyses and plots were generated in R v4.0.5.

RESULTS

Timing of mating and bamboo shooting

Giant pandas at Qinling and Qionglai differed in their timing of mating and use of bamboo shoots. In Qinling, most mating events (82.5%) were observed in March and continued into April, while in Qionglai, mating was observed from March (4.6%) to May (13.6%), with most mating events occurring in April (81.8%, Figure 1B). New bamboo shoots became available after the peak in mating events, starting in mid-April at Qinling and in early May at Qionglai (Figure 1C).

Bamboo shoot harvesting

Giant pandas preferred to forage on shoots of various bamboo species over different periods of the year at the six mountain sites (Figure 2). *Bashania* spp., *Fargesia* spp., and *Yushania* spp. were preferred by giant pandas at most locations, while *Qiongzhuea* spp. and *Phyllostachys* spp. were only selected at Daxiangling and Liangshan and at Minshan and Qionglai, respectively.

The intensity of bamboo shoot harvesting by local people varied among species and location in the early phase of bamboo shooting (Figure 2). *Qiongzhuea macrophylla*, *Q. tumidinoda*, and *Q. opienensis* experienced the highest harvesting intensity at Daxiangling and Liangshan. *Bashania fargesii* at Qinling, *F. rufa* at Minshan, and *F. robusta* and *Ph. nidularia* at Qionglai were harvested at moderate intensities. *Fargesia nitida*, *F. scabrida*, and *Ph. nidularia* at Minshan, *Y.*

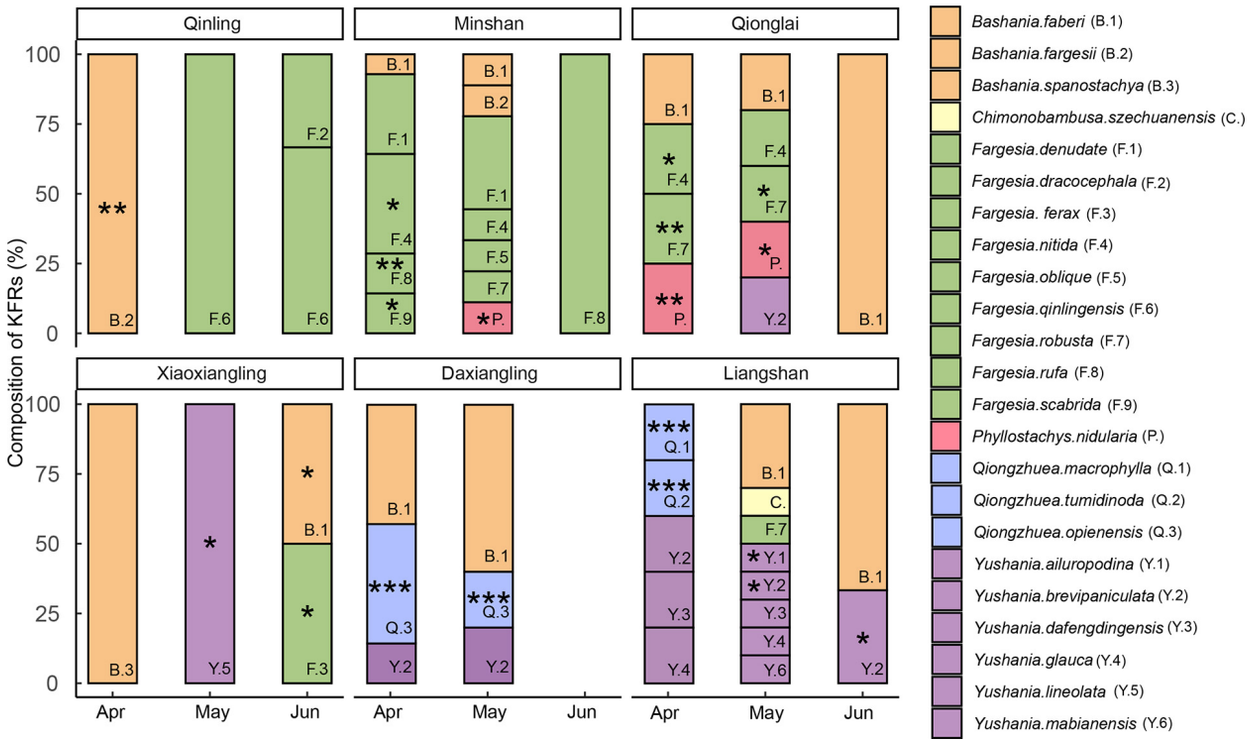

Figure 2 Composition of key food resources (KFRs) preferred by giant pandas in six mountain reserves (determined by questionnaires)
Bamboo genera are classified as follows: orange=*Bashania*, yellow=*Chimonobambusa*, green=*Fargesia*, pink=*Phyllostachys*, blue=*Qiongzhuea*, and purple=*Yushania*. Species name is abbreviated as genus letter with number. Asterisks indicate various intensities of specific bamboo shoot harvesting (***: high; **: medium; *: low).

lineolata, *B. faberi*, and *F. ferax* at Xiaoxiangling, and *Y. ailuropodina* and *Y. brevipaniculata* at Liangshan were harvested at low intensities.

The nature reserves across the six mountains under study displayed diverse harvesting statuses (Figure 3A), showing variations in intensity, duration, and policies (Figure 3B–D). High-intensity harvesting primarily occurred in southern Minshan, eastern Liangshan, and western Daxiangling (Figure 3B), while moderate-harvesting intensity occurred in Central Qinling, Qionglai, and Liangshan (Figure 3B). The duration of bamboo shoot harvesting was longest (more than 50 days) in Qionglai, Daxiangling, and parts of Xiaoxiangling, Liangshan, and Qinling (Figure 3C). However, not all reserves had implemented bamboo shoot harvesting policies, with variations in management strategies even among different reserves within the same mountain region (Figure 3D). Furthermore, our analyses revealed that the intensity of bamboo shoot harvesting had no significant effect on giant panda preference for different bamboo species (R^2=0.01, *df*=139, *P*=0.111). However, there was a negative relationship between the intensity of bamboo shoot harvesting and management (R^2=0.29, *df*=41, *P*<0.001).

Identifying and ranking protected areas for key food resources

The size of the giant panda populations varied among the six mountain sites, with areas showing larger populations found in the northern distribution range (Figure 4A). We ranked sites for key food resource protection from A (requiring high-priority protection) to E (requiring low-priority protection) based on the natural breaks method (Figure 4B). Contrary to the panda population size, fragmented panda habitats with high protection priority were mainly located in the south (Figure 4B). The intensity of bamboo shoot harvesting was greater in small than large habitats based on the area-perimeter ratio (R^2=0.134, *P*<0.001, Figure 4B). High panda population density areas experienced substantial bamboo shoot harvesting threats (R^2=0.116, *P*<0.05). There were two A level areas in Liangshan (LS-A) and Daxiangling (DXL-A). The A level areas were small and highly fragmented. Four B level areas were identified in Qionglai (QiongL-B), Xiaoxiangling (XXL-B), and Liangshan (LS-B1 and LS-B2). QiongL-B had the largest habitat area among the threatened giant panda populations and may be used as a corridor between Minshan and Qionglai, potentially enhancing future gene flow between populations. One C level area was identified in Minshan (MS-C), and three D level areas were identified in Qinling (QinL-D), Qionglai (QiongL-D), and Liangshan (LS-D).

DISCUSSION

Bamboo shoots are a key food for giant pandas and vital for their successful reproduction (Nie et al., 2015; Schaller et al., 1985). Our results from the Qionglai and Qinling Mountains revealed that giant pandas strategically time their mating behavior to coincide with bamboo shoot phenology, ensuring that their mating season coincides with a high availability of nutrition-rich bamboo shoots to meet the nutritional demands associated with mating and pregnancy. Given that giant pandas retain a typical carnivorous digestive system and are genetically deficient in cellulose-digesting enzymes (Xue et al., 2015), bamboo shoots, with their high protein content and low fiber, serve as a key food resource for pandas during this critical period. Thus, seasonally supplied bamboo shoots are the best food resources for giant pandas throughout the year.

Previous research on giant panda protection has mainly focused on population size and fragmented habitats (Li et al.,

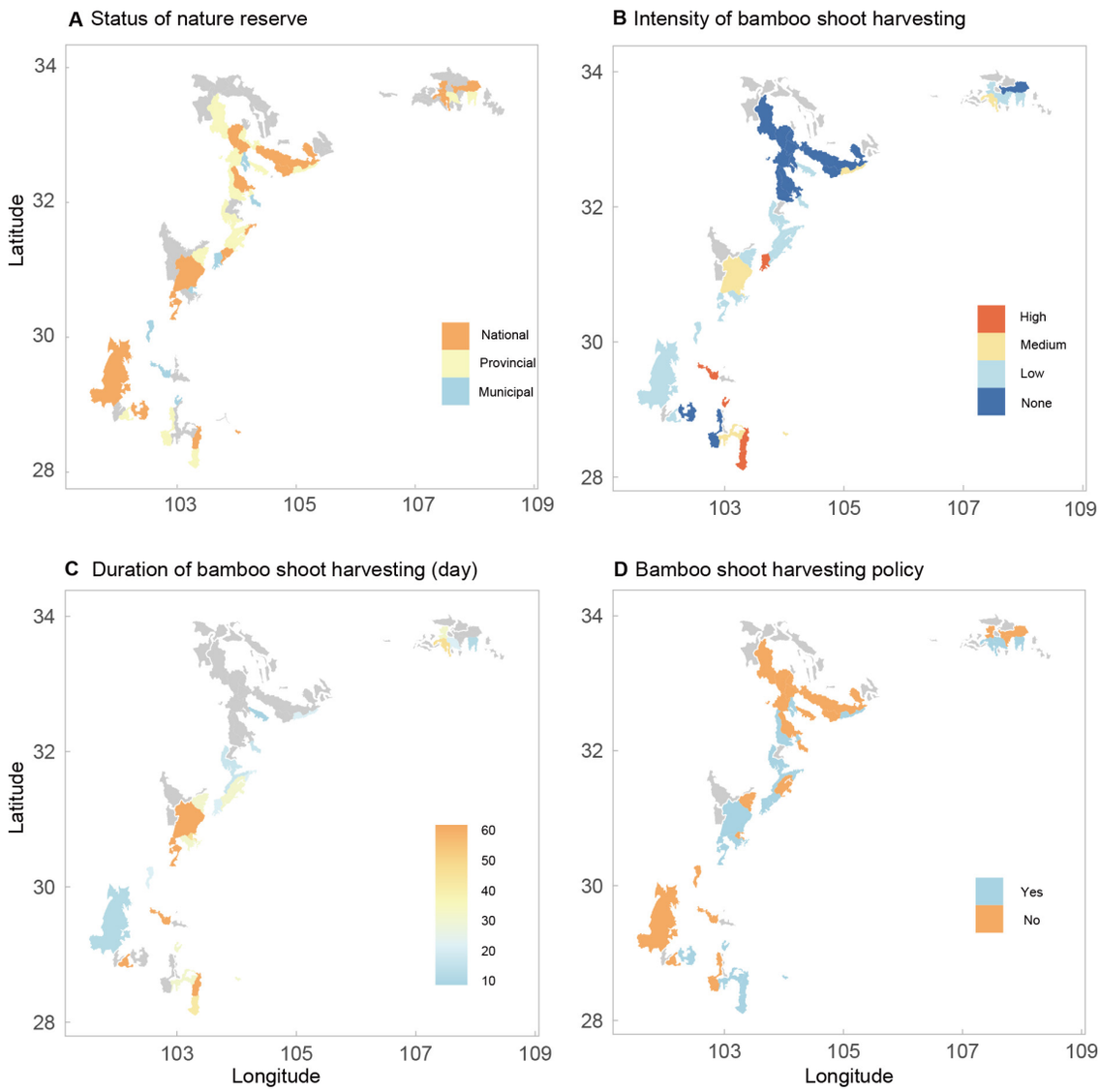

Figure 3 Bamboo shoot harvesting in six mountain regions

A: Status of panda nature reserves. B–D: Intensity (B) and duration (C) of bamboo shoot harvesting as well as presence of bamboo shoot harvesting policies (D).

2022; Swaisgood et al., 2018; Xu et al., 2017). Here, we examined the importance of key food resources for panda reproduction, specifically the availability of bamboo shoots. Our results indicated that bamboo shoot harvesting by local communities primarily occurred from April to May (73.0%) and at elevations below 3 000 m. This timing coincides with the growth period of the preferred shoots, which also tend to have a wider diameter at lower elevations (Bai et al., 2019; Wei et al., 1996; Zhang et al., 2018). Of note, these bamboo species are also staple food resources for giant pandas (Reid & Hu, 1991) and are particularly important for their successful reproduction during this period. The impact of bamboo shoot harvesting on local panda populations may include food resource shortages during nutritionally demanding reproductive stages, reduced bamboo regeneration, and avoidance of areas with intense human activity (Bai et al., 2019; Zhao et al., 2017). Our results also revealed a correlation between the area-perimeter ratio and BSHI, with more fragmented landscapes exhibiting higher bamboo shoot harvesting intensity. For example, the smaller populations in Liangshan, Daxiangling, and Xiaoxiangling faced more severe bamboo shoot harvesting, especially among isolated populations. The panda reserves in these three mountain regions also exhibited higher intensities and longer durations of bamboo shoot harvesting compared to the reserves in the other three mountain regions.

Our results indicated that A level areas, including Liangshan and Daxiangling, were located on the southern margin of the panda distribution range and hosted small, isolated populations. Local minority residents within these regions are highly reliant on bamboo shoots for both food supply and economic income (Liu, 2016; Li et al., 2019). Moreover, given the relatively limited habitat area and the highest intensity of bamboo shoot harvesting (Xu et al., 2006), targeted conservation efforts should be directed towards these regions. For example, the government could engage residents in community projects that generate alternative sources of income and promote the local cultivation of high-yield bamboo groves. The identified B level areas requiring relatively high-priority protection included Liangshan, Xiaoxiangling, and Qionglai. Xiaoxiangling harbors the smallest panda population (Sichuan Forestry Department, 2015), and is considered to be

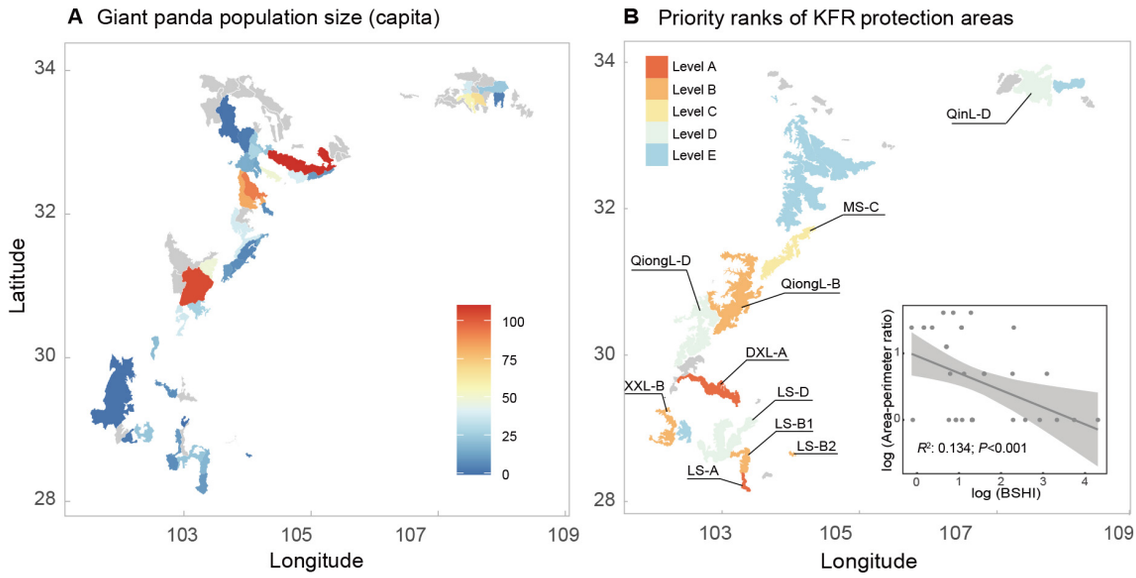

Figure 4 Key food resource (KFR) protection areas of giant pandas

A: Population size of pandas at different reserves. B: Priority rank for KFR protection areas and negative correlation between area-perimeter ratio and bamboo shoot harvesting index (BSHI). KFR protection areas were ranked in decreasing order of priority from A to E, and different small populations with the same priority level from the same mountain were numbered 1 or 2 randomly. QinL, Qinling; MS, Minshan; QiongL, Qionglai; DXL, Daxiangling; XXL, Xiaoxiangling; LS, Liangshan.

at high risk of extinction (Zhu et al., 2010). Consequently, the disturbance caused by bamboo shoot harvesting may accelerate the decline of this population to the point of collapse. Qionglai Mountains, situated between Minshan and Daxiangling, serves as a crucial link connecting these regions. Furthermore, the northern part of Qionglai, which is subject to high-intensity harvesting, contains the largest habitat area of panda populations. Thus, protecting this area is essential to enhance gene flow between the Qionglai and Minshan panda populations.

Conserving these giant pandas faces significant challenges due to the varying intensities of bamboo harvesting of different species and the heterogeneous landscapes of the six mountain ranges they inhabit. In addition, the lack of effective conservation policies and their implementation in local human populations living in and around the panda habitats contributes to the high levels of bamboo harvesting. Improving and implementing bamboo harvesting policies on a national scale is essential. In many cases, bamboo harvesters face only verbal criticism without substantial punishment, highlighting a considerable management gap. The recent establishment of the Giant Panda National Park offers an opportunity for consistent management and effective protection. To address these challenges, we recommend the following specific management measures: (1) strengthening public awareness regarding the importance of bamboo shoots for giant pandas; (2) establishing practical polices to regulate bamboo shoot harvesting, such as reducing the permitted amounts and establishing limited harvesting periods; (3) encouraging local residents to plant high-yield bamboo groves as an alternative to harvesting; and (4) implementing community development projects that provide alternative sources of income and food to alleviate dependence on bamboo shoot harvesting.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

Y.G.N., Y.J.M., and M.W.: Conceptualization, methodology, supervision, writing–original draft, writing–review & editing. Y.J.M., M.W., and X.Y.H.: Formal analysis, investigation, methodology, software, visualization, writing–original draft, writing–review & editing. X.D.G., Y.M.L., and F.W.W.: Methodology, resources, writing–review & editing. All authors read and approved the final version of the manuscript.

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