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Traditional ecological knowledge-based calendar system for sustainable seasonal grazing in the Pamir Mountains

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ABSTRACT

Indigenous mountain communities are on the cutting edge of environmental threats, their responses, and the preservation of traditional knowledge that ensures the harmony between the environment and sustainable resource use. In the context of seasonal grazing, a key livelihood activity in the eastern Pamir Mountains, this study aimed to document a traditional ecological calendar-like management system and scientifically validate its effectiveness. Through an ethno-ecological survey comprising focus group discussions and semi-structured interviews, we examined the variations in seasonal grazing practices based on ecological calendars. The study quantified and evaluated the indicators' efficacy in guiding these seasonal activities by analyzing time series satellite data of Normalized Difference Vegetation Index (NDVI). Additionally, the research assessed the potential alterations required in the future under anticipated climatic scenarios (SSP126 and SSP585) using the random forest algorithm. The findings underscored the alignment between seasonal migration patterns, grazing as the primary seasonal activity, and spatiotemporal variations in vegetation phenology. Our analysis revealed that in the future local herders may need to spend more or shorter time in pastures at different elevation compared to present because of possible change in the phenology. Our findings demonstrate the high validity of this calendar system in local resource management, and with modification it would be equally important in the future under new climatic scenarios.

1. Introduction

Seasonal resources are available in limited amounts in the high mountains that support the livelihood of mountain dwellers. The sustainable management of mountain ecosystems is thus crucial in two major aspects: supporting an adequate resource supply (Hidalgo Pizango et al., 2022) and effectively adapting to the mountain climate (Fuso Nerini et al., 2019). Aboriginal mountain people have long had a profound grasp of their surroundings and knowledge about how to effectively manage them (Castro and Sen, 2022). They have developed a highly detailed, complex ecological understanding of the interactions among plants, animals, water, weather, and other environmental

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components, and thus, they know which resources are ready for harvest in a given season and what land management activities should take place at a given time (Conway et al., 2019; Karim-Aly Kassam and Ruelle, 2011). These knowledge systems were developed using observational, practice-based approaches and have been transmitted through numerous generations by constant adaptation to the changing environment (Jansky et al., 2002). This indigenous ecological knowledge is extremely specialized in terms of understanding seasonal changes and land management and is exclusive to mountain communities worldwide (Cámara-Leret and Dennehy, 2019; Knight et al., 2022). Depending on where the knowledge has formed, there are significant differences in the number of seasons recognized in an annual cycle, the length of each season, and how seasons are locally defined and understood (Lu et al., 2022; Yang et al., 2021). The indigenous community's seasonal understanding supports many annual activities that include livelihood and cultural events (Plaganyi et al., 2013). The ability to illustrate and express their relationship with, usage of, and management of the mountain resources where their civilization has long thrived is made possible by the recording of this information by indigenous knowledge bearers (Kassam et al., 2018).

Indigenous ecological knowledge contains a significant amount of information about seasonal cycles (Turner et al., 2000). This knowledge is used to establish hunting and harvesting practices based on the seasonal availability of various species (Yang et al., 2021; Huntington et al., 2004). Many indigenous peoples still make use of the information that was once essential to their existence, and many of them still do. Some of them have used a template based on the seasonal cycle such as seasonal calendars and seasonal wheels to record their ecological knowledge (Yang et al., 2019). The ecological calendar, which is a subset of the indigenous knowledge system for interpreting the timing and location of subsistence activities (Yang et al., 2021; Kassam et al., 2018), relies primarily on the phenological regularity of local abiotic and biotic indicators, such as snow cover dates and vegetation phenology (Karim-Aly Kassam and Ruelle, 2011; Yang et al., 2019). This approach has been employed in a range of regions, such as China (Wan, 1935, 1962), Central Asia (Kassam et al., 2018), Canada (Mondragón, 2004) and certain European nations (Morisette et al., 2009), and it has a strong dependence on humans and the living environment in a specific context (Kassam and Bernardo, 2022).

The Pamir Mountains are among the world's most remote and sparsely connected mountains, and the mountain community that calls them home shares these characteristics (Kreutzmann et al., 2016). Karim et al. (2011) (Karim-Aly Kassam and Ruelle, 2011) uncovered an extraordinary Pamirian resource management that mimics an ecological calendar. The Pamir are a part of the "Roof of the World", where several mountain ranges converge (Smith and Bookhagen, 2018). Its high, icy desert and steppe are unique among alpine locations worldwide, offering native inhabitants a variety of resources, albeit sparsely (Castro and Sen, 2022; Yang et al., 2019). Livestock raising has been a significant source of livelihood and food security for the indigenous Chinese Tajik population of the eastern Pamir since ancient times (Kreutzmann et al., 2016). They engaged in seasonal grazing, which stands out for having a number of characteristics that promote sustainable resource management. As a representation of their long-standing custom of coexisting peacefully with nature, the seasonal grazing practices have been practiced for centuries (Yang et al., 2019). A sustained supply of necessary resources depends on the sustainable management of the limited resources in the region and knowledge of the season in which those resources will be available. However, indigenous people face several obstacles to keep their livelihood in these mountains, and recent phenomena such as climate change could increase such obstacles (Pepin et al., 2015). Small fluctuations in the climate in the Pamir Mountains could alter (Turner and Clifton, 2009) its ecosystem processes, and biological functions (IPCC, 2007), similar to other mountain ecosystems around the world. The livelihoods of mountain dwellers will be impacted, which may lead to societal issues with agriculture, resource and water access, health and cultural upheaval (Farrell et al., 2021; Cámara-Leret et al., 2019). Thus, it is essential to thoroughly document indigenous practices of a specific resource management cycle and integrate them with available scientific technologies in the modern era given the accessibility of sophisticated technology to monitor seasonal and climatic changes as well as meteorological recordings (Plaganyi et al., 2013; Mistry and Berardi, 2016). Carefully analyzed data and jointly created hybridized knowledge can aid in the management of natural resources in a sustainable way and improve our ability to adapt to and anticipate climate change (Huntington et al., 2004), and it will help to achieve UN Sustainable Development Goal 11 (Sustainable cities and communities) and to contribute to food security (Wheeler and von Braun, 2013). Understanding historical-typical livelihood activities in time and space is crucial, as is determining whether or not this way of life was backed by scientific evidence (Hidalgo Pizango et al., 2022; Bendixen et al., 2022).

1.1. Conceptual framework: establishing a connection between local resource management and scientific evidence

Interweaving indigenous and scientific knowledge could improve our ability to understand complex systems and provide opportunities for research that promotes dialogue, social justice, and indigenous self-determination. (Gagnon et al., 2023). Yet, identifying and quantifying the spatiotemporal characteristics of local grazing when working with qualitative indigenous knowledge is a significant challenge that must be overcome to accurately explain the mechanisms of alpine pastures' sustainable use and climate adaptation adopted by indigenous communities. It is essential to establish links between indigenous management and scientific evidence to evaluate the success of resource sustainability and to encourage climate-adapted actions. For example, in the Kitikmeot marine region of Nunavut and Indonesia, interdisciplinary approaches linking disparate and complementary indigenous knowledge and scientific data have been used to estimate important changes such as shifted dates of ice breakup and diet (Falardeau et al., 2022); this information can also be used to reduce risk and improve disaster preparedness (Hiwasaki et al., 2014). Indigenous practices in sustainable management have been measured to estimate the extent of unsustainable resource extraction in Amazon peatland forests (Hidalgo Pizango et al., 2022). Research, particularly in mountain ecosystems, is still lacking on the long-term integration of regional practices and scientific knowledge in resource management and appropriate activities.

Within the conceptual framework, we anticipated that the availability of fodder above 3400 m a.s.l., a crucial resource in the region as indicated by previous studies (Yang et al., 2019; Schaller et al., 1987), would exhibit spatial dispersion across elevation gradients. Through ethnoecological surveys, we aimed to examine the consistency between ecological indicators and local fodder management practices at both spatial and temporal scales. Our innovative approach involved analyzing the major phenological stages of these indicators using a remote sensing dataset, while considering elevation gradients set at intervals of 200 m. Additionally, we sought to explore potential variations in the spatiotemporal patterns of ecological indicators' phenological stages under future climate scenarios. By integrating these findings, we aimed to estimate the significance of indigenous grazing practices in fodder management, based on ecological calendars, across the Pamir Mountain complex. Furthermore, we aimed to anticipate and predict the adjusted grazing strategies that will be necessitated by climate change impacts. Therefore, the main objective of our research is to investigate the role of ecological calendars in indigenous resource management strategies for seasonal grazing in the Pamir Mountains and assess their potential to adapt to climate change.

The research question addressed through this paper is: How does the traditional ecological knowledge-based calendar system inform and support sustainable seasonal grazing practices in the Pamir Mountains, and how will these practices need to be adjusted in response to future climate change scenarios? By highlighting the sustainable rationale behind the historical alpine pasture management practices employed by indigenous communities, as guided by ecological calendars, and investigating how ecological indicators can inform grazing strategy adjustments in response to future climate scenarios, our study provides valuable insights into the sustainability of local resource management and the potential for enhancing climate adaptation in mountain ecosystems.

2. Methods

2.1. Study area and description

The eastern Pamir Mountains are predominantly located in China's Taxkorgan County (71.33°∼77.02°E, 35.62°∼38.67°N), and this region is the main settlement and birthplace for the Chinese Tajik people (Yang et al., 2021). It is also a significant oasis place on the Silk Roads connected to Tajikistan, Afghanistan and Pakistan (Fig. 1a). It averages 4000 m in elevation, with soaring glaciers and winding valleys (Fig. 1b).

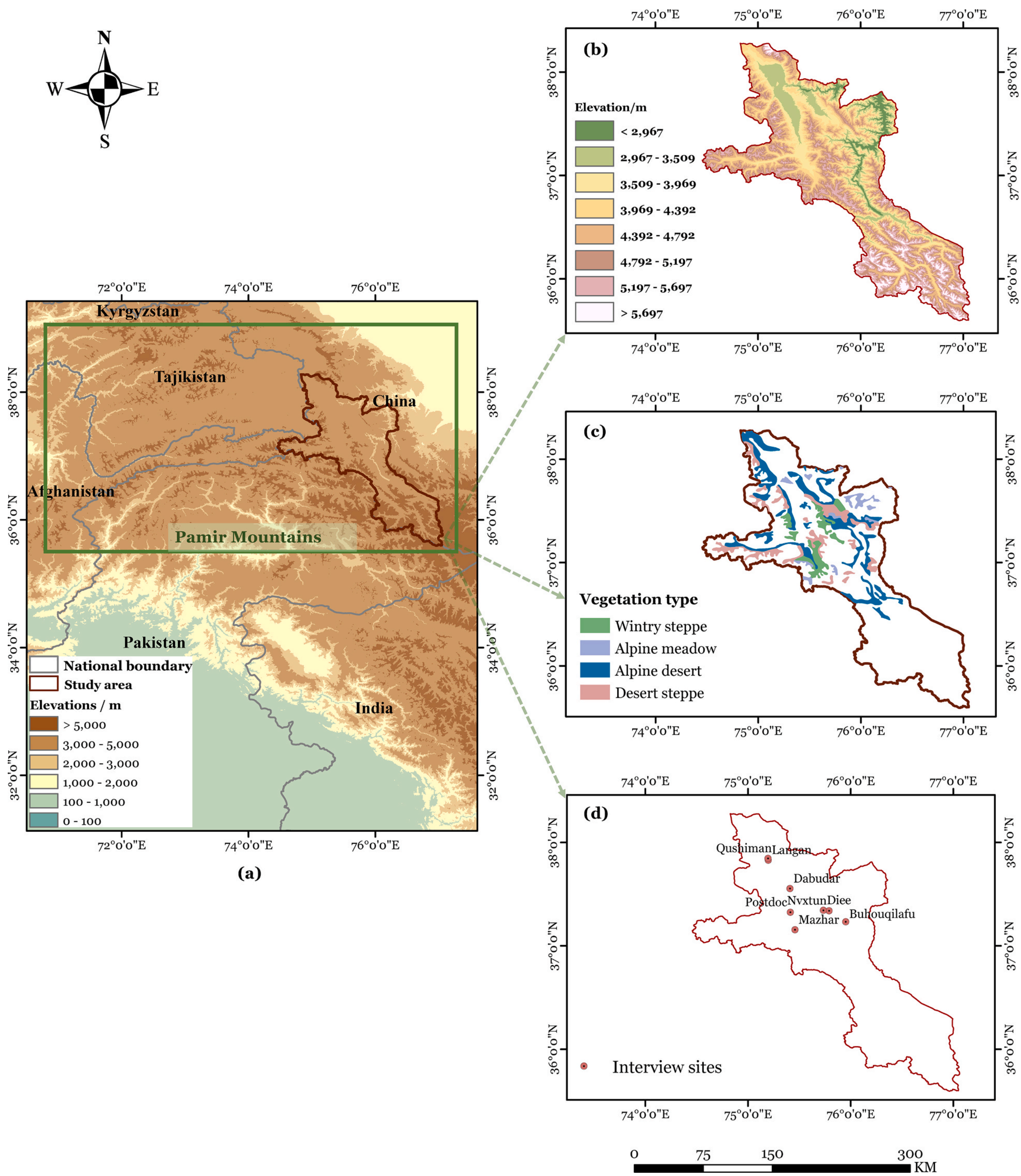

Fig. 1. Location of the study area in the Pamirs (a) with its elevation range (b), main vegetation types (c) and field interview sites (d).

Its cold desert climate is overly frigid to support forests, and its fragile ecosystem is highly sensitive to climate (Schaller et al., 1987). This region is dominated by an open alpine vegetation landscape, and trees are present only in some valleys below 3400 m because of the weather conditions (Schaller et al., 1987). The indigenous Tajik people make up 82.21% of the overall population (Bureau, 2018). Animal husbandry is regarded as the most important activity for the Tajik people. They migrate to different natural pastures along an elevation gradient according to seasonal variations, thus ensuring an adequate fodder resource supply (Liao et al., 2014). The pastures are mainly found in the flat terrain of northern Taxkorgan at elevations ranging from approximately 3400 m–5000 m (Fig. 1).

2.2. Sampling sites and ethnoecological survey

This study considered eight communities located at different elevations to understand the variation in seasonal grazing practices based on ecological calendars (Fig. 1d and Supplementary Table 1). Local activities, especially grazing activities during all seasons, were witnessed during fieldwork (from November 2017 to August 2019), and focus group discussions (FGDs) and semi-structured interviews were conducted. Informants were asked to recall the seasonal and climatic variations in recent decades, how they performed their seasonal grazing and how their indigenous observations helped with their activity arrangements. Specifically, main questions of interviews included three parts: (1) traditional knowledge regarding climate change awareness, natural phenomena, cultural ceremony, and their occurrence time in each season; (2) the time periods and locations of seasonal grazing, as well as the corresponding ecological indicators; (3) name of main fodder species and their phenological periods, as well as variations of fodder amounts in each season.

We conducted our surveys and interviews after obtaining permission from the local authority and included only the indigenous people who were willing to participate. To improve the quality of interviews and overcome the barriers of communications with local people, staff of Nature Reserve Administration with bilingual skills were invited as interpreters. The FGDs consisted of community members with ages between 31 and 85, among whom village leaders were initially invited. Then, leaders assisted us in organizing groups of knowledgeable elders and younger people who routinely engage in grazing activities. All FGD members are native to this region, where they have resided for generations. In this study, 57.5% of the total population was elderly (the population aged over 60 years). These FGDs were conducted in 17 independent groups, of which each group consisted of seven to ten members, all of whom were polled on different issues, including their seasonal grazing schedule, farming calendar, social activities, and the perception of ecological indicators. In addition, male members of FGDs outnumber female members (approximately 7:3), as male members are primarily responsible for seasonal grazing while female members are constantly engaged in household activities. The semi-structured interviews with knowledgeable people from the community were conducted in the second round of the survey to obtain in-depth information about their grazing lifestyles, local natural resources, and climate conditions. In total 40 key informants shared their built-up knowledge systems and life experiences.

Table 1
Main vegetation types with their primary formations in Taxkorgan County.

Vegetation type	Primary plant formation
Desert steppe	*Stipa* Linn.
Alpine desert	*Seriphidium rhodanthum* (Rupr.) Poljak.
Alpine meadow	*Kobresia* Willd. mixed with *Carex* Linn.
Wintry steppe	*Festuca* L.

2.3. Phenological analysis of elevation-based ecological indicators

There are four main natural vegetation types distributed in northern Taxkorgan (Table 1 and Fig. 1c) that were confirmed via the monography entitled *Xinjiang Vegetation and Its Utilization* that was coedited by the Xinjiang Comprehensive Expedition Team, CAS and the Institute of Botany, CAS (Xinjiang Comprehensive Investigation Team and C.A.o. S. C.A. o.S. Institute of Botany, 1978). Then, we obtained the vector data of spatial vegetation types from the Resource and Environment Science and Data Centre (http://www.resdc.cn/).

We used the MODIS (MOD13Q1, available from ref (Didan, 2015).) 16-day composite data at the original 250 m spatial resolution to extract the NDVI data as a proxy for vegetation phenology and productivity for the period of 2000-2019 (20 years, 457 images). The NDVI has been shown to be closely related to vegetation conditions, and phenological phases can be calculated accordingly (Hidalgo Pizango et al., 2022). We extracted the NDVI values for each pixel and removed values less than 0.1 for each year following Piao et al. (2006a). The beginning, end, and length of the growing season (hereafter, ***BGS, EGS, and LGS****, respectively*), and the NDVI value throughout the growing season (hereafter, ***gsNDVI***) at an elevation gradient were then calculated as follows:

Elevation gradient setting: in accordance with grazing activities, the NDVI data were extracted by setting a vegetation gradient every 200 m beginning at 3400 m a.s.l. for each vegetation type (Supplementary Table 2).

Harmonic analysis of time series (HANTS): HANTS is widely regarded as one of the most effective techniques for smoothing and reconstructing remote sensing NDVI data (Wang et al., 2019). This study draws on and alters the running code released by Mohammad Abouali (2020) using the MATLAB (2020) platform, and the proper parameters were determined through multiple efforts and settings (Supplementary Table 3).

Equations (1) and (2) are the reconstructed mathematical expressions based on remote sensing data:

$$\tilde{y}(t_j) = a_0 + \sum_{i=1}^{nf} \left[a_i \cos(2\pi f_i t_j) + b_i \sin(2\pi f_i t_j) \right] \tag{1}$$

$$y(t_j) = \tilde{y}(t_j) + \varepsilon(t_j) \tag{2}$$

Where y, $\tilde{y}$ and ε are the original series, the reconstructed series and the error series, respectively. t_j is the time when y is obtained (observed), where $j = 1, 2, \ldots, N$, and N as the maximum number of observations (samples) in a time series.

NDVI curve fitting using four-term of Fourier function: There were various approaches that were used to fit the NDVI curves, and the four-term of Fourier function was performed using the MATLAB platform in this study, as followed in Equation (3). A high fitting precision was found.

$$f(x) = a0 + a1 * \cos(x*\omega) + b1 * \sin(x*\omega) + a2 * \cos(x*\omega) + b2 * \sin(x*\omega) + a3 * \cos(x*\omega) + b3 * \sin(x*\omega) + a4 * \cos(x*\omega) + b4 * \sin(x*\omega) \tag{3}$$

where, *x* is the Julian date (i.e., January 1st is the first day of the year), and a*0, a1, b1, a2, b2, a3, b3, a4, and b4* are the coefficients for each curve.

Phenological stage calculation: the period of greatest increase and decrease in the seasonal NDVI time series was designated *BGS* and EGS, respectively, and the time difference between the *EGS* and *LGS* was designated the *LGS*. Then, the NDVI value throughout the growing period was calculated. We implemented the annual NDVI curves at 1-day intervals for each grid using Equation (4) (available from ref (Piao et al., 2006b).):

$$NDVI_{ratio}(t) = \left[NDVI_{(t+1)} - NDVI_t\right] / NDVI_t \tag{4}$$

where t is the time. We then used the timing of the greatest NDVI change values of $NDVI_{ratio}$, to determine the average onset dates of vegetation green-up and dormancy.

2.4. Future phenological trend simulation

Temperature is the primary driver of phenological variations in plant species (Guo et al., 2015). In light of the fact that plant species at high latitudes or altitudes are especially sensitive to temperature signals (Christian, 2004), especially in regions experiencing rapid temperature increases (Yu et al., 2010), such as the Pamir Mountains, temperature was used for future simulations in this study. Additionally, as it is largely immune to biases caused by collinearity (Lindner et al., 2022), the random forest algorithm was used with variables of the historical 1-km monthly maximum and minimum temperature datasets (2000–2017) (Shouzhang, 2020a, 2020b), and then it was used to predict the changes in phenological characteristics with future climatic data derived from WorldClim (https://worldclim.org) in the SSP126 and SSP585 scenarios (2021–2040). The Shared Socioeconomic Pathways (SSPs) are scenarios of expected worldwide socioeconomic developments up to the year 2100. They are used to generate scenarios for greenhouse gas emissions under various climate policies. It describes a set of plausible societal development trajectories based on five narratives describing alternative socioeconomic developments, such as sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development (Riahi et al., 2017), in which the SSP126 and the SSP585 are based on RCP scenarios with low (2.6 W/m^2) and high (8.5 W/m^2) radiative forcing by the end of century, respectively. (Detailed information is provided on the website: https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained/). To ensure the effectiveness of the predictive model, historical data were divided into training data (75%) and test data (25%), and Pearson correlation analysis between predictive and actual data was highly consistent ($p < 0.01$ for all vegetation types, Fig. 2), indicating that the predictive results were reliable. In addition, we used a model accuracy analysis using the percentage variance explained in out-of-bag (OOB) prediction by random forest. The "percentage variance explained" is the most relevant statistic that represents a proxy for the model R^2, which could be determined to assess the performance of the random forest regression method (Everingham et al., 2016). It performed well in our analysis, with percentage variance explained (model R^2) values of 64.08% for BGS, 46.76% for EGS, 60.07% for LGS, and 58.33% for *gsNDVI* of the entire vegetation types. The variable importance plots (VIPs) for all phenological stages varied (Supplementary Fig. 2). Random forest was implemented in R (version 4.0.2) using the "randomForest" and "varSelRF" packages.

The flowchart used in this study is provided in Supplementary Fig. 1.

3. Results

3.1. Ecological calendar-based livestock migration in fodder resource management

As a useful tool in the recognition of timing and space, the Tajik ecological calendar was divided into 36 segments in accordance with the local date-setting norms, and the criteria were as follows: there are four seasons and 12 months for one year based on the Gregorian Calendar and each has its own nomenclature. One month is further divided into three segments: "*Most Kolor*" in the Tajik language is from the 1st to the 10th of each month, "*Most Muzone*" is from the 11th to the 20th, and "*Most Alhithe*" is from the 21st to the last day of the month (Supplementary Table 4), and this segmentation can make activities more flexible. As such, we divided one ecological calendar into 36 segments (approx. 10 days). A meaningful festival called the "Shaw Gong Bahar Festival" (celebrated on 21 March) is regarded as the onset of livelihood activities.

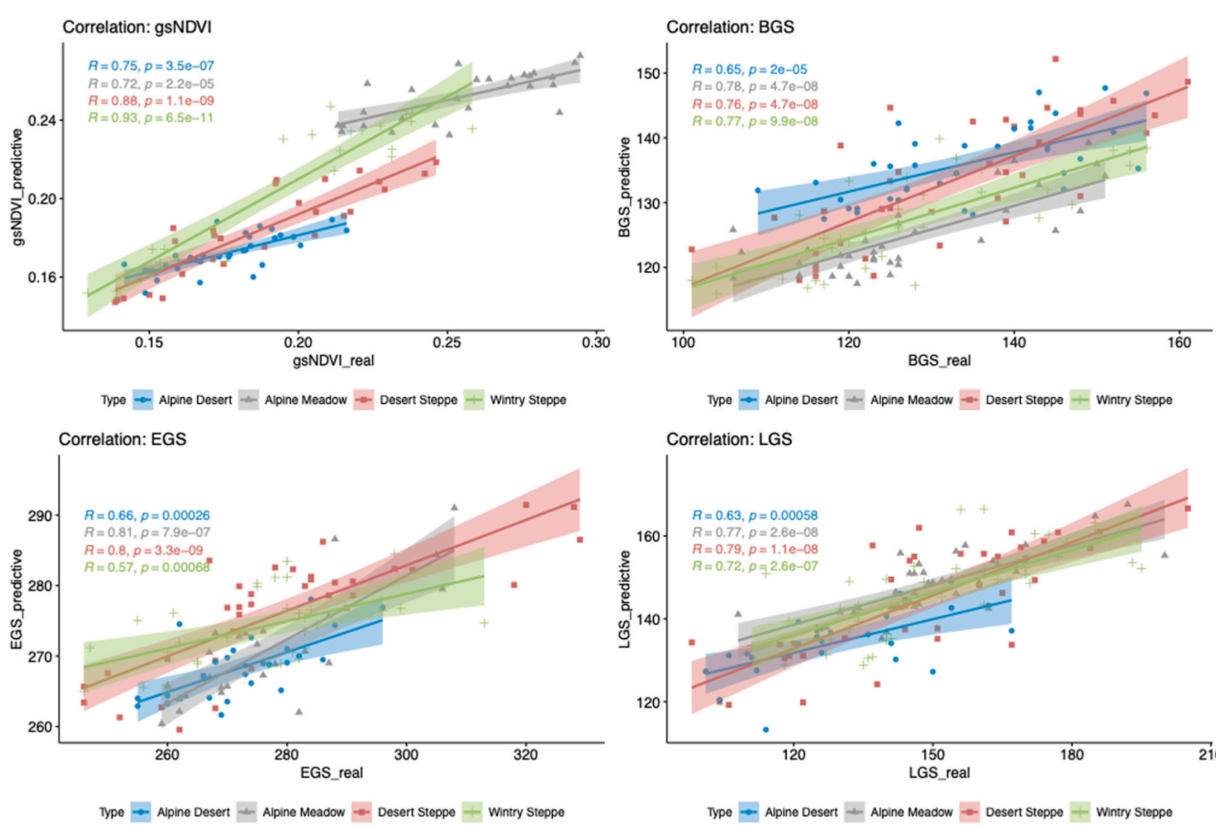

Fig. 2. Correlation test for the random forest algorithm with 75% training data and 25% test data for the gsNDVI, BGS, EGS and LGS.

Seasonal grazing was essential, constituting the majority of local activities. The Tajik people traveled two to four times a year to seasonal pastures to meet fodder needs based on local observations of indicators. Seasonal pastures designated *Wook Ailagh* (spring pasture), *Minch Ailagh* (summer pasture), *Peaze Ailagh* (autumn pasture) and *Zemstoon Ailagh* (winter pasture) were spread in accordance with elevation gradient (see Fig. 3). Summer pastures were at the highest elevation, close below the snowlines at elevations generally above 4400 m; spring and autumn pastures were at mid-elevations (same or different locations), at approx. 3800-4400 m; and winter pastures were at a lower elevation (Fig. 3b). During late summer and autumn, they collected fodder to stall-feed livestock during winter. It was also found that certain communities never moved to spring and/or autumn pastures; rather, they returned to their settlements from summer pastures, as exceptions. In general, the sequential segments for remaining in seasonal pastures were assigned as follows: 9th to 15th in spring pastures, 16th to 25th in summer pastures, 26th to 31st in autumn pastures, and the remainder of the period in winter pastures or their own settlements (Fig. 3a). Additionally, crop cultivation was practiced secondarily by villages located at lower elevations (mainly below 3500 m). In addition, making yoghourt and butter were interspersed during those activities (Supplementary Fig. 3).

Fodder phenology was regarded as the primary and crucial indicator, i.e., taking seasonal grazing in accordance with variations in fodder growth conditions. Beyond this, animal behavior, annual geological events, and hydro-climatology were indicators used to determine when to start other livelihood activities during the ecological calendar (Supplementary Fig. 3). The color and growth condition of fodder were recognized to determine the proper time to move from one pasture to another. According to our recorded information, the timing of migration up to spring pastures (mid-elevations) was determined by the earlier appearance of light green (grass reviving), with the grass height of nearly one to two knuckle widths (Supplementary Fig. 4a). When migrating to summer pastures (high elevation), the height of grass grew as high as three to five fingers under the best growth condition year round (Supplementary Figs. 4b and 4c). When migrating down to autumn pastures, the fodder grass in autumn pastures had relatively favorable growing conditions, whereas the quantity of fodder grass in summer pastures declined significantly; additionally, the time of retreat was determined by the yellowing and wilting of the fodder grass. Thus, the fodder grass phenology was carefully integrated with modern scientific monitoring technologies.

3.2. Spatiotemporal variations in fodder phenology fit well with ecological calendar-based grazing activity

To gain a better understanding of the documented grazing pattern and its underlying rationale at both temporal and spatial scales, we quantified the phenology of pasture using satellites and correlated it with local grazing activities. We used metrics of vegetation productivity (Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) data) from 2000 to 2019 to calculate the beginning, end and length of the growing season (abbreviated as *BGS*, *EGS* and *LGS*, respectively), as well as the NDVI value in the growing season (*gsNDVI*), which indicates vegetation coverage and condition (Methods and Supplementary Table 5). Harmonic analysis of time series (HANTS) and Fourier functions were used to smooth and fit curves, and phenological stages were therefore calculated as shown in the Methods.

Since the Tajik ecological calendar was in 36 segments using the local method, we calculated the 10-day average phenological values accordingly and compared the results with the spatial characteristics of seasonal grazing (Fig. 4a). In general, we observed pronounced phenological consistency in vegetation types and their elevation-based distribution. When grazing on spring pastures (9th-16th/10-day), fodder grass revival (BGS) occurred earliest at the mid-elevation range of 3800-4400 m with BGS day of the year (DOY) mean values of approximately 120.22, 132.70, 121.05, and 119.15 for desert steppe, alpine desert, alpine meadow and wintry steppe, respectively (Supplementary Table 6). Meanwhile, the NDVI values reached relatively higher levels at these elevation ranges (0.10, 0.09, 0.12 and 0.10, respectively), indicating better vegetation growth and health conditions at those elevation scales (Supplementary Table 7). When migrating to summer pastures (16th–26th/10-day), we discovered a remarkable consistency pattern for all vegetation types: at the time of grazing, the NDVI values increased rapidly and peaked at the highest elevation ranges (>4400 m), with the highest NDVI values of (on average) 0.28, 0.24, 0.36 and 0.32,

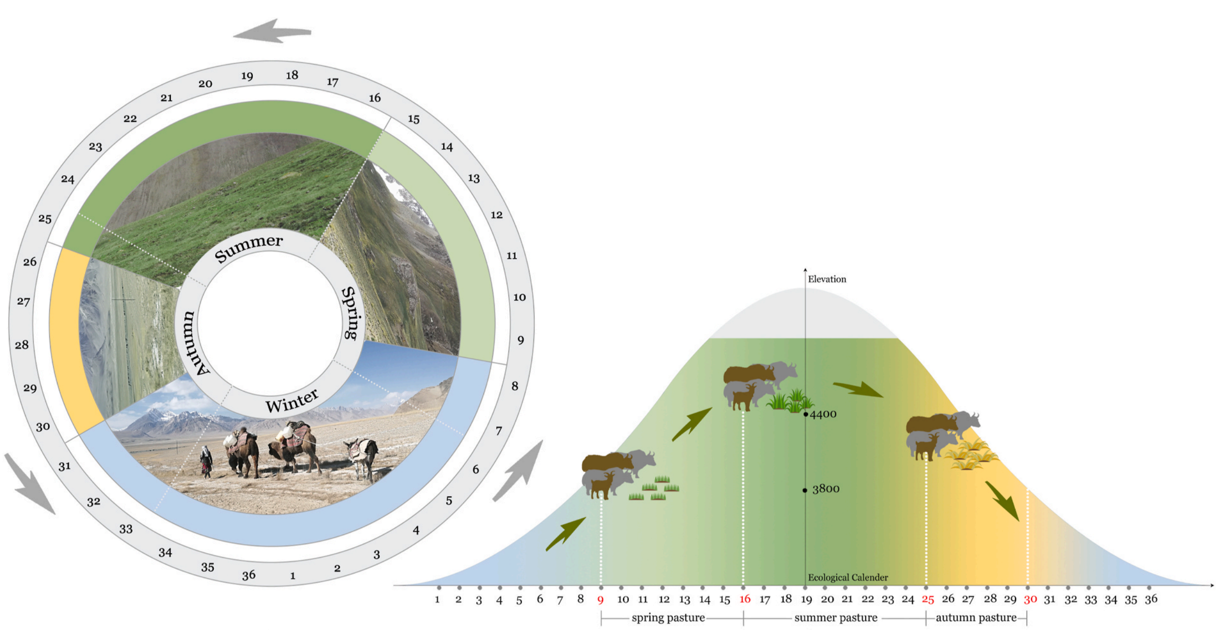

Fig. 3. Seasonal grazing based on the ecological calendar: 9th-15th to spring pasture, 16th-25th to summer pasture and 26th-31st to autumn pasture with different fodder grass conditions (a), and spatial characteristics of grazing activities with elevation (b).

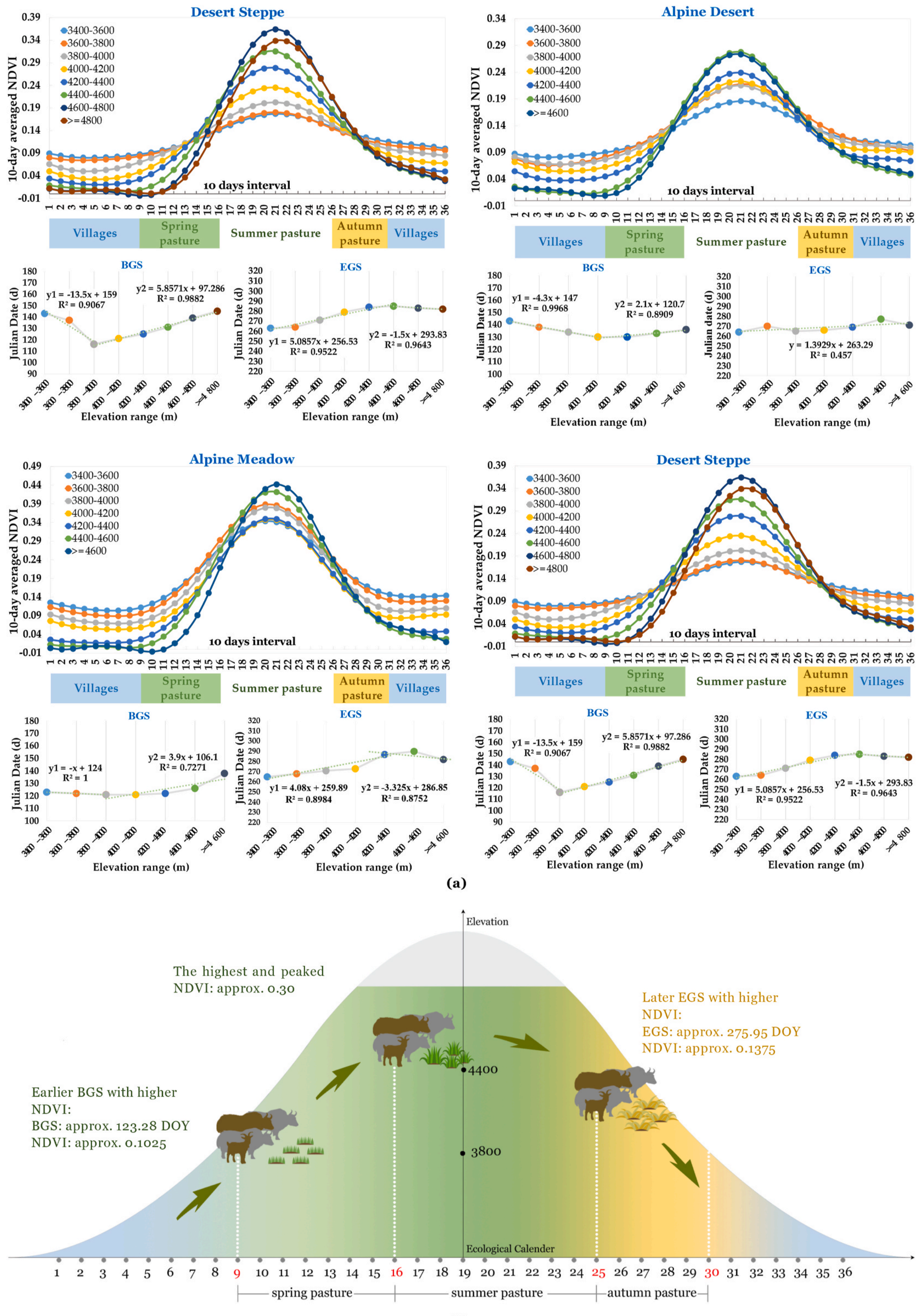

Fig. 4. Phenological characteristics in the form of ecological calendar-based grazing (a), variations in fodder grass conditions were highly fit with the grazing activity that migrates along with elevations for an adequate fodder supply (b).

respectively, which were significantly greater than those in other elevation ranges (Fig. 4 and Supplementary Table 7). In contrast, migrating to autumn pastures (26th–31st/10-day) was always accompanied by the NDVI values of summer pastures declining rapidly, indicating poorer vegetation coverage and growth conditions, whereas the values in autumn pastures were relatively higher, with specific values of (on average) 0.13, 0.13, 0.15 and 0.14, respectively. The NDVI values of autumn pastures may not be as high as those in lower elevation ranges (see Supplementary Table 7); however, they maintained a later withered and yellow period (EGS) with DOYs of approximately 280.07, 265.78, 275.93 and 282.00, indicating a longer fodder resource supply with relatively better grass conditions (Supplementary Table 8).

3.3. Modeling future changes: they may have to spend a longer time in summer pastures

It was indicated that the Tajik people used their ecological calendars to accurately identify ecological indicators that could help them conduct their seasonal grazing, which was highly consistent with seasonal patterns of fodder phenology. However, their grazing patterns might be impacted by the changing climate in the future. The relationship between the phenological features of the indicator and the corresponding climatic drivers was used to model their potential changes in the shared socioeconomic pathway (SSP) SSP126 and SSP585 scenarios using the random forest algorithm (Methods). Overall, the predicted changes in all vegetation types in varied elevation ranges would change markedly (Fig. 5).

Considering the basic elevation structure of grazing pastures, as stated previously, the timing of the initial migration was determined by the fodder BGS in spring pastures. Using the SSP126 scenario as an example, we found that, on average, the BGS would be delayed by 6.01, 3.08, 4.27 and 3.01 days in the elevation range of 3800-4400 m (Supplementary Table 9). In contrast, the BGS of all vegetation types at elevations above 4400 m would occur 8.00, 2.27, 4.87 and 5.77 days, on average, earlier, indicating that fodder supply will be available on summer pastures earlier than that under the current climate scenario. In

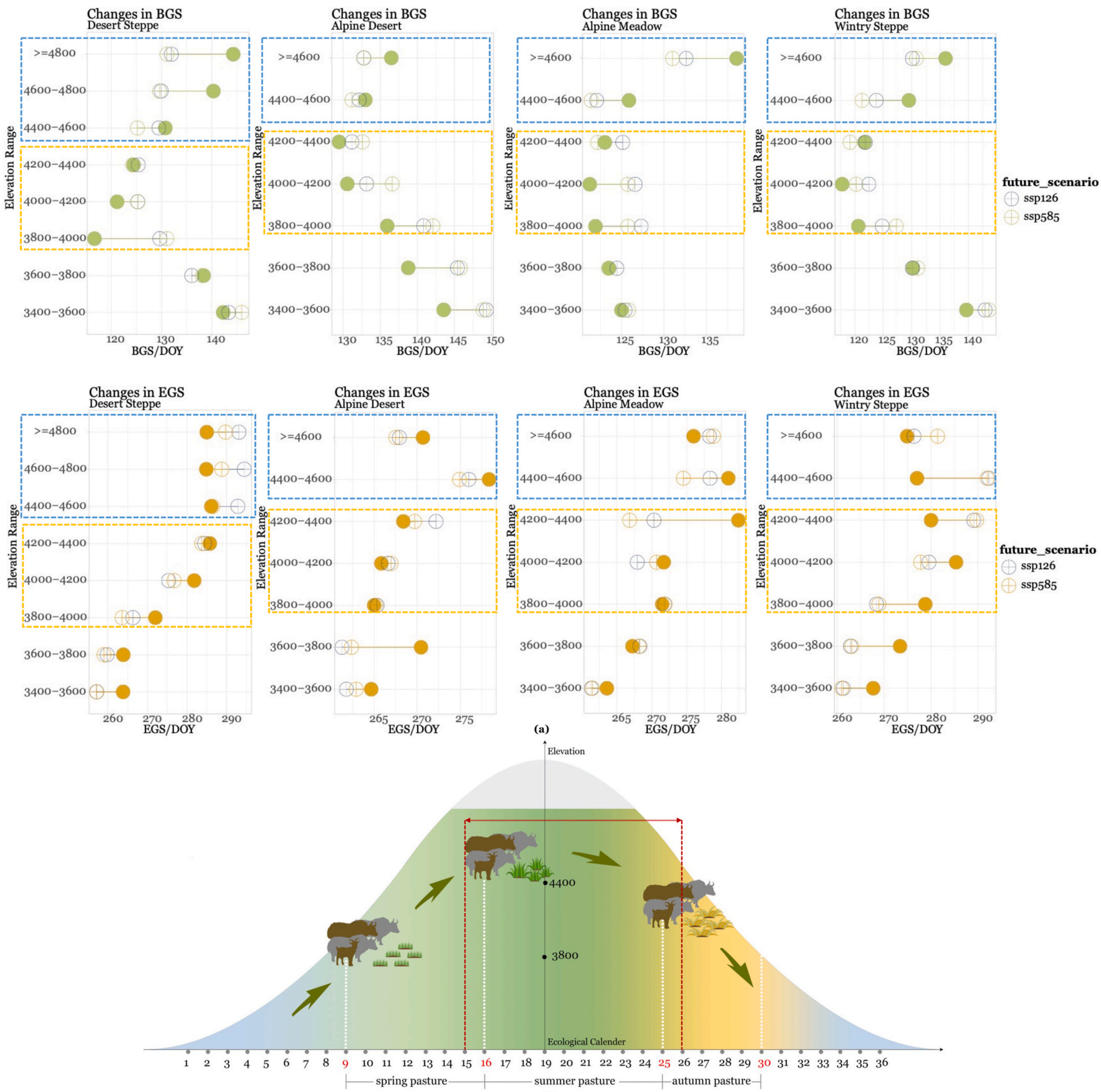

Fig. 5. Potential variations in the BGS and EGS of seasonal pastures at various elevations (a). It was expected that the BGS would occur earlier and the EGS would be delayed in summer pastures (>4400 m), indicating that indigenous people may need to spend more time ensuring an appropriate fodder supply (b).

addition, it was confirmed that the EGS in autumn pastures was the determinant for returning. However, at elevations between 3800 and 4400 m, the EGS will primarily occur 4.50, 5.19, and 2.37 days earlier in desert steppe, alpine meadow, and wintry steppe, respectively, and just 1.64 days later in alpine desert. In contrast, the EGS will be obviously delayed at elevations above 4400 m by 8.15 and 8.40 days in desert steppe and wintry steppe, respectively, and will occur earlier just 2.54 and 0.17 days earlier in the remaining vegetation (Supplementary Table 10). In summary, the occurrence of earlier and longer growing seasons will increase the availability of fodder resources at elevations above 4400 m. In addition, the coverage and growth conditions reflected by the gsNDVI values would change by approximately ±0.01 (Supplementary Tables 9 and 10), which would not significantly change the predominant patterns of fodder supply. Potential changes in the SSP585 scenarios would be comparable to those in SSP126, which are detailed in Supplementary Tables 9 and 10.

4. Discussion

By combining ethnoecological survey data, time-series remotely sensed information and dynamic simulation, we generated an extensive dataset of this novel ecological indicator correlating with the ecological calendar to explore the rationale underlying traditional grazing practices of historical resource management over the eastern Pamir Mountain complex. According to our understanding, research on traditional resource management methods and ecological calendars in the mountains is scarce, even though researchers have long been interested in mountain community livelihoods and the effects of climate change on mountain ecosystems (Knight et al., 2022). In addition, research integrating knowledge on seasonal activities and spatial data of vegetation phenology is the first of its kind. Our research on the seasonal grazing practices in the eastern Pamir Mountains provides numerous insights into the indigenous management practices for managing fodder resources, the justification for these sustainable adaptations, and the adaptability of this seasonal grazing in the face of climate change.

Millions of people in rangelands depend directly on livestock raising for their livelihoods (Gillson and Hoffman, 2007). In March 2022, the United Nations (UN) declared 2026 the International Year of Rangelands and Pastoralists ((FAO) F.a.A.O.o.t.U.N, 2022), reflecting the significant role of rangeland and fodder resource management play in creating a sustainable environment, economic growth and resilient livelihoods for communities around the world. Grazing systems provide approximately 30% and 6% of the world's ruminant meat and milk, but are frequently located on land that is unsuitable for cropping (Herrero et al., 2013), similar to the Pamir Mountains. However, it was projected that the global mean herbaceous biomass could decline by 2050 under RCP 8.5, which may result in a decline in mean biomass for large portions of rangeland due to climate change (Godde et al., 2020). Climate-related challenges to fodder resources may negatively impact actors throughout the livestock supply chain (Godde et al., 2021), and the availability, quality, affordability, safety and sensory appeal of livestock products will be partly impacted (Hallegatte and Rozenberg, 2017). In addition to climate change trends, interannual variability in fodder availability is also a concern for mountain grazing activity, and those effects will continue to lead to shifts in the grazing area as well as changes in seasonality (Godde et al., 2021). Additionally, under various climate change scenarios, by 2050 animals in the low to mid elevation regions of Xinjiang will also experience heat stress throughout the summer. Heat stress will be another destructive element that could damage livestock productivity (Ranjitkar et al., 2020). Thus, it would be safer for local herders to spend more time at summer pasture located at higher elevation during this time. In the future, staying longer in the summer pasture is suggested by our forecast that integrate traditional ecological knowledge and spatial dataset.

To take advantage of the spatial and temporal variation in limited fodder availability, grazing mobility and appropriate resource management have been crucial. However, existing adaptation strategies to changes in the availability of fodder across ecological, socioeconomic, and institutional systems and coping ranges are insufficient at the local community level (Fernández-Giménez and Fillat Estaque, 2012). Previous studies have highlighted the key adaptive capacity characteristics of people in grazing systems, demonstrating that indigenous knowledge of diverse resource management was one of the key channels (Godde et al., 2021). The effectiveness of indigenous knowledge in resource utilization and management (Selemani, 2020) and climate adapted actions (Falardeau et al., 2022) has been proven. Our documentation of the ecological calendar and the observed specific practices component are exhibited at both temporal and spatial scales, as similarly documented in previous studies (Yang et al., 2021; Mondragón, 2004). In the case of the eastern Pamir, seasonal grazing practices are likely to indicate a specific action of resource management, and it was proven that indigenous people of other regions take similar actions (Kassam et al., 2018; Liao et al., 2014). This seasonal grazing practice is sustainable, which can be largely explained by their relationship with vegetation dynamics on the pasture lands. Moreover, being mobile not only allows indigenous people to maximize the forage use throughout the year, but also avoids the excessive utilization of resources at one location (Liao et al., 2014; Barrow et al., 2007). Indigenous people are aware about availability of resources using their knowledge of ecological calendar system, and this practice can also provide the opportunity for plant to have regular growth and maintain their population. In the face of changing climate, ecological calendars will be easily adjusted because of their high sensitivity to climate: changes in fodder phenology are translated into the time and coverage degree of phenological phases that occur. The year-round grazing practices demonstrate a profound understanding of resource distribution and regenerative cycles. As a result, grazing activity can "follow" the changes in fodder condition. In order to be more sustainable and effective, future seasonal grazing policies must be built on the long-established relationships between grazing patterns and vegetation dynamics as shown in our study. Previous research has demonstrated the significance of phenology in traditional agricultural practices (Hufkens et al., 2019), particularly in communities residing in mountains, which have experienced an increase in fodder demand (Mu et al., 2016).

The local community at Pamir and other mountain communities could benefit from the integration of the ecological calendar and scientific data. Fodder phenology that is translated into spatiotemporal features is relatively easy to monitor by modern techniques (Piao et al., 2019). Associated phenological variations are primarily impacted by the climate in mountain regions, as stated by previous research (Vitasse et al., 2018). However, deep integration of such an indicator into agricultural guidance necessitates a more precise evaluation, including a broader range of knowledge systems (including indigenous knowledge) and a precise quantification procedure (Levy et al., 2000). Our findings provide a fresh perspective on how to quantify resource management patterns performed by indigenous communities. On larger spatial scales, potential phenology trends are typically observed not only in the eastern Pamirs, but also in mountains with extensive alpine vegetation (Yu et al., 2010; Piao et al., 2019). These potential changes reflect the future effectiveness of ecological indicators as a tool for managing fodder resources in mountains (Wang et al., 2018), as well as the significance of using indigenous knowledge continuously (Fu et al., 2012). Climate change-induced pressure on mountain resources can be both direct (for example, upshifting of distribution area, earlier/later phases in phenology) (Liu et al., 2018) and indirect (for example, habitat loss due to expansion of agricultural land because of a more suitable crop cultivar) (Yang et al., 2021) and may be related to other driving factors, for example, population growth and species invasiveness. In most remote mountain areas, climate warming has been identified as a dominant limiting factor, leading to an extension of the vegetation growing season at high elevations (Hu et al., 2010), which was supported by our findings. With such knowledge integration, limited resource management and food security could be achieved (Kassam and Bernardo, 2022) by proactively identifying current and future risks and hazards, monitoring environmental changes, and adjusting livelihood styles (e.g. pasture management and crop cultivar adjustment) (Klenk et al., 2017).

5. Policy implication

Indigenous peoples in high mountain pastoral regions, such as the eastern Pamirs, rely heavily on natural fodder resources for their subsistence. However, due to the limited availability of mountain resources and climate change, sustainable management of mountain ecosystems is crucial (Wu et al., 2023). The results of adapt to environmental change as usual without integration of modern scientific evidence may not always be beneficial. Sustainable management policies should not only benefit the mountain ecosystems but also consider indigenous people's lifestyle. The demands of indigenous people for survival and development using their own traditional manage systems must be respected. Analyzing the traditional ecological calendar-like management system and scientifically validating the existing practices will help create awareness of sustainable mountain resource management and specify strategies for adapting to future climate.

Therefore, the following policies could be taken:

(a) Recognition and support of indigenous knowledge and practices: policymakers should recognize and support the use of indigenous knowledge and practices in the management of natural resources, focus on increasing the utilization efficiency of natural fodder resources, and positively adapt to the environment using traditional lifestyles with scientific strategies while protecting the mountain ecosystem.
(b) Promotion of sustainable grazing practices: this study shows that seasonal grazing practices in the Pamir Mountains are crucial for sustainable livestock keeping. Thus, policymakers should promote sustainable grazing practices and discourage overgrazing, which can lead to degradation of pastures.
(c) Integration of ecological calendars in resource management: this study demonstrates the effectiveness of using ecological calendars in managing seasonal grazing and predicting changes in fodder phenology. Therefore, policymakers should consider integrating ecological calendars in resource management plans and encourage their use among local communities.

6. Research limitations and future works

Even though this study has made significant contributions to sustainable mountain resource management, which provides valuable insights into the role of ecological calendars in managing seasonal grazing and adapting to climate change, it also has several limitations that can be addressed in future research.

Firstly, although we conducted multiple rounds of interviews in various forms, conducted participatory surveys in seasonal pastures for several years, and incorporated modern scientific evidences, it does not explore other factors that may also influence grazing patterns, such as changes in land use or economic factors. In the future, based on this research, we will select and incorporate appropriate socioeconomic factors to enhance our understanding of the rationale behind sustainable mountain resource management.

Secondly, this study was unable to obtain sufficient other bioclimatic variables along with elevation gradient, such as photoperiods, despite the fact that previous research had demonstrated that temperatures is the most significant factor affecting vegetation phenology (Guo et al., 2015; Yu et al., 2010), and our study used the same factors. In the future, long-term tracking surveys will be required to acquire a greater variety of elevation-based bioclimatic factors to develop future strategies with greater precision. In addition, it is necessary to include new study areas and expand the survey's scope.

7. Concluding remarks

The main source of income for the Tajik people of the eastern Pamir is livestock keeping, seasonal grazing is an important annual activity, and the communities continue to use fodder phenology phases as an ecological indicator for managing grazing and seasonal migration. Our research shows that seasonal fluctuations in fodder grass phenology greatly support the indigenous strategy of seasonal migration. Additionally, we correctly predicted potential changes in the phenology of fodder in the future, indicating that summer pastures will serve as a source of fodder for a longer period. To use resources sustainably and to help mountain ecosystems adapt to climate change, our study offers strong scientific evidence in support of indigenous resource management approaches. In addition, the obvious advantages of using ecological calendars to maintain a sufficient supply of sustenance for indigenous communities will be encouraged at the local level. These findings show the potential of indigenous knowledge in preserving climatic adaptability and the viability of indigenous management practices for sustainable resource usage in mountain ecosystems that can be adopted in other mountain regions in the world. The findings show how indigenous people have sustainably used the scarce natural resources in mountain ecosystems and how a thorough comprehension of the underlying logic can be used to design a strategy for improved climatic adaptation policies.

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CRediT authorship contribution statement

Huizhao Yang: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Deli Zhai:** Writing – review & editing. **Sailesh Ranjitkar:** Supervision, Writing – review & editing. **Micai Zhong:** Writing – review & editing. **Chang'an Guo:** Visualization. **Xiong Zhang:** Visualization. **Jianwei Yang:** Investigation. **Weikang Yang:** Supervision, Project administration. **Jianchu Xu:** Conceptualization, Supervision, Funding acquisition. **Yuhua Wang:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Abouali, M., 2020. MATLAB implementation of harmonic ANalysis of time series (HANTS). *https://www.mathworks.com/matlabcentral/fileexchange/38841-matlab-implementation-of-harmonic-analysis-of-time-series-hants*. MATLAB Central File Exchange.

Barrow, E., et al., 2007. Pastoralists' Species and Ecosystems Knowledge as a Basis for Land Management, 3. IUCN Eastern Africa Regional Office Policy Brief.

Bendixen, M., et al., 2022. Opportunistic climate adaptation and public support for sand extraction in Greenland. Nat. Sustain.

Bureau, X.S., 2018. Xinjiang Statistical Yearbook 2018. Xinjiang Statistical Bureau, China.

Cámara-Leret, R., Dennehy, Z., 2019. Information gaps in indigenous and local knowledge for science-policy assessments. Nat. Sustain. 2 (8), 736–741.

Cámara-Leret, R., et al., 2019. Climate change threatens New Guinea's biocultural heritage. Sci. Adv.

Castro, B., Sen, R., 2022. Everyday Adaptation: theorizing climate change adaptation in daily life. Global Environ. Change 75.

Christian, K., 2004. Mountain biodiversity, its causes and function. AMBIO A J. Hum. Environ. 33 (sp13), 11–17.

Conway, D., et al., 2019. The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. Nat. Clim. Change 9 (7), 503–511.

Didan, K., 2015. MOD13Q1 MODIS/Terra vegetation indices 16-day L3 global 250m SIN grid V006. NASA EOSDIS Land Processes DAAC 10, 415.

Everingham, Y., et al., 2016. Accurate prediction of sugarcane yield using a random forest algorithm. Agron. Sustain. Dev. 36 (2).

Falardeau, M., et al., 2022. Biophysical indicators and Indigenous and Local Knowledge reveal climatic and ecological shifts with implications for Arctic Char fisheries. Global Environ. Change 74.

(FAO), F.a.A.O.o.t.U.N, 2022. UN names 2026 as the international year of rangelands and Pastoralists. Available from. https://www.fao.org/newsroom/detail/un-names-2026-as-the-international-year-of-rangelands-and-pastoralists/en.

Farrell, J., et al., 2021. Effects of land dispossession and forced migration on Indigenous peoples in North America. Science 374 (6567), eabe4943.

Fernández-Giménez, M.E., Fillat Estaque, F., 2012. Pyrenean Pastoralists' ecological knowledge: documentation and application to natural resource management and adaptation. Hum. Ecol. 40 (2), 287–300.

Fu, Y., et al., 2012. Climate change adaptation among Tibetan Pastoralists: challenges in enhancing local adaptation through policy support. Environ. Manag. 50 (4), 607–621.

Fuso Nerini, F., et al., 2019. Connecting climate action with other sustainable development goals. Nat. Sustain. 2 (8), 674–680.

Gagnon, C.A., et al., 2023. Climate, caribou and human needs linked by analysis of Indigenous and scientific knowledge. Nat. Sustain.

Gillson, L., Hoffman, M.T., 2007. Rangeland ecology in a changing world. Science 315 (5808), 53–54.

Godde, C.M., et al., 2020. Global rangeland production systems and livelihoods at threat under climate change and variability. Environ. Res. Lett. 15 (4).

Godde, C.M., et al., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Secur. 28, 100488.

Guo, L., et al., 2015. Responses of spring phenology in temperate zone trees to climate warming: a case study of apricot flowering in China. Agric. For. Meteorol. 201, 1–7.

Hallegatte, S., Rozenberg, J., 2017. Climate change through a poverty lens. Nat. Clim. Change 7 (4), 250–256.

Herrero, M., et al., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. U. S. A. 110 (52), 20888–20893.

Hidalgo Pizango, C.G., et al., 2022. Sustainable palm fruit harvesting as a pathway to conserve Amazon peatland forests. Nat. Sustain. 5 (6), 479–487.

Hiwasaki, L., et al., 2014. Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. Int. J. Disaster Risk Reduc. 10, 15–27.

Hu, J., et al., 2010. Longer growing seasons lead to less carbon sequestration by a subalpine forest. Global Change Biol. 16 (2), 771–783.

Hufkens, K., et al., 2019. Monitoring crop phenology using a smartphone based near-surface remote sensing approach. Agric. For. Meteorol. 265, 327–337.

Huntington, H., et al., 2004. Matching traditional and scientific observations to detect environmental change: a discussion on arctic terrestrial ecosystems. Ambio 33 (SPEC. ISS. 13), 18–23.

IPCC, 2007. *Climate Change: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jansky, L., et al., 2002. Global mountain research for sustainable development. Global Environ. Change 12 (3), 231–239.

Karim-Aly Kassam, U.B., Ruelle, Morgan, 2011. Ecology of time: calendar of the human body in the Pamir Mountains. J. Persianate Stud. 4 (2), 146–170.

Kassam, K.S., Bernardo, J., 2022. Role of biodiversity in ecological calendars and its implications for food sovereignty: empirical assessment of the resilience of indicator species to anthropogenic climate change. Geohealth 6 (10), e2022GH000614.

Kassam, K.S., et al., 2018. Anticipating climatic variability: the potential of ecological calendars. Hum. Ecol. Interdiscip. J. 46 (2), 249–257.

Klenk, N., et al., 2017. Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. Wiley Interdisciplinary Reviews: Clim. Change 8 (5), e475.

Knight, C.A., et al., 2022. Land management explains major trends in forest structure and composition over the last millennium in California's Klamath Mountains. Proc. Natl. Acad. Sci. U. S. A. 119 (12), e2116264119.

Kreutzmann, H., 2016. Pamir or Pamirs: perceptions and interpretations. In: Herrmann, K., Teiji, W. (Eds.), Mapping Transition in the Pamirs. Springer, Cham, pp. 17–40.

Levy, J.K., Hipel, K.W., Kilgour, D.M., 2000. Using environmental indicators to quantify the robustness of policy alternatives to uncertainty. Ecol. Model. 130 (1), 79–86.

Liao, C., et al., 2014. Following the green: coupled pastoral migration and vegetation dynamics in the altay and tianshan mountains of Xinjiang, China. Appl. Geogr. 46, 61–70.

Lindner, T., Puck, J., Verbeke, A., 2022. Beyond addressing multicollinearity: robust quantitative analysis and machine learning in international business research. J. Int. Bus. Stud. 53 (7), 1307–1314.

Liu, H., et al., 2018. Shifting plant species composition in response to climate change stabilizes grassland primary production. Proc. Natl. Acad. Sci. U. S. A. 115 (16), 4051–4056.

Lu, J., et al., 2022. Scaling up co-produced climate-driven decision support tools for agriculture. Nat. Sustain. 5 (3), 254–262.

Mistry, J., Berardi, A., 2016. Bridging indigenous and scientific knowledge. Science 352 (6291), 1274–1275.

Mondragón, C., 2004. Of Winds, Worms and Mana: The Traditional Calendar of the Torres Islands, Vanuatu. Oceania 74 (4), 289–308.

Morisette, J.T., et al., 2009. Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century. Front. Ecol. Environ. 7 (5), 253–260.

Mu, J., et al., 2016. Traditional grazing regimes promote biodiversity and increase nectar production in Tibetan alpine meadows. Agric. Ecosyst. Environ. 233, 336–342.

Pepin, N., et al., 2015. Elevation-dependent warming in mountain regions of the world. Nat. Clim. Change 5 (5), 424–430.

Piao, S., et al., 2006a. NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China. Global Environ. Change 16 (4), 340–348.

Piao, S., et al., 2006b. Variations in satellite-derived phenology in China's temperate vegetation. Global Change Biol. 12 (4), 672–685.

Piao, S., et al., 2019. Plant phenology and global climate change: current progresses and challenges. Global Change Biol. 25 (6), 1922–1940.

Plaganyi, E.E., et al., 2013. Integrating indigenous livelihood and lifestyle objectives in managing a natural resource. Proc. Natl. Acad. Sci. U. S. A. 110 (9), 3639–3644.

Ranjitkar, S., et al., 2020. Will heat stress take its toll on milk production in China? Climatic Change 161 (4), 637–652.

Riahi, K., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168.

Schaller, G.B., et al., 1987. Status of large mammals in the taxkorgan Reserve, Xinjiang, China. Biol. Conserv. 42 (1), 53–71.

Selemani, I.S., 2020. Indigenous Knowledge and Rangelands' Biodiversity Conservation in Tanzania: Success and Failure. Biodivers Conserv, pp. 1–14.

Shouzhang, P., 2020a. 1-km Monthly Maximum Temperature Dataset for China (1901-2017). National Tibetan Plateau Data Center.

Shouzhang, P., 2020b. 1-km Monthly Minimum Temperature Dataset for China (1901-2017). National Tibetan Plateau Data Center.

Smith, T., Bookhagen, B., 2018. Changes in seasonal snow water equivalent distribution in High Mountain Asia (1987 to 2009). Sci. Adv. 4 (1), e1701550.

Turner, N.J., Clifton, H., 2009. It's so different today": Climate change and indigenous lifeways in British Columbia, Canada. Global Environ. Change 19 (2), 180–190.

Turner, N.J., Ignace, M.B., Ignace, R., 2000. Traditional ecological knowledge and wisdom of aboriginal peoples in British columbia. Ecol. Appl. 10 (5), 1275–1287.

Vitasse, Y., Signarbieux, C., Fu, Y.H., 2018. Global warming leads to more uniform spring phenology across elevations. Proc. Natl. Acad. Sci. U. S. A. 115 (5), 1004–1008.

Wan, M., 1935. Textual research on Chinese 24-solar terms and 72 phenological phases (in Chinese). J. Meteorol. 24–34.

Wan, M., 1962. Phenology and farming schedual (in Chinese). Journal of the Public Science 3.
Wang, J., et al., 2018. Large-scale assessments and mapping of snow hazards in pastoral areas of the Tibetan Plateau using microwave remote sensing data and ground records. Nat. Hazards 90 (1), 461–476.
Wang, S., Azzari, G., Lobell, D.B., 2019. Crop type mapping without field-level labels: random forest transfer and unsupervised clustering techniques. Rem. Sens. Environ. 222, 303–317.
Wheeler, T., von Braun, J., 2013. Climate change impacts on global food security. Science 341 (6145), 508–513.
Wu, J., et al., 2023. Pastoral household natural resource dependence and contributions of grassland to livelihoods: a case study from the Tibetan Plateau in China. J. Clean. Prod. 402.
Xinjiang Comprehensive Investigation Team, C.A.o.S., C.A.o.S. Institute of Botany, 1978. The Vegetation and It's Utilization in Xinjiang. Science Press, Beijing, China, p. 378.
Yang, H., et al., 2019. Role of traditional ecological knowledge and seasonal calendars in the context of climate change: a case study from China. Sustainability 11 (12).
Yang, H., et al., 2021. Crop-climate model in support of adjusting local ecological calendar in the Taxkorgan, eastern Pamir Plateau. Climatic Change 167 (3–4).
Yu, H., Luedeling, E., Xu, J., 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. Proc. Natl. Acad. Sci. U.S.A. 107 (51), 22151–22156.