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Mapping and evaluating plant phenology in the Qinghai-Tibet Plateau: A digital approach using the plant Phenological Index (PI)

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ABSTRACT

A new plant Phenological Index (***PI***) has been developed based on the visibility of plants, communities, and ecosystems. An evaluation and assessment of Zhang's Phenological Index (***PI***) were further examined based on the field observations of Alpine Shrub and Alpine Meadow vegetation at Haibei Alpine Ecosystem Research Station in the Northwest Qinghai-Tibetan Plateau.

Zhang's ***PI*** is a measure of the plant's phenological status on the time intervals, calculating the accumulation of ***PI*** area in two dimensions. Two phenological variables were described as the Phenological Average Ratio (***PAR***) and the Lasted Days (***LD***). The ***LD*** may overlap when a certain percentage of the plant population has a nutritional stage that lasts longer than one additional phenological stage or occurs between two phenological stages. Correspondingly, the standard deviations of the observed multiple plant species represent plant population variations. After reviewing the ***PI*** applications for phenology studies on Alpine Shrub and Alpine Meadow vegetation, we found that they provide a means of measuring and comparing plant phenology at various levels - population, community, and ecosystem.

During the start and end of the season in the Alpine Plateau region, plant phenological changes were significantly constrained by the environmental factors. However, during the summer season, Sunlight Hours (*X4*), Accumulated Ground Temperature (X3) and Accumulated Air Temperate (X1) above 0 °C had a more uniform impact on plant phenology across the region.

Zhang's ***PI*** can be used for climate change research by altering warming temperatures, water conditions, and nutrient levels. We also discussed the concern of applying Zhang's ***PI*** to global warming research. Moreover, the Seasonal Phenological Index (***SPI***) can be described on a regional scale and used with ***ASOS***, ***AEOS***, ***SPAR***, and ***SLD*** characters to evaluate the changes in the timing of seasonal events in Eqs. (3)(4)(5).

1. Introduction

Phenology studies were essential contents in biology and ecology, from digital mapping of insects, birds, and vegetation, to phenological analysis of plant populations and communities and global changes [1–4]. Based on the distance and visibility of a subject [5], the phenology change and character are identified and described as a simple code [6], Phenological Index (***PI***) [7], ***NDVI***, and ***EVI*** [8]. Plant phenology, describing the annually recurring sequence of plant developmental stages, is a primary plant biological function and ecosystem feature and reflects biophysical and biogeochemical feedback to the climate system. Plant cyclical biological events are significant indicators of the seasonality of the environment, revealing the implications of rising temperatures on vegetation functioning [6–8].

Plant phenology studies were based on changes in the timing of seasonal events, such as budburst, flowering, fructification, and senescence [8–10]. Plant phenology has received increasing public and scientific attention due to the growing evidence that the timing of developmental stages is mainly dependent on environmental conditions and agricultural activity [9,11].

Plant phenology is directly related to climatic conditions and is essential in ecosystem processes, such as carbon and nutrient cycling, adaptive mechanisms, and survival strategies [12–14]. Furthermore, at the individual plant level, phenology has been shown to influence fitness and reproductive success [12] and has played a direct role in species distribution [15]. Eventually, changes in phenology not only have their

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consequences on affecting species distribution and disrupting species interactions but also altering the carbon cycle and influencing global climate impacts [16–18]. Early Studies of the phenological characteristics were restricted to the simple occurrence data [1,2,9,10,19], the trigger of leaf onset/offset, and variations of leaf area throughout the phenological periods [20]. Therefore, modeling, assessing, and monitoring phenological dynamics are fundamental to understanding how plants and communities respond to the changing climate and how these changes influence the ecosystems and their functions [7,12–14]. An initial phenology study at Alpine Meadow was conducted in 1983 and 1984 [21]. Twenty-one plant species were observed to study the relationship between plant biomass and phenological stages. However, the phenological two-dimension diagram raised a question [21,22] about obtaining the Digital mapping result, Phenological Index [7].

Land Surface Phenology (LSP) on a large scale has been established from remote sensing-based vegetation indices (VIs) data. They reflect the relationship between the LSP data and vegetation growth status for the start and end of growing seasons as different vegetation indices with the algorithms [23,24]. The leaf area index (LAI) was used in DGVMs as Phenology schemes, and land surface models can be established using satellite observational data. The statistical models were based on the relationship between phenology and climate and dynamic carbon models [20].

In this paper, we will present Plant Phenological Index Digital Mapping and discuss the methods of monitoring phenology. (1) Time series-based human visual observations on the individual scale. (2) Digital Plant Phenology Index Mapping from subtracting multiple-variable model. (3) Remote sensors-based observations for a local and regional phenology study. The visibility of the plant community presents the principle of plant phenological retrieval and allows for remotely capturing phenological variations at both small and large scales [4,8]. West's Phenological Index Score (*PIS*) [6] will be reviewed and discussed. In the phenological study and plant phenological index mapping, Zhang's ***PI*** (1994) had been examined as a numerical tool for estimating plant growth and will enable improved vegetation monitoring, particularly of plant and community phenology related to digital mapping, clustering phenological types, and phenological change rate, and relationship with environmental climate factors.

2. Materials and methods

2.1. Study site

The research sites are located near Haibei Alpine Meadow Ecosystem Research Station (37°N, 101°E) at 3200–3350 m. The vegetation types of the field sites are typical of *Kobresia Humilis* Meadow and *Potentilla Fruticosa* Shrub [15]. The field experiments were initiated and completed in the summer of 1988 and 1989 [7,18] and 1999 [13]. The plots at *Potentilla Fruticosa* Shrub and *Kobresia Humilis* Meadow were selected and located separately on the homogeneous vegetation sites of 50 × 50 m^2. Twenty dominant plant species were selected, and twenty same species duplicates were labeled for statistical observation; the plant population phenological rate (PR) is from 10% at the Start Of Status (***SOS***) to great than 90% at the End Of Status (***EOS***). Similar studies [13,14] were conducted at *Kobresia Humulis* meadow.

2.2. Measurement and data collection

When the plant phenology status was changing quickly, the observation date was once three days; when the plant phenology status was changing slowly, the observation date was once from five to seven days. The meteorological data were measured and recorded at Haibei Alpine Meadow Ecosystem Station daily for the same period. Plant population phenological status is reported and based on nutritional stage, bud stage, flowering stage, fruit stage, and after-fruit-matured nutritional stage, flavescent and dormancy period [7,13]. The dormitory stage starts on Oct. 20 when the average air temperature reaches zero degrees in the study area or the last-observed plant populations reach over 90% flavescent.

2.3. Zhang's *PI* description

In Plant Population Phenology mapping (Fig. 1), the top line presents the Start Of Status (***SOS***) at 10%, with increasing the percentage of the status over time (t_1, t_2, t_3, t_4), the mapping line reaches the bottom at t_4. The Maximum Of Status (***MOS***) is great than 90%, up to 100%. At a dataset [7], the certain time of ***MOS*** passed, the End Of Status (***EOS***) reduced from t5, t6, t7, and t8 at 0–10% ending (Fig. 1). Hence, according to Zhang's ***PI***, we calculate and obtain ***PI***s of six plant-growing phenological stages. An example of one plant ***PI*** calculation for one phenological stage is shown in Table 1. Two interpretations were matched when comparing Zhang's and Zhou's phenological reports [7,13].

To distinguish other defined ***PI***s [3,4,8], Zhang (1994) described the mapping procedure of plant Phenological Index (***PI***) as the measured area (Fig. 1), and repeatedly used for different plant population phenological stages (Fig. 3).

$$\text{Zhang's } \boldsymbol{PI} = \sum_{i=1}^{k} \frac{1}{2} * (PR_{i+1} + PR_i) * (T_{i+1} - T_i) \tag{1}$$

$$\boldsymbol{PAR} = \frac{\boldsymbol{PI}}{\boldsymbol{LD}} \tag{2}$$

where ***PI*** — Phenological Index
$\boldsymbol{PR_i}$, $\boldsymbol{PR_{i+1}}$ — Phenological Rate observed at the time i and i + 1
PAR — Phenology Average Rate between T_i and T_{i+1}
LD — Lasted Days, Time at $i = 1, 2, 3, \ldots\ldots$ n, n ≤(k)

2.4. Average values and variants of *PI, PAR, LD,* and environmental factors

A rate of 10% terminated the SOS, and 90% ended the EOS of plant phenology status. Thus, each plant species' lasted days (***LD***) was calculated. ***PI***, ***PAR***, and ***LD*** were calculated for six plant phenology stages for 20 species. We calculated the Average Values and Standard Deviation of the plant Phenology Index (***PI***) of the Alpine Shrub vegetation (Table 3) [7]. The Standard Deviation presents the differences among the 20 plant species, not the error variant from the same plant populations. And the same experiment and calculation were completed for Alpine Meadow vegetation [13].

2.5. Clustering plant phenological types

The responses of plant phenology to environmental factors relatively exhibit similarities and dissimilarities. As shown in Fig. 4, the correlative-clustering methods [7,13,15] were employed to categorize plant species of Alpine Shrub into distinct phenological types. Also, Zhou et al. (2002) [13] classified the plant phenological types of alpine

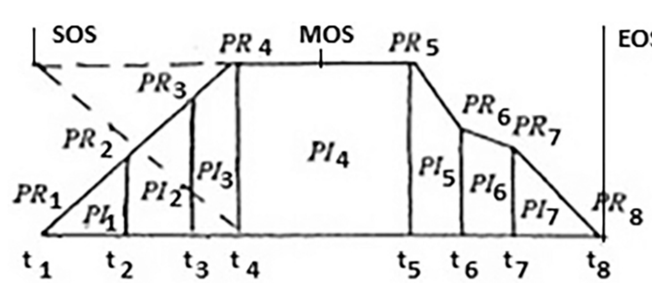

Fig. 1. Typical Plant Phenology Mapping in terms of SOS at the top line and EOS at the bottom line.

Table 1
Examples of observation records, and a calculated ***PI***, and ***LD*** for one phenological stage.

Date	Apr. 5	10	15	22	30	May 5	10	15	22	PI
PR_i (%)	0	10	20	35	100	100	60	30	10	
LD (Days)		5	5	7	8	5	5	5	7	47.00
PI over 1[2]		0.25	0.75	1.96	6.40	5.00	4.00	2.25	1.05	21.66
PI 100% [1]		25	75	196	640	500	400	225	105	2166

Dataset Notes: unit [1]. Zhang et al. 1994 [7], [2]. Zhou et al. 2002 [13].

species studied in the Alpine Meadow. Ye et al. (2014) [14] classified the plant phenological types based on lasted days (***LD***) of the Alpine Meadow.

3. Results and discussion

3.1. Phenology observations and primary plant phenological index mapping

West and Wein (1971) found that genetic differences increased variability and made quantification more difficult when ecologists studied the plant competitions among the species. As a result, they developed Phenological Index Scores(***PIS***), numerical ratings of more closely defined phenological stages that would permit the data to be used in statistical tests for different sites or treatments. The ***PIS*** is a set of numbers for plant phenological stages. However, the same number of phenological index scores were based on specific plant characteristics. For example, the base scores of 1, 2, 3, 4, 5, and 6 for *Atriplx nuttallii* are the Winter Dormancy, Leaves Regreening and Buds Swelling, Twigs Elongating, Floral Buds Developing, Flowers Opening, and Fruit Developing, respectively. Same base scores for *Hilaria jamesii* are Winter Dormancy, Growth Initiation, 2 Leaf Stage, 3 Leave Stage, 4 Leaf Stage, and 5 Leave Stage, respectively, in Fig. 2 [6].

The percentage of plant phenological stages based on twenty plant duplications were recorded as x.10 for 10%, x.20 for 20%, …… x.90 for 90%. West's ***PIS*** method described the plant phenological index technique linearly. It did give an indication of the growth process. However, there were limitations in comparing the phenology among the different plant species if we did not use the commonly defined phenology stages [1,2,7].

West et al. developed a plant phenological index that was presented by the base scores and mapped in the two-dimension diagram with 95% confidence limits. It provided a clearer picture of plant species' phenological change with seasonal times. ButWest's ***PIS*** is not used as a direct index to plant physiological processes.

3.2. Plant phenology diagram mapping in SOS, MOS, EOS, PR, and LD for 20 plant species

With precise and detailed records of plant species' phenological status, the two-dimension diagram of Alpine Shrub was completed in Fig. 3 [7,18]. Zhang and Shi reported the two-dimension diagrams of Alpine Meadow in 1989 [18,21]. Each plant species had records of ***SOS***, ***MOS***, ***EOS***, PR_i, and ***LD,*** and the further calculations of plant Phenological Index (***PI***) and ***PAR*** were based on Eqs. (1)(2) and referred to an example in Table 1.

3.3. Clustering alpine plant phenology types by the plant PIs and LDs

Zhang's ***PI***, ***PAR,*** and ***LD*** are key phenological characters and variables for studying plant phenology. The correlational analysis of ***PI*** verse ***LD*** and ***PI*** Verse ***PAR*** was carried out in Table 2. The ***PI*** verse ***LD*** presented significant relations in six plant phenological stages ($p < 0.01$). Likewise, the ***PI*** verse ***PAR*** was significantly related to plant phenological stages (p < 0.01). Therefore, Zhang's ***PI***, ***PAR***, and ***LD*** provided a digital approach for studying the phenology of plant populations applying to different phenological stages.

According to the plant ***PI***s, Zhang et al. used the correlation

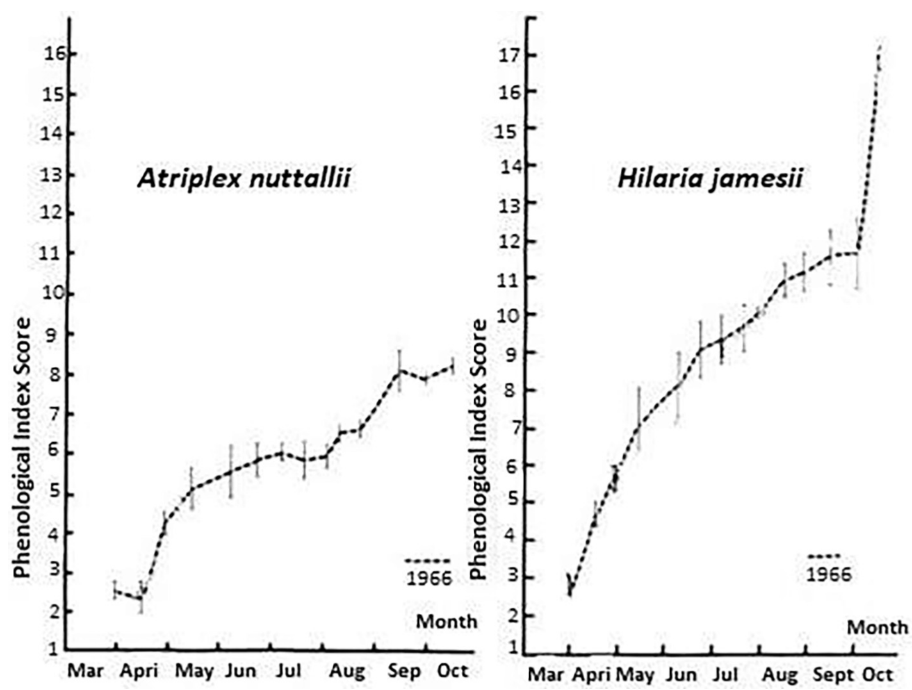

Fig. 2. West's Phenological Index Score Diagram, Growth Season in 1966 Dataset [6]: West and Wein in 1971.

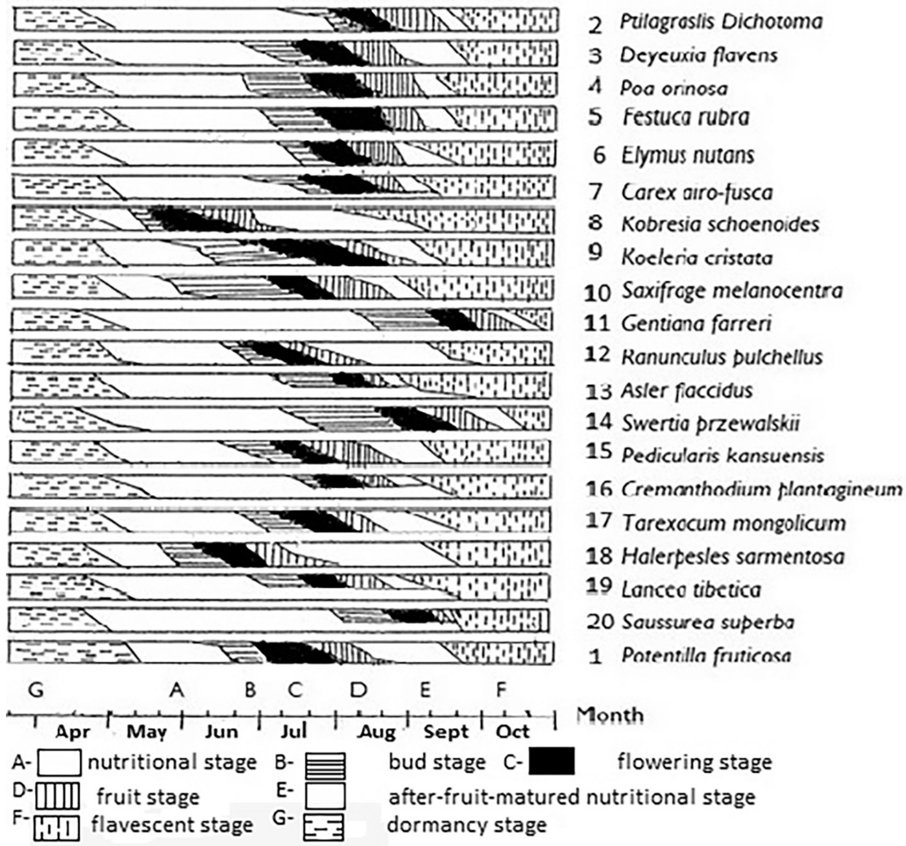

Fig. 3. Plant phenology mapping in Alpine Shrub for 20 plant species [7].

Table 2
Correlational analysis ($P < 0{,}01$, $R = 0.537$) of ***PI*** vs ***LD***, ***PI*** vs ***PAR*** in six plant phenological stages of Alpine Shrub.

	Stages					
Relations	Nutritional stage	Bud stage	Flowering stage	Fruit stage	After-fruit-matured nutritional stage	Flavescent stage
PI vs *LD*	0.909	0.785	0.703	0.726	0.932	0.923
PI vs *PAR*	0.658	0.785	0.817	0.817	0.783	0.598

Correction: The dormitory stage starts on Oct. 20 when the average air temperate reaches zero degrees in the study area. Then ***PI*** vs ***PAR*** correlational analysis is approved ($p < 0.01$, $R = 0.598$) in flavescent stage based on 20 plant species [7].

coefficient [15] to cluster six plant phenological types based on 20 plants of Alpine Shrub. And Zhou et al. used the relative Euclidean distance [13] to cluster three to six plant phenological types based on 19 plants of Alpine Meadow. Additionally, based on the studied 12 plant ***LD***s [14], Ye et al. clustered three plant phenological types (Fig. 4 A. B. C.).

The clustered plant phenological types of Alpine Shrub and Alpine Meadow (Fig. 4) presented common characteristics primarily as follows:

1) Dominant plant species are always in a phenological group with their accomplished species, e.g., *Potentila fruticose* A III (1,12), and *Kobresia humilis* in B I (21,22,23,26).
2) Vigorous flowering plants can be identified in a phenological group, e.g., in A II (13,16,20) and B II-d (11,20,24)
3) A higher percentage of nutritional growth of perennial herbs and sages was clustered in a phenological group, e.g., A I (2,3,4,5,6,11,14,15,17), B III (7,10,15,17,27,28,29)
4) Based on ***LD*** clustering, dominant plant types and sage groups were identified, e.g., in C II (21,22) and C III (20,24), respectively; C I group (4,6,7,25,29,30,31,32) as early greenness, nutritional stage longer, and heading stage in July.

With plant ***PI***s in six plant phenological stages, Zhou et al. (2002) [13] carried out Principal Component Analysis. They obtained three dimensions' ordinary of the phenological index of the main plant population in Alpine Meadow. The first three main principal components presented over 80–85% information. And detailed six phenological types were lined up in three dimensions. They reflected the first principle of the nutritional stage and after- fruit- matured nutritional stage, the second principle of the flavescent stage, and the third principle of the flowering stage. The exploration of the ***PI*** application demonstrated that Zhang's ***PI***, ***PAR***, and ***LD*** have practice values for plant phenology observations, studies, and research. They can help ecologists to find plant population phenological mechanisms and the relation of the physiological processes [13–15].

3.4. Phenology characteristics and relation with environmental factors in alpine vegetation

We can calculate the ***PI***s, ***LD***s and ***PAR***s for six phenological stages of Alpine shrub and Alpine Meadow (Table 3).

Table 3 shows the nutritional stage had the largest ***PI***, ***LD***, and ***PAR*** within six phenological stages for Alpine Shrub and Alpine Meadow. The growth season ***PI's*** total of Alpine Shrub is 132.24, and smaller than that

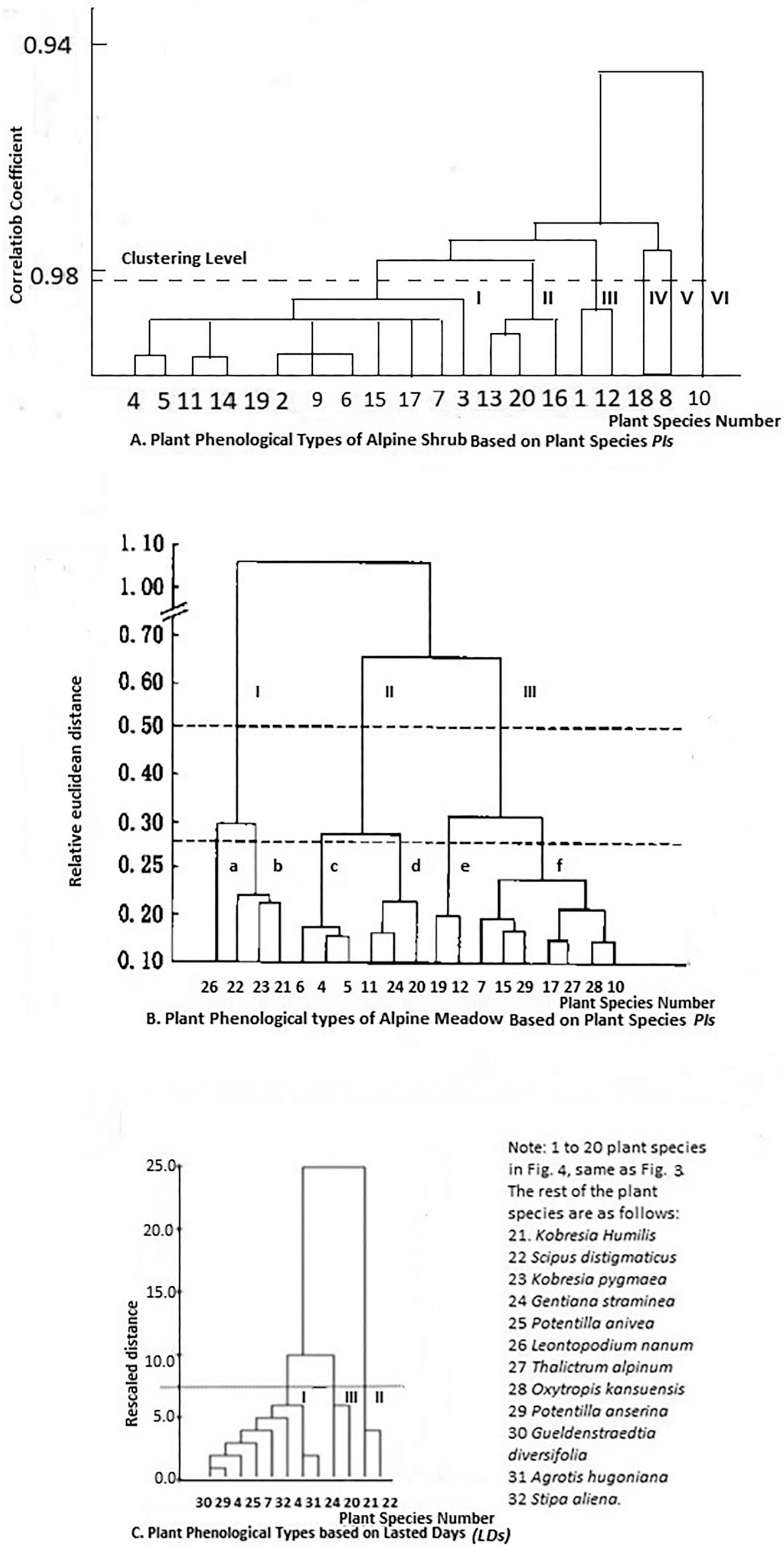

Fig. 4. Clustering alpine plant phenology types based on ***PI*s** (A, B) and ***LD*s** (C). Dataset [7,13,14].

Table 3
Plant ***PI***, ***LD***, and ***PAR*** in six phenological stages of Alpine Shrub and Alpine Meadow.

Stages	Nutritional stage	Bud stage	Flowering stage	Fruit stage	After-fruit-matured nutritional stage	Flavescent stage	Total
Shrub's	59.40	17.00	14.82	14.14	18.64	8.24	132.24
PI	±22.00	±10.78	±6.81	±7.15	±15.42	±4.08	
LD (days)	80.1	35.8	32.8	30.8	34.6	17.2	231.30
	±25.0	±14.6	±11.6	±9.7	±18.3	±9.4	
PAR (%)	73.2	42.6	43.8	43.5	48.1	49.1	Av. 50.05
	±11.1	±18.8	±15.9	±18.5	±19.7	±8.4	
Meadow's ***PI***	56.82	7.52	14.20	6.61	39.59	12.67	137.41
	±28.97	±4.96	±7.57	±5.46	±18.05	±7.07	
LD (days)	70.95	27.53	34.00	17.11	64.63	23.84	238.06
	±30.02	±11.78	±15.02	±9.53	±30.19	±10.90	
PAR (%)	77.00	27.00	42.00	39.00	60.00	50.00	Av. 49.16
	±10.00	±12.00	±13.00	±16.00	±9.00	±14.00	

Notes: Average values and Standard Deviations of 20 plant species ***PI***, ***LD***, and ***PAR*** on the alpine shrub and Alpine Meadow. For example, ***PI***'s value in the flowering stage is 14.82 ±6.81 based on the 20 observation species. And **the Standard Deviation presents the differences of 20 observed plant species, not the error variant in this case.** Dataset [7,13].

of Alpine Meadow, 137.41. The growth season ***LD's*** total of Alpine shrub is 231.30, smaller than that of Alpine Meadow, 238.30. As the defined variable, **the phenological lasted days (*LD*) may overlap if a certain percentage of plant species experienced a stage that lasted longer than one more phenological stages (**Table 3**)**, or during the periods between two phenological stages. For instance, in Fig. 3, these ware observed in plant species such as 13 *Asler flaccidus*, 16 *Cremanthodium plantagineum*, 19 *Lancea tibetica*, and 20 *Saussurea superba*. Their average ***PARs*** in the growing season are closer to 50.05 for Alpine Shrub and 49.16 for Alpine Meadow. Therefore, the calibrated annual growing days for Alpine Shrub in the study area is 153.5 ± 14.8 [7,21] and 164.16 ± 10.22 for Alpine Meadow [13].

We can calculate the environmental factors in six phenological stages for Alpine Shrub and Alpine Meadow. Zhang et al. [7] and Zhou et al. (2002) studied the relationship between ***PI*** and environmental factors in six phenological stages. In each phenological stage, we identified the environmental factor's correlation coefficient, ranking them in order of 1, 2, and 3, labeled on the upright corner of the numbers for comparison (Tables 4 and 5).

Alpine Shrub was predominantly found on the northwest slope, where Sunlight Hours (*X4*) had the greatest influence on its phenology, ranking first in five out of six stages. Similarly, Accumulated Ground Temperature (*X3*) and Accumulated Air Temperature (*X1*) above 0 °C significantly impacted most Alpine Shrub plant phenological stages over the growing season. Precipitation or snowfall (*X5*) had the most impact on the after-fruit-maturated nutritional stage and was ranked first only once and second in the flavescent stage of Alpine Shrub (Table 4).

On the other hand, Alpine Meadow was distributed on a flat landscape, where Sunlight Hours (*X4*) ranked first in the bud, flowering, and after-fruit-matured nutritional stages. Accumulated Ground Temperature (*X3*) above 0 °C ranked first in the nutritional and fruit stages. In contrast, Accumulated Air Temperature (*X1*) above 0 °C ranked first in the flavescent stage, showing a more critical influence over time. Precipitation or snowfall (*X5*) ranked second and had negligible impacts on the after-fruit-maturated nutritional status of Alpine Meadow (Table 5), indicating a slight difference in the environmental factors that affect Alpine Meadow phenology.

In the nutritional stage, the environmental factors produced the constraints for plant growth beginning, and in the flavescent stage, the environmental factors influenced the ending of plant growth. Therefore, the relationships between ***PI***s and environmental factors were considerably associated with the higher coefficients. On the other hand, during the bud and flowering stages, environmental factors had fewer constraints on plant growth and were favorite to plant phenological growths. Thus, their correlation coefficients were reduced to lower levels. The diagrams present these relationships as "V" shape from nutrition, bud, flowering, fruit, after-fruit-maturated nutritional, and flavescent stage according to Table 4 and Table 5.

3.5. Seasonal Phenological Index (SPI) based on ASOS, AMOS, and AEOS

The essential content in the plant population ecology is studying plant phenological changes in different stages [7]. Thus, Zhang's ***PI***, ***PAR***, and ***LD*** in Eqs. (1) (2) are practice methods for obtaining plant population phenological characteristics and comparing them in timing matter. However, when we study the seasonal growth at the plant community level, the growing season will be divided into Average Start OF Season (***ASOS***) at t_1, Average Maximum OF Season (***AMOS***) at t_2 and t_3, Average End OF Season (***AEOS***) at t_4 (Fig. 5).

Consequently, we express the Seasonal Phenological Index (***SPI***), Seasonal Phenological Average Ratio (***SPAR***), and Seasonally Lasted Days (***SLD***) in Fig. 5 as follows:

$$\begin{aligned} \boldsymbol{SPI} &= \frac{1}{2}(PR_1 + PR_2)*(t_2 - t_1) \\ &\quad + (PR_2 + PR_3)*(t_3 - t_2) \\ &\quad + \frac{1}{2}(PR_3 + PR_4)*(t_4 - t_3) \end{aligned} \tag{3}$$

$$\boldsymbol{SPAR} = \boldsymbol{SPI}/\boldsymbol{SLD} \tag{4}$$

$$\boldsymbol{SLD} = \boldsymbol{ASOS}\text{–}\boldsymbol{AEOS} = t_4\text{–}t_1 \tag{5}$$

Table 4
Correlation(R) between ***PI***s and environmental factors in six phenological stages of Alpine shrub.

	Stages					
Evn.Factors	Nutritional stage	Bud stage	Flowering stage	Fruit stage	After-fruit-matured nutritional stage	Flavescent stage
≥0 °C Accum. Air Temp (*X1*)	0.883^{3}	0.654^{3}	0.583^{3}	0.610^{2}	0.915^{3}	0.728^{3}
≥5 °C Accum. Air Temp (*X2*)	0.878	0.612	0.537	0.578	0.901	0.694
≥0 °C Accum. Ground T (*X3*)	0.894^{2}	0.669^{2}	0.598^{2}	0.605^{3}	0.919^{2}	0.720
Sunlight Hours hrs (*X4*)	0.896^{1}	0.793^{1}	0.703^{1}	0.718^{1}	0.911	0.859^{1}
Precipitation mm (*X5*)	0.865	0.591	0.479	0.585	0.925^{1}	0.847^{2}

Note: The number on the upright corner is the rank of the correlation (R) in Table 4, and Table 5.

Table 5
Correlation(R) between ***PIs*** and environmental factors in six phenological stages of Alpine Meadow.

	Stages					
Evn.Factors	Nutritional stage	Bud stage	Flowering stage	Fruit stage	After-Fruit- Matured Nutritional stage	Flavescent stage
≥0 °C Accum. Air Temp (*X1*)	0.961	0.438 ^{3}	0.574 ^{3}	0.900 ^{2}	0.957	0.957 ^{1}
≥5 °C Accum. Air Temp (*X2*)	0.978 ^{2}	0.294	0.531	0.888	0.936	0.924 ^{2}
≥0 °C Accum. Ground T (*X3*)	0.982 ^{1}	0.446 ^{2}	0.620 ^{2}	0.913 ^{1}	0.962 ^{3}	0.968 ^{3}
Sunlight Hours hrs (*X4*)	0.965	0.595 ^{1}	0.736 ^{1}	0.890 ^{3}	0.970 ^{1}	0.964
Precipitation mm (*X5*)	0.977 ^{3}	0.306	0.524	0.860	0.963 ^{2}	0.926

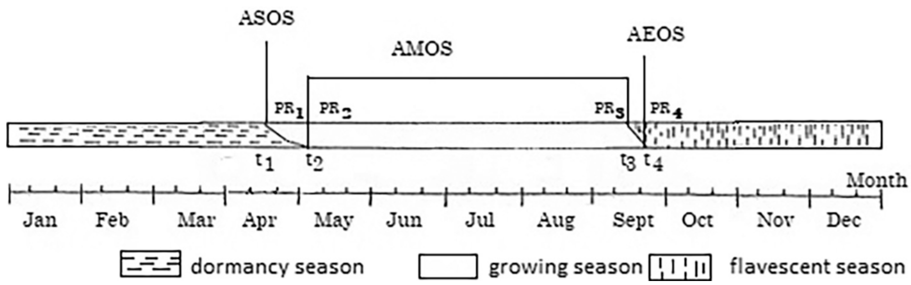

Fig. 5. Seasonal Phenological Index (***SPI***) based on ***ASOS***, ***AMOS***, and ***AEOS***.

where ***SPI*** — Seasonal Phenological Index

PR_i — Phenological Rate observed at the time i, $0 < i \leq (4)$

SPAR — Seasonal Phenology Average Rate

SLD — Seasonally Lasted Days

The ***SPI*** in Eqs. (3)(4) has the benefit of eliminating the overlapping on the seasonally lasted days (***SLD***) compared with ***LD*** in Eq. (2).

Extensional study of Plant phenology has been applied for seasonal and interannual variations in climate. In dynamic global vegetation models (DGVMs), the impacts of phenology on the ecosystem are considered through the changes in leaf area index (LAI) [20]. With the concern of global climate change and its potential impacts, establishing international phenology had rapid progress in remote sensing technologies. The expanded scope of phenology studies dramatically improved the understanding of vegetation phenology from local to the globe [23–25].

Accurate monitoring of vegetation phenology (e.g., the start and end of status) [25] helps understand the impacts of climate change on vegetation and the terrestrial carbon cycle. The enhanced vegetation index (EVI) and normalized difference greenness index (NDGI) are the primary data sources for phenology monitoring at regional and global scales [4].

Yang and He et al. (2017) comprised about 3000 trees from forested areas across the Tibet Plateau. They found that the start of the growing season and the end of the growing season were indicators of climate change [26,27]. Scaling up this analysis may improve understanding of climate change effects, phenology, and plant productivity on a global scale.

With standardized recording systems, ground-based phenological data can be recorded in the future. Such data are essential for better understanding and predicting future environmental processes. In addition, ground-based camera systems and automated image analysis can provide high temporal resolution for calibrating satellite-based monitoring initiatives [28,29].

4. Conclusion

The phenological studies on plant populations showed that different species exhibited variations in their ***PIs***, ***PARs***, and ***LDs***. These differences demonstrated that certain individuals went through complete phenological stages while others only went through the nutritional stage (as shown in Fig. 3) in the alpine ecoregion. Accordingly, the mapping results of ***PIs***, ***PARs***, and ***LDs*** were associated with the timing of ***SOS***, ***MOS***, ***EOS*** of the various phenological stages. Zhang (1994) primarily developed a new plant Phenological Index (***PI***), Phenological Average Ratio (***PAR***), and Lasted Days (***LD***) based on the observations of the different plant phenological stages. For example, the total ***PI*** for Alpine Shrub in the growing season is 131.23, and the total ***LD*** is 231.3; the total ***PI*** for Alpine Meadow in the growing season is 137.41, and the total ***LD*** is 238.16 from Table 3. The calibrated annual growing days for Alpine Shrub in the study area is 153.5 ± 14.8 [7,21] and 164.16 ± 10.22 for Alpine Meadow [13,30]. Moreover, to study phenology at a regional scale, it is highly recommended to use the Seasonal Phenological Index (***SPI***), which considers seasonal and interannual variations. ***SPI*** is calculated using Eq. (3), while ***SPAR*** and ***SLD*** are calculated using Eqs. (4) (5).

In the individual population scale, the phenology studies focused on identifying phenological stages that take time to complete over a year [1,7,22,31]. During the start and end of the season in the Alpine Plateau region, plant phenological changes were significantly constrained by the environmental factors. And during the summer season, Sunlight Hours (*X4*), Accumulated Ground Temperature (X3) and Accumulated Air Temperate (X1) above 0 °C had a more uniform impact on plant phenology and plant growth across the region [30,32]. However, for remote sensing and mapping data, the focus was on identifying and localizing plant species based on species-specific phenological characteristics [2–5]. In recent studies, a wide range of Deep Learning methods has been applied, showing their great potential to take plant phenology research to the next level [28].

The vegetation phenology directly indicates that ecosystems respond to environmental changes, which has attracted increasing attention from the academic community. Long-term vegetation phenology data is critical for conducting phenological research. The phenological parameters obtained through experimental observations have become an independent indicator of terrestrial ecosystem change [7,13,14,27,31,33,34].

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Author's contributions

All Authors contributed to data collection, research, and writing manuscripts.

Declaration of Competing Interest

There is no conflict of interest, and we agree to publish the article in Acta Ecologica Sinica journal.

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