

Leaf Stoichiometry of *Potentilla Fruticosa* Across Elevations Ranging from 2400 m to 3800 m in China's Qilian Mountains (Northeast Qinghai-Tibetan Plateau)

Wei Liu

Key laboratory of Ecohydrology of Inland River Basin, Qilian Mountains Eco-environment Research Center in Gansu Province, Northwest Institute of Ecology and Environmental Resource, Chinese Academy of Science

yanyan Qin (✉ qinyy06@lzb.ac.cn)

Northwest Institute of Plateau Biology: Northwest Institute of Eco-Environment and Resources

<https://orcid.org/0000-0003-2732-2125>

Zhang Xiaofang

University of Chinese Academy of Sciences

Jan F. Adamowski

McGill University

Asim Biswas

University of Guelph

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Abstract

Background: Plant species have developed their individual leaf stoichiometries to adapt to changes in the environment. Changes in plant leaf stoichiometry with elevation are largely undocumented, but could provide information critical to protecting or enhancing a species' growth and development and manage the ecosystem housing it. We investigate the leaf stoichiometry of *Potentilla fruticosa* L. along with different elevations in China's Qilian mountains (Northeast Qinghai-Tibetan Plateau). This study aims to reveal how elevations effect of the leaf stoichiometry of *Potentilla fruticosa* L. along with various soil properties in China's Qilian mountains .

Results: In our study, we selected seven elevations 2,400 m, 2,600 m, 2,800 m, 3,000 m, 3,200 m, 3,500 m, and 3,800 m elevation. We sampled leaves at top and middle of *P. fruticosa* from each of seven elevations. Maximum and minimum leaf carbon (C) concentrations ($[C]_{\text{leaf}}$) of 523.59 g kg⁻¹ and 402.56 g kg⁻¹ were measured at 2,600 m and 3,500 m, respectively. Showing a generally increasing trend with elevation, leaf nitrogen (N) concentration ($[N]_{\text{leaf}}$) peaked at 3,500 m (27.33 g kg⁻¹). Leaf phosphorus (P) concentration ($[P]_{\text{leaf}}$) varied slightly over elevations of 2,400 m to 3,200 m, then dropped to a minimum (0.60 g kg⁻¹) at 3800 m. While $[C]_{\text{leaf}}:[N]_{\text{leaf}}$, $[C]_{\text{leaf}}:[P]_{\text{leaf}}$ and $[N]_{\text{leaf}}:[P]_{\text{leaf}}$ varied little between 2,400 m and 3,000 m, at higher elevations they fluctuated somewhat, the latter two showing a decrease at 3,200 m followed by an increase at higher elevations. The soil organic C, pH, and soil total P were the main factors influencing *P. fruticosa* leaf stoichiometry. The limiting nutrients were P.

Conclusions: We highlight the dependency of leaf stoichiometry on slope aspect and elevation. As *P. fruticosa* is a major alpine shrub in this region and plays an important role in maintaining ecological functions and services on the Qinghai-Tibetan Plateau, measures should be adopted to improve *P. fruticosa* growth by preventing P loss, especially at higher elevations where significant P losses occur due to high precipitation and sparse vegetation.

Background

Native to the northern U.S., Canada, Europe and Asia, and supporting many ecosystem functions in regions sensitive to global warming (Yuichiro et al., 2010), the rosaceous shrub *Potentilla fruticosa* L. (a.k.a. shrubby Potentilla or shrubby cinquefoil), is a vigorous, floriferous, deciduous shrub of high genetic diversity (Shimono et al., 2010). A cold region species of interest (Elkington, 1969; Miliauskas et al., 2010) it has been widely studied with regard to its chemical composition (Ganenko et al., 1988; Zeng et al., 2019), edibility and cosmetic properties (Nkiliza, 1997; Liu et al., 2016), antioxidant content (Miliauskas et al., 2010; Luo et al., 2016), ornamental characteristics (Innes et al., 1989), contribution to pollen production and insect visitors (Denisow et al., 2013), geospatial distribution (Remm, 2016), role in ecosystem CO₂ fluxes (Yuichiro et al., 2010) and on the expression of key enzymes of glucose and lipid metabolism and plant hormones (Yan et al., 2019). Similarly, factors such as transportation and industrial pollution influence its leaf morphology and the elemental composition of its organs (Lugovskaya et al., 2018). Likewise, salinity (NaCl and Na₂SO₄) influence its leaves' physiological and biochemical characteristics (Liu et al., 2013), while grazing influences its nutritive value (Yao et al., 2019).

Leaf stoichiometry reflects the balance and limitations in the uptake of plant nutrients (C, N, P), thereby influencing plants' growth rate and overall life history strategy (Baxter and Dilkes, 2012; Liu et al., 2015; Zhu et al., 2020) and global C, N, P biogeochemical cycles (Moe et al., 2005; Liu et al., 2018). The leaf stoichiometry *P. fruticosa* remains relatively underexplored. Leaf stoichiometry information is critical to understand nutrient cycling processes, in developing biogeochemical models, and in predicting plant responses to global changes in climate (Zhao et al., 2014; Zhao et al., 2018). Previous studies have shown that leaf stoichiometry can be affected by a wide range of edaphic, climatic and topographic factors (*e.g.*, Cao et al., 2020) and other disturbances such as increased CO₂ and N availability (Esmeijer-Liu et al., 2009), livestock grazing and P addition (Bai et al., 2012; Scott et al., 2013).

Topography, an important factor in soil formation (Jenny, 1941), can directly (*e.g.*, water distribution) or indirectly (*e.g.*, microclimate) affect a plant's growing environment, particularly so in mountainous regions. However, how topography might affect soil nutrient content and leaf stoichiometry of *P. fruticosa* at different elevations is not well understood. Accordingly, the present study's overall objective was to examine the effects of elevation (from 2400 m to 3800 m) on leaf stoichiometry of *P. fruticosa*, a major alpine shrub. The study was conducted in the Qilian mountains of the Qinghai-Tibetan Plateau (QTP), the world's highest elevation plateau. Since mean annual precipitation (MAP) and mean annual temperature (MAT) and soil nutrients vary with elevation (Table 1), our hypothesis was that leaf stoichiometry of *P. fruticosa* would vary with elevation, and, based on Cao et al. (2020), that P would be a limiting nutrient for *P. fruticosa* growth.

Table 1
Changes of temperature, precipitation, and soil properties at different elevations

Parameter	Elevation						
	2,400 m	2,600 m	2,800 m	3,000 m	3,200 m	3,500 m	3,800 m
SOC (g kg ⁻¹)	13.12 ± 0.73 a	12.05 ± 0.52 a	15.08 ± 0.63 b	12.28 ± 0.61 a	35.60 ± 3.19 c	58.64 ± 1.65 d	50.14 ± 1.65 e
STN (g kg ⁻¹)	1.46 ± 0.08 ab	1.41 ± 0.08 ab	1.62 ± 0.09 a	1.35 ± 0.10 b	3.48 ± 0.23 c	5.24 ± 0.13 d	4.72 ± 0.13 e
STP (g kg ⁻¹)	0.53 ± 0.02 abd	0.58 ± 0.02 ad	0.44 ± 0.02 bcd	0.32 ± 0.03 c	0.53 ± 0.03 d	0.27 ± 0.05 c	0.54 ± 0.12 d
SOC:STN	9.01 ± 0.19 a	8.96 ± 0.46 a	9.40 ± 0.27 ab	9.24 ± 0.35 a	10.09 ± 0.32 bd	11.22 ± 0.10 cd	10.61 ± 0.23 d
SOC:STP	26.03 ± 2.27 a	20.90 ± 0.67 a	35.48 ± 1.50 b	41.29 ± 4.03 b	67.50 ± 3.43 c	487.13 ± 133.29 d	183.40 ± 32.61 c
STN:STP	2.89 ± 0.24 a	2.43 ± 0.12 a	3.77 ± 0.14b	4.46 ± 0.36 b	6.69 ± 0.26 c	42.74 ± 11.46 d	17.32 ± 3.18 c
pH	8.43 ± 0.04 a	8.54 ± 0.02 b	8.36 ± 0.04 a	8.51 ± 0.03 b	8.08 ± 0.04 c	6.44 ± 0.05 d	6.12 ± 0.03 e
LONG	100°21'55"	100°17'3"	100°14'28"	100°14'26"	100°22'35"	101°21'0"	101°22'12"
LAT	38°37'5"	38°33'17"	38°33'9"	38°33'22"	38°38'15"	37°40'48"	37°41'24"
MAT (°C)	2.26	1.17	0.08	-1.02	-2.13	-3.61	-5.26
MAP (mm)	304.71	331.32	355.7	379.22	398.58	518.42	553.62
SOC = soil organic carbon, STN = soil total nitrogen, STP = soil total phosphorus, LONG = longitude, LAT = latitude, MAT = mean annual temperature, and MAP = mean annual precipitation. Row-wise non-matching letters indicate a significant difference among elevations ($p < 0.05$).							

Results

Environmental characteristics and soil properties at different elevations

Strong variations were observed in the environmental characteristics and soil properties across elevations. Compared to elevations below 3,000 m, SOC and STN significantly increased (3- to 4-fold) at elevations 3,200 m and above. However, STP did not show this trend, as it peaked at 2,600 m (0.58 g kg⁻¹). Unlike SOC:STP and STN:STP, variation in SOC:STN across elevations was small, with the largest value (11.22) at 3,500 m and the smallest (8.96) at 2600 m. However, for SOC: STP and STN:STP, the largest and the smallest values were 487.13 (3,500 m) and 20.90 (2,600 m), and 42.74 (3,500 m) and 2.43 (2,600 m), respectively. pH values changed from basic (>8.0) at or below 3,200 m, to acidic (<6.5) at ≥3,500 m. The MAT showed a decreasing trend from 2,400 m to 3,800 m, while MAP showed a converse trend (Table 1).

Leaf stoichiometry of *P. fruticosa* at different elevations

At 3,500 m, the $[C]_{\text{leaf}}$ (402.56 g kg^{-1}) was significantly lower than at any other elevation, while at 2600 m the $[C]_{\text{leaf}}$ (523.59 g kg^{-1}) was significantly greater than at any other elevation except 3,000 m (Fig 1A). The $[N]_{\text{leaf}}$ showed an increasing trend with increasing elevation. At 3,500 m, $[N]_{\text{leaf}}$ (27.33 g kg^{-1}) was significantly greater than at other elevations, while $[N]_{\text{leaf}}$ (18.15 g kg^{-1}) at 2,800 m was significantly lower than at any other elevation (Fig 1B). While the $[P]_{\text{leaf}}$ changed slightly at elevations between 2,400 m and 3,200 m, there was a decreasing trend of $[P]_{\text{leaf}}$ at elevations of 3,500 m and 3,800 m, with the lowest value (0.60 g kg^{-1}) recorded at 3,800 m, where it was significantly lower than at 2,600 m, 3,200 m or 3,500m (Fig 1C). From 2,400 m to 3,000 m, $[C]_{\text{leaf}}$: $[N]_{\text{leaf}}$ varied little, but was significantly greater than at $\geq 3,200$ m. However, from 3,200 m to 3,800 m, $[C]_{\text{leaf}}$: $[N]_{\text{leaf}}$ showed a decreasing trend first and then an increasing trend, with the value at 3,500 m (14.74) being significantly lower than at other elevations (Fig 1D). Changes in $[C]_{\text{leaf}}$: $[P]_{\text{leaf}}$ and $[N]_{\text{leaf}}$: $[P]_{\text{leaf}}$ along the elevation gradients were similar. For example, both $[C]_{\text{leaf}}$: $[P]_{\text{leaf}}$ and $[N]_{\text{leaf}}$: $[P]_{\text{leaf}}$ varied slightly between 2,400 m and 3,000 m; however, at 3,200 m, both values decreased and reached their lowest values (392.29 and 19.43, respectively), while, in contrast, at 3,800 m, both values increased and reached at their peaks (1097.46 and 62.79, respectively) (Fig 1E,F).

Effects of elevation on soil properties and leaf stoichiometry of *P. fruticosa*

Elevation influenced all measured soil parameters, including pH, SOC, STN, STP and their stoichiometric ratios. However, for *P. fruticosa* leaf stoichiometries, only $[C]_{\text{leaf}}$, $[N]_{\text{leaf}}$, and $[C]_{\text{leaf}}$: $[N]_{\text{leaf}}$ were significantly affected by elevation, whereas $[P]_{\text{leaf}}$, $[C]_{\text{leaf}}$: $[P]_{\text{leaf}}$ and $[N]_{\text{leaf}}$: $[P]_{\text{leaf}}$ were not (Table 2).

Dominant factors influencing leaf stoichiometry of *P. fruticosa* at different elevations

The eigenvalues of the first and axes were 0.27 and 0.021, respectively, explaining about 29% of the total variation (Fig 2). Except STP, all other parameters were significantly related to two axes. Across elevations, SOC, STP, and pH had the greatest impact on leaf stoichiometry of *P. fruticosa* (Table 3).

Discussion

Reasons for variation in soil properties and leaf stoichiometry of *P. fruticosa* with elevation

Elevation regulates temperature and precipitation (Lozano-García et al., 2014; Zhu et al., 2019), and by their influences the distribution of vegetation. For example, in the Qilian Mountains, temperature decreases and precipitation increases with elevation (Chang et al., 2014) result in shifting vegetation types: < 2400 m, steppe desert; 2,400 m to 3,300 m, forest steppe; 3,300 m to 3,600 m, subalpine scrub and grassland ; 3,600 m to 3,900 m, alpine scrubs and meadow; > 3,900 m, ice and snow (Zhu et al., 2019). Likewise, different elevations differ in vegetation types, biomass, quantity and quality of litter, roots and soil microbial communities (Macinnis-Ng and Schwendenmann, 2015; Bargali et al., 2018; Yang et al., 2018), which in turn affect soil physical and chemical properties (Table 1, 2) (Zhou et al., 2013; Cherubin et al., 2018, Qin et al., 2019). In addition, micro-landforms such as slope aspect, slope position and slope gradient can also influence soil properties by reshaping hydrothermal conditions and patterns in the movement of the material and energy (Maren et al., 2015; Nabiollahia et al., 2018; Zhang et al., 2020). In the present study, all sampled sites were from the sunny slope

aspects, but slope gradients and positions were different (data unpublished). Thus, soil properties in the study area were also affected by these micro-landforms.

With changes of biotic and abiotic environments with elevation, leaf stoichiometry of *P. fruticosa* also varied with elevation (Fig. 1), concurring with other studies (Badano et al., 2005; Zhang et al., 2019). However, in the present study, only $[C]_{\text{leaf}}$, $[N]_{\text{leaf}}$, and $[C]_{\text{leaf}}:[N]_{\text{leaf}}$ of *P. fruticosa* were significantly affected by elevation (Table 1), partly supporting our hypothesis of elevation affecting leaf stoichiometry of *P. fruticosa*. In contrast, Cao et al. (2020) found that except for $[N]_{\text{leaf}}:[P]_{\text{leaf}}$, leaf stoichiometries of *Oxytropis ochrocephala* Bunge at different altitudes in the Qilian Mountains were significantly affected by elevation. This suggests that each species may have its unique strategies to adapt to local environmental changes. From 2,400 m to 3,800 m, $[C]_{\text{leaf}}$ of *P. fruticosa* showed a decreasing trend (Fig. 1A), which was in contrast with Zhao et al. (2014) and Rong et al. (2016), who found that $[C]_{\text{leaf}}$ increased as temperature decreased to balance the osmotic pressure of cells and resist freezing. This result may reflect that the fact that low temperatures inhibit photosynthesis in *P. fruticosa*. In contrast, $[C]_{\text{leaf}}$ and $[N]_{\text{leaf}}$ of *P. fruticosa* showed an increasing trend with a decrease in temperature (Fig. 1B), as reported by others (e.g., Oleksyn et al., 2010; Li and Sun 2016; Cao et al., 2020). This may be because $[N]_{\text{leaf}}$ can enhance metabolic activity and the growth rate of tissues in cold habitats and short growing seasons (Ågren, 2008; Zhang et al., 2017). With a $[C]_{\text{leaf}}$ decrease and $[N]_{\text{leaf}}$ increase, the overall trend of *P. fruticosa* $[C]_{\text{leaf}}:[N]_{\text{leaf}}$ was one of decreased with rising elevation (Fig. 1D). Similar observations were reported by Xie et al. (2014) and Sun et al. (2017). Generally, $[C]_{\text{leaf}}:[N]_{\text{leaf}}$ reflects a plant's ability to simultaneously absorb C and N, and a low value can benefit plant growth (He et al., 2008; Yan et al., 2015).

The Dominant Environmental Factors Influencing Leaf Stoichiometry Of *P. fruticosa*

Based on RDA (Fig. 2, Table 3), it is clear that SOC, STP, and pH had a greater effect on leaf stoichiometry of *P. fruticosa* than temperature or precipitation in the Qilian Mountains. This is in slight contradiction with others studies (Sardans et al., 2011; Zhang et al., 2012; Cao et al., 2020); for example, Cao et al. (2020) found that, across various elevations in the Qilian Mountains, temperature significantly affected leaf stoichiometry of *O. ochrocephala*, as it could dictate or control nutrient availability in soils, root absorption, and the plant nutrient budget (Reich and Oleksyn, 2004; Isles et al., 2017; Liu et al., 2019). Likewise, Zhang et al. (2012) found that temperature and precipitation directly affected the spatial patterns of leaf elements across China, as precipitation regulates the mobilization of soil nutrients (Müller et al., 2017).

Although SOC, STP and pH were the main contributors to differences in leaf stoichiometry of *P. fruticosa*, STP was not related to any index of leaf stoichiometry (Table 4), suggesting that it had a synthetic effect on leaf stoichiometry of *P. fruticosa* in the Qilian Mountains, but this needs further study. Except $[P]_{\text{leaf}}$, leaf nutrient concentrations and their ratios were all significantly related to SOC or pH or both (Table 4). SOC was negatively related to $[C]_{\text{leaf}}$, which was not consistent with Niu et al. (2016) who found that they were positively correlated because the C in leaves can enter the soil through litter. In the present study, elevations $\geq 3,200$ m had greater SOC but lower temperature (Table 1), which limited photosynthesis and thus resulted in lower $[C]_{\text{leaf}}$ (Fig. 1A). This suggests that the relationship between $[C]_{\text{leaf}}$ of *P. fruticosa* in the Qilian Mountains may not represent a

true causality. This may also suggest that the C in soil is the structural basis for plants (Schade et al., 2003; Liu et al., 2011) due to less C from atmosphere being captured by leaves under low temperatures. The SOC was positively related to $[N]_{\text{leaf}}$ of *P. fruticosa*, because SOC from amino acid metabolism contains N and it can be transferred from soil to plants by the process of nutrient cycling (Delgado-Baquerizo et al., 2015; Zhang et al., 2019). Given the positive relationship between SOC and $[N]_{\text{leaf}}$, there exists a negative or positive relationship with $[C]_{\text{leaf}}:[N]_{\text{leaf}}$, or $[N]_{\text{leaf}}:[P]_{\text{leaf}}$ (Table 4). Generally, SOC and pH are negatively correlated, as acidic soil is beneficial to adsorption of organic C (Zhang et al. 2012; Hobara et al. 2016). Therefore, the relationships between pH and leaf stoichiometry of *P. fruticosa* were converse to relationships between SOC and leaf stoichiometry (Table 4).

Table 4
Relationships between leaf stoichiometry of *P. fruticosa* and the dominant factors from the RDA

Leaf stoichiometry	SOC (g kg ⁻¹)	STP (g kg ⁻¹)	pH
$[C]_{\text{leaf}}$ (g kg ⁻¹)	-.639**	0.175	.562**
$[N]_{\text{leaf}}$ (g kg ⁻¹)	.869**	-0.216	-.867**
$[P]_{\text{leaf}}$ (g kg ⁻¹)	-0.055	0.045	0.167
$[C]_{\text{leaf}}:[N]_{\text{leaf}}$	-.929**	0.206	.882**
$[C]_{\text{leaf}}:[P]_{\text{leaf}}$	0.199	-0.192	-.263*
$[N]_{\text{leaf}}:[P]_{\text{leaf}}$.367**	-0.216	-.416**

In the present study, the measured parameters can only explain about 30% the total variation of leaf stoichiometry of *P. fruticosa* (Fig. 2), indicating that other factors, such as plant community composition (Wang et al., 2014; Zhang et al., 2019), may also control the variations. As the plant community in the study area changed with elevation, effects of intra- and inter-species competitions on leaf stoichiometry of *P. fruticosa* should also be considered to achieve a comprehensive understanding.

Limiting Nutrients For *P. Fruticosa* Across Elevations

It is well known that $[N]_{\text{leaf}}:[P]_{\text{leaf}}$ rather than $[N]_{\text{leaf}}$ or $[P]_{\text{leaf}}$ individually, can provide a better assessment of plants' nutrient limitations (Li et al., 2018). In the present study, the $[N]_{\text{leaf}}:[P]_{\text{leaf}}$ of *P. fruticosa* was > 16 (Fig. 1F), suggesting that by the criteria provided by Koerselman and Meuleman (1996), P was limiting to the growth of *P. fruticosa*. Soil P deficiency is common across China (Han et al., 2005; Zhao et al., 2016), including the whole QTP (Niu et al., 2016) and the Qilian Mountains (Zhang et al., 2019; Xu et al., 2018a, 2019; Cao et al., 2020). However, Reich and Oleksyn (2004) concluded that plant growth in high elevations was more limited by N. This suggests that limitation of nutrient elements for plants is dependent on region.

Furthermore, at elevations $\geq 3,500$ m, the $[N]_{\text{leaf}}:[P]_{\text{leaf}}$ was > 50 (Fig. 1F), suggesting that *P. fruticosa* growth was greatly restricted by a lack of P. It is well known that in the Qilian Mountains, soil surface coverage by

vegetation decreases as elevation increases. In combination with P leaching through the soil profile (Chardon and Schoumans, 2007), the lack of vegetative cover at high elevations can easily increase P losses through erosion and surface run-off (Vanden Nest et al., 2014) and can make P more scarce. To reduce P loss, vegetation at these high elevations must be offered some protection.

Conclusions

In the Qilian Mountains of the QTP, elevations ranging from 2,400 m to 3,800 m affected *P. fruticosa* $[C]_{\text{leaf}}$, $[N]_{\text{leaf}}$ and $[C]_{\text{leaf}}:[N]_{\text{leaf}}$ mainly through the effects on SOC, STP and pH. From low elevation to high elevation, the $[C]_{\text{leaf}}$ and $[P]_{\text{leaf}}$ decreased, whereas $[N]_{\text{leaf}}$ increased, partly supporting the temperature-physiology hypothesis. In the study area, *P. fruticosa* growth was commonly limited by soil P. Moreover, the areas at higher elevations were particularly lacking in soil P. Due to high precipitation and sparse vegetation at higher elevations, loss of soil P is greater. Accordingly, disturbances such as livestock grazing must be excluded to prevent soil erosion and reduce run-off in this area. As *P. fruticosa* is a major alpine shrub on the QTP, improving its growth conditions will play an important role in maintaining the ecologically integrated functions and services of the whole QTP.

Methods

Plant material and soil sampling

Study area

With a mean elevation of 4000 m (closer to 3000 m in the northeast), MAP of 400 mm, and MAT of $< -4^{\circ}\text{C}$, the Qinghai-Tibetan Plateau covers $2.5 \times 10^6 \text{ km}^2$. Ranging in elevation from 2,200 to 5,500 m, and located in the northeastern portion of the QTP, the Qilian Mountains mainly present two slope aspects; south-facing and north-facing. On the south-facing slope aspects, grasslands growing on sandy-textured chestnut soils are the dominant vegetation type, while on the north-facing slope aspects, Qinghai spruce (*Picea crassifolia* Kom.), growing on silty-sand-textured grey cinnamon soils, is the dominant species (Qin et al., 2016).

Field sampling

In August and September 2018, when most plant species were at the late flowering or fruiting stages, leaves at top and middle of *P. fruticosa* were sampled from three random 10 m \times 10 m plots situated at each of seven elevations: 2,400 m, 2,600 m, 2,800 m, 3,000 m, 3,200 m, 3,500 m, and 3,800 m elevation. *Potentilla fruticosa* were identified by Yong Zhang, who is a Professor of Hexi University, he has been engaged in the study of botany taxonomy of Qilian Mountains and has published a book of Atlas of Vascular Plants in Qilian Mountains. In each plot, multiple soil samples were collected from three quadrats (1 m \times 1 m) along the diagonal. A 35-mm diameter soil drill allowed sampling from 3 depth profiles (0-0.10 m, 0.10-0.20 m and 0.20-0.40 m).

Laboratory analyses

Using established laboratory methods, $[C]_{\text{leaf}}$, $[N]_{\text{leaf}}$, $[P]_{\text{leaf}}$, soil organic carbon (SOC), soil total nitrogen (STN), and soil total phosphorus (STP) were measured (more details in Cao et al. (2020)), while soil water content (SWC) was determined from oven drying of samples at 105°C to a constant mass (Qin et al., 2019).

Statistical analysis

The MAT and MAP (Table 1) were based on Zhao et al. (2005, 2006). For the Qilian Mountain region, they were calculated as:

$$MAT = 20.96 - 5.49 \times 10^{-3} ELEV - 0.17LAT + 8.9 \times 10^{-3} LONG \quad (1)$$

$$R^2 = 0.98$$

$$MAP = 1.68 \times 10^3 + 0.12 ELEV + 12.41LAT - 75.26 LONG \quad (2)$$

$$R^2 = 0.92$$

where MAT = mean annual temperature (°C), MAP = mean annual precipitation (mm), ELEV = elevation (m), LAT = latitude (°), and LONG = longitude (°). R^2 indicates the coefficient of determination.

All data were expressed as mean and standard deviation (SD), and analyzed with SPSS 22.0 for Windows (SPSS, Inc., Chicago, IL). One-way ANOVA and univariate general linear model were used to explore differences in leaf stoichiometry and soil nutrients at different elevations, and the effects of elevation on soil nutrients, respectively. The Pearson Correlation Coefficient was used to determine the correlation between leaf stoichiometry and abiotic factors. Redundancy analysis (RDA) was performed to find the dominant environmental variables influencing leaf stoichiometry of *P. fruticosa* (Maccherini et al. 2011; Yang et al. 2018a) using the R 'vegan' package (Yang et al., 2018b). The significance of the eigenvalues of the canonical axes was tested by a reduced Monte Carlo model with 270 unrestricted permutations (Yuan, 2017; Sun et al., 2017).

Abbreviations

QTP

Qinghai-Tibetan Plateau; MAP:mean annual precipitation; MAT:mean annual temperature; SOC:soil organic carbon; STN:soil total nitrogen; STP:soil total phosphorus; SWC:soil water content; SD:standard deviation; ANOVA:one-way analysis of variance; LSD:least significant difference; RDA:Redundancy analysis; $[C]_{\text{leaf}}$:leaf carbon (C) concentrations; $[N]_{\text{leaf}}$:leaf nitrogen (N) concentration; $[P]_{\text{leaf}}$:Leaf phosphorus (P) concentration.

Declarations

Ethics approval and consent to participate

This study collected all of the samples of *potentilla fruticosa* was allowed by my instution (Northwest Institution of Eco-Environment resources, Chinese Academy of Sciences, Which has several field stations, including Haibei National Field Research Station of Alpine Grassland Ecosystem and Qilian Mountain Comprehensive Observation Research Station of Glaciers and Eco-environment station, experiment samples were colleted from the two field stations around).

Consent for publication

Not applicable.

Availability of data and materials

The data related to this study were deposited in the my Institute.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Conception and design of the research: YQ; acquisition of data: XZ and YQ; analysis and interpretation of data: WL; statistical analysis: XZ; drafting the manuscript: WL, XZ and YQ; revision of manuscript for important intellectual content: JA and AB. All authors read and approved the final manuscript.

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Figures

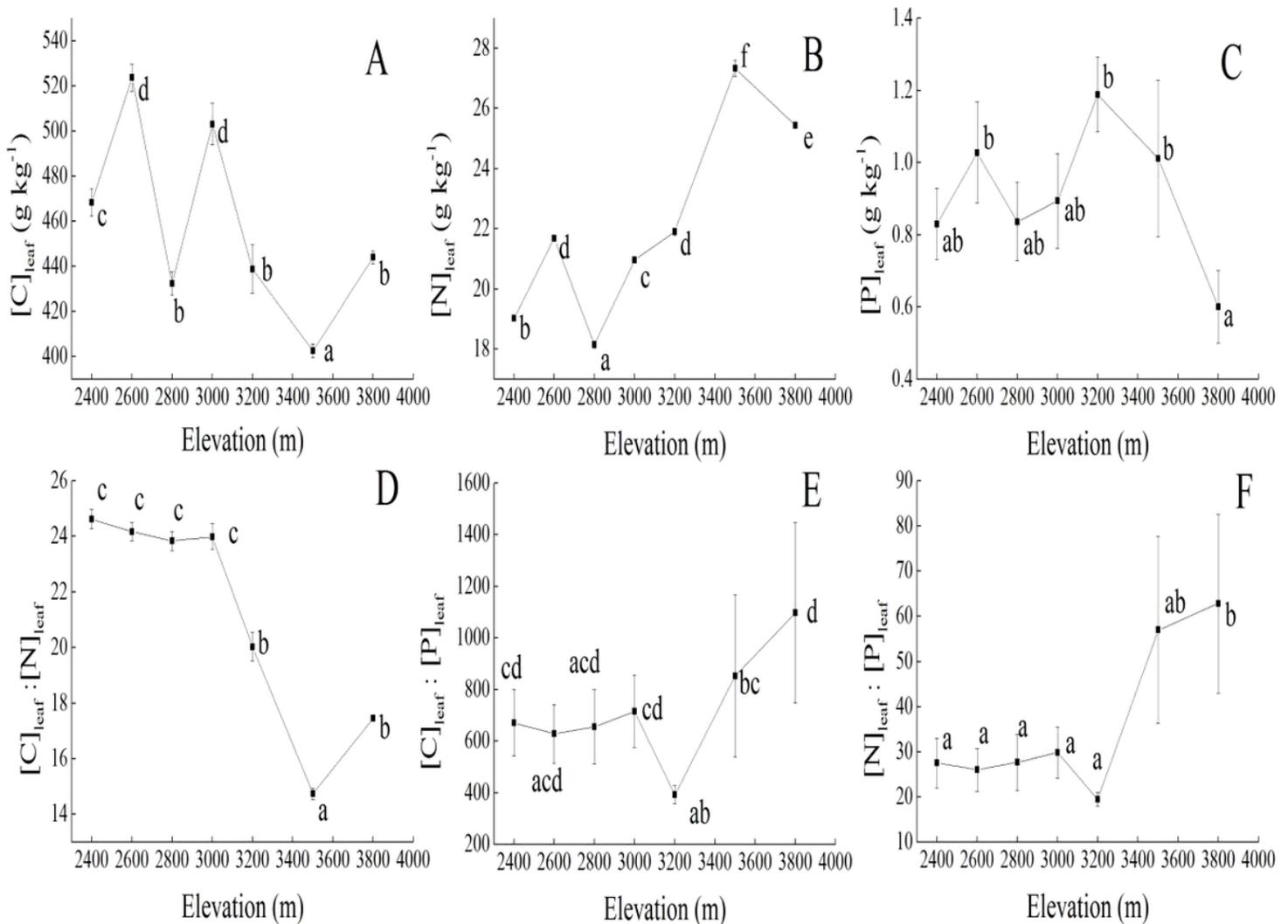


Figure 1

Leaf stoichiometry of *P. fruticosa* at different elevations *P. fruticosa* [C]_{leaf} (A), [N]_{leaf} (B), and [P]_{leaf} (C) and [C]_{leaf}: [N]_{leaf} (D), [C]_{leaf}: [P]_{leaf} (E), and [N]_{leaf}: [P]_{leaf} (F) ratios: from 2400 m to 3800 m. [C]_{leaf} = leaf C concentration, [N]_{leaf} = leaf N concentration, and [P]_{leaf} = leaf P concentration. Different lowercase letters indicate a significant difference among elevations.

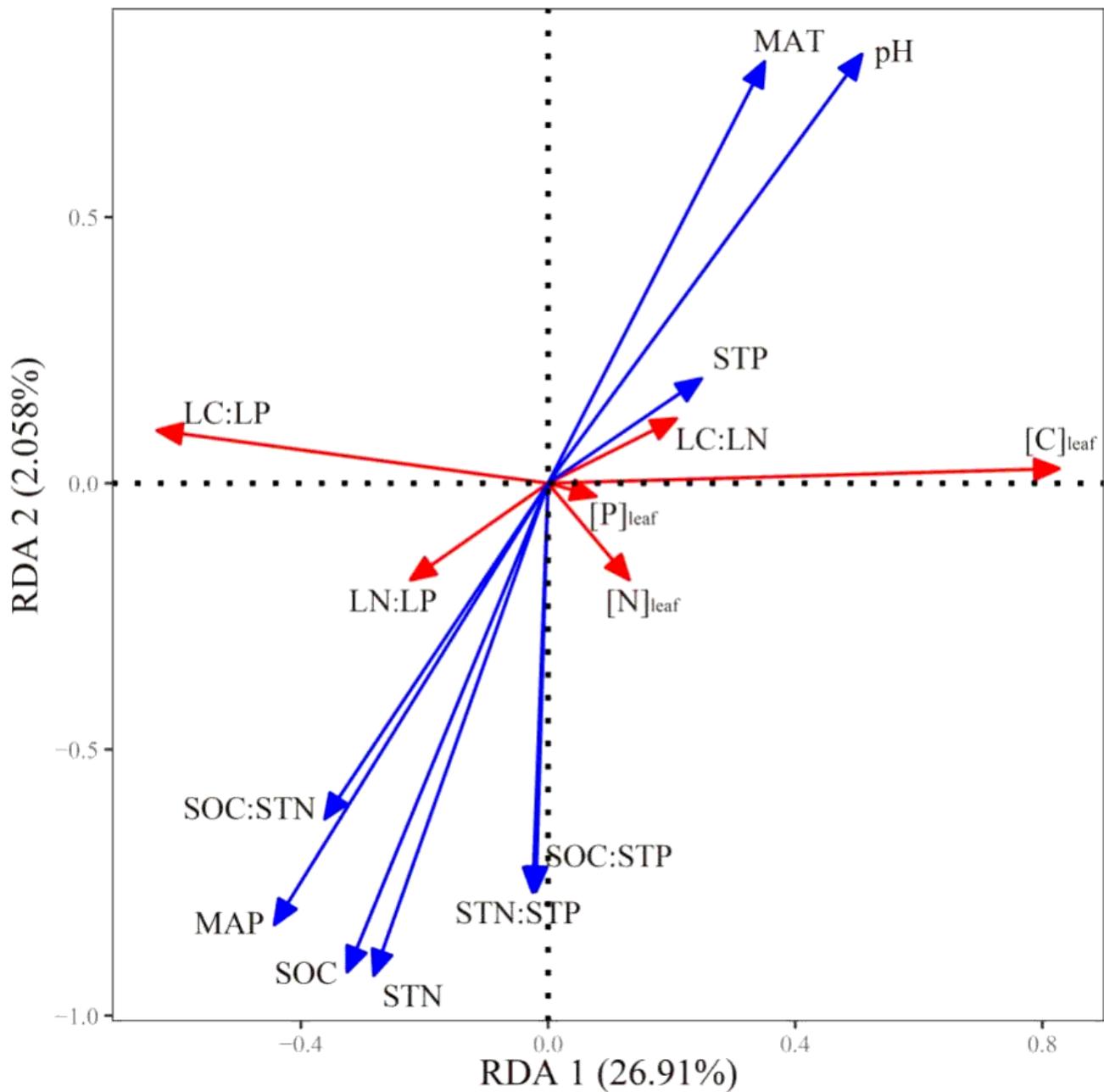


Figure 2

Redundancy analysis (RDA) for the leaf stoichiometric indices of *P. fruticosa*, with soil parameters, MAT, and MAP as the explanatory variable. SOC = soil organic carbon, STN = soil total nitrogen, STP = soil total phosphorus, [C]_{leaf} = leaf C concentration, [N]_{leaf} = leaf N concentration, [P]_{leaf} = leaf P concentration, MAT = mean annual temperature, and MAP= mean annual precipitation.