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ORIGINAL ARTICLE

Degradation of wetlands on the Qinghai-Tibetan Plateau causing a loss in soil organic carbon in 1966–2016

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Abstract

Aims Reveal the soil organic carbon (SOC) stock change in the Qinghai-Tibetan Plateau (QTP) alpine wetlands in the past fifty years. The Qinghai-Tibetan Plateau (QTP) has a large area of alpine marshland and wet meadows. Artificial drainage, overgrazing and climate change have caused severe degradation of the alpine wetlands. However, little is known about the effects of wetland degradation on SOC stock, and studies only focused on the Zoige marshland, the biggest marshland of China. Direct SOC observations from the extensively distributed wet meadows remain scarce.

Methods SOC in the soil surface layer (0–50 cm) were investigated at four wetland sites where degradation has continued for decades. One site is in marshland, and three are in wet meadows of the QTP. Using datasets from the literature and the field measurements of the present study, we estimated the loss of alpine wetland SOC.

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Results and conclusions Initially, marshland degradation to wet meadows prompted the accumulation of SOC; however, grazing in wet meadows reduced SOC accumulation. Wetland degradation to dried meadows led to a much greater SOC loss than that in the initial degradation stage, and grazing exacerbated the loss of SOC. An exponential decay rate of SOC was found in the grazed dried meadows. The wetlands of the QTP, have lost 141 ± 25 Tg in 1966–2016, representing 15% of the SOC stock.

Keywords Wet meadow · Marshland · Drainage · Grazing · Soil organic carbon · Qinghai-Tibetan Plateau

Introduction

As areas of marsh, fen, peat land, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salty, including areas of marine water the depth of which at low tide does not exceed six meters, wetlands cover less than 9% of the terrestrial land surface (Mitra et al. 2003; Zedler and Kercher 2005) but account for approximately 30% of the terrestrial soil organic carbon (SOC) pool (Malone et al. 2013; Mitsch et al. 2012). Because of their anaerobic wet conditions, undisturbed wetlands provide an optimal natural environment for sequestering and storing carbon from the atmosphere (Fung et al. 1991; Mitsch et al. 2012). Therefore, wetlands are important in the global carbon cycle and global climate change (Millennium Ecosystem Assessment 2005). However, wetlands can easily become a source of atmospheric carbon, such as when they are converted to other land-use types. After conversion, the organic carbon stock in wetlands will decline and be released to the atmosphere mostly due to an increase in microbial respiration (Lal 2004b; Mitra et al. 2005; Yang et al. 2013). Because of the large carbon pool in wetlands, even a small increase in the SOC decomposition rate may lead to large carbon outflows into the atmosphere (Lal 2004a; Ma et al. 2016a, b). Due to the impacts of human activities and climatic change during the twentieth century, 50% of the world's wetlands have been lost (Moser et al. 1996; Revenga et al. 2000). In boreal and subarctic regions, long-term drainage and fuel combustion of peat may cause a loss in peatland carbon of 34.5 Tg C a^{-1} (Gorham 1991).

The QTP is the highest (average elevation is 4000 m) and largest plateau on earth. One third of wetland area in China are situated on the QTP (Niu et al. 2012); Wei et al. 2015). In contrast to peatlands in the tropics and boggy peatlands in high-latitude regions, wet meadows and marshlands dominate the alpine wetlands, with wet meadows constituting 50% and marshlands constituting 6%, riverine and lacustrine wetlands constituting 44% of the alpine wetlands of the Qinghai-Tibetan Plateau (QTP) (Wei et al. 2015). Wet meadows are mostly distributed across the central and western QTP, while marshes are mostly located on the Zoige wetland, at the eastern edge of the plateau (Wei et al. 2015).

The mean annual ground temperature of the QTP increased by 0.36℃ during 1950–2005(Xu and Wu 2019).Climatic change and manmade ditch drainage expose wet meadows and marshlands to grazing animals. Overgrazing and livestock trampling damage fragile alpine wet meadows by destroying vegetation and soil structures. Both of these disturbances are closely related to the decrease in SOC, and the alpine wetlands of the QTP have recently experienced severe accelerated degradation, resulting in dramatic wetland loss attributable to human activities and climate change (Gao et al. 2011; Wang et al. 2007a, b; Zhang et al. 2011). Zoige, in the eastern part of the QTP, contains the largest alpine marshland in the world (Guo et al. 2013; Xiang et al. 2009). The human population increase in Zoige has led to wetland degradation, which was initially caused by drainage to provide room for increasing numbers of livestock (Luan et al. 2014a). Ditch drainage altered the hydrologic conditions and caused rapid wetland losses (Cui et al. 2015; Guo et al. 2013; Li et al. 2015; Wang et al. 2007a, b; Xiang et al. 2009). Based on a remote sensing-based study (Niu et al. 2012), the natural wet meadow and marshland area in the QTP decreased by 21% from 1978 to 2008. Following the increase in rainfall (Yang et al. 2017; Zhang et al. 2017) and glacial melting (Niu et al. 2012) from 2000 to 2008, the wetland area partially recovered (Wei and Wang 2017). However, due to the complex topography and the heterogeneity of the climate and human activities

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in the region, the degradation of alpine wetlands is still a challenge to ecosystems on the QTP.

Studies of the SOC changes after wetland degradation in the QTP have focused mostly on the Zoige marshland (Xiang et al. 2009; Huo et al. 2013; Ma et al. 2016b; Zhou et al. 2016), there were no representative observations of the extensively distributed wet meadows (Wei et al. 2015). Estimations of the wetland SOC dynamics over the entire QTP based on those limited and poorly representative observations of marshlands in only Zoige may have significant bias from the truth. The lack of sufficiently representative observations also impedes the model development of carbon cycling over the entire region of the QTP (Ma et al. 2016a).

Wetland degradation might last for many years, depending on the intensity of human activities and the magnitude of climatic changes. When long-term wetland degradation monitoring and corresponding soil sampling data were not available in the QTP, space-for-time substitution was usually used as an alternative, e.g., in the study by Luan et al. (2014b) on SOC changes caused by wetland degradation in Zoige. Given that the reference site in these studies was far from the degradation sites (a distance > 20 km), the differences in SOC contents of the paired samples may not be substantially related to wetland degradation. Spatially, neighboring wetlands of different degradation situations are preferred for the application of this approach. When marshland desiccates, the degradation stages can be divided into marsh (permanently inundated wetland), wet meadow (seasonally inundated wetland), and dry meadow (no inundated meadow) (Luan et al. 2014b).

We hypothesized that the wet meadow degradation of the QTP would lead a large SOC loss and may last for many years, and the loss of wet meadow may follow comparatively the same pattern as marshland. In this study, we sampled wetland soil at four sites, one at the marshland of Zoige and three at wet meadows in the inner area of the QTP, to improve the representativeness of the SOC sampling over the entire plateau (Fig. 1). At each site, we located subsequent degradation plots for sampling to exclude the influences of the spatial heterogeneity of SOC on the estimation of SOC dynamics after wetland degradation as much as possible. The objectives of this study were to 1) interpret the SOC changes caused by wetland (in this paper we only focused on the study of marsh and wet meadow, hereinafter "wetland" refer specifically to "marsh and wet meadow") degradation, 2) identify the impacts of desiccation and grazing on SOC, 3) delineate the decadal SOC dynamics of the alpine wetlands after degradation, and 4) estimate the regional wetland SOC loss during the last 50 years on the QTP.

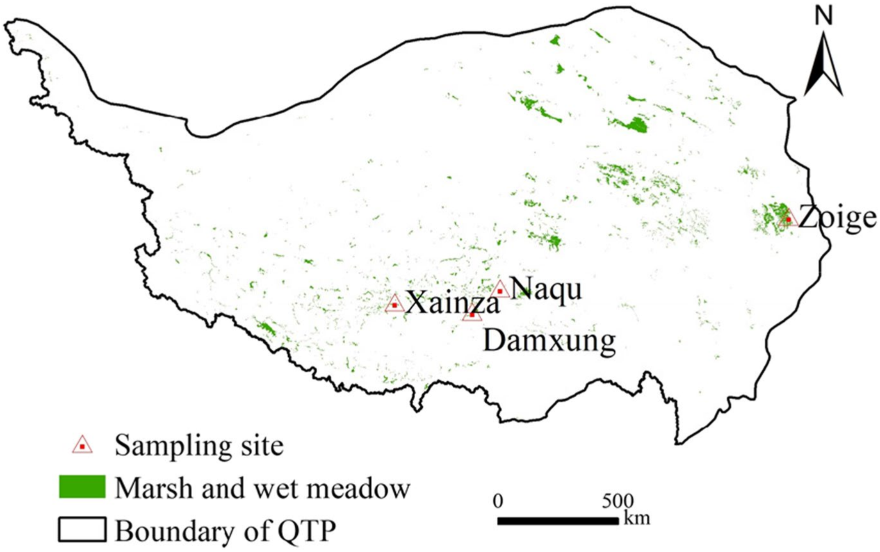


Fig. 1 Study area and the sampling sites. The marshland and wet meadow distribution (green) is from the wetland map of Niu et al. (2012)

Materials and methods

Site description

We located the sampling sites at Zoige (Sichuan Province), Damxung, Naqu and Xainza (Tibet Autonomous Region) (Fig. 1, Table S1). The climatic mean annual temperature and mean annual precipitation of the four sites were 1.4 °C and 651.5 mm, 1.9 °C and 469.8 mm, -0.8 °C and 436.9 mm, 0.2 °C and 318.9 mm, respectively.

At the Zoige site, seven plots were involved, including one pristine marshland (ZNM, permanently inundated), three secondary wet meadows (ZNW, ZGW1, and ZGW2, seasonally inundated or water saturated, formed by marshland degradation) and three dried meadows (ZND, ZGD1, and ZGD2, formed by further marshland degradation) (Table S1). The pristine marshland plot ZNM is covered with 10–20 cm of water. The area is not grazed because it is inaccessible to grazing animals. The wet meadows ZNW, ZGW1 and ZGW2 have no standing water except for occasional inundation during the growing season. Plot ZNW is located in the Zoige Wetland National Nature Reserve, where grazing has been excluded since the 1980s. Plot ZGW1 is not grazed except during winter (October to March). Plot ZGW2 is grazed year-round. Plot ZND is located in the courtyard of the Meteorological Bureau of Zoige County. It has been transformed from marshland and has been enclosed by fencing to prevent grazing since the 1970s. Plots ZGD1 and ZGD2 were artificially drained by ditching in the 1990s. The ditches are 5-m wide and 1.5-m deep, and both the ditches and the meadows are dry. The two plots are both grazed year-round. Plot ZGD1 has been invaded by *pika* (*Ochtona Thibetana*) and *zokor* (*Myospalax baileyi*), but plot ZGD2 has not been invaded. Detailed plot information is provided in Table S1.

At the Damxung, Naqu and Xainza sites, seasonally inundated wet meadows are used as grazing pastures and managed by local farmers. As wet meadows degrade, the dominant vegetation, *Kobresia tibetica* (Gao et al. 2011; Wu et al. 2009) dies, and the meadow surface turns black in color, showing a clear boundary between the degraded and undegraded areas (Fig. S1). The Damxung sample site is 2 km from the Damxung grassland station (91°04′15″E, 30°29′47″N) of the Chinese Ecosystem Research Network. Wet meadow degradation has lasted for more than 50 years. Along the degradation gradient, we located six plots representing undegraded wet meadow (DGW) and degraded samples for approximately 1-, 2-, 3-, 4- and 5-decades (DGD1, DGD2, DGD3, DGD4 and DGD5) (Table S1). The time tag of each plot was determined by local records and verified by land owners. The exact date of degradation cannot be determined, and we are confident only about the decadal degradation intervals The sampling site of Naqu is approximately 1.2 km from the Naqu Integrated Observation and Research Station of Ecology and Environment (92°6′19"E, 31°16′34"N). The sample site of Xainza is 50 km from the Xainza Alpine Steppe and Wetland Ecosystem Observation Station (88°42′15"E, 30°56′48"N). Plots of the undegraded wet meadow (NGW, and XGW) and degraded samples for approximately 1-, 2- and 3-decades (NGD1, NGD2, and NGD3 for Naqu site; XGD1, XGD2, and XGD3 for Xainza site) were located at the two sites (Table S1).

Sampling and analyses

Field work was performed from July to August 2016 at the Zoige site and from July to August 2017 at the other three sites. In each plot, four replicates of soil samples were taken at depths of 0–10 cm, 10–30 cm and 30–50 cm use soil auger. For each replicate, a square quadrat (3 m×3 m) was drawn, and four soil cores were collected at corners of the quadrat and pooled for each soil layer (Fig. S2). A soil core was also taken at the center of the quadrat for the determination of soil bulk density (BD).

Soil samples were air dried, and all visible roots and organic residues were removed. They were then ground and passed through a 0.149-mm mesh sieve. The soil organic carbon in the samples was measured in the laboratory by the potassium dichromate-oxidation external heating method (Zhang et al. 1999). The principle of the potassium dichromate-oxidation external heating method is similar to the Walkley & Black chromic acid wet oxidation method, that is recommend by the Food and Agriculture Organization of the United Nations. The oxidizable organic carbon in the soil is oxidized by potassium dichromate ($K_2Cr_2O_7$) solution in concentrated sulfuric acid. The $Cr_2O_7^{2-}$ reduced during the reaction with soil is proportional to the oxidizable organic C present in the sample. The organic carbon was then estimated by measuring the remaining unreduced dichromate after back-titrating with ferrous sulphate using diphenylamine as an indicator.

The soil samples for bulk density measurement were oven dried at 105 °C for 12 h and then weighed using the method of Bai et al. (2010). When analyzing changes in the SOC contents of the sampling plots, we assumed that the plots of different degradation situations at each site represented the degradation process of the wetland.

SOC density calculation and statistical analysis

The SOC density ($SOCD$, kg C m^{-2}) of soil layer i was calculated by Eq. (1):

$$SOCD_i = BD_i \times SOC_{C,i} \times D_i \times 0.01 \tag{1}$$

where BD (g cm^{-3}) is the soil bulk density, SOC_C (g kg^{-1}) is the SOC content, and D (cm) is the thickness of the soil layer. The subscript i stands for the sampling soil layers of 0–10 cm, 10–30 cm and 30–50 cm. After calculating the SOC density of each layer, the values were then summed to obtain the SOC density of the whole soil profile of 0–50 cm. The SOC of the QTP wetlands were mainly located in the 0–50 cm layer, we summarized the 0–50 cm layer SOC in this study to facilitate the comparative analysis with literatures when most published studies provided SOC densities of the 0–50 cm layer. For the convenience of the readers, the SOC density values for individual depth 0–10, 10–30 and 30–50 cm were enclosed in Table SII.

The differences in SOC contents and SOC densities among the sampling plots were analyzed using one-way ANOVA (the LSD method for the POC test), with a statistical significance level of 0.05 ($\alpha = 0.05$). The average data are all reported as the $mean \pm SE$ in this paper.

The degradation of the grazed dry meadow plots in this study had lasted for different years (Table S1). Based on the analysis of the sampling data and the research of (Huang et al. 2010), a first-order exponential model (Eq. 2) was established to simulate changes in the SOC densities of the grazed wetlands after degradation.

$$SOCD_t / SOCD_0 = a * exp(-k * t) \tag{2}$$

where $SOCD_0$ and $SOCD_t$ are the soil organic carbon densities of the undegraded marshland and wet meadow plots and dried meadow plots degraded for t decades, respectively.

When sampled from four different regions, we performed mixed effect model analysis to check the variance between the different sampling sites (S.3 of the Supporting information). With Wald $Z = 0.921$ ($P = 0.357$), the inter-site differences were not statistically significant. Data from the field measurements at the four sites were, therefore, used to calibrate the parameters a and k by Eq. 2 by employing a nonlinear iterative algorithm in SPSS with the least squared error methods.

Datasets and estimation of SOC loss in the QTP due to wetland degradation since the 1960s

With the data of changes in wetland area by remote sensing of QTP (Table 1), the sampling data of marsh and wet meadows degradation in this study and the data from publications concerning QTP wetlands (Table 2), we made estimation of the SOC loss owing to wetland degradation in the entire QTP. The changes in wetland area are mainly adopted from Niu et al. (2012) (Table 1). In the study by Niu et al. (2012), four wetland maps for all of China were produced based on Landsat and CBERS-02B remote sensing data of 1978, 1990, 2000, and 2008.

The wetland areas in 1966 and 2016 were estimated based on information from the literature.

Table 1 Marsh and wet meadow areas in 1966–2016

Year	Wetland area (km^2)	
	Other parts of QTP except Zoige	Zoige
2016	23,891.8^{ab*}	3163.2^{ab}
2008	23,891.8^{a*}	3385.3^{a}
2000	23,891.8^{a}	4154.7^{a}
1990	25,814.7^{a}	4178.3^{a}
1978	32,653.7^{a}	4759.5^{a}
1966	32,653.7^{ac}	5015.6^{ad}

The data were obtained from a: (Niu et al. 2012); b: (Zhang & Guo 2019); c: (Wang et al. 2007a, b); d: (Bai et al. 2009)

[*] excluded the newly formed wet meadows

Table 2 Soil organic carbon densities for marshes and wet meadows

Soil layer	SOC density (kg m^{-2})		Reference
	Marsh	Wet meadow	
0-50 cm	31.3	29.5	This study
		28.1	
		18.6	
		37.9	
		36.5	
		38.0	
	19.6		(Zhou 2015)
	29.2		
	34.3		(Huo et al. 2013)
	35.6		(Gao et al. 2010)
	17.9		(Cai 2012)
		23.5	(Zhao et al. 2018)
Average	28.0	30.3	
SE	3.1	2.9	

During 1966–1986, the wetland area in Zoige decreased by 837.3 km^2 (Bai et al. 2009), and wetland shrinkage mainly occurred in the 1970s (Bai et al. 2009). Therefore, we assume that the wetland shrinkage during 1986–1990 in the Zoige wetland can be neglected; thus, the wetland area in Zoige was estimated to be 5015.6 km^2 in 1966. In the other regions of the QTP except Zoige, the wetland area shrinkage occurred mainly after 1986. We assumed that the wetland area in 1966 was equal to that in 1978 according to the report that the wetland area shrinkage was trivial (Wang et al. 2007a, b). During 2009–2016, the wetland area loss rate in Zoige was 0.82% a^{-1} (Zhang & Guo 2019); hence, we estimated that the wetland area of Zoige in 2016 was 3163.2 km^2. There was almost no wetland loss in the other regions of the QTP during this stage (Zhang & Guo 2019), the wetland area of the other regions of the QTP in 2016 approximately equal to the area in 2008.

When there was no statistically significant difference in the SOC densities between the pristine marshland and the grazed wet meadows, we didn't calculate the SOC stock change of marshland transformed into wet meadow, and only the SOC loss after marshland and wet meadow degraded into dried meadow was calculated. After wetland desiccation, almost all the dried meadows were under grazing in the QTP, and changes in the SOC of the grazed sites can be described by the first-order decay kinetics model (Eq. 2). The initial SOC densities of the marshlands and wet meadows were estimated based on the field measurements of the present study and those in the literature (Table 2). As the marshlands of the QTP were mostly in Zoige and the wet meadows were distributed mostly in the center of the QTP (Wei et al. 2015); thus, we separately estimated the changes in wetland SOC of Zoige and those in the other regions of the QTP.

Loss of SOC was calculated by Eq. (3) and (4). Equation (3) calculated the annual SOC loss, at year T, of all the lost wetlands, and Eq. (4) calculated the total SOC loss by summing up the annual SOC loss since 1996.

$$E_{SOC\_T} = \sum_{i=0}^{T}(SOCD_{T-i} - SOCD_{T-i+1})A_i \tag{3}$$

$$A_{SOC\_T} = \sum_{T_0}^{T_e} E_{SOC\_T} \tag{4}$$

where T$_0$ and T$_e$ represents 1966 and 2016, respectively, and T represents the year number since 1966 by assuming 1966 as 0. A_i is the area of the lost wetland (the area of marsh and wet meadow degraded to dried meadow) in the ith year. E_{SOC_T} is the annual loss of SOC at year T because of wetland area loss (A_i) where the degradation stage of A_i at Year T was represented by $T–i$ in Eq. 3. The $SOCD_{T-i}$ and $SOCD_{T-i+1}$ were calculated with Eq. (2). To calculate the annual SOC loss, we assumed that the wetland area lost at a uniform annual rate during each period, e.g. during the period of 1966–1978, the annual wetland area loss rate is (5015.6–4759.5) / (1978–1966) = 21.34 km^2 when we had only the data of wetland area at 1978 and 1966, respectively.

Results

SOC densities in plots with different grazing and hydrological conditions

The SOC density (0–50 cm) of the pristine non-grazed marshland ZNM at Zoige was 31.3 ± 2.4 kg m^{-2} (Fig. 2a). Of the non-grazed wet meadow ZNW, the SOC density was 37.9 ± 1.5 kg m^{-2}, account for 120% of the pristine non-grazed marsh ZNM. In the grazed wet

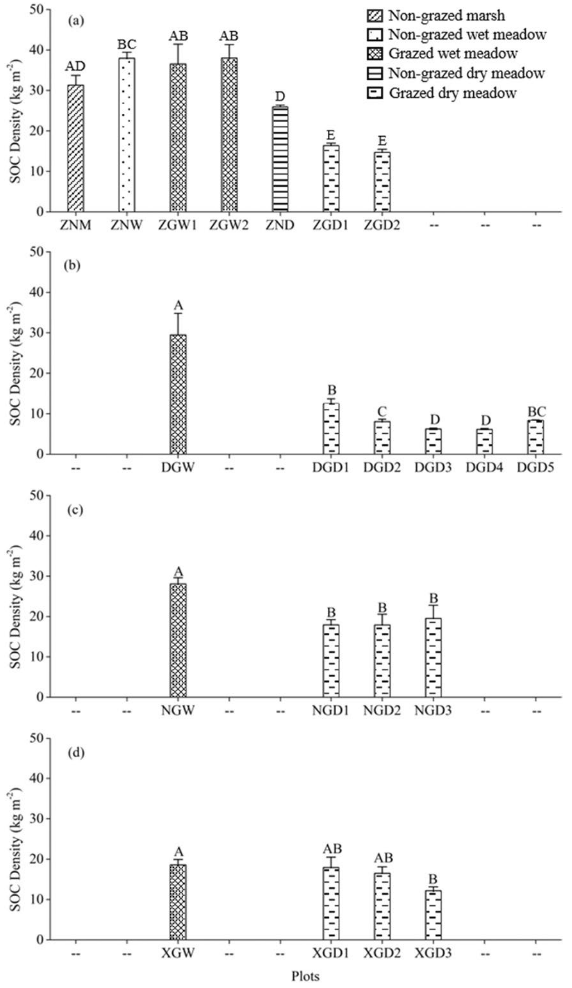


Fig. 2 SOC densities (0–50 cm) in the sampled plots of Zoige (**a**), Damxung (**b**), Naqu (**c**) and Xainza (**d**); Vertical bars represent standard errors (SE); Different letters indicate a statistically significant difference ($P < 0.05$) between the plots in the same sampling site

meadow plots at ZoigeZGW1 and ZGW2 the SOC densities were 36.5 ± 4.9 and 38.0 ± 3.3 kg m^{-2}, respectively. There was no statistically significant difference in the SOC densities between the pristine marshland and the grazed wet meadows. Of the non-grazed dry meadow ZND, the SOC density was 25.9 ± 0.5 kg m^{-2}, accounting for 68% of the non-grazed wet meadow ZNW. In the grazed plots ZGD1 and ZGD2, the SOC densities were 16.3 ± 0.6 and 14.7 ± 0.8 kg m^{-2}, respectively, and these were 63% and 57% of that of the non-grazed dry meadow plot ZND.

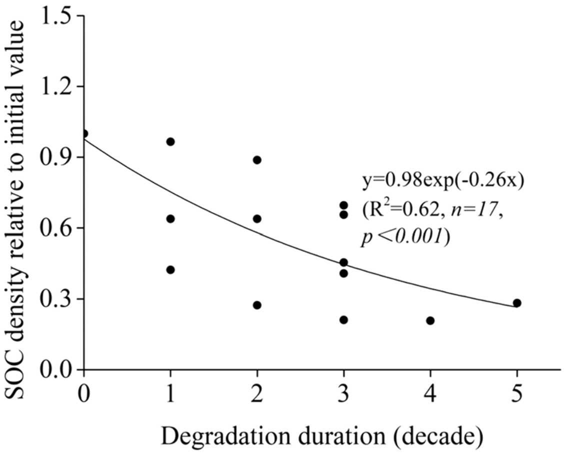


Fig. 3 Nonlinear fit of the observed changes in soil organic carbon density (SOCD) (0–50 cm). The observed SOCD from different sites was normalized by $SOCD_t/SOCD_0$ to generate a comparable data series. $SOCD_0$ and $SOCD_t$ are the soil organic carbon densities in the non-degraded wetland plots and the plots degraded for t decades, respectively

The SOC densities in 0–50 cm layer of the undegraded wet meadow plots (DGW, NGW, and XGW) at Damxung, Naqu and Xainza, were 29.5 ± 5.3, 28.1 ± 1.6 and 18.6 ± 1.3 kg m^{-2} (Fig. 2b – d), respectively. After degradation, the mean data of the dried meadow plots, were 8.2 ± 0.6, 17.7 and 15.5 kg m^{-2}, account for 28%, 63% and 83% of the undegraded wet meadow plots, respectively, at each site.

For all the sampling sites, the SOC density mean data of the wet meadow was 30.9 ± 1.9 kg m^{-2}, and has no statistically significant difference with the pristine marshland. The mean data of all the sampled dried meadow was 14.0 ± 0.8 kg m^{-2}, account for 45% of the wet meadow plots. For the grazed wet meadow plots, the mean SOC density was 29.3 ± 2.2 kg m^{-2}, there was no statistically significant difference between the grazed and non-grazed wet meadow plots. However, the mean data of the grazed dried meadow plots was 13.3 ± 0.8 kg m^{-2}, only account for 51% of the non-grazing dried meadow plots.

Changes in SOC densities with wetland decadal degradation gradients

For all the sampled sites, the relationship between the SOC density and the decadal degradation gradient (*t*) can be expressed by a first-order decay kinetics model (Fig. 3), $SOCD_t/SOCD_0 = a*exp\ (-k*t)$, $a = 0.98 \pm 0.09$

(mean ± SE), *k = 0.26 ± 0.06 (mean ± SE)*. $R^2 = 0.62$, *n = 17*. $SOCD_0$ and $SOCD_t$ are the soil organic carbon densities of the non-degraded wetland plots and the plots degraded for t decades, respectively.

Loss of SOC due to wetland degradation in the QTP

The average SOC loss rate (Fig. 4) in Zoige was 0.10 ± 0.09 Tg in 1966–1978. Then, over the next 40 years, the average SOC loss rates in Zoige were 0.36 ± 0.18, 0.42 ± 0.32, 0.66 ± 1.02 and 0.82 ± 1.10 Tg a^{-1} in 1978–1990, 1990–2000, 2000–2008 and 2008–2016, respectively. In the other regions of the QTP, the average SOC loss rates were 2.34 ± 2.18, 3.95 ± 3.67, 3.54 ± 4.51 Tg a^{-1} and 2.88 ± 4.42 Tg a^{-1} during 1978–1990, 1990–2000, 2000–2008 and 2008–2016, respectively. The total SOC loss over the past 50 years (Fig. 4) was estimated to be 21.5 ± 4.2 Tg and 119.0 ± 24.8 Tg in Zoige and the other regions of the QTP, respectively. The initial SOC stock (0–50 cm) was 140.5 ± 14.3 and 813.3 ± 81.6 Tg in Zoige and the other regions of the QTP, respectively, which means that approximately 15.3% and 14.6%, respectively, of the initial SOC was lost over the 50 years due to wetland degradation. In summary, the QTP lost 140.5 ± 25.1 Tg over the past 50 years, representing 14.7% of the wetland SOC stock.

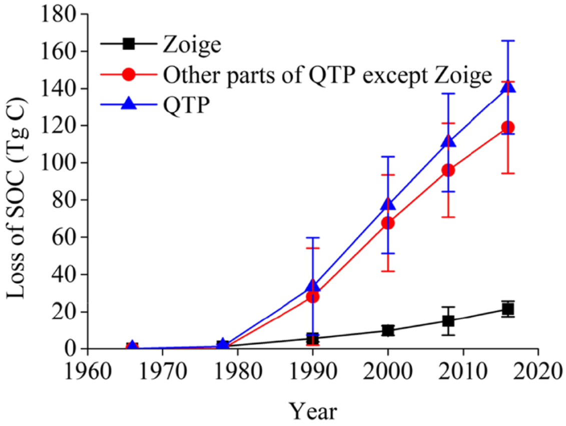


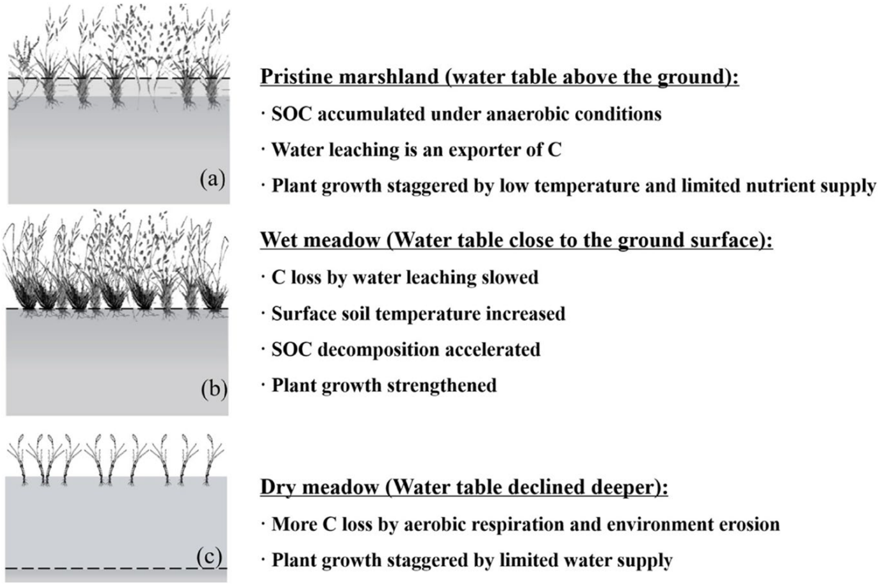
Fig. 4 Accumulated SOC loss from marshlands and wet meadows in the QTP during the period 1966–2016

Discussion

Grazing and hydrological effects on wetland SOC

The changes in the wetland SOC after the water table decline resulted from the balance between the inputs and outputs of soil organic matter (SOM), which mainly include litter and root production, soil respiration and exportation (Fig. 5). Under flooded conditions, carbon accumulates due to the slow organic carbon decomposition rate in anoxic environments (Fig. 5a) (Fung et al. 1991; Mitsch et al. 2012). In

Fig. 5 Schematic illustration of the stages of wetland degradation and the effect on SOC and plant growth



the initial stage of degradation, the water table of the flooded wetland dropped to a level near the ground surface (Fig. 5b); however, most of the time, the soil remained saturated and anoxic. The acceleration of SOC decomposition may be stimulated by rising soil temperature (Hirota et al. 2006) and aerobic respiration (Bergman et al. 1999). With the water table falling, more heat and oxygen can diffuse into the soil. Leaching water in flooded wetlands can also cause SOC loss by exporting dissolved and dispersed colloidal organic carbon (Bai et al. 2005; Freeman et al. 2001; Qualls et al. 2003). When the water table drops, the carbon lost by leaching slows in contrast to the strengthened soil respiration. Vegetation litter is the primary carbon input to wetland soil. The conversion of flooded areas to grass plantations increases the area available for grass growth when water is not a limiting factor. In the pristine marshland plot ZNM, the vegetation coverage was approximately 70% (Table S1), while the plot ZNW had a higher grass coverage of 95%. The rapid decomposition of SOM increases nutrient availability and promotes vegetation growth (Ma et al. 2016a). Zhou (2015) showed that the non-grazed annual aboveground biomass of a drained marshland in Zoige was 680.7 g m^{-2}, significantly higher than that of pristine marshland, 234.9 g m^{-2}. However, whether the drying wetland in this stage turns into a carbon source or sink depends on the balance between the rate of soil organic matter decomposition and the rate of organic matter replenishment from vegetation litter. After the water table declined from 30 to 0 cm, the SOM in the top layer of wetlands in Zoige increased from 40.8 to 63.8 g kg^{-1} (Bai et al. 2005). The SOC content also increased from 206.37 to 241.66 g kg^{-1} when the water table declined from 13 to 3 cm (Zhou 2015; Zhou et al. 2016). The SOM increased from 95 g kg^{-1} to approximately 320 g kg^{-1} as the water table declined from 5 to 2 cm (Gao 2006). In the present study, the SOC density in the top layer increased from 31.3 ± 2.4 kg m^{-2} g kg^{-1} in the ZNM plot to 37.9 ± 1.5 kg m^{-2} in the ZNW plot (Fig. 2). However, a decrease in SOC content was found as the marshlands changed into wet meadows (Gu et al. 2017).

When wet meadows degraded into dried meadows (Fig. 5c), the vegetation density of the dominant sedge species, *Kobresia tibetica*, decreased (Gao and Li 2016; Gao et al. 2011; Zhang et al. 1995). The populations of drought-tolerant plant species then became dominant. During this stage, the vegetation coverage and biomass decreased dramatically (Table S1). A decline in the water table facilitated oxygen diffusion and increased soil aerobic respiration (Wang et al. 2014). Soil anaerobic respiration was replaced by aerobic respiration at greater depths of the soil profile, and more SOC in the soil was released to the atmosphere in the form of CO_2 (Cao et al. 2017; Li et al. 2004; Malone et al. 2013).

In the present study the mean SOC density in the 0-50 cm layer of the dried meadows was only account for 45% of the wet meadows (Fig. 2).Grazing reduced plant litter and SOC density (Luan, et al. 2014a; Piñeiro et al. 2010; Wu et al. 2010). The drying of wetlands increased the risk of decreasing SOC and converting alpine wetlands from C sinks to C sources.

Loss of SOC due to wetland desiccation in the QTP

The QTP wetland maintained an almost primary landscape until the 1960s. Then, the wetland dried mainly due to artificial drainage, which starting in Zoige and was accompanied by SOC loss. Over the next 40 years from the late 1970s, the SOC loss rate continually increased, e.g., from an average of 0.10 ± 0.09 Tg a^{-1} during 1966–1978 to 0.82 ± 1.10 Tg a^{-1} in the 2000s due to marshland degradation in Zoige. In the other regions of the QTP where wet meadows dominated, the average SOC loss rate had the same trend as that of the degraded marshland in Zoige. In Northeast China, where approximately 29,100 km^2 or 55% of the pristine marshland has been cultivated for cropland, the SOC loss rate was 6.04 ± 0.56 Tg a^{-1} and the total value was 238 ± 22 Tg during 1950–2000, representing approximately 50% of the SOC stock in the wetlands (Huang et al. 2010). The wetland loss area was 8,115.4 km^2, accounting for 21.5% of the initial wetland area in the 1960s in the QTP, and the wetland SOC loss in the QTP was 140.5 ± 25.1 Tg, averaging 14.7% of the initial SOC stock over approximately 50 years, was much less than that in Northeast China. Literally, the tillage in croplands after wetland cultivation in Northeast China might cause extra SOC losses compared to that caused by drainage, when in the QTP, the drained wetlands were left without further direct radical disturbance other than treatment by grazing animals. When animal treatment destroyed the structure of the surface soil and subsequently caused soil erosion and nutrient loss, the existence of hardy hummocks had the effect of resisting the degradation of soil structure. Furthermore, after the degraded wetland turned black in color, which indicated the thorough extinction of vegetation, there was almost no treading disturbance and therefore less SOC loss. However, the observed unit area SOC loss after wetland drainage in the QTP was larger than that in Northeast China, which was ascribed to the difference in litter return into the soil between the two scenarios. In Northeast China, part of the crop residues will be left and incorporate into the soil after crop harvest. According to Zhang et al. (2014), the average crop residues was 123 g C m^{-2} in croplands of the northeast of China. The field investigation of the study showed that the aboveground biomass of the dried meadows was only 44 g C m^{-2}. Croplands have more litter inputs to balance SOC losses than the dried meadows in QTP, which implies the severe consequences of wetland degradation.

In boreal and subarctic regions, drainage and fuel combustion of peat may cause a much greater, e.g., up to 34.5 Tg C a^{-1}, loss of peatland carbon (Gorham 1991). During the EI Niño event in 1997, a widespread fire burned 0.19–0.23 Pg C surface soil carbon in the peatlands of Indonesia (Page et al. 2002). Compared with the other regions of the world, the wetland SOC loss of the QTP was relatively low in terms of mass, but it is a key indicator of environmental degradation in this fragile region.

In Zoige, there was no statistically significant difference in the SOC densities between the marshland and the secondary wet meadows (formed from marshland desiccation). We therefore did not count the SOC change in the marshland-to-wet meadow. The drainage of the wetland may cause soil compaction, resulting in a larger BD that leads to an overestimation of the SOC stock in the drained wetlands and thereafter an underestimation of the SOC loss when we adopt the depth-based calculation of the SOC density. In this study, however, we found no significant compaction effects on the BD in the samples (Fig. S2).

When making regional estimates of SOC loss due to wetland degradation, the wetland area of different time periods and some of SOC density data were retrieved from the literature, where the analytical methods (e.g., field observation and data processing method) of the individual studies and their inter-comparisons may introduce errors into the estimates. For example, the interpretation accuracy of the remote sensing data used by Bai et al. (2009) was 90% and that of Niu et al. (2012) was only 70%.

In this study, we sampled only the 0–50 cm layer SOC, and together with the remarkable SOC changes in the surface soil layer, the SOC content in the 30–50 cm layer of the dried land and wetland were significantly different, which implied that there might also be changes in the deeper soil layer below the 50 cm depth. More detailed and in-depth research is still needed to obtain further information on the SOC changes after wetland degradation. As a limitation of the research method, we did not consider the impact of climate change on the dynamics of wetland SOC, and based on the experimental data in this research, in the future, we will combine the model to further study this issue.

Conclusions

Marshland degrade into wet meadow may not lead to significant SOC density change; however, wet meadow degrade into dry meadow will result a loss of SOC, and grazing can exacerbate the SOC loss. After the wet meadow turned into dried meadow, the SOC density decadal dynamics can be described by an exponential decay model. Due to wetland degradation, during 1966–2016 the SOC pool of the marsh and wet meadow in the QTP lost 141 ± 25 Tg C, with a 15% reduction of the initial SOC stock. There is still large uncertainty regarding the SOC change from the alpine wetlands, and further efforts are needed to reduce this uncertainty.

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Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflicts of interest We have no potential conflict of interest.

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