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Trace elements apportionment in forage, soil, and livestock in rangeland ecosystems along climatic gradients

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ABSTRACT

Background: Alpine meadows, typical steppes, and deserts are among the globally important rangeland types that are generally distributed along temperature and precipitation gradients. Mineral losses caused by grazing are one of the key factors that can lead to instability or even degradation of these rangeland ecosystems.
Methods: We examined the concentrations of Cu, Fe, Mn, and Zn in soil, forage, and livestock dungs from diverse rangeland types in northwest China, to determine the relationships between these trace elements (TEs) concentrations and climatic factors (i.e., temperature, precipitation, and humidity), and to evaluate the potential risks of TEs deficiencies or excesses in these rangeland ecosystems.
Results: Forage Zn concentrations in forage of all three types of rangeland, and Cu concentrations in forage of the alpine meadow did not meet the growth requirements of grazing livestock. Concentrations of Cu, Fe, and Mn in forage and Fe, Mn, and Zn in livestock dungs had quadratic parabola relationships with temperature, precipitation, and humidity, but the relationships between climate factors and Cu, Fe, and Mn concentrations in soil were not significant. In addition, the abilities of the plant to absorb Cu, Fe, and Zn from soil were stronger in the typical steppe than that in the alpine meadows and desert. Also, the abilities of livestock to return TEs to soil were stronger in the alpine meadow than that in the typical steppe and desert.
Conclusion: We derived a conceptual mode that the ratio of TE concentrations of the plant to soil and of livestock dung to forage represents the abilities of plants to absorb TEs from the soil matrix and livestock to return TEs to soil or to absorb TEs from forage, respectively. Results indicate potentially more serious risks of TEs deficiencies, especially that of Zn than previously considered in typical steppes and desert rangelands.

Authors contributions

Jiao Ning: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing -review & editing. **Shengsheng Liu**, **Yi Sun**, **Lei Xu**, **Hua Wang**, **Minglei Zhang:** Investigation, Methodology. **Shenghua Chang:** Resources, Data curation, Validation, Supervision. **Charles P. West** and **Muhammad Kamran:** Writing -review & editing. **Fujiang Hou:** Conceptualization, Writing -review & editing, Project administration, Funding acquisition.

1. Introduction

Trace elements (TEs) are essential for the growth, maintenance, and reproduction of plants and grazing livestock, and for the stability of rangeland ecosystems (Trengove and Judson, 2010; Kumar et al., 2016). The TEs are persistent in environments, and their excessive accumulations can reduce the decomposition of soil organic matter, inhibit plant growth, and disrupt biogeochemical cycling (Kabata-Pendias, 2011; Shtangeeva et al., 2020). However, TE deficiencies remain important causes of livestock loss in many rangeland ecosystems. Rangelands account for 41.7% of China's land area, of which alpine meadow, typical steppe, and desert constitute 10.0%, 37.4%, and 17.3% of the total rangeland area, respectively (Hou et al., 2016). These three types of rangeland also support much of the global livestock industry (Hou et al., 2021). Therefore, achieving a better understanding of TE apportionment in these rangeland types is vital to improve rangeland and livestock

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health and thus sustain food security.

Rangeland ecosystems are differentiated along temperature and precipitation gradients (Polley et al., 2013; Dixon et al., 2014; Chen et al., 2015). Spatial changes in plants, soil, and livestock associated with climate factors may impact the accumulation and bioavailability of TEs in ecosystems (Wang et al., 2014; Madejon et al., 2018). Previous researchers have contributed data on soil TE contents in rangelands to determine ambient background values but limited attention has been given to investigating TEs in forage and livestock. This data gap limits the ability to accurately predict excessive or insufficient levels of TEs in forage and to monitor nutritionally relevant TE changes in rangeland ecosystems. Although the soil is the main source of TEs for plants, their uptake and accumulation depend more on the plant and the climatic conditions than on TE concentrations in the soil (Nirupa and Prasad, 2008; Nedjimi, 2018). Different taxonomic groups, and even botanically similar plant species, can absorb different amounts of TEs under the same soils (Norton et al., 2009; White et al., 2015; Mišljenović et al., 2018; Guarino et al., 2019). These differences are amplified when the plants are grown in different soils (Zhang et al., 2011; Memoli et al., 2017). Concentrations of TEs have a large spatial variability, both in the same plant species and between plant species, and the uptake of TEs from soils by plants varies significantly with changes in precipitation and temperature (Munoz and Faz, 2014; Zhang et al., 2014).

Direct monitoring of TEs in plants is desirable to assess their levels in forage for grazing animals and to assess potential TEs losses through the export of marketed animals (Wang et al., 2014; Nedjimi, 2018). The plant-to-soil ratio of TEs represents the plants' ability to absorb TEs from the soil matrix (Jiang et al., 2018). Thus, adapted plant community and TE uptake profiles can contribute to maintaining the productivity, sustainability, and resilience of rangeland ecosystems (Touceda-Gonzalez et al., 2017; Madejon et al., 2018). Grazing livestock plays a key role in the regulation of TE statuses in rangeland ecosystems through their cycling of minerals via forage ingestion and excretion patterns, and retention in the tissues. Trace element output from the ecosystem is mainly via the marketed livestock, while TEs are partly returned to the soil via livestock dung. The ratio of TE concentrations of livestock dung to forage implies the ability of livestock to return TEs to soil or to absorb from forage (Kumar et al., 2016). Along a climatic gradient, both ratios vary and have different influences on TE levels in rangeland ecosystems (Bosatta, 1998; Spohn and Sierra, 2018).

Copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) are involved in many vital processes for organisms in rangeland ecosystems, including the transport of oxygen, protein synthesis, and enzyme activities (Trengove and Judson, 2010). To determine the changes of TE apportionment in plants, soil, and livestock along gradients of increasing air temperature and decreasing precipitation, three types of rangeland, i.e., alpine meadow, typical steppe, and desert in an inland region were chosen for the study. The objectives were to: (1) investigate the TE statuses of Cu, Fe, Mn, and Zn in these rangeland ecosystems, and (2) determine the relationships between TE concentrations in forage, soil, livestock dung, and climatic factors. The growth of plants and livestock in the arid and semi-arid rangelands of northern China is often co-limited by the availability of different mineral nutrients and water (Xu et al., 2012). According to biological characteristics, plants, soil, and livestock commonly share optimum or unfavorable environmental conditions for absorbing or accumulating TEs (Wang et al., 2014; Jiang et al., 2018). Therefore, the relationships of TE concentrations in herbage, soil, and sheep dung with environmental conditions including temperature, precipitation, and humidity could be explained with polynomial regression more accurately. The relatively low air temperature in alpine meadows (Fan et al., 2019; Hou et al., 2016) and relatively low precipitation in deserts (Niu et al., 2008) are the main factors restricting the function and production of plants and livestock. We, therefore, put forward two hypotheses: (1) the ability of plants to absorb TEs from soil is stronger in the typical steppe than in the alpine meadows and desert, and (2) the ability of livestock to return TEs from forage to soil is weaker in the typical steppe than in the alpine meadows and desert (Fig. 1).

2. Materials and methods

2.1. Site description

The study was conducted on three types of rangeland in northwest China: the alpine meadow of the eastern Tibetan Plateau, the typical steppe of the western Loess Plateau, and the desert of the Northwestern Inland Arid Region (Fig. 2) (Hou et al., 2021).

The alpine meadow site is located in Maqu County (35.97°N, 101.88°N), Gansu Province. Mean elevation is ~3,500 m above sea level. The mean annual precipitation and temperature were 616 mm and 2.5 °C in the past 10 years; mean temperature in 2012 and 2013 was 2.7 °C, while annual precipitation across the experimental years was 625.5 mm (Fig. 3). The soil is a clay loam and classified as a Mat-Cryic Cambisol (Sun et al., 2015). The mean soil pH (± standard error) was 6.75 (±0.31), and soil organic carbon (SOC) and total nitrogen (TN) concentrations were 48.33 (±6.72) g kg^{-1} and 2.26 (±0.40) g kg^{-1}, respectively. Yak (*Bos grunniens*) and Tibetan sheep (*Ovis aries*) were the main grazing livestock.

The typical steppe site is located in Huan County (36.58°N, 106.95°E), Gansu Province. Mean elevation is ~1,650 m above sea level. Mean annual temperature in 2012 and 2013 was 8.1 °C, and annual precipitation in 2012 and 2013 was 261 mm, of which 89.6% was recorded from May to September (Fig. 3), with 1,993 mm of annual potential evapotranspiration. The soil is sandy and classified as Loessial (Li et al., 2021). Soil pH was 7.03 (±0.45), and the SOC and TN concentrations were 14.19 (±2.05) g kg^{-1} and 1.28 (±0.28) g kg^{-1}, respectively. The Tan breed of sheep and Qinchuan cattle (*Bos taurus*) were the most common livestock managed with a continuous stocking regime.

The desert site is located in Minqing County (38.88°N, 103.82°E), Gansu Province. The mean elevation is 1,440 m above sea level. Mean annual temperature in 2012 and 2013 was 10.2 °C (Fig. 3a). The mean annual precipitation in 2012 and 2013 was 107 mm, and rainfall from June to September accounted for 84.5% of the annual precipitation (Fig. 3b), with 2,623 mm of annual potential evapotranspiration. The desert soil is sandy and is classified as Aridisols, and the pH was 7.48 (±0.63), while the SOC and TN concentrations were 3.09 (±0.66) g kg^{-1} and 0.254 (±0.082) g kg^{-1}, respectively. The Bactrian camel (*Genus species*) and Mongolia type of sheep were the predominant grazing livestock at this site.

2.2. Sampling and analysis of forage, soil, and livestock dung

To determine the TE concentrations in forage, soil, and livestock dung, three blocks (each of 5 hectares), treated as three replications, were set in each rangeland (distances between blocks in each rangeland were more than 10 km). On July 15–25 in both 2012 and 2013, 30 quadrats in each block were randomly selected. In the alpine meadow and typical steppe, each quadrat was 1 × 1 m, and in the desert, 3 × 3 m. The edible plant species were determined and sampled. Forage in each block was mixed, washed, and oven-dried at 65 °C to constant weight for calculating biomass, and then ground through a 0.5-mm sieve for analyzing TE concentrations. At the time of forage sampling, 30 fresh livestock dung samples from different dung spots in each block were manually collected. Meanwhile, 30 soil samples at 0–30 cm depth were collected in each block using a wooden spade. All soil and dung samples were air-dried, then ground through a 0.25-mm nylon sieve.

After acid digestion of forage, dung, and soil samples, total Cu, Fe, Mn, and Zn concentrations were measured by atomic absorption spectrophotometry (Harlyk et al., 1997). Soil pH was measured using the potentiometric method in a soil/water suspension (1:2.5 ratio). Soil organic carbon was measured by chromic acid redox titration (Nelson and Sommers, 1996). Soil total nitrogen was measured following the

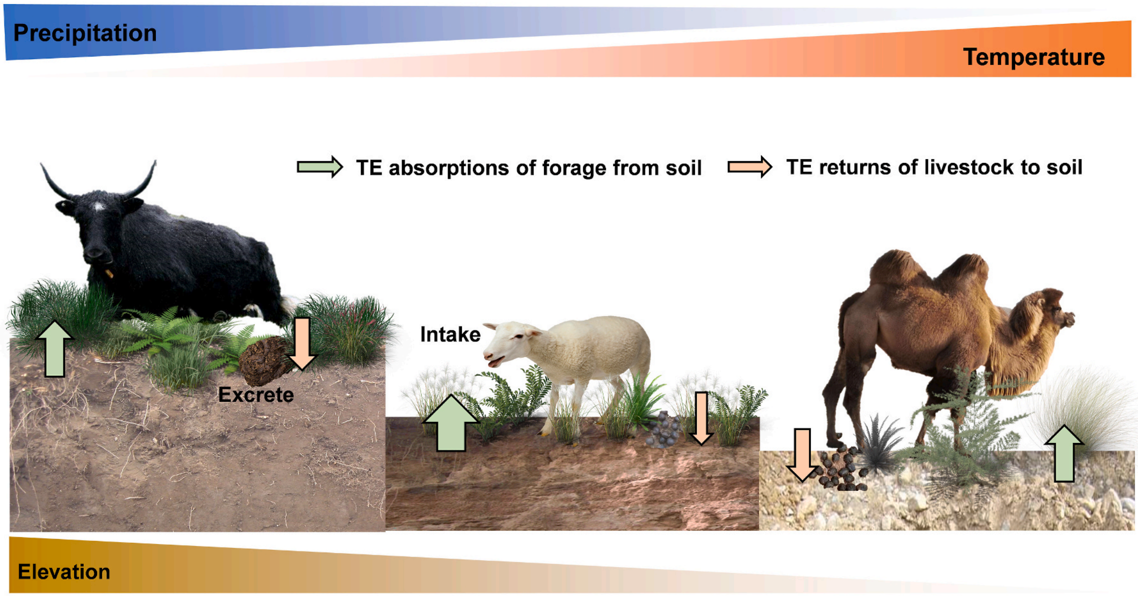

Fig. 1. The conceptual diagram of TE cycles among soil, forage, and livestock in rangeland ecosystems along climatic gradients. The width of arrows indicates the ability of TE absorptions of plants from soil and TE returns of livestock to soil in the hypotheses, where precipitation, air temperature, and elevation are illustrated as a gradient from dark color to light color (those are, high to low).

methods of Bremner and Mulvaney (1982).

2.3. Calculations and statistical analysis

The moisture index (K) was calculated according to (Ren et al., 1965):

$$K = \frac{r}{0.1\sum\theta}$$

where r is the annual precipitation, and $\sum\theta$ is > 0 °C is the accumulated temperature.

All statistical analyses were conducted using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Results of a Shapiro–Wilk test (UNIVARIATE Procedure) indicated the data collected for the study were normally distributed. The ANOVA (GLM) indicated that the independent effects of year and the interaction effect of year and rangeland type on TE concentrations in forage, soil, and livestock dungs were not significant, so the mean values of two years for TE concentrations in forage, soil, and livestock dung were applied to subsequent analyses and plots. A least significant difference (LSD) test was used to compare the mean differences in TE concentrations among different sampled materials and the ratios of TE concentrations among rangeland types. The relationships between TE concentrations in forage, soil, and livestock dung and annual precipitation, mean annual temperature, and humidity, and the correlations of TE concentrations in forage and soil, forage and livestock dung, and soil and livestock dung were determined using polynomial regression (GLM Procedure).

3. Results

3.1. TE concentrations in forage, soil, and livestock dung

Soil Zn concentration was significantly greater in the alpine meadow than in the typical steppe and desert, and forage Cu, Fe, and Zn concentrations in the typical steppe were the greatest (Fig. 4). The Cu and Zn concentrations in soil were significantly greater than those in forage but significantly lower than those in livestock dung in the three types of rangeland, except that there was no significant difference in Zn concentration between soil and dung in the desert (Fig. 4). The Fe and Mn concentrations in dung were significantly greater than those in forage but significantly lower than those in soil in the three types of rangeland.

3.2. Relationships between TE concentrations and climate factors

Zn concentration in soil had an upward-curving relationship with temperature, precipitation, and humidity (Fig. 5a). There was no significant relationship between Cu, Fe, and Mn concentrations in soil and climate factors.

The relationships between air temperature and Cu, Fe, and Zn concentrations in forage, and between precipitation and Cu and Fe concentrations in forage presented downward curves (Fig. 5b). However, Mn concentration in forage had an upward-curving relationship with temperature, precipitation, and humidity.

In livestock dung, annual precipitation, annual mean temperature, and humidity had downward-curving relationships with Zn concentration and an upward-curving relationship with Mn concentration. Iron concentration in livestock dung presented a downward curve with temperature and an upward curve with precipitation and humidity.

3.3. Trace element cycles in three types of rangeland

There was no significant correlation between the concentrations of Cu, Fe, Mn and Zn in soil and forage, in forage and livestock, and in soil and livestock, except that Fe in forage and dung and Zn in soil and dung (Table 1).

The ratio of forage to soil for Cu concentration was significantly greater in the typical steppe than in the alpine meadow (Fig. 6a). The ratios of forage to soil for Fe, Mn, and Zn concentrations were significantly greater in the typical steppe and desert than in the alpine meadow. The ratios of dung to forage for Cu, Fe, Mn, and Zn in the alpine meadow were significantly greater than those in the typical steppe and desert (Fig. 6b). Additionally, the ratios of dung to forage for Cu and Zn in the typical steppe were significantly lower than those in the desert, but the ratio for Mn was significantly greater in the typical steppe than in the desert.

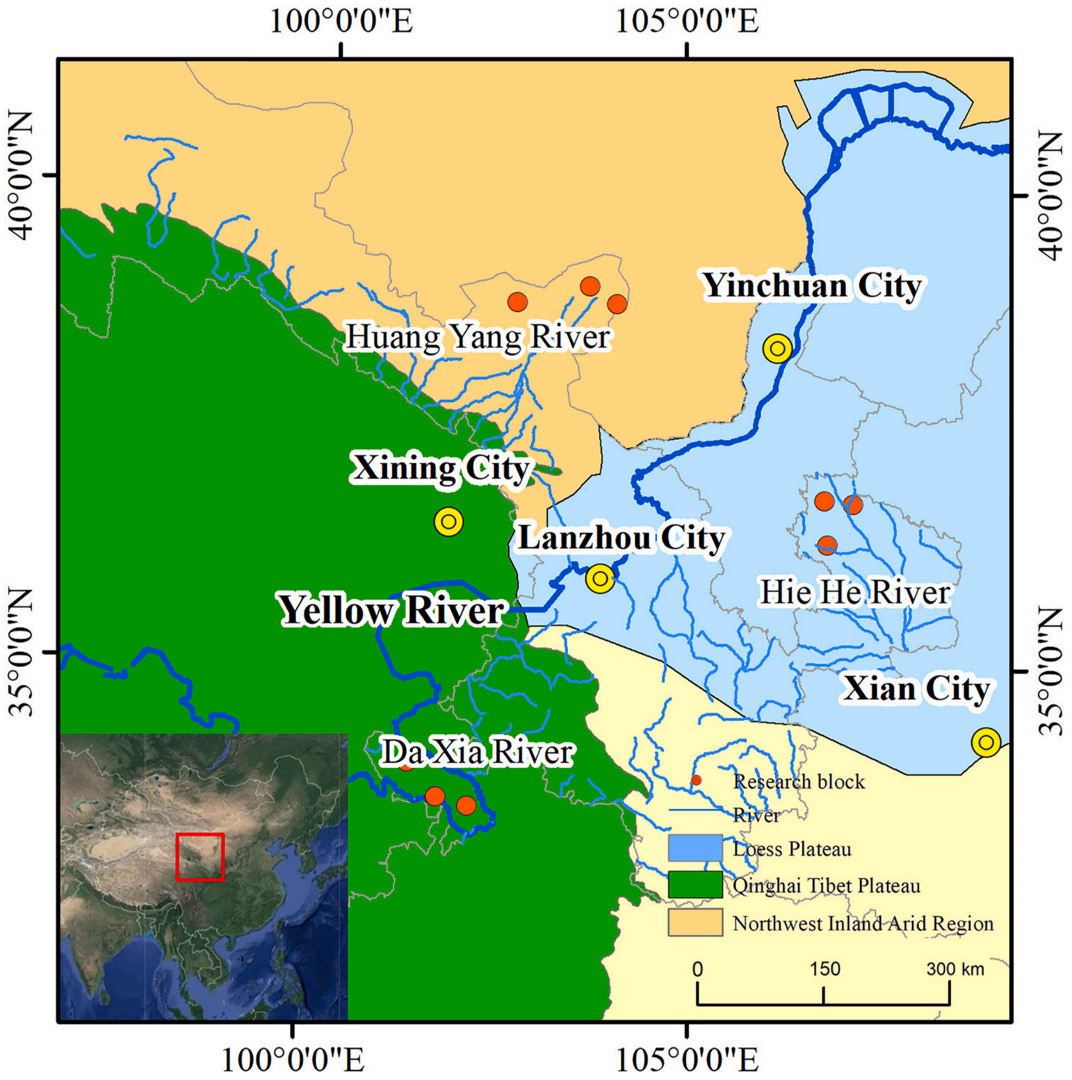

Fig. 2. Location of the sample sites.

4. Discussion

4.1. *Trace element statuses*

The possible reasons for TE excesses or deficiencies across different rangeland types vary with climate and soil (Fan et al., 2019). For grazing livestock, it is primarily forage-based: if the soil cannot supply sufficient TEs to plants consumed by grazing livestock, TE deficiencies occur. Soil TE concentrations may indicate gross TE deficiency or excess, this may be used only as a guide when considering the TE statuses of plants and livestock. According to Zhang et al. (2010), the average TE values of soil in China were reported as follows: Cu (22.6 ± 11.4 mg kg^{-1}), Fe (2.94 ± 0.95%), Mn (583 ± 363 mg kg^{-1}), and Zn (74 ± 33 mg kg^{-1}).Results from the present study showed that soil Fe and Mn concentrations in the three rangelands and Zn concentrations in the typical steppe and desert were far lower than the average values in China, while the other concentrations were not different from the average values. This suggested that these soils were not yet contaminated by rapid industrial development.

Forage has wide variations in TE concentrations due to soil condition, vegetation type, and geographical distribution (Vondráčková et al., 2014; Khan et al., 2017). According to the recommendations of the NRC (2007) and ARC (1980), the present study observed that the forage Fe and Mn concentrations in the three types of rangeland were within the recommended levels for ruminant livestock, but forage Cu concentration in the alpine meadow and Zn concentration in all rangelands were lower than the recommended levels of livestock.

Neutral-pH- soil conditions are beneficial to the absorption of Fe by plants (Kumaresan et al., 2010), which may be responsible for greater forage Cu, Fe, and Zn concentrations in the typical steppe without the highest soil Cu, Fe Zn concentration (Fig. 4). Although the TE concentrations in the alpine meadow soil were not low, but they were the lowest in forage among all the rangelands. Previous studies have indicated that the availability of TEs to plants may depend on plant species rather than the element concentrations in the soil, and the TE dilution effect can be more obvious in high-biomass forage (Nedjimi, 2018). The greater biomass in the alpine meadow (Figure S1) may have resulted in low TE concentrations in forage.

TE statuses of livestock are diagnosed indirectly by dung. Cu and Zn are the most important essential minerals for the growth and development of livestock (Yildiz and Balikci, 2004). Greater TE concentrations in dung imply lower TE absorption by livestock (Deng et al., 2014). In the present study, a low Mn and Zn concentration in forage but high Mn and Zn concentration in dung in the alpine meadow compared with other rangeland types indicated that Mn and Zn absorption of livestock may be lower in the alpine meadow than in typical steppe and desert, or that the climate in the alpine meadow limits Mn and Zn absorption by livestock.

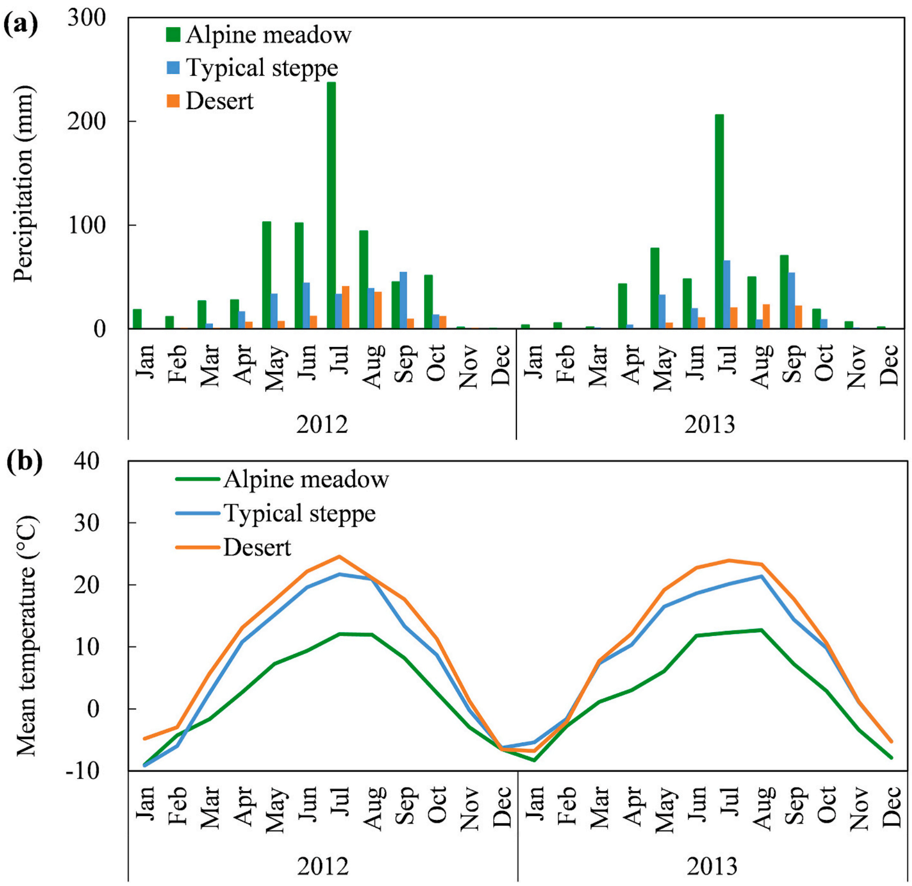

Fig. 3. (a) Monthly precipitation and (b) monthly mean temperature in 2012 and 2013 at the three types of rangeland.

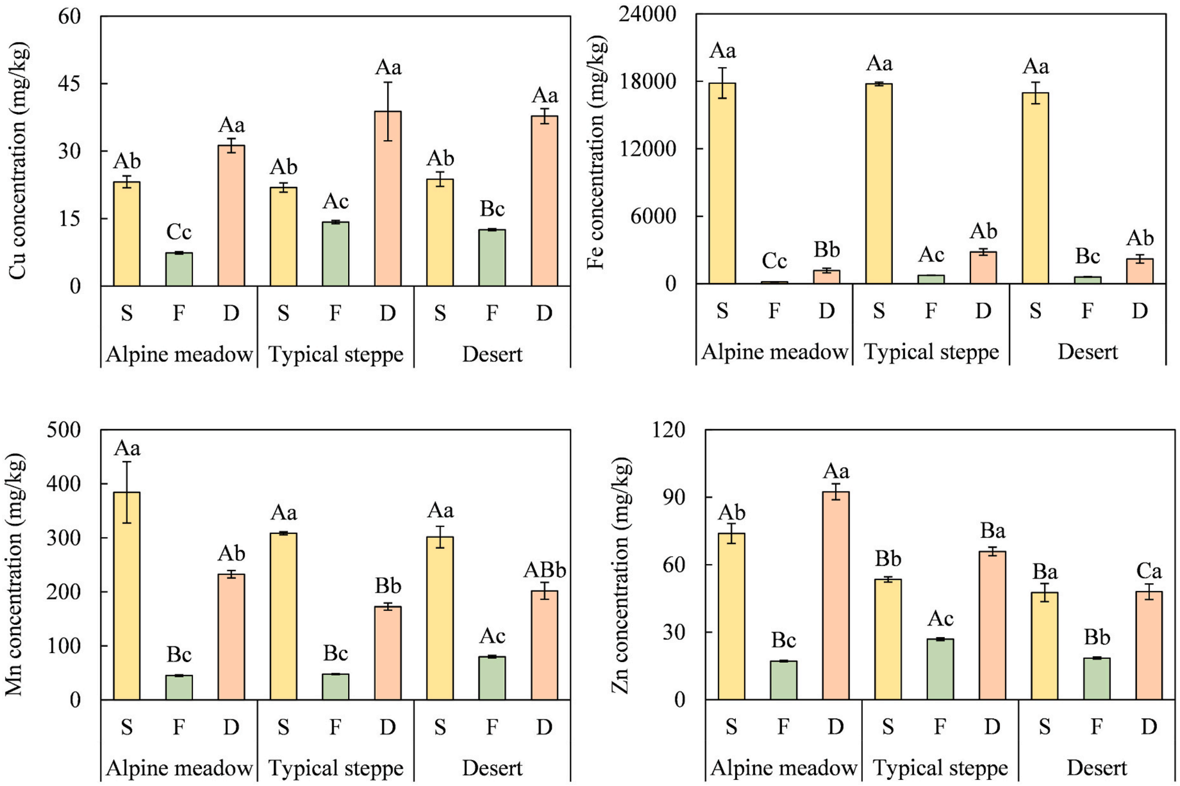

Fig. 4. The Cu, Fe, Mn, and Zn in forage (F), soil (S), and livestock dung (D) at the three types of rangeland. Means with the same lower-case letters between different samples or with the same uppercase letters between different rangeland types are not significantly different ($P > 0.05$).

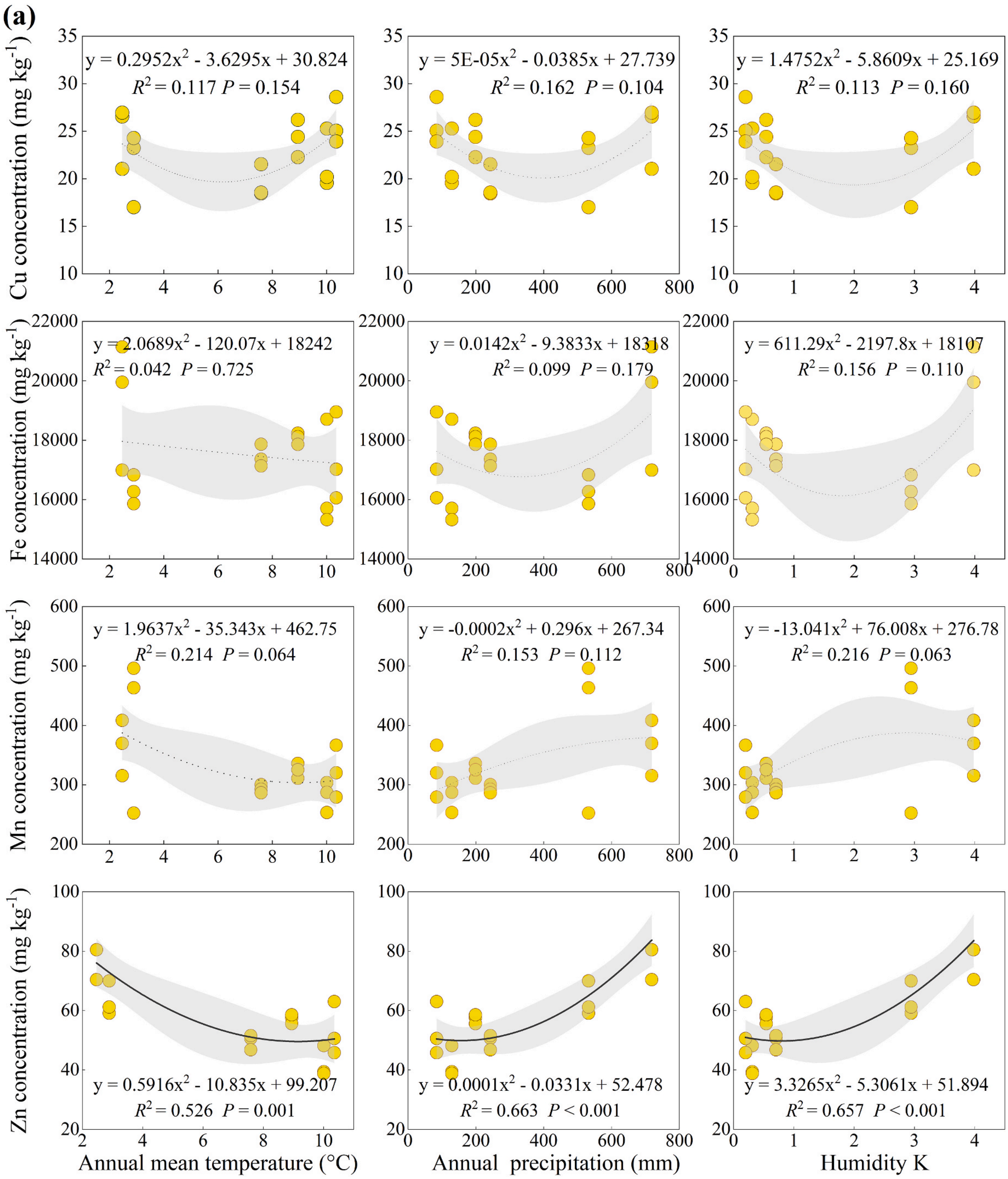

Fig. 5. The relationships between TE concentrations in (a) soil, (b) forage, and (c) livestock dung and annual mean temperature, annual precipitation, and humidity K value.

4.2. Relationships between trace elements and climate factors

Air temperature and precipitation are the most important climatic factors in controlling the survival of plants and their distribution (Le Houérou, 2001; Slimani et al., 2010), and as a result, they cause a large spatial variability in extractable mineral elements (Munoz and Faz, 2014; Zhang et al., 2014). Too low or too high temperatures inhibit plant growth and the activity of soil microorganisms, which in turn can constrain the accumulation of organic matter and uptake of minerals. Studies have shown that organic matter has significant implications for TE speciation, transport, and bioavailability (Dong et al., 2017; Blankson et al., 2017), and the increase of organic matter in soil can increase TE concentrations in plants. Khan et al. (2006) reported low availability of TEs at a high temperature in a semiarid region. These findings contribute to the explanation of the downward curve of the associations between temperature and Cu, Fe, and Zn contents in fodder in the current study (Fig. 5b). Mineral solution rates in soil increase then decrease with increasing water input (Weis and Weis, 2004). In addition, increased plant growth can dilute TE concentrations in plants. Previous studies have shown a decreasing trend of plant TEs under conditions of increasing soil water (Wang et al., 2014; Cai et al., 2017a). Our results showing a downward-curving relationship between Cu and Fe

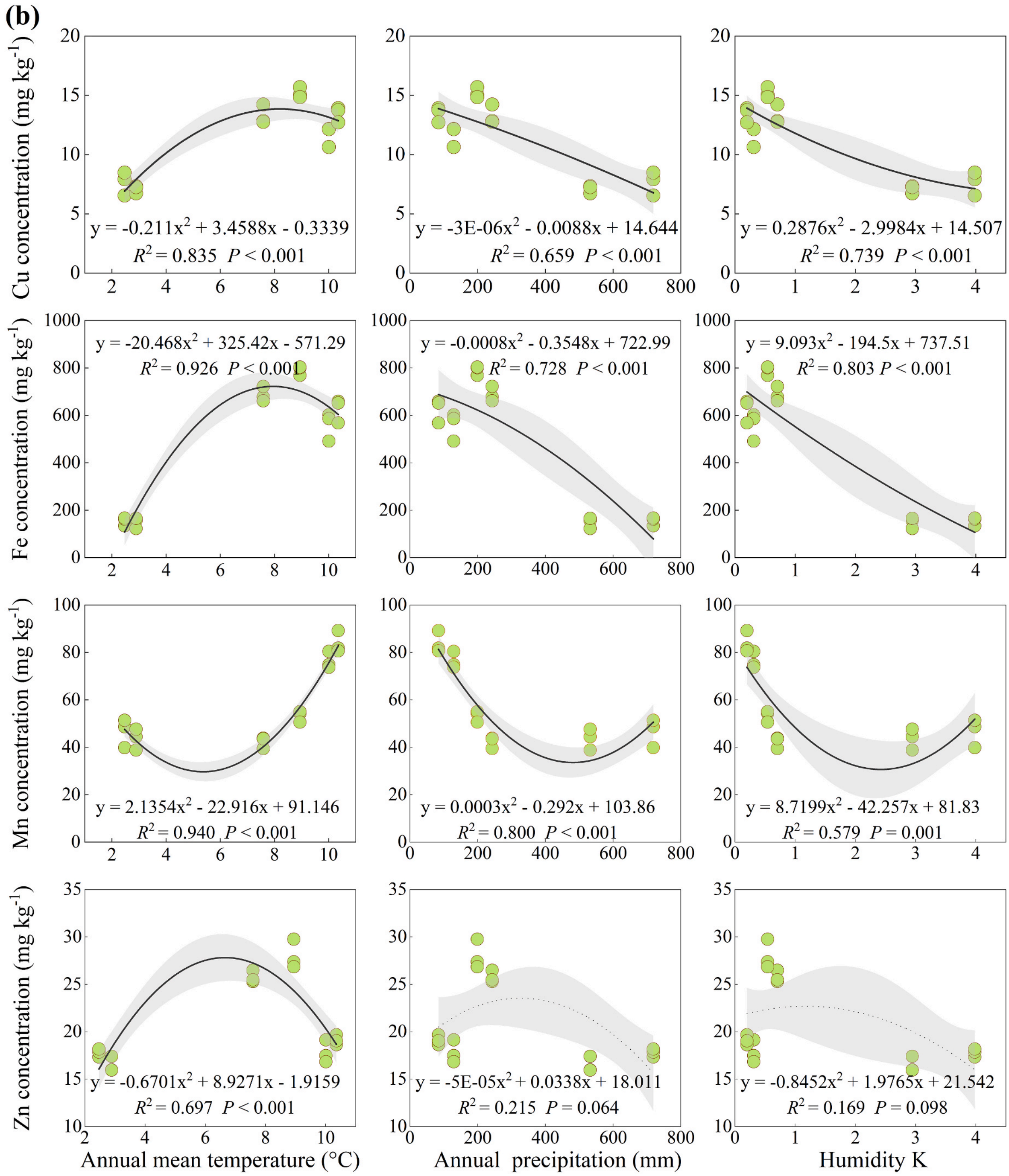

Fig. 5. (*continued*).

concentrations in forage and precipitation agreed with the above conclusion (Fig. 5b). Drought may inhibit general plant function, including uptake of soil minerals, and thus severely restrict plant growth (Lipiec et al., 2013; Dixon et al., 2014). Therefore, it is reasonable to suggest that the Fe concentration in forage may present an upward trend as precipitation changes from low to moderate. The interactions of TEs during forage uptake could be a reason for the decoupling of TE stoichiometry between plant and soil—for example, the antagonistic interactions of Mn with Fe, Cu, and Zn (Kabata-Pendias and Mukherjee, 2007; Cai et al., 2017b). The accumulation of Mn in plants can cause Fe deficiency, since Mn competes with Fe for binding sites during transportation (Eroglu et al., 2016; Tian et al., 2016). Indeed, the relationships between forage Mn and temperature and precipitation, as opposed to that between forage Cu, Fe, and Zn and temperature and precipitation, found in the present study (Fig. 5b) suggested antagonism between Mn and Cu, Fe, and Zn in plants.

The TEs in rangeland ecosystems will eventually be reflected in grazing livestock: TE concentrations in forage have a crucial influence on the content and balance of TEs in livestock (Wang et al., 2014). The digestion and absorption of TEs by grazing livestock are also affected by livestock species and climate factors (Fan et al., 2019). Therefore, the relationships between TE concentrations in livestock dung and temperature, precipitation, and humidity K value are similar but not identical to the relationships between TE concentrations in forage and these same climate factors.

Previous studies have shown that the characteristics of TE content in

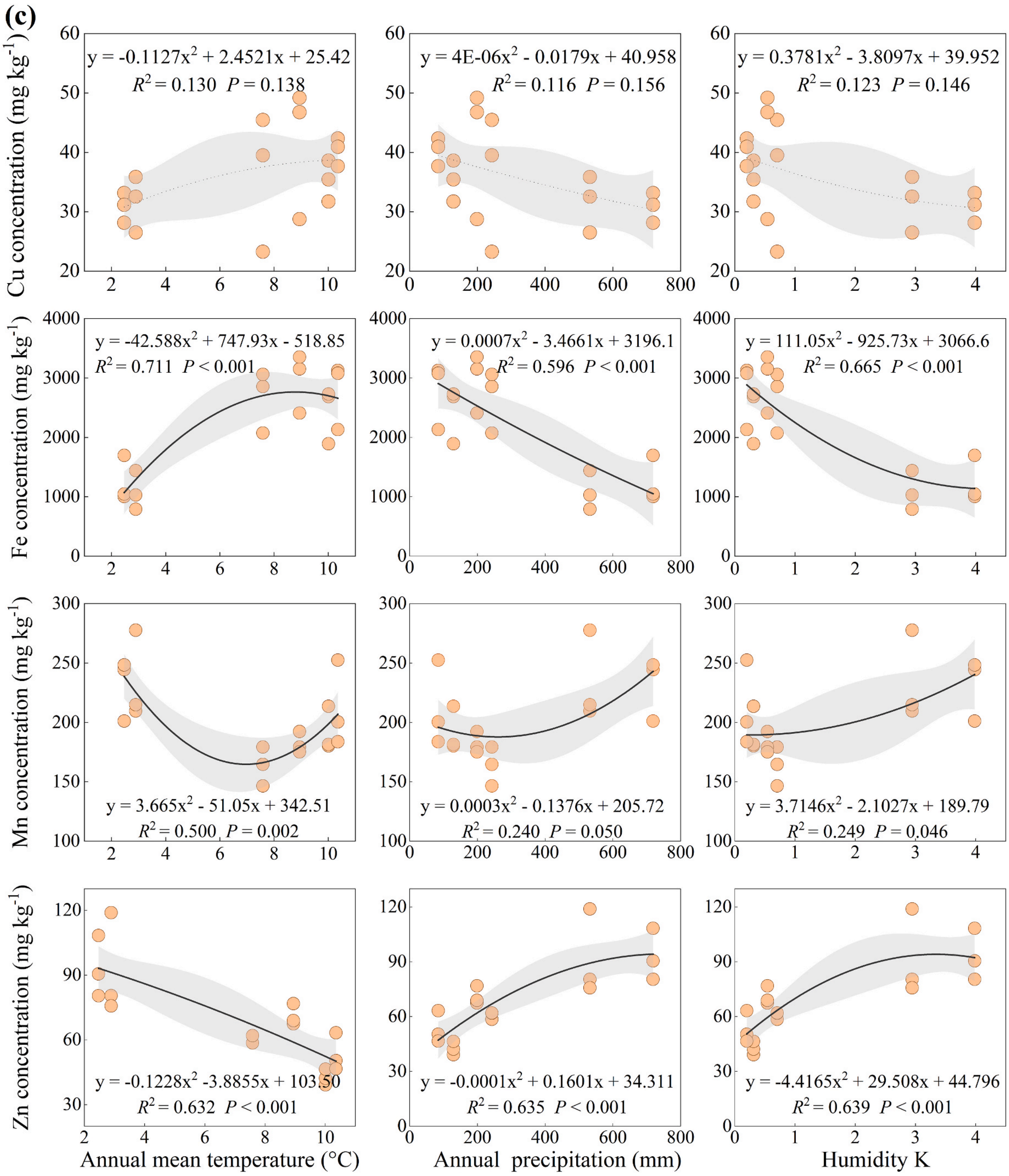

Fig. 5. (*continued*).

soil have regional differences. Variable geology is one of the main causes of the difference in TE levels across rangelands around the globe (Kabata-Pendias, 2011; Khan et al., 2017). Existing studies on the changes of soil TEs with temperature and precipitation were generally carried out in a single region (Cai et al., 2017b; Nedjimi, 2018), air temperature and precipitation have limited effects on TE concentrations of regional soils. The findings of the current study (Fig. 5a) could be explained by variations in soil chemistry and parent material between various rangelands or the limited range of climatic zones. Therefore, we recommend that future research on TE allocation in rangelands should focus more on seasonal fluctuations.

Table 1
Soil–forage–dung relationships (Pearson correlations) in relation to TE status.

Trace element	Cu	Fe	Mn	Zn
Soil-forage				
Pearson correlation value	−0.184	−0.081	−0.415	−0.390
P-value	0.635	0.836	0.267	0.299
Forage-dung				
Pearson correlation value	0.548	0.856[a]	−0.238	−0.238
P-value	0.127	0.003	0.791	0.537
Soil-dung				
Pearson correlation value	−0.273	0.164	0.262	0.808[a]
P-value	0.477	0.164	0.262	0.008

[a] Indicate the correlations were significant ($P < 0.01$).

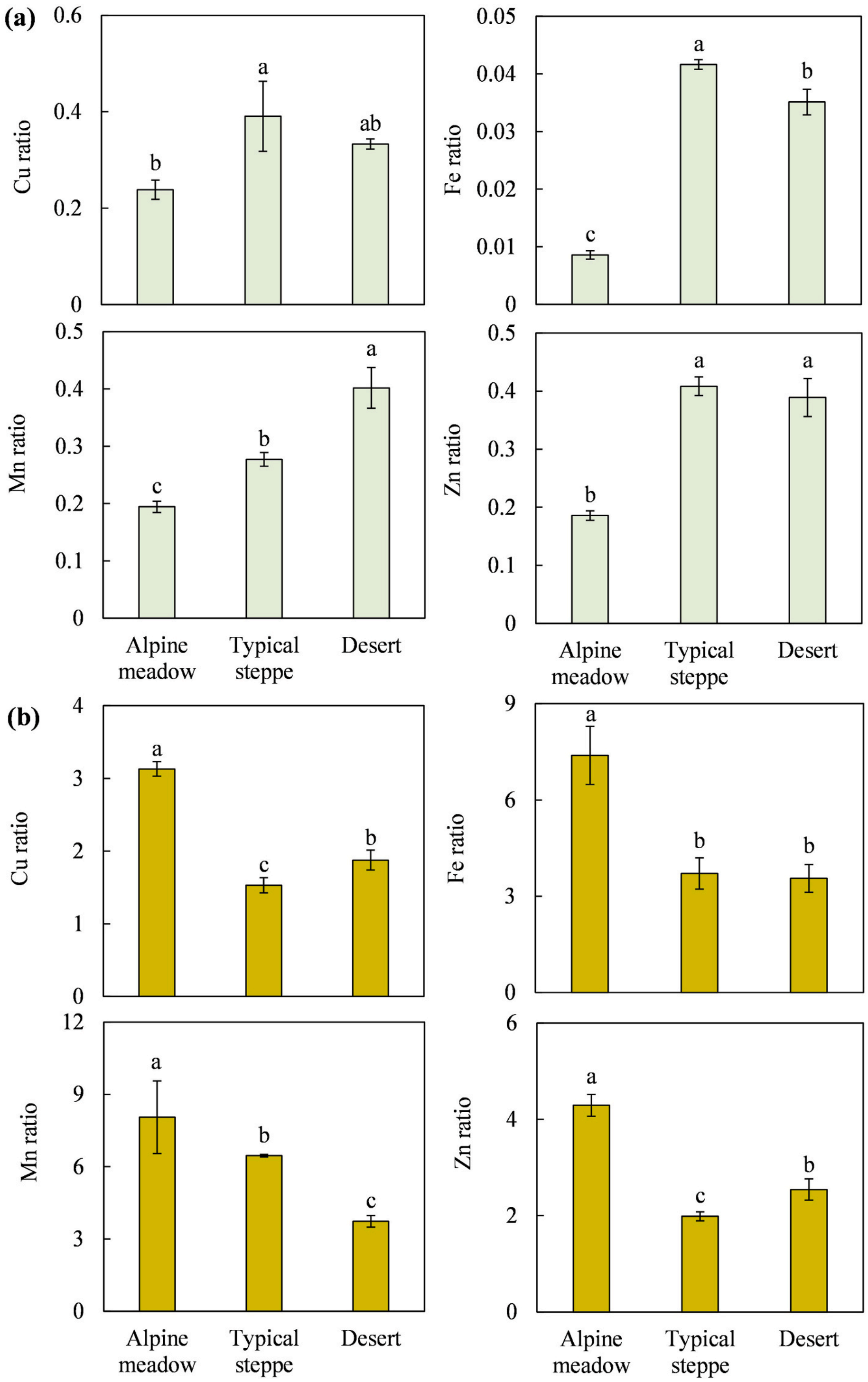

Fig. 6. The ratios of Cu, Fe, Mn, and Zn concentrations of (a) forage to soil and (b) livestock dung to forage in the three types of rangeland. Means with the same lower-case letters are not significantly different between rangeland types ($P > 0.05$).

4.3. *Evaluations of trace elements in the three types of rangeland*

Previous studies have shown significant correlations between soil and forage and between forage and sheep for some TEs (Grzegorczyk et al., 2014; Oliveira et al., 2015; Desjardins et al., 2018; Fan et al., 2019). However, in the present study, except for the correlations between Fe in forage and livestock dung and Zn in soil and livestock dung, the correlations between other TEs in soil and forage, forage and dung, and soil and dung were not significant (Table 1). These results could be attributed to variations in TE complex utilization efficiency depending on the needs of plants and livestock in various rangelands (Dong et al., 2009; Nedjimi, 2018). Our findings agree with those of Wang et al. (2014) and Khalili et al. (1993), who reported no correlations of TEs between soil, forage, and sheep serum. Although most of the correlations in TEs between both forage, soil, and livestock dung were not significant, their ratios have great ecological significance (Han et al., 2011). The TE ratios of forage to soil and livestock dung to forage can be used, respectively, as ability indicators of TE absorption of plants from soil and of TE returns of livestock in rangeland ecosystems (Galinha et al., 2010; Deng et al., 2014). These indicators can be used to assess the stability of rangelands and forecast TE changes in these rangelands.

Consistent with our first hypothesis, the abilities of plants to absorb Cu, Fe, and Zn from soil were stronger in the typical steppe than in the alpine meadows and desert (Fig. 6a). Many studies have reported the antagonistic interactions of Mn with Fe, Cu, and Zn in the plants (Kabata-Pendias and Mukherjee, 2007; Cai et al., 2017b), which explained why the ability of Mn absorption of plants in the typical steppe was not the strongest. Our results agreed with the assertion that low precipitation and high temperature in the desert restricted plants to absorb some mineral elements (Niu et al., 2008). The low air temperature in alpine meadows may limit the absorption of mineral elements by plant (Fan et al., 2019). In addition, the dilution effect of biomass in alpine meadows may be the main factor directly resulting in low TEs concentration in plants and indirectly limiting the ability of plants to absorb TEs from the soil (Nirupa and Prasad, 2008; Xu et al., 2012; Nedjimi, 2018).

Consistent with our second hypothesis, the ability of livestock to return Cu and Zn from forage to soil is weaker in the typical steppe than in the alpine meadows and desert (Fig. 6b). A higher return ability of TEs for livestock in alpine meadow may be owing to (1) low temperature in alpine meadows may restrict TE absorptions of livestock (Niu et al., 2008; Fan et al., 2019; Hou et al., 2016), and (2) lower TE concentrations of forages in the alpine meadow. The accumulations of TEs in ecosystems may impact the activities of soil organisms (microorganisms, microfauna, macrofauna), alter food web functioning, reduce the organic matter decomposition rate, and disrupt biogeochemical cycling (Kabata-Pendias, 2011; Shtangeeva et al., 2020). Results of the current study showed that all three rangeland ecosystems were not overly contaminated by TEs; instead, the concentrations of TEs in soils or plants were lower than recommended levels, suggesting that the these rangelands are at risk of TE losses. TE deficiencies may impair the growth and reproduction of livestock and even lead to their death, which results in enormous economic loss to the herders (Xin et al., 2011; Wang et al., 2014; Fan et al., 2019). Except for atmospheric deposition, grazing livestock dung is the main TE input path in natural rangeland. Therefore, the lower ability of TE returns of livestock in the typical steppe and desert indicated that typical steppes and deserts were at greater risk of TE losses than the alpine meadows, suggests raising awareness among herders to address Cu and Zn deficiencies in the typical steppes and deserts..

5. Conclusions

Spatial variations of TEs in soil, plant, and livestock associated with ecological and environmental factors can affect the cycling of TEs in ecosystems. Therefore, we investigated Cu, Fe, Mn, and Zn concentrations in forage, soil, and livestock dung in three different types of rangeland along a climatic gradient. Grazing livestock in the three types of rangeland should be provided with Zn supplements, and grazing livestock in alpine meadows should be supplemented with an appropriate amount of Cu for improving the production of grazing livestock. Climatic factors have greater relationships with TE concentrations in forage than in soil and livestock dungs, and temperature rather than precipitation and humidity may better explain the changes in TE concentrations in forage. The bioavailability of TEs to livestock nutrition, especially for Fe and Mn, mainly depends on plants rather than their concentrations in soils. Furthermore, we predict that continuous grazing may cause typical steppes and deserts to be at greater risk of TEs losses than alpine meadows.

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.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envres.2022.114222.

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