TiP-Leaf: A dataset of leaf traits across vegetation types on the Tibetan Plateau

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Abstract. Functional trait databases are emerging as a crucial tool for a wide range of ecological studies, including the next-generation vegetation modelling across the world. However, few large-scale studies have been reported on plant traits in the Tibetan Plateau (TP), the cradle of East Asian flora and fauna with specific alpine ecosystems, no report on plant trait databases could be found. In this work, an extensive dataset of 11 leaf functional traits (TiP-Leaf) mainly for herbs and shrubs and a few trees on the TP was compiled through field surveys. The TiP-Leaf dataset, which was compiled from 336 sites distributed mainly in the plateau surface and the northern margin of the TP across alpine and temperate vegetation regions and sampled from 2018 to 2021, contained 1692 morphological trait measurements of leaf thickness, leaf fresh weight, leaf dry weight, leaf dry-matter content, leaf water content, leaf area, specific leaf area and leaf mass per area and 1645 chemical element trait measurements of leaf carbon, nitrogen and phosphorus contents. Thus, 468 species that belong to 184 genera and 51 families were obtained and measured. In addition to leaf trait measurements, the geographic coordinates, bioclimate variables, disturbance intensity and vegetation types of each site were also recorded. The dataset could provide solid data support to effectively quantify the modern ecological features of alpine ecosystems, thereby further evaluating the response of alpine ecosystem to climate change and human disturbances and improving the next-generation vegetation model. The dataset, which is available from the National Tibetan Plateau Data Center (TPDC; Jin et al., 2022a; https://doi.org/10.11888/Terre.tpdc.272516), can make a great contribution to the regional and global plant trait databases.

1 Introduction

Plant traits of morphological, anatomical, physiological and phenological characteristics respond to changes in the living environment, affect ecosystem functions (Díaz & Cabido, 2001) and drive species coexistence under environmental constraints (Violle et al., 2007). Over the past three decades, a growing body of trait analyses has quantified the global and regional distribution patterns of key functional traits, such as leaf (Reich & Oleksyn, 2004; Wright et al., 2004), seed size (Moles et al., 2007), plant height (Moles et al., 2009), wood (Chave et al., 2009), plant form and function (Díaz et al., 2016), root (Ma et al., 2018) and flower (Roddy et al., 2021). Such studies have successfully linked plant traits with environmental changes (Meng et al., 2009, 2015; Myers-Smith et al., 2019; Maes et al., 2020; Wang et al., 2022), natural and anthropogenic disturbances (Díaz et al., 2007) and ecosystem functions (Reichstein et al., 2014). Findings from plant trait–environment–ecosystem function interaction could be further utilised to map the spatial pattern of plant traits (Butler et al., 2018), build the next-generation of vegetation model (Berzaghi et al., 2020), predict vegetation distribution (van Bodegom et al., 2014) and function (Wang et al., 2017) and be incorporated into the Earth system model (Wullschleger et al., 2014). New insights into ecosystem traits (He et al., 2019) and trait network (He et al., 2020) are bridging multiple dimensions of biology, macroecology and geoscience. All these works require global and regional plant trait databases, such as the TRY (Kattge et al., 2011, 2020), Growth-Form (Taseski et al., 2019), Global Inventory of Floras and Traits (Weigelt et al., 2019), Fine-Root (Iversen et al., 2017), GRoot (Guerrero-Ramírez et al., 2021), and tundra traits (Bjorkman et al., 2018), Plant Trait for Mediterranean Basin Species (BROT) (Tavşanoğlu & Pausas, 2018), China traits (Wang et al., 2018), AusTraits (Falster et al., 2021) and LT-Brazil (Mariano et al., 2021).

Plant trait databases across various biomes at global, continental and regional scales have been raised largely, even in some remote areas with logistical difficulties, including the tundra (Bjorkman et al., 2018) and tropical regions (Mariano et al., 2021). However, the Earth still has under-sampled regions. The Tibetan Plateau (TP), includes the two major regions of Qinghai Province and Xizang Autonomous Region, and partial areas from northwestern Gansu Province, western Sichuan Province and northwestern Yunnan Province in China, is also called ‘Qinghai-Tibetan Plateau’. As the world’s ‘Third Pole’, ‘Asia Water Tower’ and the cradle of the East Asian flora, TP is the most under-representative region in global and regional plant trait databases. The first version of the Chinese plant trait database (Wang et al., 2018) does not contain data from the TP, and the global plant trait database TRY (Kattge et al., 2020) has only a few collections from various sources with non-systematic sampling. Field-based, local studies of plant functional traits on the TP had made some interesting advances. For example, Luo et al. (2005) linked the plant traits with ecosystem functions, He et al. (2006) explored the influencing factors on plant traits, Geng et al. (2004) quantified the patterns of plant trait correlations between above- and below-ground components, Wang et al. (2020) compared their work with global dataset, and Xu et al. (2021) analysed the mechanism of plant trait variation along the altitude pattern. Yet such works, where the sampling sites have been mostly along the main roads in East TP, were also limited. Plant trait records from Central to West TP are extremely rare. However, the TP has the richest temperate alpine flora (Ding et al., 2020) and the most abundant plant diversity in the world (Wang & Hong, 2022). It was also an evolutionary cradle for the herbaceous genera of China (Lu et al., 2018). The uplift of the TP and its unique alpine vegetation are important to the monsoon climate system and vegetation of East Asia (Chang et al., 1983) and regional and global climate change studies (Piao et al., 2019).

As the largest and highest plateau in the world, the TP has not only changed the regional and global climate system, geological structure, topography and hydrology (Yao et al., 2012) but also influenced the evolution of the flora, fauna and biodiversity strongly (Ding et al., 2020). It has 8876 vascular species from 1371 genera and 211 families, including 6475 herbaceous and 2401 woody plants, of which 1706 were endemic to the TP (Yan et al., 2013). Here has three biodiversity hotspots of the world (Sloan et al., 2014; Wang & Hong, 2022). Vegetation changes from the southeast to northwest, from lowland broad-leaved evergreen forests, including tropical rainforest and subtropical evergreen forest, montane mixed evergreen and deciduous forest, subalpine conifer forest to alpine shrubland, meadow, steppe and desert along an annual precipitation gradient from ca. 3000 mm to 50 mm (Chang, 1983). In physiognomy, the unique alpine vegetation looks similar to the arctic tundra but has different species composition. The plateau has amplified changes in climates (Chen et al., 2015), and rapid climate change has led to profound changes in alpine species and ecosystems (Zhang et al., 2015; Piao et al., 2019). Plant traits, as the link amongst species, environment and ecosystem functions, are the best tools to study the impacts of climate change on vegetation. Therefore, the establishment of TP plant trait database and further analysis of plant trait–environment–ecosystem function relationships are of great significance to understanding the future change and sustainable development of the unique alpine vegetation on the roof of the world.

In this work, a TP leaf trait dataset (TiP-Leaf) was established, and 11 leaf traits from 468 species of 1692 leaf samples were collected from 336 sites across five of the six vegetation types on the TP. The climate data of the sites were also provided. This dataset is not only an update of the Chinese plant trait database but also a great contribution to the global trait database.

2 Study areas

The leaf traits of dominant and common plant species of the TP distributed mostly across the plateau surface were sampled and measured from July to August in the summer of 2018–2021. Vegetation surveys were conducted in four regions (Fig. 1), namely, the source area of the Three Rivers in Qinghai Province in Northeast TP (2018); Southern Xizang Autonomous Region in Southeast and Middle TP (2019); Ngari Prefecture in Northwest TP and the Qaidam Basin of Northeast TP (2020); and the Qilian Mountains, the Altun Mountains and the Kunlun Mountains in the northern margin of the TP, passing through the southern margin of the Tarim Basin in Xinjiang Autonomous Region (2021).

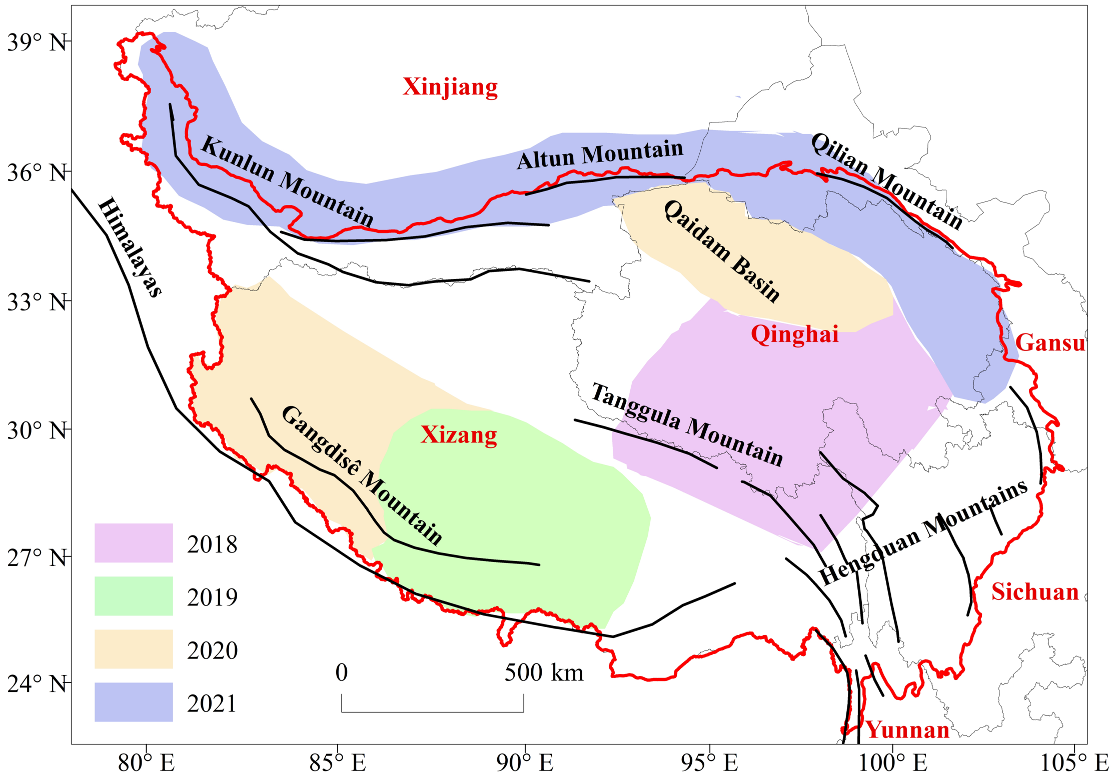

Figure 1. Location and administrative division of the TP. The red line indicates the boundary of the TP in China, which involves six administrative divisions (light black lines): Xizang, Qinghai, Sichuan, Xinjiang, Gansu and Yunnan. The bold black lines represent important mountains. Four blocks with different colours represent the approximate areas of four investigations conducted in various years. The background map is from the Chinese National Bureau of Surveying and Mapping.

3 Materials and methods

3.1 Sampling sites

Considering the zonal vegetation types and the precipitation gradient, 336 sites (Fig. 2) were selected to investigate the vegetation with less grazing and other anthropogenic disturbances. Shrubby and herbaceous vegetation were mainly selected (332 sites) along with the forest vegetation in the four sites (but removed for further analysis). In each site, 1–3 plots were set up to survey the species composition, abundance, coverage and plant height. The plot areas for herbaceous vegetation, shrubby vegetation and forest vegetation were 1 m × 1 m, 2 m × 2 m or 5 m × 5 m and 10 m × 10 m, respectively. Geographical locations, natural and human disturbances, and vegetation types were also recorded (Jin et al., 2022b). The dominant and common plant species in each site were determined by visual inspection, the leaf samples of these plants were picked up, and the leaf traits were measured. Root samples were obtained using soil pit method. The root traits were also measured but not shown in this paper.

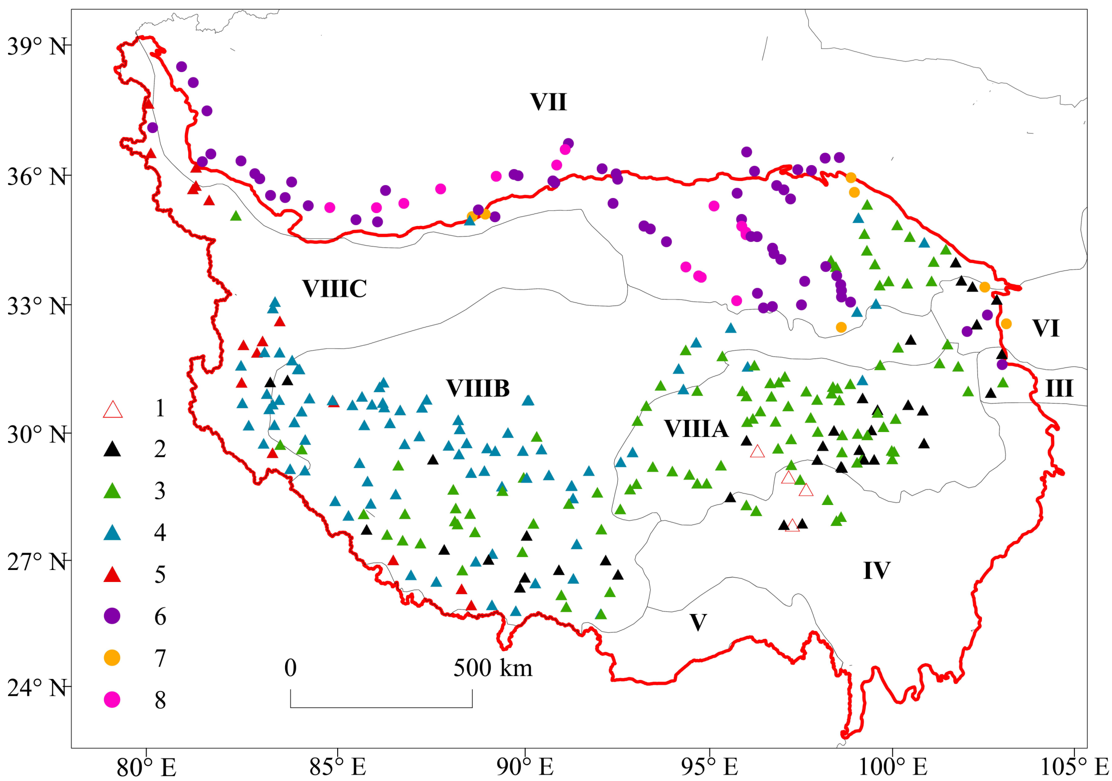

Figure 2. Site distribution of the TiP-Leaf dataset. Vegetation regions were extracted from the vegetation regionalisation of China (ECVMC, 2007b). III, Warm Temperate Deciduous Broad-leaf Forest Region; IV, Subtropical Broad-leaf Evergreen Forest Region; V, Tropical Monsoon Rain Forest and Rain Forest Region; VI, Temperate Steppe Region; VII, Temperate Desert Region; VIII, TP Alpine Vegetation Region. VIIIA, East TP Alpine Scrub and Alpine Meadow Subregion; VIIIB, Middle TP Alpine Steppe Subregion; VIIIC, Northwest TP Alpine

Desert Subregion. Vegetation types were classified on the basis of field records. Numbers indicate the vegetation types recorded in the field. 1, coniferous forest; 2, alpine shrubland; 3, alpine meadow; 4, alpine steppe; 5, alpine desert; 6, temperate desert; 7, temperate steppe; 8, temperate meadow. The background map is from the Chinese National Bureau of Surveying and Mapping.

The vegetation type of the TP was classified into eight types: high-cold (alpine) shrubland, meadow, steppe and desert, temperate steppe, meadow and desert, and coniferous forest, on the basis of field records (Fig. 2). Alpine shrubland is dominated by evergreen broad-leaved shrubs (*Rhododendron*), deciduous broad-leaved shrubs (*Salix*, *Dasiphora*, and *Sibiraea*) and evergreen coniferous shrubs (*Juniperus*) that are distributed in the cold and semi-humid Southeast TP (ca. 600–1000 mm/year). Alpine meadow is widely developed in East TP, where cold and wet climates are prevalent (ca. 600 mm/year), dominated by several *Kobresia* species and mixed in with perennial forbs and cushion plants. Alpine steppe is in the middle TP, with a large continuous distribution, adapted to the cold and semi-dry continental climate (ca. 200 mm/year) and mainly composed of *Stipa* and *Artemisia*. Alpine desert is mainly distributed in Northwest TP, where the climate is extremely continental (ca. 50 mm/year) and dominated by *Krascheninnikovia compacta* and *Ajania tibetica*. Temperate meadow, steppe and desert are distributed in the northern margin of the TP and Qaidam Basin of Northeast TP, where elevations are lower, and the climate is relatively dry, dominated by several xerophytes, especially *Haloxylon ammodendron*, *Halogeton glomeratus*, *Phragmites australis*, *Ephedra*, *Kalidium*, *Calligonum* and *Tamarix*. Subalpine coniferous (*Abies* and *Picea*) forests are found on the southeast and east margins. Therefore, the vegetation of the plateau is distributed along a transitional gradient from southeast to northwest, arraying from subalpine forests, alpine meadow and scrub, through alpine steppe and temperate desert to alpine desert. The alpine vegetation in the vegetation classification of China was usually called high-cold vegetation [Editorial Committee of Vegetation Map of China (ECVMC), The Chinese Academy of Sciences, 2007a]. Lowland tropical and montane subtropical evergreen forests do not exist in the sampling area. Hence, they are not included in this study.

Each site was also assigned to a vegetation region on the basis of the vegetation regionalisation of China (ECVMC, 2007b). The TP has six vegetation regions, namely, Alpine Vegetation Region, Temperate Steppe Region, Temperate Desert Region, Warm Temperate Deciduous Broad-leaf Forest Region, Subtropical Broad-leaf Evergreen Forest Region and Tropical Monsoon Rain Forest and Rain Forest Region. The sampling sites were mainly concentrated in the Alpine Vegetation Region. Therefore, in accordance with the degree of drought, the Selianinov drought index used in the Vegetation Regionalisation Map of China (ECVMC, 2007b), TP vegetation was further divided into three subregions from southeast to northwest, namely, East TP Alpine Scrub and Alpine Meadow Subregion, Middle TP Alpine Steppe Subregion and Northwest TP Alpine Desert Subregion.

The plant name was determined in accordance with *Flora of China* (Editorial Committee of Flora of China, 1959–2004), *Flora of Qinghai* (Editorial Committee of Flora of Qinghai, 1996–1999), *Flora of Xizang* (Comprehensive Scientific Investigation Team of Qinghai-Tibet Plateau, Chinese Academy of Sciences, 1985–1987), *Flora of Gansu* (Editorial Committee of flora of Gansu, 2005), *Flora of Xinjiang* (Editorial Committee of flora of Xinjiang, 1993–1996) and *Flora of Deserts* in China (Liu, 1985). The final species correction was based on the iPlant website (http://www.iplant.cn/), which merged all of the information from the Chinese and English versions of *Flora of China* on the basis of APG IV classification (Angiosperm Phylogeny Group, 2016).

3.2 Leaf trait measurements

At each site, 2 to 3 mature and disease-free complete leaves from each individual of dominant and common plant species were collected, and at least 30 individuals were selected to meet the needs of trait measurement and element analysis. When the single leaf was small, micro or leptophyllous, 100–200 leaves were picked. In total, 11 leaf functional traits (e.g. leaf thickness, LT; fresh weight, FW; dry weight, DW; leaf dry-matter content, LDMC; leaf water content, LWC; leaf area, LA; specific leaf area, SLA; leaf mass per area, LMA; leaf carbon content, LCC; leaf nitrogen content, LNC; and leaf phosphorus content, LPC) were measured and calculated on the basis of the handbook of standardised measurement for plant functional traits worldwide (Cornelissen et al., 2003; Pérez-Harguindeguy et al., 2013).

LT (mm) was measured on the sampling day by using Vernier callipers with an accuracy of 0.01 mm. The thickness in the middle of the vein and margin of each leaf was measured, and then the average of the five leaves was taken as the LT of a species. In addition to LT, 20–30 leaves for normal-leaved plants and 100–200 leaves for small- to leptophyll-leaved plants were generally selected for other trait variable measurements. FW (g) was obtained by weighing with 1/100 electronic balance. Subsequently, the fresh leaves were oven dried at 75 °C for 48–72 hours to obtain the DW (g). LDMC was measured as follows: LDMC ($g \cdot g^{-1}$) = DW/FW. LA (cm^2) was measured using a scanner (EPSON Perfection V 700 Photo Scanner) and a software (WinFOLIA Pro, Canada). SLA and LMA were measured as follows:

SLA ($cm^2·g^{-1}$) = LA/DW and LMA ($g·m^{-2}$) = DW/LA×10^4. The dried leaves were further used for chemical analysis. LCC ($mg·g^{-1}$), LNC ($mg·g^{-1}$) and LPC ($mg·g^{-1}$) were determined by outside-temperature hot potassium dichromate oxidation–volumetric method (Wu, 2007), distillation–titration method and vanadium molybdate yellow colorimetric method (Fang et al., 2011), respectively.

3.3 Climate data

The climate data of each sampling site were extracted from the climate and bioclimate datasets of China (Cheng et al., 2022; Wei et al., 2022). China's climate dataset consists of three variables (monthly temperature, precipitation and sunshine percentage) that were averaged from long-term records from 1981 to 2010 at 2152 meteorological stations across China (China Meteorological Data Service Centre, http://data.cma.cn). These three climate factors and the absolute maximum and minimum temperatures during the 30-year period of 1981–2010 were interpolated into 1 km grid cells by using a surface fitting technique of thin-plate smoothing spline (ANUSPLIN version 4.4, Hutchinson & Xu, 2013; Xu & Hutchinson, 2013) that considered the impact of elevation on climates on the basis of the digital elevation model of the Shuttle Radar Topography Mission (Farr et al., 2007). The interpolated climate data were used to drive a bioclimate software (Gallego-Sala et al., 2010) to calculate the mean annual temperature (MAT), mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA), annual growing degree days above 0 °C (GDD_0) and 5 °C (GDD_5), mean annual precipitation (MAP), growing season precipitation (GP), annual drought index (1-AET/PET) and annual moisture index (MAP/PET), where AET and PET refer to the annual actual evapotranspiration and annual potential evapotranspiration, respectively.

3.4 Data analysis

Beside the data description of leaf trait characteristics, six key leaf functional traits (e.g. LT, LDMC, SLA, LCC, LNC and LPC), that reflect the key ecological significances of plants that grew in high altitude and extremely cold environment, were selected in this paper for further simple statistical analyses. LT affects the water supply and storage of leaves and the exchange process of matter and energy in photosynthesis; LDMC reflects the ability of plants to acquire surrounding environmental resources; SLA is considered the first choice index for studying plant physiological and ecological strategies under specific environmental conditions; LCC is the main structural material of plants; LNC characterises the ability of plants to absorb and utilise nutrient elements; and LPC is the second largest element that affects plant growth. The mean, minimum, maximum, standard deviation and coefficient variation of traits at each site were calculated to generally show the pattern of leaf traits of the Tibetan ecosystems. The linear relationships between leaf traits of site average were analysed and mapped using the Origin software (The Origin Lab, 2022) to reveal the trade-off between different traits in the special alpine ecosystem. The detailed analyses of all the leaf traits, their variations and spatial patterns, within and amongst functional groups and at species and site levels, will be further analysed in another paper.

4 Data description of sampling sites

4.1 Spatial distribution of sites

A total of 11 key plant leaf traits of 1692 individuals of 468 species from 336 sites were measured (Fig. 1 and 2).

The sampling sites were located in the northeast, middle to southwest, and north margin of the TP, along with 145 sites in Xizang, 121 sites in Qinghai, 43 sites in Xinjiang, 16 sites in Gansu and 11 sites in Sichuan (Fig. 1). Southeast TP, where forest ecosystems are distributed, has few plant trait data. However, field measurements are being conducted in the Hengduan Mountains to measure the leaf, twig and root traits of dominant and common trees and shrubs. Other ecologists have worked on some parts of this region to perform leaf and other trait studies (Luo et al., 2005; Shi et al., 2012; Vandvik et al., 2020; Xu et al., 2021). The Hoh Xil dead zone in Central North to Northwest TP is logistically not accessible during the plant growing season when the frozen ground is melting. Therefore, the plant trait data have been not available to date.

4.2 Altitudinal range of sites

The altitudinal range of the sampling sites was between 805–5343 m, in which 69.3% of the sites were located in the high altitudes (> 3500 m), 18.5% of the sites were located in the Qaidam Basin and the East Qinghai with lower altitudes (2500–3500 m) and 12.2% of the sites were located in the northern margin of the TP with lowest altitudes (< 2500 m).

4.3 Vegetation types of sites

In accordance with the field records, the vegetation was divided into eight types, along with 108 sites in alpine meadow, 87 sites in alpine steppe, 61 sites in temperate desert, 38 sites in alpine shrubland, 16 sites in alpine desert, 15 sites in temperate meadow, 7 sites in temperate steppe and 4 sites in forest. In addition, the number of sites in the TP Alpine Vegetation Region was the most abundant (63.1%), and its three subregions, namely, the Middle TP Alpine Steppe Subregion (33.9%), the East TP Alpine Scrub and Alpine Meadow Subregion (20.8%) and the Northwest TP Alpine Desert Subregion (8.3%), followed by the Temperate Desert Region (29.4%) and other vegetation regions (7.5%), which are Subtropical Evergreen Broad-leaved Forest Region (3.9%), Temperate Steppe Region (2.4%) and Warm Temperate Deciduous Broad-leaved Forest Region (1.2%), as shown in Fig. 2.

5 Data description of species and traits

5.1 plant species

A total of 1692 leaf samples were collected and measured in the TiP-Leaf dataset, including 468 species that belong to 184 genera in 51 families (amongst them, 17 samples were identified as genera, 6 samples were identified as families and 1 sample could not be identified). Some species were sampled frequently. For example, *Kobresia pygmaea* occurred 52 times, mainly in East and South TP; *Stipa purpurea* occurred 47 times, mainly in Middle and West TP; and *Potentilla bifurca* occurred 41 times, mainly in South, West and Northeast TP. However, in some sites, only one or two species were sampled, especially in the Qaidam Basin and the northern margin of TP. The top five families with the largest number of sampled species were as follows: Asteraceae (83 species and 24 genera), Poaceae (47 species and 18 genera), Fabaceae (46 species and 11 genera), Cyperaceae (29 species and four genera) and Rosaceae (28 species and 10 genera). Amongst the 468 species, 79 species, including *Rhodiola smithii*, *Pomatosace filicula*, *Oxytropis sericopetala*, *Arenaria gerzensis*, *Onosma waltonii*, *Delphinium qinghaiense*, *Metaeritrichium microuloides* and *Androsace cuttingii*, were unique to the TP. Furthermore, two (e.g. *Rosa rugosa* and *Rheum globulosum*) were endangered species, seven (e.g. *Arnebia guttata*, *Tamarix taklamakanensis*, *Rhodiola smithii*, *Juniperus tibetica*, *Reaumuria kaschgarica*, *Rheum tanguticum* and *Metaeritrichium microuloides*) were vulnerable species and 10 (e.g. *Myricaria prostrata*, *Euphorbia kozlovii*, *Hippophae tibetana*, *Phlomis pygmaea*, *Physochlaina praealta*, *Gentiana siphonantha*, *Astragalus handelii*, *Androsace cuttingii*, *Carex nakaoana* and *Leiospora exscapa*) were near-threatened species in the TiP-Leaf dataset.

5.2 Leaf trait variations

The site-level leaf traits are shown in Table 1. The variation of each leaf trait was significant. In particular, DW, FW and LA varied by more than 150%, followed by LT and LWC. The variations of LMA, SLA, LDMC, LCC, LNC and LPC were slightly stable.

Table 1 Summary of leaf functional traits in the TiP-Leaf dataset.

Traits	Mean ± SD	Max	Min	CV (%)
LT (mm)	0.42 ± 0.22	1.55	0.06	52.38
FW (g)	0.14 ± 0.31	3.82	0.0001	221.43
DW (g)	0.04 ± 0.07	0.62	0.00003	175.00
LDMC ($g \cdot g^{-1}$)	0.37 ± 0.09	0.75	0.08	24.32
LWC ($g \cdot g^{-1}$)	2.41 ± 1.25	11.11	0.33	51.87
LA (cm^2)	3.22 ± 5.23	44.51	0.01	162.42
SLA ($cm^2 \cdot g^{-1}$)	142.10 ± 46.67	333.85	33.16	32.84
LMA ($g \cdot m^{-2}$)	91.49 ±34.28	308.11	17.22	37.36
LCC ($mg \cdot g^{-1}$)	386.54 ± 43.46	487.42	212.57	11.24
LNC ($mg \cdot g^{-1}$)	23.08 ± 4.75	45.83	7.18	20.58
LPC ($mg \cdot g^{-1}$)	1.62 ± 0.51	3.76	0.43	31.48

5.3 Leaf trait relationships

The fitting of linear models of the site averages of the six leaf traits (Fig. 3) showed that LT was significantly negatively correlated with LDMC ($r^2 = 0.1339$; $p < 0.05$; Fig. 3a), SLA ($r^2 = 0.0533$; $p < 0.05$; Fig. 3b) and LCC ($r^2 = 0.2755$; $p < 0.05$; Fig. 3c) with downward trends. No relationship was found between LT and LNC ($r^2 = -0.0028$; $p > 0.05$; Fig. 3d) nor LPC ($r^2 = 0.0055$; $p > 0.05$; Fig. 3e). The results also revealed that LDMC was significantly negatively correlated with SLA ($r^2 = 0.0630$; $p < 0.05$; Fig. 3f), LNC ($r^2 = 0.0335$; $p < 0.05$; Fig. 3h) and LPC ($r^2 = 0.0649$; $p < 0.05$; Fig. 3i) and significantly positively correlated with LCC ($r^2 = 0.0526$; $p < 0.05$; Fig. 3g). In addition, linearly inversed relationships were observed between SLA and LCC ($r^2 = 0.0371$; $p < 0.05$; Fig. 3j) and LNC ($r^2 = 0.0566$; $p < 0.05$; Fig. 3k) and LPC ($r^2 = 0.1776$; $p < 0.05$; Fig. 3l). The three leaf chemical traits were also related to one another, and the relationship between LNC and LPC ($r^2 = 0.2481$; $p < 0.05$; Fig. 3o) was closer than that between LNC and LCC ($r^2 = 0.0552$; $p < 0.05$; Fig. 3m) and between LPC and LCC ($r^2 = 0.0879$; $p <$

0.05; Fig. 3n).

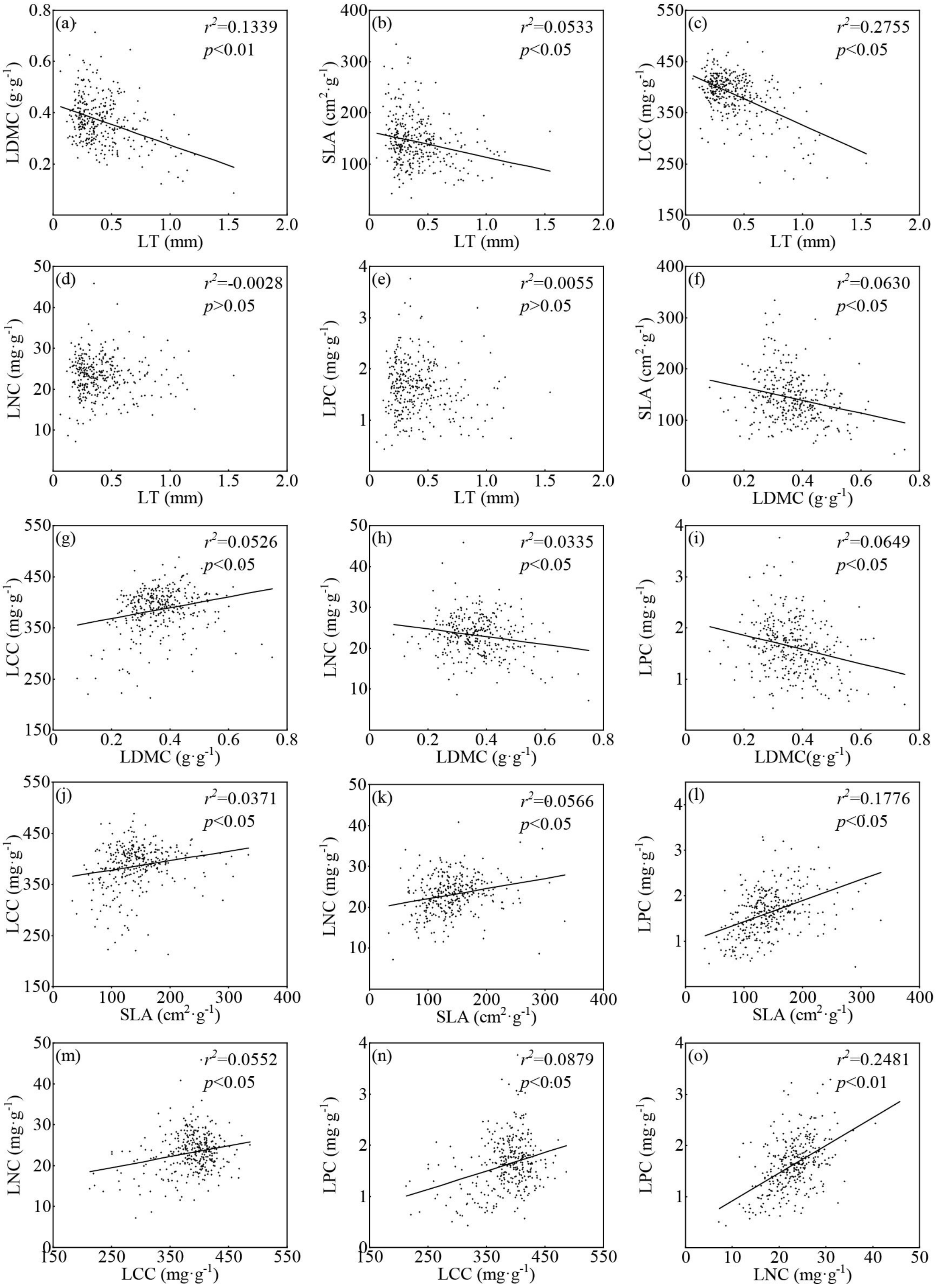

Figure 3. Relationship between site-based average of key leaf traits in the TiP-Leaf dataset. The black dot indicates the mean leaf trait measurements of all species in the site, and the straight line represents the fitting of the linear model. r^2 is the adjusted r^2, and *p* represents the probability value of the regression model.

6 Data availability

The TiP-Leaf dataset comprises three data sheets in Microsoft Excel format, namely: (a) a data sheet named 'variables', which describes the header information of the geographical coordinates, climate and traits in the dataset (Table 2); (b) a data sheet (site information) that reports the site location and climate data; and (c) a data sheet (plant traits) of the complete trait data of each plant species in each sampling site. As studies based on the TiP-Leaf dataset are already underway, researchers interested in using such data previously are strongly recommended to contact the authors to avoid overlapping studies. The dataset will be available through the National Tibetan Plateau Data Center (TPDC; Jin et al., 2022a; https://doi.org/10.11888/Terre.tpdc.272516) and shall also be made available via the global TRY plant trait database (Kattge et al., 2011, 2020; www.try-db.org/).

Table 2 Summary information found in TiP-Leaf dataset

Heading	Description	Type
Site	Site number based on sampling time	Code
Lat	Latitude (decimal degrees)	Numeric
Lon	Longitude (decimal degrees)	Numeric
Elev	Elevation (m)	Integer
Animal intensity	Animal activity intensity	Character
Human intensity	Human interference intensity	Character
Vegetation type	Vegetation type from field survey	Character
Vegetation region	Vegetation region from vegetation map	Character
MAT	Mean annual temperature (°C)	Numeric
MTCO	Mean temperature of the coldest month	Numeric
MTWA	Mean temperature of the warmest month	Numeric
GDD_0	Annual growing degree days above 0 °C	Numeric
GDD_5	Annual growing degree days above 5 °C	Numeric
MAP	Mean annual precipitation (mm)	Numeric
GP	Growing season precipitation (mm)	Numeric
MI	Moisture index	Numeric
DI	Drought index	Numeric
Soil type	Soil type from Resource and Environment Science and Data Center	Numeric

	(http://www.resdc.cn)	
Species	Scientific name	Character
Family	Botanical family	Character
Growth form	Trees, shrubs, semi-shrubs and herbs	Character
Life form	Deciduous and evergreen; Annual and perennial	Character
LT	Leaf thickness (mm)	Numeric
FW	Fresh weight (g)	Numeric
DW	Dry weight (g)	Numeric
LDMC	Leaf dry-matter content ($g \cdot g^{-1}$)	Numeric
LWC	Leaf water content ($g \cdot g^{-1}$)	Numeric
LA	Leaf area (cm^2)	Numeric
SLA	Specific leaf area ($cm^2 \cdot g^{-1}$)	Numeric
LMA	Leaf mass per area ($g \cdot m^{-2}$)	Numeric
LCC	Leaf carbon concentration ($mg \cdot g^{-1}$)	Numeric
LNC	Leaf nitrogen concentration ($mg \cdot g^{-1}$)	Numeric
LPC	Leaf phosphorus concentration ($mg \cdot g^{-1}$)	Numeric

7 Summary

The TiP-Leaf dataset was compiled from direct field measurements, covering a great proportion of plant species and vegetation types on the highest plateau in the world. The dataset provides important data foundation not only for quantitative analyses of modern alpine vegetation but also for the prediction of future responses of alpine ecosystem to climate change and improvement of next-generation vegetation models. It could also be used to promote the vegetation protection and restoration on the TP and contribute to the global plant trait database. However, the dataset also presents some unavoidable limitations. For example, the establishment of sampling sites and the judgment of dominant and common species are mostly subjective. The leaves of some plants are extremely small, resulting in incomplete recognition when scanning the LA. Due to harsh field conditions, measuring the plant traits in time occasionally becomes impossible. Prevent some leaves from losing too much water to withering is still inevitable, although we have taken protective measures for the leaves. Inadequate collection of some leaf samples results in less data of plant chemical element content than that of morphological traits. In any case, performing large-scale collection of plant traits on the TP, which requires a lot of manpower and material resources, as well as overcoming the adverse environment of high altitude and extreme variability, is not easy.

The dataset in this study provides more leaf trait measurements and covers more sampling sites, which were located not only along the main roads but also the accessible pathlets, than previous studies (Luo et al., 2005; He et al., 2006; He et al., 2010; Geng et al., 2014; Wang et al., 2020; Xu et al., 2021). This dataset is the first plant trait dataset that represents all of the alpine vegetations on the TP. However, more collections of trait data are needed in remote areas with assessable difficulty, such as the Hoh Xil dead zone in Northwest TP (alpine meadow, steppe and desert vegetation) and in the mountainous areas of East and Southeast TP with less trait studies (subalpine and alpine forest and shrubland vegetation). These works could enhance the representativeness of the whole TiP-Leaf trait database in terms of geographical space and vegetation type. Given the complex topography of the plateau, more sites are requested to be surveyed. Given the flourishing of alpine flora, traits from more plant species should be measured. At present, the TiP-Leaf dataset consists of leaf traits only. The TiP-Root trait dataset is underway and the trait data of twig and branch of woody species will be measured further.

Author contributions. JN conceived the study. KL, YJ and JN led the field works. YJ and other co-authors collected leaf samples and measured plant traits. YJ, HW and JX processed the dataset, performed the analyses and wrote the first draft. JN and YJ improved the manuscript. All authors approved the final version of the submitted manuscript.

Competing interests. The (co-)authors declare that they have no conflict of interest.

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