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Review

# Degradation of Tibetan grasslands: Consequences for carbon and nutrient cycles

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ABSTRACT

The Tibetan Plateau hosts the world's largest alpine pastoral ecosystems, dominated by the endemic sedges *Kobresia pygmaea* and *Kobresia humilis*. Owing to the very harsh environment and also to soil nitrogen (N) and phosphorus (P) limitations, these pastoral ecosystems are very sensitive to disturbances (e.g. anthropogenic activities and climate change) and recover extremely slowly. Overgrazing on the Tibetan Plateau has caused severe degradation of vegetation and soils in the last 30–50 years. For the first time, for *Kobresia* pastures in Tibetan Plateau, we have summarized and generalized the consequences of pasture degradation for soil organic carbon (SOC) and nutrient (N, P) stocks, and evaluated the main biotic and abiotic mechanisms of their loss. Based on 44 literature studies as well as own data, we demonstrated that 42% of SOC stocks were lost, relative to non-degraded pastures. These SOC losses are similar to the decreases in N stocks (-33%), and aboveground (-42%) and belowground (-45%) plant biomass. Although P losses are lower (-17%), its precipitation reduces its availability for plants. These losses are in fact underestimates, since undisturbed natural sites no longer exist on the Tibetan Plateau. The losses are much higher in the upper 10 cm and in some areas extend to complete removal of soil cover. This has dramatic repercussions for local livestock, human populations and river pollution. While some rehabilitation projects have shown positive outcomes, the complete recovery of degraded pastures (e.g. soil fertility, ecosystem stability) is infeasible, because of very slow pedogenic processes, slow vegetation restoration, as well as continuously increasing anthropogenic pressure and climate change. Considering the rapid losses of SOC and nutrients, and the very slow recovery potential, Tibetan pastures in some regions may disappear in the next few decades without proper and effective recovery strategies.

## 1. Introduction

The *Kobresia* pastures, commonly known as “alpine meadow”, cover the southeastern quarter of the Tibetan Highlands and form the world's largest alpine pastoral ecosystem (Babel et al., 2014). Several major Asian rivers, such as the Huang He, Salween River, Yangtze River, Mekong River etc., originate on the Tibetan Plateau and flow through *Kobresia* pastures (Fig. 1). These rivers collectively constitute the main water resource for billions of people in the adjacent regions of southeastern Asia (Pomeranz et al., 2013). The *Kobresia* pastures provide important grazing grounds for livestock (i.e. yaks, sheep and goats) and thus ensure the livelihood of the Tibetan herders (Harris, 2010). Approximately 4.0% of the world's grassland soil carbon (C) is stored in soils under Tibetan pastures (ca. 10.7 Pg C; Ni, 2002). Around 920 Tg nitrogen (N) is preserved in the Tibetan pasture soils, which represents 0.7-1.0% of total global N storage (Tian et al., 2006) and is required for sufficient forage production. Consequently, Tibetan pastures are of considerable importance to livestock productivity, Tibetan herders (ca. 5 million), nutrient cycling and ecosystem stability.

The Tibetan pastures are developed over centuries in extreme environments: low mean annual temperatures (below 0 °C, Frauenfeld et al., 2005), low annual mean precipitation (~437 mm, Xu et al., 2008), very high solar radiation (Liu et al., 2012), very short plant growing season (~3.5 months, Leonard and Crawford, 2002), strong erosion by wind and water (48 t $ha^{-1}$ $yr^{-1}$, Yan et al., 2000), very limited nutrients (e.g. N and phosphorus (P); Li et al., 2014a), very shallow soil profiles (~30–50 cm, Chang et al., 2014) and low air pressure and $CO_2$ concentration. These harsh conditions make the

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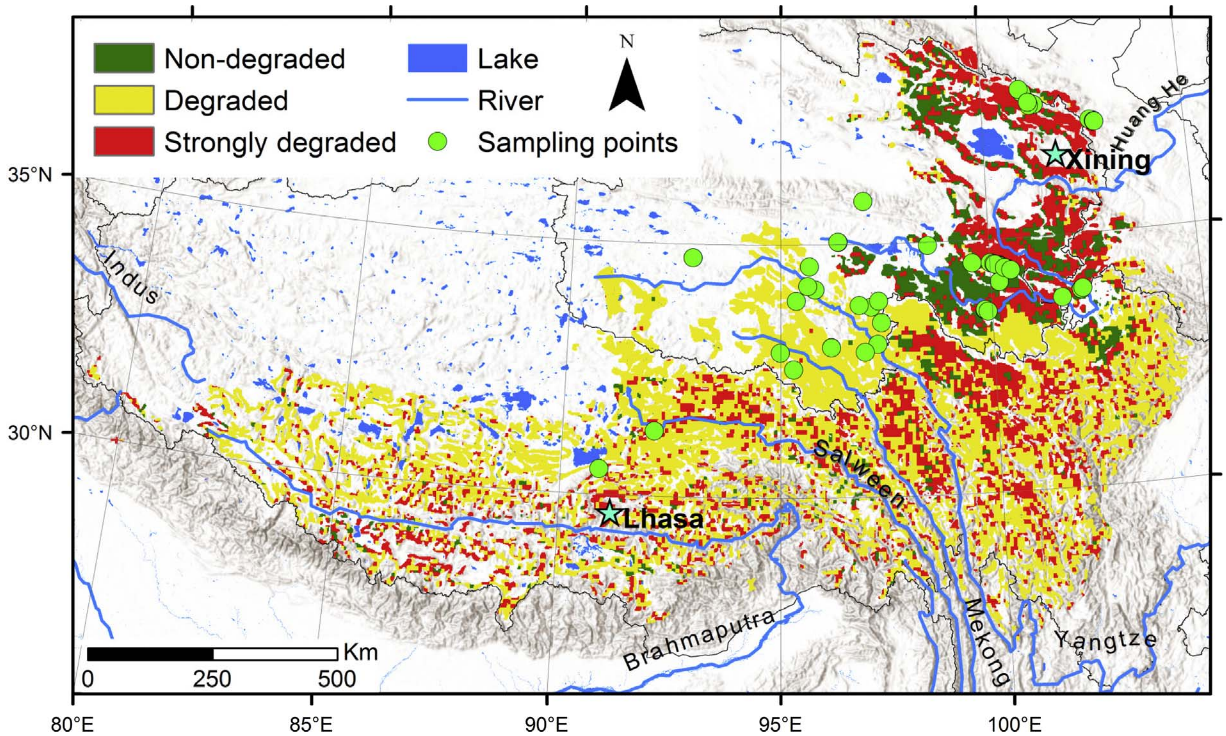


**Fig. 1.** Degradation of pastures on the Tibetan Plateau. The circular green points are the locations of the study sites included in the literature review. The extent of Tibetan pastures is taken from Lehnert et al. (2015). Tibetan pastures include *Kobresia pygmaea* pastures and *Kobresia humilis* pastures. The degradation status on Tibetan Plateau was derived from an information database from land degradation assessment at global level (Nachtergaele et al., 2011). The three degradation stages were classified by integrating the current status (low or high degradation) and future trend (degrading or improving) of four aggregated biophysical ecosystem factors (plant biomass, soil, water and plant biodiversity). This map was created in ArcGIS 10.3 based on the extent and degradation information for Tibetan pastures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

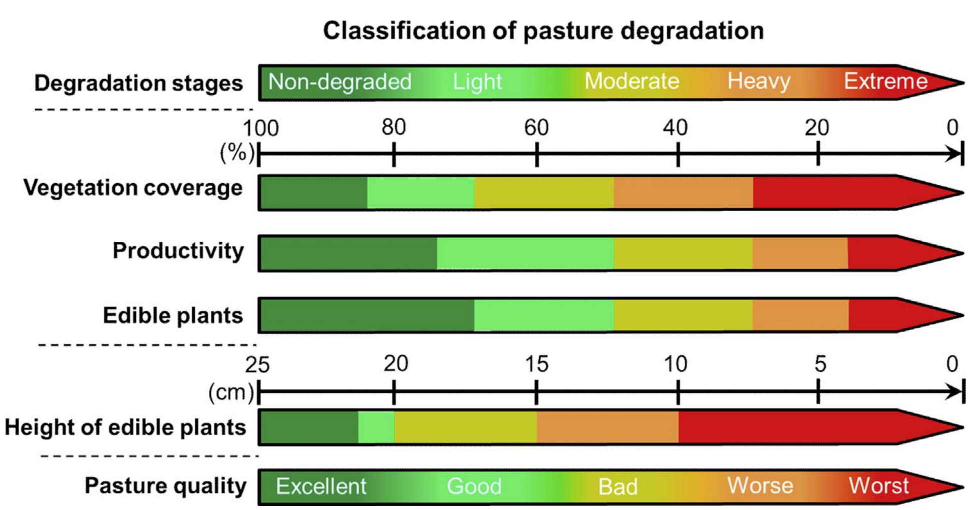


**Fig. 2.** Classification of Tibetan pasture degradation. The degradation stages were determined based on vegetation coverage, plant productivity, portion of edible plants and height of edible plants.

region very sensitive to changes in environmental and socio-economic disturbances (Wang et al., 2008b). For instance, warming across the whole plateau is greater and faster than the global mean (Kuang and Jiao, 2016). In response to this, glaciers retreat dramatically and permafrost thaws rapidly. The water table subsequently drops, erosion is exacerbated, and soil fertility declines (Chen et al., 2013). This directly contributes to the removal of the shallow soil profile, soil organic carbon (SOC) and nutrient losses, i.e. the degradation of vulnerable Tibetan pastures.

The Tibetan pastures have suffered from serious degradation for several decades, due to frequent and very strong anthropogenic pressure (e.g. overgrazing) and large-scale environmental changes (e.g. climate change). This has had a variety of ecological consequences, including decreased plant species richness (Wang et al., 2009), accelerated soil erosion (Wu and Tiessen, 2002) and shrinking grazing ground (Wu and Du, 2007). To characterize the degradation problems and compare the situation in various pastures, the term "pasture degradation" needs to be defined. Considering differences in which pasture conditions are emphasized (e.g. pastoral productivity, vegetation composition, biological diversity, soil fertility, C and nutrient stocks), making a general and globally accepted definition is challenging (White et al., 2000). Instead, various indicators, for instance soil properties (Kimetu et al., 2008; Alados et al., 2007), plant species composition (Van der Westhuizen et al., 2005; Jordaan et al., 1997), species abundance of wildlife, and death rate of domestic livestock (Behnke and Scoones, 1993; White et al., 2000), have been recommended to assess pasture degradation. Among them, vegetation characteristics (i.e. vegetation coverage, productivity and proportion of edible plants) are most frequently proposed (Zeng et al., 2013), as vegetation status not only relates to animal productivity but also reflects soil fertility. For instance, Ma et al. (2002) divided the degradation of Tibetan pastures into five stages: non-degradation, light degradation, moderate degradation, heavy degradation and extreme degradation (Table S1, Fig. 2). This is the most frequently used degradation classification for pastures of the Tibetan Plateau. Similar classification systems have also been applied in other studies, but with variable percentage ranges (Zeng et al., 2013). In this review, we use the classification of degradation stages proposed by Ma et al. (2002). We define “pasture degradation” as the retrogressive succession of a pasture ecosystem affected by interference of rational and irrational anthropogenic (e.g. overgrazing, deforestation, and infrastructure construction) and/or environmental factors (e.g. permafrost melting and climate change) leading to decreases in plant biomass, SOC and nutrient (N, P) stocks etc.

When applying this classification to pasture degradation, the primary concern is the assessment of SOC and nutrient status, due to their fundamental roles in biogeochemical cycles, plant productivity and ecosystem stability. By far, several studies have been implemented at the local scale and reached varied conclusions. Meanwhile, mechanisms for SOC and nutrient losses and the consequences have also been investigated (Babel et al., 2014; Liu et al., 2016; Li et al., 2015) and strategies to restore soil fertility have been proposed and examined (Dong et al., 2012; Feng et al., 2010). However, regional-scale generalization with a better understanding of SOC and nutrient status in Tibetan pastures and the current degradation situation remains unknown.

To clarify these points and provide generalizations, the literature that has classified the pastures’ degradation using vegetation characteristics was assembled and the data concerning SOC, N and P content or stocks were extracted. We focused this review on degradation-related losses of two nutrients (N and P) because these are the most limiting nutrients worldwide (Vitousek et al., 2010) and especially on Tibetan Plateau (Li et al., 2014a; Tian et al., 2012; Yang et al., 2014; Zong et al., 2013).

Our objectives were to: 1) quantify SOC and nutrient losses under five degradation stages of Tibetan pasture ecosystems; 2) relate vegetation characteristics and a broad range of soil properties to SOC and nutrient losses; 3) comprehensively understand how socio-economic and environmental factors contribute to pasture degradation and 4) identify the negative feedbacks of degradation to ecosystem services and functions.

## 2. Materials and methods

### 2.1. Data collection

Literature about the effects of pasture degradation on SOC and nutrient content was assembled mainly through four channels: 1) Web of Science V.5.22.1 (available online), 2) ScienceDirect (Elsevier B.V.), 3) Google Scholar and 4) Chinese-language literature using the China Knowledge Resource Integrated Database (CNKI). The search terms were “degradation gradient/stages”, “alpine meadow”, “Tibetan Plateau” and “soil”.

The criteria for inclusion in this review were: (1) the classification of degradation stages is clearly stated; (2) the literature includes analysis of SOC (or soil organic matter), total nitrogen (TN), total phosphorus (TP), vegetation characteristics or other soil physical and chemical properties; (3) the non-degradation stage (stage 1 according to Table S1) is necessarily included as the “reference”, to enable the “effect size” analysis. At least one of the degradation stages (light degradation, moderate degradation, heavy degradation and extreme degradation) is also presented in relation to the “reference”; and (4) the sampling depth and study location are clearly presented. Totally, 44 literature studies were found (Table S2, Fig. 1).

### 2.2. Data analysis

Data examination and standardization was performed to standardize the units of each parameter. Data illustrated in original publications as graphs were extracted using g3data (v.1.5.1) software (http://www.frantz.fi/software/g3data.php). When soil organic matter content was presented, this was converted to soil organic carbon content using a conversion factor of 2.0 (Pribyl, 2010). Soil organic C and nutrient stocks were calculated using the following equation:

$$\text{Stock} = 100 \times \text{Cont} \times \text{BD} \times \text{Depth} \quad (1)$$

Where Stock is C or nutrient (N, P) stock [kg ha$^{-1}$]; Cont is soil C or nutrient (N, P) content, [g kg$^{-1}$]; BD is soil bulk density, [g cm$^{-3}$]; and Depth is the soil sampling depth, [cm]. To continue this conversion, only studies were considered which took samples in 10 cm intervals because of the relatively large database size compared to other depth intervals. In some studies, bulk density was not presented. To calculate stocks for these studies, significant relationships between SOC or nutrient content and their stocks were established using existing data (Fig. S1). Based on these relationships, SOC or nutrient stocks were calculated.

Linear regressions between vegetation coverage and SOC or nutrients (N, P) for the five degradation stages were performed. When studies presented ranges for vegetation coverage, we took the median value. The effect sizes of individual variables (i.e. SOC, nutrients, bulk density and plant biomass) were quantified to illustrate differences between the non-degraded and the degraded stages. The following equation was used:

$$ES = (D - R)/R \times 100\% \quad (2)$$

Where *ES* is the effect size, in%; *D* is the value of the corresponding variable in the relevant degradation stage (light degradation, moderate degradation, heavy degradation and extreme degradation); and *R* is the value of each variable in the non-degradation stage (reference site). When *ES* is positive, zero or negative, this indicates an increase, no change or a decrease, respectively, of the parameter compared to the non-degradation stage. 95% confidence intervals were also calculated and illustrated in the figures. Because pH is the negative of the base 10 logarithm of the $H^+$ concentration, the effect size of degradation on soil pH cannot be quantified by Eq. (2). Therefore, we used the difference: $D - R$, which was expressed as ΔpH. For instance, when $D = 8$ and $R = 7$, $\Delta pH = 1$, meaning that pH increases by one pH unit with degradation to the relevant extent, i.e. $-\log 10^{-8} - (-\log 10^{-7}) = -\log 10^{-1}$ or 1. Significant differences of effect size among the degradation stages were tested using one-way analysis of variance (ANOVA). Before ANOVA was applied, data were checked for normality (Shapiro–Wilk test, $p > 0.05$) and homogeneity of variance (Levene test, $p > 0.05$). When data did not meet the normality test (e.g. effect size of SOC), the data were transformed by logarithm or square root. After a significant omnibus test result was obtained, a post hoc test (Tukey’s honestly significant difference test) was conducted for multiple comparisons.

Sensitivity of 1) soil fertility (e.g. TN, TP) and 2) vegetation (e.g. aboveground plant biomass (AGB), belowground plant biomass (BGB)) indicators to SOC losses were evaluated for each degradation stage. All parameters were standardized to the non-degraded stage as reference (every indicator of the non-degraded stage equals to 1.0). Consequently, all the values range from 1.0 to 0. The standardized SOC contents were then plotted against the standardized soil fertility and vegetation indicators.

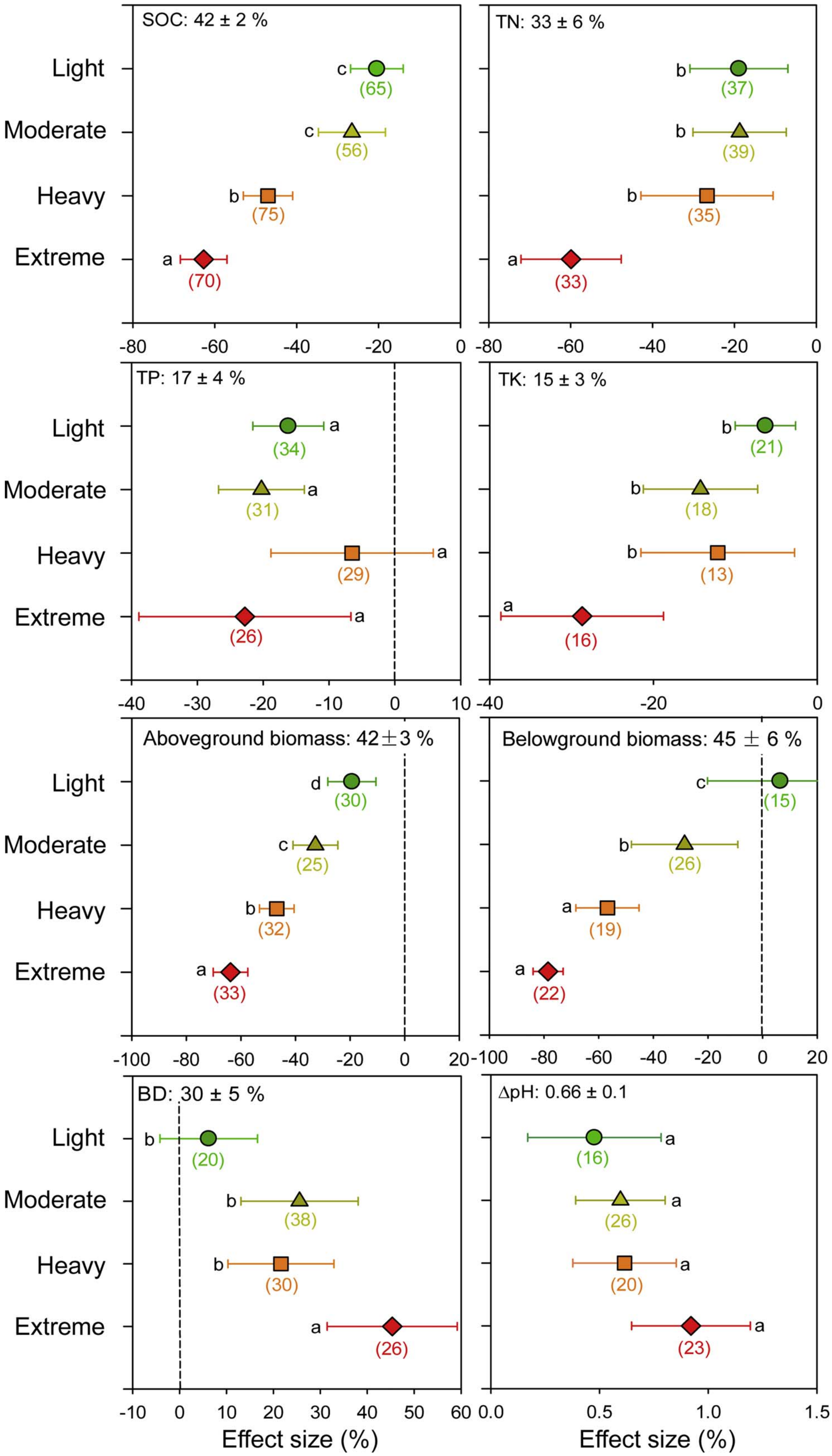


**Fig. 3.** Effect sizes of SOC content, nutrient content, plant biomass, soil bulk density (BD) and soil pH for four degradation stages compared to non-degraded pastures. The effect size is calculated by Equation 2 and presented as percent (except for pH, which is expressed as $\Delta pH = pH_{Degraded} - pH_{Non\text{-}Degraded}$). Colors represent degradation stages. The percentage value at the top shows the average effect size of four degradation stages. The number in the parenthesis is the number of sampling points. Low-case letters show the significant differences between the degradation stages. (Detailed information is presented in Fig. S5).

## 3. Results and discussion

### 3.1. Degradation-induced losses of soil carbon, nitrogen and phosphorus

Degraded Tibetan grasslands have lost on average 42 ± 2% of their SOC content relative to the non-degraded pastures (Fig. 3). Soil total N contents had declined by 33 ± 6% (Fig. 3) and total P and potassium (K) content were reduced by 17 ± 4% and 15 ± 3%, respectively (Fig. 3). Furthermore, SOC, N and K losses significantly increase from light to extreme degradation, while the difference of P loss is insignificant among degradation stages. Because the non-degraded stage is defined by wide ranges for several indicators (Table S1; Fig. 2), the reference sites may also have experienced some degradation compared to completely intact sites (i.e. 100% vegetation coverage, highest percentage of edible plants and so on). Therefore, the SOC and nutrient losses reviewed here are actually underestimations and should be considered as minimum values. This suggests that more urgent intervention is required on Tibetan pastures.

SOC and nutrients are inherently related to vegetation characteristics (AGB, BGB) and other soil physical and chemical properties (e.g. pH, BD, clay content etc.) (Li et al., 2014b, 2016; Wang et al., 2009). Therefore, these parameters directly contribute to variations in SOC and nutrient composition. In the following, we present the responses of vegetation characteristics and other soil physical and chemical properties to pasture degradation and discuss how they can be related to SOC and nutrient losses.

(1) Degradation effects on vegetation.

Plants assimilate $CO_2$ and allocate part of this C belowground. The amount of C incorporated into the SOC pool from this newly assimilated C largely depends on plant biomass and vegetation coverage (Phillips et al., 2011). Pasture degradation leads to strong decreases in plant coverage, aboveground biomass (AGB, ~42 ± 3%) and belowground biomass (BGB, ~45 ± 6%) (Fig. 3) and consequently decreases C input into soil, with negative feedbacks on SOC storage. Further, plants take up nutrients, recycle them within the ecosystem, and thus protect them from being leached. Following degradation, however, there is less nutrient preservation in vegetation and they are more prone to leaching (Liu et al., 2017). Furthermore, pasture degradation in Tibetan Plateau decreases plant species richness and diversity and changes functional groups from graminoids and legumes in favour of forbs (Wang et al., 2009, 2014; Li et al., 2014b). In sum, a decrease in vegetation cover and changes in species composition reduce C assimilation and nutrient uptake (i.e. less complementarity and facilitation) and so have negative effects on the total productivity of plant communities (Vicca et al., 2007), and ultimately on SOC storage and nutrient retention.

High vegetation coverage significantly increases SOC and nutrient stocks (Fig. 4) by: i) facilitating photosynthesis (McAllister et al., 1998), which induces more belowground C input, including roots and the organic compounds released through roots; ii) protecting SOC and nutrients from being lost directly (decreasing water and wind erosion rates) and indirectly (storing nutrients in the living biomass) (Mchunu and Chaplot, 2012; Chaplot et al., 2005; Wu and Tiessen, 2002); and iii) preventing soil heating by absorbing strong solar radiation, which subsequently decreases soil temperature and slows down SOC decomposition and $CO_2$ release (Schrott, 1991; Liu et al., 2012).

Though pasture degradation leads to lower C input from plants, it does not necessarily mean microbial decomposition of SOC will be limited and C losses via respiration will decrease after degradation. Two mechanisms support this statement: First, additional C supply from root litter (i.e. dying and dead roots) is available for microbes following Tibetan pasture degradation (Liu et al., 2016). Second, the decrease of root biomass eliminates the competition between plants and microbes for limited nutrients (especially nitrogen, Kuzyakov, 2002; Xu et al., 2006). In fact, a significant increase in soil $CO_2$ emission from degraded Tibetan pastures has been confirmed (Li et al., 2015; Wang et al., 2010), indicating stimulated microbial activities that lead to more C loss via SOC and root litter decomposition. This demonstrates that degraded grassland ecosystems release more $CO_2$ and lose more C than will be sequestered from plant input into the soil (i.e. net $CO_2$ loss).

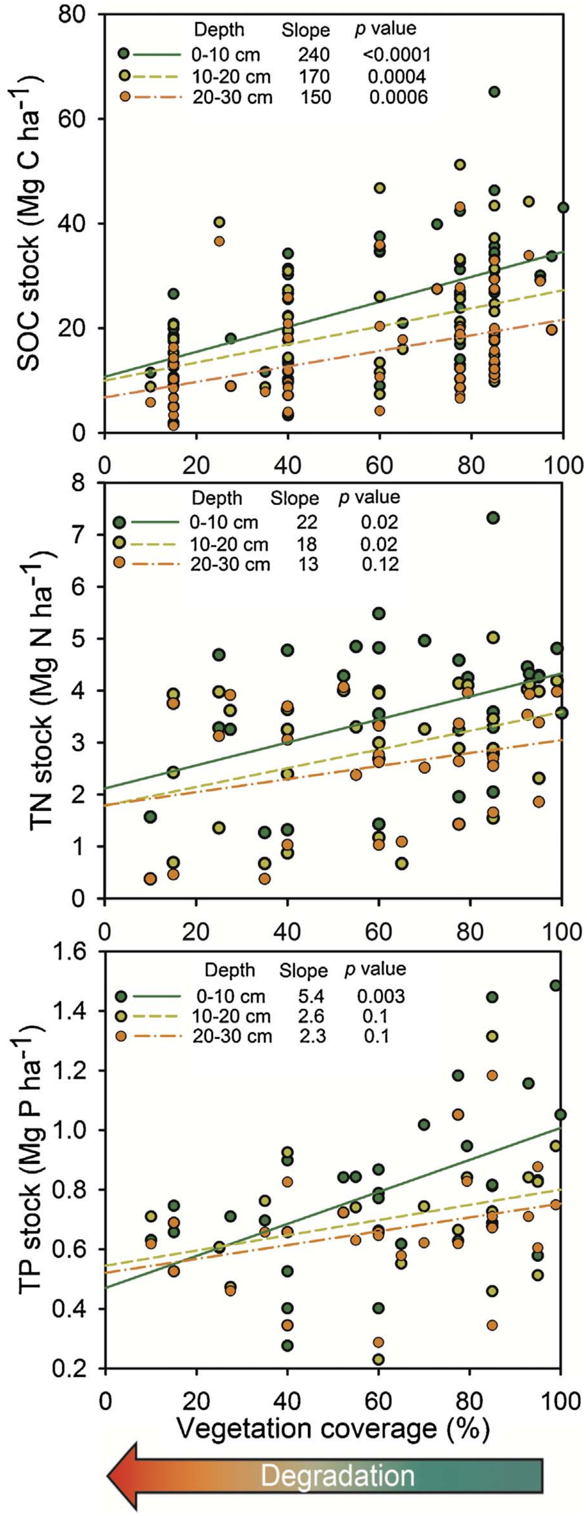


**Fig. 4.** Relationships between vegetation coverage (in% of area) and stocks of soil organic carbon: SOC (top), total nitrogen: TN (middle) and total phosphorus: TP (bottom) for three depth intervals (0–10, 10–20 and 20–30 cm). 'Slope' shows the slopes of the regression lines. p values represent the significance of the regressions. The Y axis for C, N, and P are presented at ratios: 50:5:1. All regressions show clear decreases of the closeness (slope) and significance (p) of the degradation (here as vegetation coverage) with depth, confirming that degradation starts from the vegetation and topsoil.

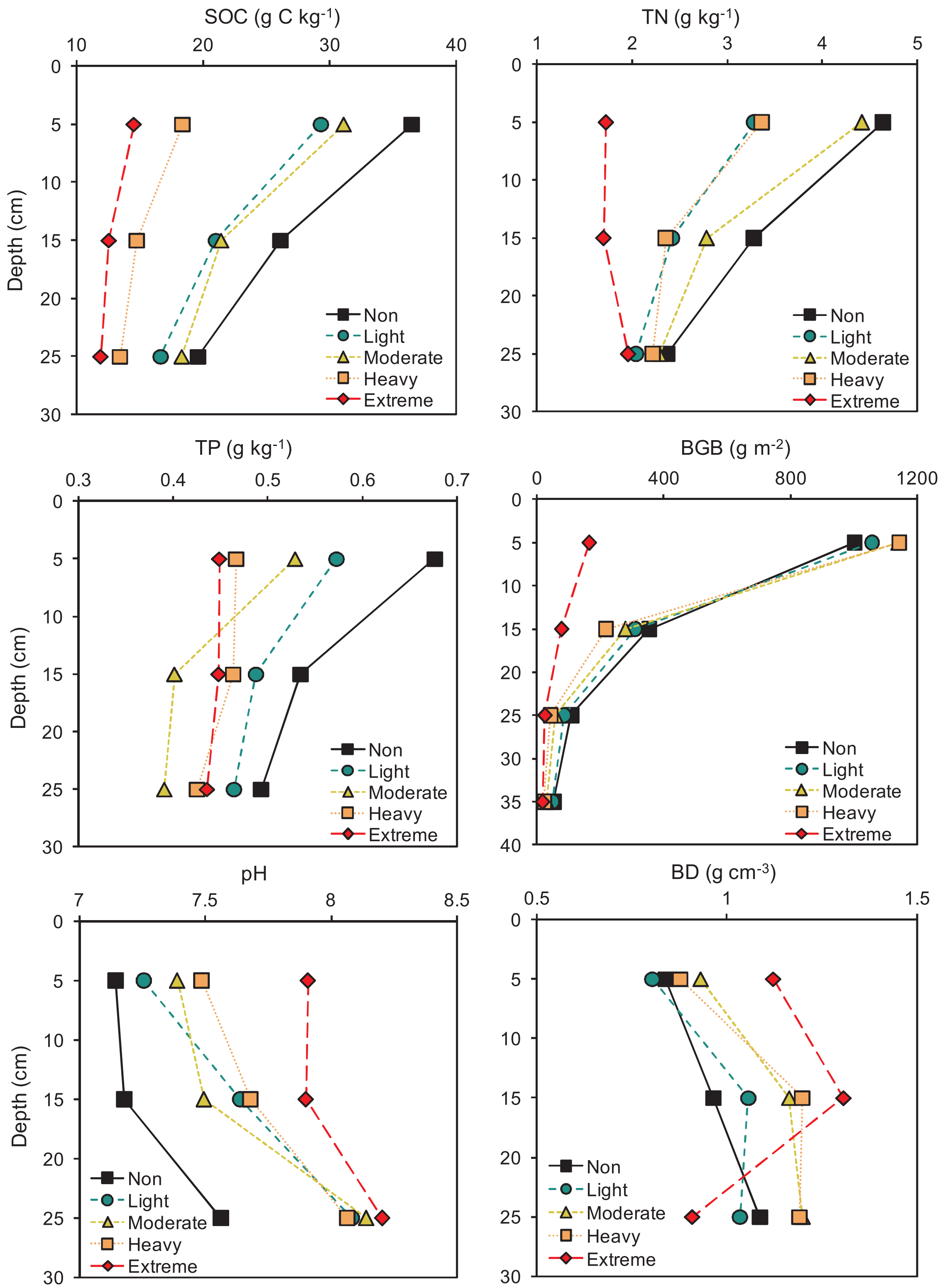


**Fig. 5.** Soil organic carbon (SOC) and nutrient contents, belowground biomass (BGB) and other soil physical and chemical properties depending on depths. “Non”, “Light”, “Moderate”, “Heavy” and “Extreme” represent non-degraded, light degradation, moderate degradation, heavy degradation and extreme degradation stages, respectively. For a better overview, the standard errors (SE) are deleted here (Detailed information is presented in Fig. S6).

Decreased plant biomass and vegetation coverage are also accompanied by intensified soil erosion, leading to removal of nutrient-enriched topsoil containing highest organic compound contents and exposure of the underlying soil layer (FAO, 1990; Tan, 2000). In consequence, in the absence of organic compounds, soil aggregation decreases (Cao et al., 2016), bulk density increases and pH may also increase due to higher $CaCO_3$ content in the subsoil. These changes in soil physical and chemical properties may further affect microbial activity and contribute to the modification of SOC and nutrient status and cycles.

(2) Degradation effects on soil chemical properties.

Soil pH increased by 0.66 units on average over the full range of degradation ($\Delta pH = 0.66 \pm 0.1$; Fig. 3). The common sources of acidity in soil are either $H^+$ released via roots to take up basic cations or dissociated $H^+$ from functional groups of organic matter. Intensified degradation will decrease both acidity sources, and so soil pH will be mostly controlled by $CaCO_3$ from parent materials (including continuous loess deposition) and/or hydrolysis of basic cations. This causes increased soil pH following intensified degradation. Soil erosion can also elevate the pH by exposing the subsoil, which generally has higher pH than the removed surface soil (Wu and Tiessen, 2002). Increased soil pH facilitates microbial activity, which stimulates SOM mineralization and may thus further increase nutrient release into the soil solution (Pietri and Brookes, 2008; McLaren and Cameron, 1996).

Soil with high cation exchange capacity (CEC), like *Kobresia* root mats, can protect the nutrients from being leached. However, Tibetan pasture degradation substantially decreased CEC (effect size: −19 to −40%, Wang et al., 2007; Wu and Tiessen, 2002), because of the decrease in clay and SOM content and increase in soil pH, reducing both the soil permanent and pH-dependent charges (Zeng et al., 2013; McLaren and Cameron, 1996). Consequently, the released nutrients will be more easily leached following pasture degradation.

Soil inorganic carbon (SIC) content showed inconsistent responses to pasture degradation, with its effect size ranging from −60 to +80% (Wen et al., 2013; Liu et al., 2015; Li et al., 2014b). SIC density (on average 11.9 kg C $m^{-2}$ down to 1 m depth) in Tibetan pastures has very high spatial heterogeneity across the whole plateau (Yang et al., 2010b). This largely depends on underlying parent materials: In sites with non-calcareous parent materials, SIC content decreases with depth and degradation stage (Liu et al., 2015). The higher SIC in the topsoil derives from $CaCO_3$-containing dusts. In soils developed from calcareous parent materials (e.g. loess, limestone, marl), SIC content increases with depth and degradation stage (Wen et al., 2013; Li et al., 2014b). Because of these two contrasting scenarios − parent materials with or without $CaCO_3$ − soil pH responds to pasture degradation in different directions, and therefore the overall effect of pasture degradation on pH has the strongest variability (Fig. 3).

(3) Degradation effects on soil physical properties.

Clay content decreases (effect size: −29 to −91%; Zeng et al., 2013; Lu et al., 2014; Li et al., 2015, 2016) and BD increases by 30 ± 5% (Fig. 3) with pasture degradation. This is the result of soil erosion that preferentially removes the fine particles (Lal, 2003) and simultaneously exposes the deeper, often clay-depleted subsoil. Decreased clay content results in less formation of organic-clay complexes and less protection of incorporated SOC against microbial and enzymatic attacks. This additionally facilitates SOC decomposition and $CO_2$ emission rates in degraded pastures. $CO_2$ emission has already been shown to be higher in degraded pasture than in non-degraded pasture (Li et al., 2015; Liu et al., 2016). However, this stimulation of SOC mineralization may disappear and $CO_2$ release decline, when the labile OC stock is not sufficient to support microbial activity (Vinton and Burke, 1995; Kuzyakov et al., 2009). This may occur at extreme degradation stages, where plant coverage is generally around 15% and belowground C stocks are even less than ~13 Mg C $ha^{-1}$ for 0–10 cm as shown in Fig. 4 (top).

### 3.2. Depth profiles of SOC and nutrient contents

SOC and nutrient contents decrease with depth for all degradation stages (Fig. 5 & S6). In Tibetan pastures, 60 – 80% of roots are concentrated at 0–10 cm (Fig. 5, Wang et al., 2009; Li et al., 2011). Therefore, C and nutrient inputs through root litter decomposition and rhizodeposition are the highest in the topsoil. Furthermore, other sources of C and nutrients (e.g. animal excretion, atmospheric deposition) are also readily incorporated into the topsoil.

The differences in SOC and nutrient contents between degradation stages is most marked in the top 10 cm of soil, and gradually decreases for 10–20 and 20–30 cm depths. This suggests that 1) the degradation starts from the topsoil, and 2) SOC and nutrients in the topsoil are the most sensitive to losses. The main mechanism is the intensive disturbance (e.g. animal trampling, human activities and soil erosion) at the topsoil where contains the highest amount of SOC and nutrients. This sensitivity is also revealed by the significant relationships between vegetation coverage and SOC or nutrient stocks (Fig. 4): All regression lines show the highest slope for the 0–10 cm depth, meaning that with one unit decrease in vegetation coverage, SOC and nutrient contents in the top 10 cm show the highest decrease. Consequently the degradation, which initiates from and is more intensive in the topsoil, has especially strong relevance for nutrient losses.

### 3.3. Sensitivity of soil nutrients and plant biomass losses to the decreasing SOC due to pasture degradation

According to the trend lines (Fig. S2), high consistency of TN and some resistance of TP to SOC losses are evident. The trend line between the decreasing SOC and decreasing TN fits well with a 1:1 line, indicating that TN losses are accompanied by SOC decrease. Even though the loss rate of TN is similar to that of SOC, the pathways of losses are different. Pathways of SOC losses include 1) SOC mineralization to $CO_2$; 2) leaching of DOM and 3) wind and water erosion of particulate organics. In contrast, soil N is lost by 1) gas emissions (e.g. $N_2O$, ~0.1 Tg N $yr^{-1}$ for Tibetan pastures; Du et al., 2008) through nitrification and denitrification; 2) leaching of N, mainly in inorganic form (i.e. $NO_3^-$, Liu et al., 2016); 3) surface soil erosion; and 4) removal of N by grazing animals.

In contrast, P losses are generally less than SOC and N losses, as indicated by the trend line for decreasing TP and SOC, which is above the 1:1 line (Fig. S2). Available P in soils of Tibetan pastures accounts for only 0.3–2.2% of the TP (Shang et al., 2016; Li et al., 2016), indicating that most P is insoluble, and would thus be lost mainly by erosion. Even though SOM decomposition releases soluble P, in soils with pH more than 7.0 (Fig. 5 & S6) this P i.e. leached from surface SOM-rich horizons will finally be precipitated as insoluble or less soluble P containing minerals such as calcium phosphate (McLaren and Cameron, 1996). This precipitation reduces P losses by leaching, but causes less P availability for plant growth.

The trend between decreasing plant biomass (AGB and BGB) and decreasing SOC content almost overlaps with the 1:1 line (Fig. S2), suggesting that most of the SOC stocks are closely related to degradation of vegetation cover. As plant biomass decreases due to pasture degradation, the labile C input and subsequently total SOC stocks decrease. This means that the SOC stock is quite fragile and very sensitive to pasture degradation, and emphasizes the importance of pasture preservation.

## 4. Synthesis

### 4.1. Potential factors inducing pasture degradation

Multiple potential factors are responsible for degradation of Tibetan grasslands and consequently for the SOC and nutrient losses. These can be classified into two groups: (1) environmental factors and (2) socio-economic factors (Wang et al., 2015b; Harris, 2010).

(1) Environmental factors: Very harsh conditions of climate, soils, relief etc. (Table 1) have existed on the Tibetan Plateau for millennia. The natural Tibetan pastures were adapted to this harsh environment and a dynamic equilibrium existed between vegetation, grazing livestock and burrowing animals as well as local nomads. However, this equilibrium has been disturbed because of fast climate change, which induced widespread permafrost degradation and glacial retreat. Permafrost degradation, for instance, increases the thickness of the active layer and lowers the groundwater table. Deeper groundwater decreases water availability for plants during dry seasons, and hence reduces total plant biomass and coverage and also SOC content (Fig. S3; Yang et al.,

**Table 1**
Potential factors, drivers and consequences of pastures degradation on Tibetan Plateau[a].

| Factors inducing degradation | | | Consequences | References[b] |
|---|---|---|---|---|
| ○ Environmental | | ● Glacial retreat; snow melting | - Irregular water fluxes → Accelerated vegetation drying; | Wang et al., 2015b |
| | | ● Permafrost degradation (Fig. S3) | - Deeper groundwater table; Less plant water availability; Soil shrinking | Yang et al., 2010a |
| | | ● Drying of wetlands | | Cheng and Wu, 2007 |
| | | ● Shrinking of lakes | | Wang et al., 2012 |
| | | ● Destruction of root mats by rodents | - Plant dying; Root-mat destruction; Increased erosion | Qin et al., 2015 |
| ○ Socio-economic | ○ Socio | ● Overgrazing (Fig. S4) | - Soil compaction; Plant dying; Removal of nutrients | Wu et al., 2009 |
| | | ● Population growth | - High resource demand from pastures; Pasture deterioration | Harris, 2010 |
| | | ● Sedentarization of nomads | - Habitat fragmentation; Very strong local overgrazing | Lu et al., 2009 |
| | | ● Privatization of pastures | - Intensive pasture use; Strong local overgrazing | Yan et al., 2005 |
| | | ● Removal and burning of yak dung | - Nutrient losses; Increased GHG ($CH_4$, $N_2O$) emissions | Wang, 2009 |
| | | ● Deforestation | - Stronger soil erosion; Nutrient leaching; GHG emissions | Cui and Graf, 2009 |
| | | ● Land use change | | |
| | ○ Economic | ● Mining | - Water contamination by heavy metals; Reduced vegetation coverage; Complete soil destruction | Huang et al., 2009 |
| | | ● Road construction (Fig. S4) | - Habitat fragmentation; Root-mat destruction | Zheng and Cao, 2015 |
| | | ● Dam construction | - High evaporation from the reservoir → Changing microclimate | Zheng and Cao, 2015 |
| | | ● Booming tourist industry (Fig. S4) | - Trampling; Contamination; Increase of all kinds of anthropogenic pressure | Foggin, 2012 |

| Drivers accelerating degradation | | Consequences | References[b] |
|---|---|---|---|
| ○ Soil | ● Shallow soil depth (~30–50 cm) | - High soil erosion; Slow recovery; Low nutrient stocks | Harris, 2010 |
| | ● Nutrient (N, P) limitation (Fig. 6) | - Limited plant growth; Slow recovery | Zong et al., 2014 |
| | ● Nutrient-poor parent materials | - Low compensation of nutrient losses by weathering | |
| | ● Slow weathering (because of climate) | - Slow recovery; Slow compensation of lost nutrients | |
| ○ Climate | ● Very strong solar radiation (21 MJ $m^{-2}$ $day^{-1}$) | - Higher bare soil temperature; Plant damage; Decreased plant productivity and species richness | Liu et al., 2012 |
| | ● Low mean annual temperature (< 0 °C) | - Slow plant growth; Slow SOM decomposition and nutrient release | Xu et al., 2008 |
| | ● High variation of spatial and temporal precipitation | - Uneven plant water availability | Chen et al., 2013 |
| | ● Low mean annual precipitation (~440 mm) | - Low plant water availability; Slow litter and SOM decomposition | |
| | ● Low $CO_2$ pressure | - Low photosynthetic rate | Fan et al., 2011 |
| ○ Vegetation | ● Very short vegetation period (< 3.5 months) | - Very low primary production; Poor recovery potential | FAO, 2005 |
| | ● Poor plant germination | - Slow and poor recovery potential | |
| ○ Topography | ● Steep slopes | - Strong erosion; Water redistribution | |
| | ● Slope exposition | - Contrasting solar radiation on different slopes → Diverse plant community composition | |

[a] Please note that any disturbance in natural plant coverage of Tibetan Plateau by means of any factor matters here. In some cases the consequences of degradation are also the drivers. These potential factors and drivers may induce pasture degradation at least in some specific regions for example close to the road.
[b] Only some of the references are mentioned to the respective topic; they do not cover all the literature sources.

2010a; Wang et al., 2012, 2006). Rodent densities have strongly increased in the past due to overgrazing and climate change (Bai et al., 2002; Li et al., 2013; Liu et al., 1999). Burrowing activity by pika (*Ochotona curzoniae*; a small diurnal and non-hibernating mammal) and plateau zokors (*Myospalax baileyi*, a small blind subterranean rodent) causes an additional ~8-23% loss of SOC stock in the topsoil by improving soil aeration, decreasing plant C input and transferring underlying nutrient-poor soil to the surface (Qin et al., 2015; Li et al., 2009). These and other environmental factors (Table 1) make the Tibetan pastures very fragile and very slow-recovering ecosystems.

(2) Socio-economic factors: For thousands of years, domestic yaks, sheep and goats on the eastern Tibetan Highlands have grazed on the pastures (Miehe et al., 2014; Guo et al., 2006), and the ecosystem has remained stable. This has changed markedly since the 1960s because of a rapid increase in population and food and energy demand (Chen et al., 2013). Increasing population led to land-use change from pastures to cropland, as well as higher livestock density (particularly of yak) causing severe overgrazing. Large pressures on Tibetan pastures also arise from two widely-implemented policies based on two assumptions: 1) Sedentarization of Tibetan nomads with the hope that this would benefit the herdsmen and their families (Lu et al., 2009); 2) Privatization of pastures, assuming that open access to common pastures for privately owned livestock was the underlying cause of degradation (Yan et al., 2005). Both raising of yaks and removal of yak dung for heating and cooking also cause large SOC and nutrient losses and regional redistribution. For instance, of the ca. 40 million tons of dung produced by livestock in 2006, about 60% was removed. Carbon, N and P contents in yak dung comprise about 40, 2 and 0.4% of dung dry weight, respectively (Cai et al., 2013). This implies that a total of 16 million tons C, 0.8 million tons N and 0.2 million tons P are removed annually from the pasture ecosystems. This equates to 0.1, 0.1 and 0.3% per year of the total C, N and P (ca. 77 Tg P) stocks, respectively, in Tibetan pastures (Ni, 2002; Tian et al., 2006; Lu et al., 2015a).

In addition to the direct effects of higher population and grazing intensity, economic growth led to a rapid increase in infrastructure construction (Table 1, Fig. S4; Gao et al., 2015; Wang et al., 2015a), which further intensified soil and land disturbance (Cui and Graf, 2009; Harris, 2010; Wang et al., 2015b). From 2000 to 2014, the length of highways increased 3.6 times (Fig. S4). Such construction directly fragmented the pastures and destroyed the soil cover. The terrestrial ecosystems adjacent to this construction were also severely affected by excavation, road dust, blockage of natural water fluxes and heavy metal and gasoline contamination.

Overall, the interferences of all these environmental and socio-economic factors in recent decades, and their interactions, have intensified Tibetan pasture degradation and accelerated SOC and nutrient losses (Qiao and Duan, 2016). In contrast to environmental factors, socio-economic factors have stronger, continuously increasing and more rapid negative impacts on Tibetan pastures. This is because 1) socio-economic activities are more intensive at local scales, compared to regional environmental effects; and 2) socio-economic activities, such as fossil-fuel burning, fertilization and pollutant release, subsequently accelerate environmental changes.

### 4.2. Socio-economic and environmental consequences of pasture degradation

Besides SOC and nutrient losses, pasture degradation has substantial negative impacts on the ecosystem services and functions of Tibetan pastures (Table 1). Pasture degradation directly exacerbates N and P limitation (Vitousek et al., 2010) by inducing greater losses of both these nutrients. This impacts plant establishment and survival, and forage production rapidly declines. The reduction of forage production directly impedes development of animal husbandry, which decreases the economic income of the local population (Wen et al., 2013).

Degradation-induced leaching of nutrients also pollutes surface and groundwater (Zhang et al., 2013). Increasing frequency of strong wind and dust storms was also evident after pasture degradation in northeastern Tibetan Plateau (Wang et al., 2008a). Each year, $90 \times 10^9$ kg of soil and sand are carried into the rivers by erosion (Dong et al., 2013). About 20% of all settlements in the central-west part of Nagqu Prefecture are at risk of being covered with transported sand (Squires and Zhang, 2009).

### 4.3. Strategies for pasture recovery and restoration

The high SOC and nutrient (N, P) losses and their far-reaching consequences require urgent intervention to slow pasture degradation or even improve the grassland's status (Li et al., 2014b; Chen et al., 2013).

Direct recovery strategies: Considering overgrazing as the major driver of degradation, grazing exclosure has been most frequently undertaken for pasture recovery. Weeding, fertilization and rodenticide applications were generally tested in light and moderate degradation stages (Dong et al., 2013). For heavy and extreme degradation stages, reseeding is also proposed in addition to the above-mentioned strategies. Nevertheless, these recovery strategies have produced inconsistent outcomes (Harris, 2010): (1) grazing exclosure decreased soil C sequestration and C input as assessed by plant $^{13}CO_2$ pulse labelling in northeastern Tibetan Plateau, because high C allocation belowground requires moderate grazing (Hafner et al., 2012). Positive (Wu et al., 2009; Sun et al., 2014) or insignificant (Zhang et al., 2015; Lu et al., 2015b) effects of grazing exclosure on soil fertility were also reported. (2) Nitrogen and P fertilization or combined applications of both fertilizers on Tibetan pastures showed a significant promotion of AGB production by 37–110% (Fig. 6). However, the fertilizer applications also contribute to nutrients leaching in degraded pastures, which may hamper pasture recovery and exasperate headwater pollution (Liu et al., 2017). (3) Reseeding in eastern Tibetan Plateau was ineffective (Dong et al., 2012) or had positive effects (Feng et al., 2010) on ameliorating soil fertility. In fact, recovery strategies must be implemented over a long period of time to realize improvements in soil fertility (Cao et al., 2014). To return SOC and nutrient contents to the status before degradation, at least hundreds of years are required (Preger et al., 2010). This reflects the time necessary for soil formation, restoration of the eroded soil and accumulation of nutrients – by weathering and $N_2$ fixation. Therefore, to improve soil fertility, a complex of various strategies is necessary.

Indirect recovery strategies: Improving stove efficiency, use of solar energy and construction of household or communal biogas plants have been proposed as effective strategies to reduce yak dung collection for energy (Wang, 2009). This is because yak dung collection (ca. 53% of Tibet's total rural energy consumption) prevents the return of nutrients from dung to the soil, and so continuously decreases soil fertility. All these strategies, however, require large investments at the regional, local and household scales and are impossible without strong governmental support.

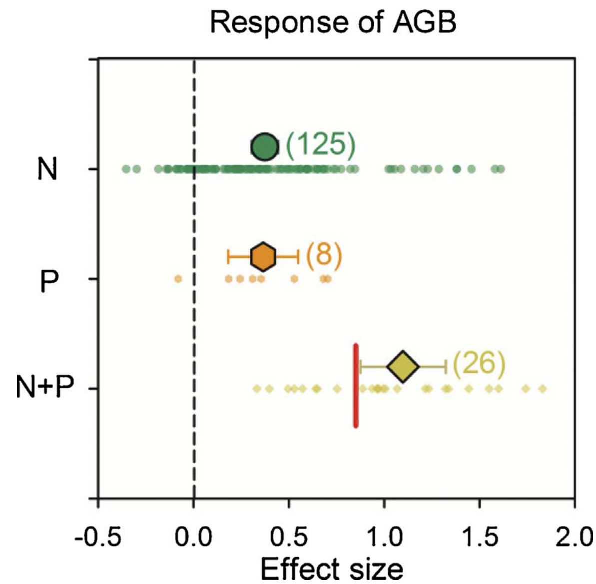


**Fig. 6.** Response of aboveground biomass (AGB) to single and combined additions of N and P. The short red line represents the calculated N + P effect without N + P interactions. The higher response of AGB to simultaneous N and P addition reflects the positive effect of interactions between the nutrients for higher AGB. The fertilization includes applications of inorganic and organic fertilizers. Organic fertilizer only refers to application of urea. The numbers in parenthesis show the number of experiments. This figure was generated based on the database from Miehe et al.'s (unpublished) literature. Error bars show standard errors (SE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 4.4. Current degradation status and expected patterns of future change

Tibetan pasture degradation status is estimated at various spatial and temporal scales and is conducted by remote sensing techniques coupled with spatial modelling. These estimations mostly focus on vegetation state (i.e. vegetation coverage and net primary production) and disregard soil degradation. From 1987 to 2004, 34% of the total grassland area has been degraded in the source region of the Three Rivers, which caused an annual decrease of aboveground biomass by 4–16 kg $ha^{-1}$ $yr^{-1}$ (Li et al., 2013). A similar rate of decrease in aboveground biomass (22 kg $ha^{-1}$ $yr^{-1}$, Wang et al., 2008c) from 2001 to 2004 was also observed on the northeastern Tibetan Plateau. Even if the decrease in grassland productivity remains the same (~4–22 kg $ha^{-1}$ $yr^{-1}$) for the whole plateau, the grassland will disappear over the next 30–170 years, given the estimated total AGB for Tibetan grasslands in 2001–2004 (688 kg $ha^{-1}$, Yang et al., 2009).

Since the beginning of the century, a series of ecological projects and special policies were implemented, mostly in the source regions of the Three Rivers, to restore the Tibetan grasslands and save their ecosystem functions. Countermeasures in these projects include various combinations of the above-mentioned recovery strategies. Some positive results, at least for vegetation characteristics, have been achieved. For instance, positive trends in NDVI residues and net primary production have been seen since the implementation of these projects, indicating significantly restored vegetation (Cai et al., 2015; Wang et al., 2016). Nevertheless, it is still challenging (and may be impossible) to completely recover the degraded Tibetan pastures because of very strong and continuously ongoing SOC and nutrient losses and much slower pedogenetic processes and vegetation recovery, compared to rapid and increasing anthropogenic pressures and climate change.

## 5. Conclusions

Highly intensive anthropogenic activities (e.g. overgrazing) have occurred for decades across the whole Tibetan Plateau at the demand of fast socio-economic development. These, in addition to a warming rate of about twice the global mean, have exerted extreme pressure on the vulnerable alpine pastoral ecosystems and induced widespread pasture degradation. The literature review elucidated that degradation on the Tibetan Plateau has triggered significant losses of SOC (42 ± 2%), N (33 ± 6%) and P (17 ± 4%) contents compared to the non-degraded pastures. Because of the absence of natural, undisturbed pastures, all these values are underestimations of the real losses. Various vegetation characteristics and soil properties are closely related to SOC and nutrient losses. While losses of TN and plant biomass are found to be accompanied by SOC losses, TP loss is resistant to the decreasing SOC content because of its precipitation as insoluble or less soluble P containing minerals. Though various strategies have been implemented to cease and even reverse the degradation processes, their effects on soil quality are still ambiguous, and restoration is impossible without strong support and cooperation at regional, local and household scales. If pasture degradation in the Tibetan Plateau continues, the natural *Kobresia* root mats in some regions will disappear in the coming decades without effective recovery strategies. This will dramatically destabilize these unique alpine ecosystems and have strong negative impacts on global environmental changes.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.10.011.

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