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Influences of human activity and climate change on growing-season soil moisture in the Qinghai–Tibet grasslands from 2000 to 2020

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Soil moisture (SM) serves as a vital indicator reflecting environmental water conditions, but significant uncertainties still persist regarding how human activity and climate change affect SM. In this study, we quantified the influences of human activity and climate change on growing-season SM in the Qinghai–Tibet grasslands from 2000 to 2020. Climate change led to a decline in spatially mean SM at a rate of −0.01 and −0.06 g g^{-1} $year^{-1}$ at 0–10 and 10–20 cm, respectively. Nonetheless, climate change caused the soil to become wetter in 39.97% and 22.29% areas at 0–10 and 10–20 cm, respectively. Human activity resulted in a decline in spatially mean SM by 36% and 21% at 0–10 and 10–20 cm, respectively. Nonetheless, human activity caused soil to become wetter in 2.82% areas at 0–10 cm and 30.03% areas at 10–20 cm. Therefore, both climate change and human activity have contributed to a pattern where the whole Qinghai–Tibet grasslands became drier while specific parts became wetter during the last 20 years. In addition to temperature and precipitation change, we should also pay attention to the response of SM to radiation change.

KEYWORDS

soil drying, soil quality, random forest, alpine region, data mining

1 Introduction

Soil moisture (SM), as a vital water resource, plays a crucial role in plant growth (Baumann et al., 2009; Bell et al., 2009; Berdanier and Klein, 2011). Under global change scenarios, SM undergoes significant alterations, which can subsequently impact plant growth through feedback mechanisms (Brito et al., 2013; Buttler et al., 2015; Berg et al., 2017). Numerous studies have explored the response of SM to climate change or human activity and their feedback, resulting in valuable scientific research achievements (Berg et al., 2017; Rigden et al., 2020; Humphrey et al., 2021). These achievements provide crucial support for the high-level development of human society (Flanagan and Johnson, 2005; Engel et al., 2009; Craine and Gelderman, 2011). However, previous studies have certain limitations in two ways. First, they have primarily focused on the influences of climate warming/cooling and decreased/increased precipitation on SM and their feedback to terrestrial ecosystems, whereas the influence of radiation change on SM and its feedback to terrestrial ecosystems are still lacking (Barron-Gafford et al., 2011; Fu et al., 2018). Radiation change is an integral part of climate change, and under global climate change, radiation decreases (You et al., 2010). It has been proven that radiation change can have obvious effects on the nutritional quality and storage of plant herbage, species diversity, and soil pH, which is even more important than climate warming and precipitation change (Fu et al., 2022; Tian and Fu, 2022). Considering the close relationships between SM and forage nutrition quality, species diversity, soil pH, etc. (Fu et al., 2018; Fu and Sun, 2022), further studies are imperative to understand the influence of brightening/dimming on SM. Second, whether climate change or human activity leads to soil drying or wetting is still controversial, and this uncertainty might be related to the relative intensity of changes in various key factors of human activity and climate change (Yu et al., 2019; Zhang and Fu, 2021). If precipitation does not change or decrease, warming should cause a decrease in surface SM (Fu et al., 2018; Han et al., 2023). Nonetheless, the influence of climate change on SM becomes uncertain when both temperature and precipitation increase simultaneously (Fu et al., 2018; Yu et al., 2019). If the increased magnitude of SM triggered by elevated precipitation is greater than the decreased magnitude of SM triggered by climate warming, climate change will cause soil to become wet; otherwise, it will cause the soil to become dry (Shen et al., 2015). Grazing reduces transpiration by harvesting herbage from herbivores, whereas nitrogen fertilizer addition generally increases transpiration by increasing grassland productivity (Fu and Shen, 2016; Zhang and Fu, 2021). The response of SM to grazing activities differs with increasing grazing intensity and grazing season in grassland ecosystems (Sun et al., 2021; Zhang and Fu, 2021). Accordingly, it is essential to further strengthen studies on the influences of human activity and climate change on SM.

The grasslands on the Qinghai–Tibet Plateau (TP) are important parts of global grassland ecological systems. It is commonly believed that climate warming and increased precipitation on the TP led to an overall improvement of grassland ecological systems, but they also caused deterioration in some specific areas (Hu et al., 2020; Li et al., 2020). Nonetheless, many studies have demonstrated that, in comparison to precipitation, SM is more closely associated with grassland productivity and forage nutrient quality, offering a better reflection of the influence of environmental water conditions on these aspects (Baumann et al., 2009; Fu et al., 2018). Therefore, SM serves as a key limiting factor in grassland ecosystems, affecting herbage yield, nutrient quality, and the development of animal husbandry on the TP. Unfortunately, understanding its response to human activities and climate change is limited and has been mainly studied on a small scale (Fu et al., 2018; Dai et al., 2022), which hinders accurate quantification of its influence on grassland ecosystems across the region. Accordingly, it is essential to strengthen studies on the response of SM to human activity and climate change in the TP grasslands.

The objective of this study is to examine the response of growing season SM to human activity and climate change at 0–10 and 10–20 cm in the TP grasslands during the period of 2000–2020. This study is expected to provide valuable insights into managing soil water dynamics under the influence of human activity and climate change. Furthermore, agricultural sector managers can better identify soil drought by exploring the influence law of human activity and climate change on SM. We hypothesized that climate change caused soil wetting over the whole TP grasslands. Based on previous studies (Sun et al., 2023; Zhang et al., 2023), we hypothesized that human activities may alter the sensitivities of SM to climate change.

2 Materials and methods

We utilized random forest models to derive monthly mean soil moisture data ($SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, and $SM_{a\_10\text{-}20}$) during the growing season (May–September) from 2000 to 2020 across the TP grassland region (Wang and Fu, 2023). The randomForest package of the R software was used to construct the random forest models of SM (Wang and Fu, 2023). Observed SM at 0–10 cm, air temperature, precipitation, and radiation data inside the enclosure were used to obtain the random forest models of $SM_{p\_0\text{-}10}$ (Wang and Fu, 2023). Observed SM at 0–10 cm, air temperature, precipitation, radiation, and normalized difference vegetation index (NDVI) data outside the enclosure were used to obtain the random forest models of $SM_{a\_0\text{-}10}$ (Wang and Fu, 2023). Similarly, the random forest models of $SM_{p\_10\text{-}20}$ and $SM_{a\_10\text{-}20}$ were constructed (Wang and Fu, 2023).

$SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, and $SM_{a\_10\text{-}20}$ referred to the potential SM at 0–10 cm, actual SM at 0–10 cm, potential SM at 10–20 cm, and actual SM at 10–20 cm, respectively. Detailed descriptions of the monthly precipitation, temperature, radiation, and/or NDVI from 2000 to 2020 were reported in our previous studies (Fu et al., 2022). We obtained growing season mean $SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, and $SM_{a\_10\text{-}20}$ using corresponding monthly $SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, and $SM_{a\_10\text{-}20}$ in 2000–2020, respectively. We also calculated growing season total precipitation, mean temperature, total radiation, and mean NDVI (GST, GSP, GSRad, and GSNDVI) using monthly total precipitation, mean temperature, total radiation, and NDVI, respectively. All these values were computed for all pixels with a spatial resolution of 1 km × 1 km across the entire TP grasslands.

The slope is often used to reflect the change trend of a specific variable (Fu et al., 2022; Wang et al., 2022; Sun et al., 2023) since we obtained the slope of GSP (ΔGSP), GST (ΔGST), GSRad (ΔGSRad), GSNDVI (ΔGSNDVI), $SM_{p\_0\text{-}10}$ ($\Delta SM_{p\_0\text{-}10}$), $SM_{a\_0\text{-}10}$ ($\Delta SM_{a\_0\text{-}10}$), $SM_{p\_10\text{-}20}$ ($\Delta SM_{p\_10\text{-}20}$), and $SM_{a\_10\text{-}20}$ ($\Delta SM_{a\_10\text{-}20}$) using the sens.slope function of the trend package. The ggscatter function of the ggpubr package was used to obtain the relationship between $SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, or $SM_{a\_10\text{-}20}$ and longitude, latitude, elevation, GST, GSP, GSRad, ΔGST, ΔGSP, and ΔGSRad. The ggscatter function of the ggpubr package was also used to obtain the relationship between $SM_{a\_0\text{-}10}$ or $SM_{a\_10\text{-}20}$ and GSNDVI and ΔGSNDVI. The varpart function of the vegan package was used to quantify the relative impacts of the three geographic variables (i.e., longitude, latitude, and elevation), or the three mean climate condition variables (i.e., GST, GSP, and GSRad), or the three climate change variables (i.e., ΔGST, ΔGSP, and ΔGSRad) on $SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, or $SM_{a\_10\text{-}20}$. We quantified the relative impacts of geographic position, mean climate conditions, and climate change on $SM_{p\_0\text{-}10}$, $SM_{a\_0\text{-}10}$, $SM_{p\_10\text{-}20}$, or $SM_{a\_10\text{-}20}$.

The $R_{SM\_0\text{-}10}$ was the ratio of $SM_{a\_0\text{-}10}$ to $SM_{p\_0\text{-}10}$, and the $R_{SM\_10\text{-}20}$ was the ratio of $SM_{a\_10\text{-}20}$ to $SM_{p\_10\text{-}20}$ (Equations 1 and 2).

$$R_{SM\_0-10} = \frac{SM_{a\_0-10}}{SM_{p\_0-10}} \tag{1}$$

$$R_{SM\_10-20} = \frac{SM_{a\_10-20}}{SM_{p\_10-20}} \tag{2}$$

Both the $SM_{p\_0\text{-}10}$ and $SM_{p\_10\text{-}20}$ were only affected by climate change, whereas both the $SM_{a\_0\text{-}10}$ and $SM_{a\_10\text{-}20}$ were simultaneously affected by climate change and human activity. In other words, both the $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ exclude the effects of climate change, and they are only affected by human activity. Therefore, the $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ can indicate the effects of human activity on SM at 0–10 and 10–20 cm, respectively. We obtained the change slope of $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ (i.e., $\Delta R_{SM\_0\text{-}10}$ and $\Delta R_{SM\_10\text{-}20}$) (Fu et al., 2022). The ggscatter function of the ggpubr package was used to obtain the relationship between $R_{SM\_0\text{-}10}$ or $R_{SM\_10\text{-}20}$, or $\Delta R_{SM\_0\text{-}10}$ or $\Delta R_{SM\_10\text{-}20}$ and longitude, latitude, elevation, GST, GSP, GSRad, GSNDVI, ΔGST, ΔGSP, ΔGSRad, and ΔGSNDVI. We quantified the relative impacts of the three geographic variables (i.e., longitude, latitude, and elevation), or the three mean climate condition variables (i.e., GST, GSP, and GSRad), or the three climate change variables (i.e., ΔGST, ΔGSP, and ΔGSRad) on $R_{SM\_0\text{-}10}$, $R_{SM\_10\text{-}20}$, $\Delta R_{SM\_0\text{-}10}$, and $\Delta R_{SM\_10\text{-}20}$. We quantified the relative impacts of geographic position, mean climate conditions + GSNDVI, and climate change + ΔGSNDVI on $R_{SM\_0\text{-}10}$, $R_{SM\_10\text{-}20}$, $\Delta R_{SM\_0\text{-}10}$, and $\Delta R_{SM\_10\text{-}20}$. The statistical software used was R.4.2.2.

3 Results

3.1 ΔSM and its relationships with environmental variables

Different regions exhibited different patterns for $\Delta SM_{p\_0\text{-}10}$, $\Delta SM_{p\_10\text{-}20}$, $\Delta SM_{a\_0\text{-}10}$, and $\Delta SM_{a\_10\text{-}20}$ (Figure 1). Spatially mean values of $\Delta SM_{p\_0\text{-}10}$, $\Delta SM_{p\_10\text{-}20}$, $\Delta SM_{a\_0\text{-}10}$, and $\Delta SM_{a\_10\text{-}20}$ were −0.01 (from −0.46 to 0.54 g g^{-1} $year^{-1}$), −0.06 (from −0.42 to 0.27 g g^{-1} $year^{-1}$), 0.02 (from −0.42 to 0.51 g g^{-1} $year^{-1}$), and −0.02 g g^{-1} $year^{-1}$ (from −0.56 to 0.49 g g^{-1} $year^{-1}$), respectively. There were 39.97%, 22.29%, 56.60%, and 34.71% areas showing increasing trends for $\Delta SM_{p\_0\text{-}10}$, $\Delta SM_{p\_10\text{-}20}$, $\Delta SM_{a\_0\text{-}10}$, and $\Delta SM_{a\_10\text{-}20}$, respectively. In contrast, there were 60.03%, 77.67%, 43.40%, and 65.29% areas showing decreasing trends for $\Delta SM_{p\_0\text{-}10}$, $\Delta SM_{p\_10\text{-}20}$, $\Delta SM_{a\_0\text{-}10}$, and $\Delta SM_{a\_10\text{-}20}$, respectively. Longitude had higher influences on $\Delta SM_{p\_0\text{-}10}$ and $\Delta SM_{a\_0\text{-}10}$ than latitude and elevation (Figure S1). In contrast, latitude had higher influences on $\Delta SM_{p\_10\text{-}20}$ and $\Delta SM_{a\_10\text{-}20}$ than longitude and elevation (Figure S2). Compared to GST and GSRad, GSP had higher influences on $\Delta SM_{p\_0\text{-}10}$, $\Delta SM_{p\_10\text{-}20}$, and $\Delta SM_{a\_10\text{-}20}$ (Figures S3, S4). In contrast, compared to GST and GSP, GSRad had a greater effect on $\Delta SM_{a\_0\text{-}10}$ (Figure S3). The ΔGSP had the greatest effects on $\Delta SM_{p\_0\text{-}10}$ and $\Delta SM_{a\_0\text{-}10}$, and the ΔGST had the

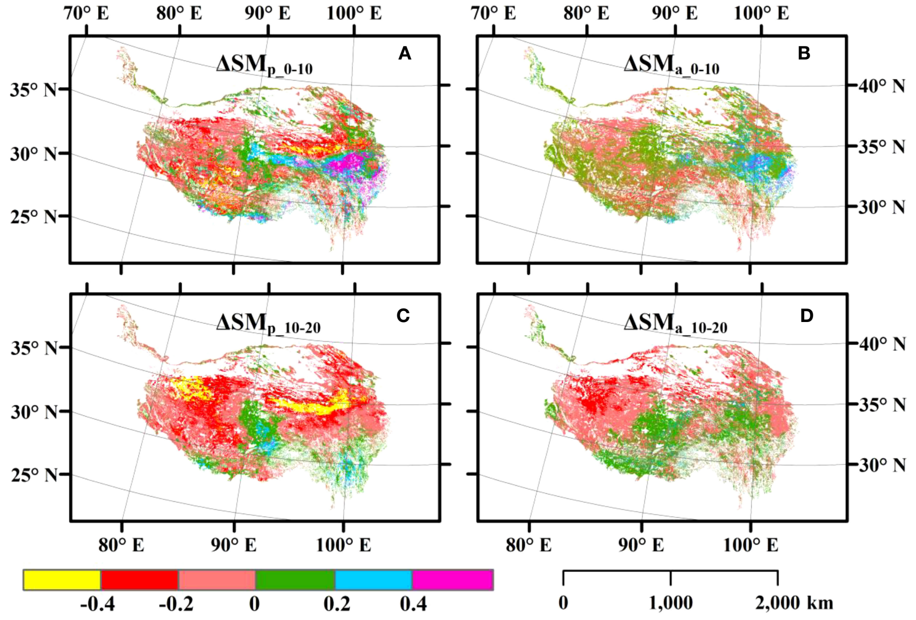

FIGURE 1
Spatial distribution for **(A)** $\Delta SM_{p\_0\text{–}10}$, **(B)** $\Delta SM_{a\_0\text{–}10}$, **(C)** $\Delta SM_{p\_10\text{–}20}$, and **(D)** $\Delta SM_{a\_10\text{–}20}$.

lowest effects on $\Delta SM_{p\_0\text{-}10}$ and $\Delta SM_{a\_0\text{-}10}$ among the three variables of climate change (Figure S5). In contrast, compared to ΔGST and ΔGSP, ΔGSRad had higher influences on $\Delta SM_{p\_10\text{-}20}$ and $\Delta SM_{a\_10\text{-}20}$ (Figure S6). The ΔGST, ΔGSP, and ΔGSRad had higher influences on $\Delta SM_{p\_10\text{-}20}$ than $\Delta SM_{p\_0\text{-}10}$ (Figures S5, S6). The overall effect of the three variables of climate change on the $\Delta SM_{p\_10\text{-}20}$ was greater than that on $\Delta SM_{p\_0\text{-}10}$ (Figure S7). The ΔGSP had greater exclusionary influences on $\Delta SM_{p\_0\text{-}10}$ and $\Delta SM_{a\_0\text{-}10}$, but the ΔGSRad had higher exclusionary influences on $\Delta SM_{p\_10\text{-}20}$ and $\Delta SM_{a\_10\text{-}20}$ among the three variables of climate change (Figures S7, S8). The GSNDVI and ΔGSNDVI significantly affected $\Delta SM_{a\_0\text{-}10}$ and $\Delta SM_{a\_10\text{-}20}$ (Figure S9). Climate change had the greatest exclusionary effects on $\Delta SM_{p\_0\text{-}10}$, $\Delta SM_{a\_0\text{-}10}$, $\Delta SM_{p\_10\text{-}20}$, and $\Delta SM_{a\_10\text{-}20}$ than geographical position and mean climate conditions (Figure 2). Mean climate conditions had higher exclusionary influences on $\Delta SM_{p\_0\text{-}10}$ and $\Delta SM_{p\_10\text{-}20}$ than geographical position (Figure 2). Mean climate conditions and geographical position had the same exclusionary effects on $\Delta SM_{a\_0\text{-}10}$ and $\Delta SM_{a\_10\text{-}20}$ (Figure 2).

3.2 R_{SM} and its relationships with environmental variables

Spatially mean values of $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ were 0.64 (from 0.28 to 1.45) and 0.79 (from 0.33 to 1.97), respectively (Figure 3). There were only 2.82% and 30.03% areas where $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ values were greater than one, respectively. In contrast, there were 97.18% and 69.97% areas where $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ values were lower than one, respectively. Longitude had the strongest effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$, but latitude had the least effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ among the three geography variables (Figure S10). The GSP had the strongest effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$, but the GST had the least effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ among the three variables of mean climate conditions (Figure S11). Compared to the three variables of mean climate conditions, the GSNDVI had higher influences on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ (Figure S11). The ΔGSP had the strongest effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$, but the ΔGSRad had the least effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ among the three variables of climate change (Figure S12). The ΔGSNDVI also had some effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ (Figure S12). Longitude had the greatest exclusionary effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$, but elevation had the least exclusionary effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ among the three geography variables (Figure S13). Compared to the three variables of mean climate conditions, the GSNDVI had the greater exclusionary influences on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ (Figure S13). The GST had the greatest exclusionary effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$, but the GSRad had the lowest exclusionary effects on $R_{SM\_0\text{-}10}$ and $R_{SM\_10\text{-}20}$ among the three variables of mean climate conditions (Figure S13). The ΔGST had the strongest exclusionary influences on $R_{SM\_0\text{-}10}$, but the ΔGSP had the strongest exclusionary

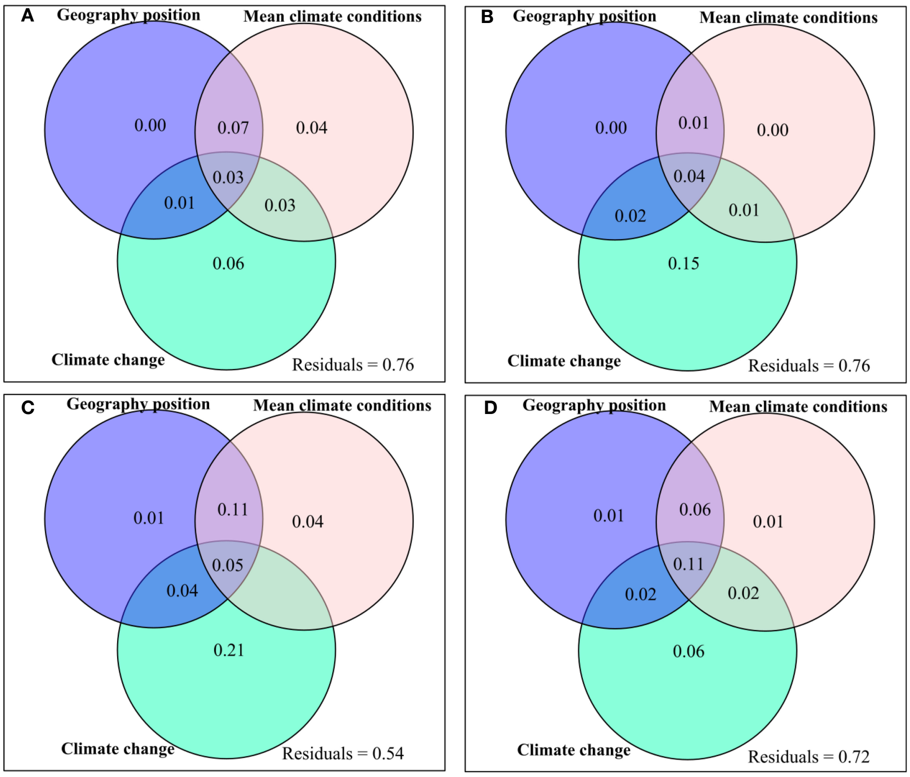

FIGURE 2
Relative influences of geographical position, mean climate conditions, and climate change to **(A)** ΔSM_{p_0-10}, **(B)** ΔSM_{a_0-10}, **(C)** ΔSM_{p_10-20}, and **(D)** ΔSM_{a_10-20}.

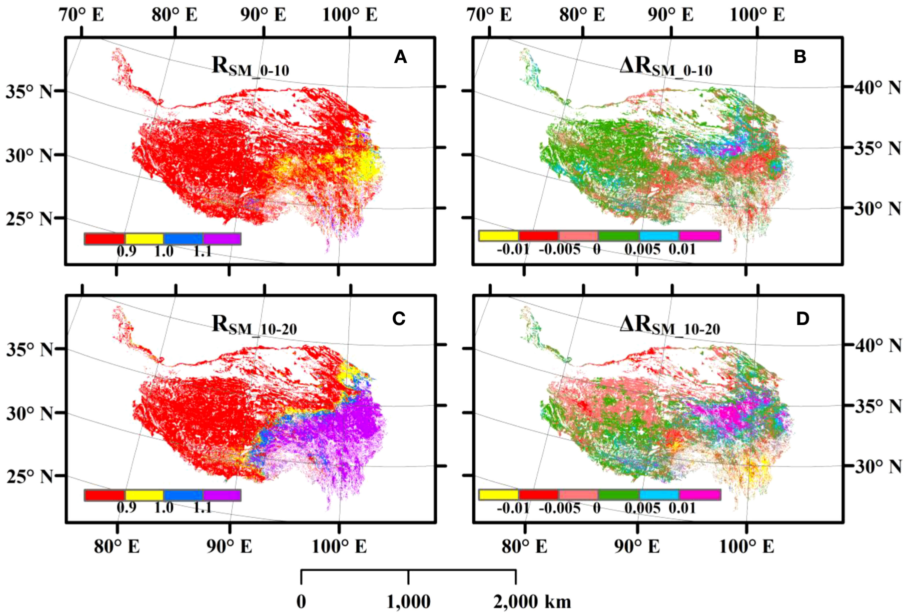

FIGURE 3
Spatial distribution for **(A)** R_{SM_0-10}, **(B)** ΔR_{SM_0-10}, **(C)** R_{SM_10-20}, and **(D)** ΔR_{SM_10-20}.

influences on R_{SM_10-20} among the three variables of climate change (Figure S13). The ΔGSRad had the lowest exclusionary effects on R_{SM_0-10} and R_{SM_10-20} among the three variables of climate change (Figure S13). The ΔGSNDVI also had some exclusionary effects on R_{SM_0-10} and R_{SM_10-20} (Figure S13). Mean climate conditions + GSNDVI had the greatest exclusionary effects on R_{SM_0-10} and R_{SM_10-20}, but the geographical position had the lowest exclusionary effects on R_{SM_0-10} and R_{SM_10-20} (Figure 4).

3.3 ΔR_{SM} and its relationships with environmental variables

Spatially mean values of ΔR_{SM_0-10} and ΔR_{SM_10-20} were 0.0011 (from −0.0287 to 0.0263) and 0.0013 (from −0.0590 to 0.0564), respectively (Figure 3). There were 63.78% and 53.36% areas showing increasing trends for ΔR_{SM_0-10} and ΔR_{SM_10-20}, respectively. In contrast, there were 36.22% and 46.64% areas showing decreasing trends for ΔR_{SM_0-10} and ΔR_{SM_10-20}, respectively. The three geography variables and GSNDVI had some effects on ΔR_{SM_0-10} and ΔR_{SM_10-20} (Figures S14, S15). The GSP had the strongest effects on ΔR_{SM_0-10} and ΔR_{SM_10-20}, but the GST had the lowest effect on ΔR_{SM_0-10} and ΔR_{SM_10-20} among the three variables of mean climate conditions (Figure S15). Compared to the three variables of climate change, the ΔGSNDVI had the higher influences on ΔR_{SM_0-10} and ΔR_{SM_10-20} (Figure S16). Compared to the three variables of climate change, the ΔGSNDVI had the higher exclusionary influences on ΔR_{SM_0-10} and ΔR_{SM_10-20} (Figure S17). Climate change + ΔGSNDVI had the greatest exclusionary effects on ΔR_{SM_0-10} and ΔR_{SM_10-20}, but the geographical position had the lowest exclusionary effects on ΔR_{SM_0-10} and ΔR_{SM_10-20} (Figure 4).

4 Discussion

4.1 Climate change

Inconsistent with the hypothesis, this study implies that climate change resulted in soil drying trends across the entire TP grassland region during the past 20 years. The finding is likely attributed to the elevated evapotranspiration triggered by climate warming offsets and even exceeds the water increase triggered by increased precipitation (Berg et al., 2017). These findings contradict previous studies that suggested a general increase in wetness across the TP grasslands in recent years (Lu and Liu, 2010; Diffenbaugh and Field, 2013). Moreover, this study also showed that the proportion of soil drying (≥43.40%) outweighed the proportion of drought trend based on precipitation (22.57%) in the TP grassland regions during the last 20 years. These discoveries indicated that previous assessments of climate humidity trends based solely on precipitation may have underestimated the extent of drying. It is important to note that precipitation does not always effectively support plant growth, and SM may be more associated with plant growth (Fu et al., 2018; Rigden et al., 2020).

Climate warming, changes in precipitation, and radiation can significantly affect SM in the TP grasslands. This finding is consistent with previous research (Yu et al., 2019; Fu and Shen, 2022; Han et al., 2023). Notably, the exclusionary effects of radiation change on SM emphasize the necessity of considering the impacts of radiation change on grassland ecosystems in addition to climate warming and decreased/increased precipitation, particularly on the TP. These exclusionary effects of radiation change on SM also align with some previous findings that demonstrated its notable impact on vegetation carbon use efficiency, plant physiological

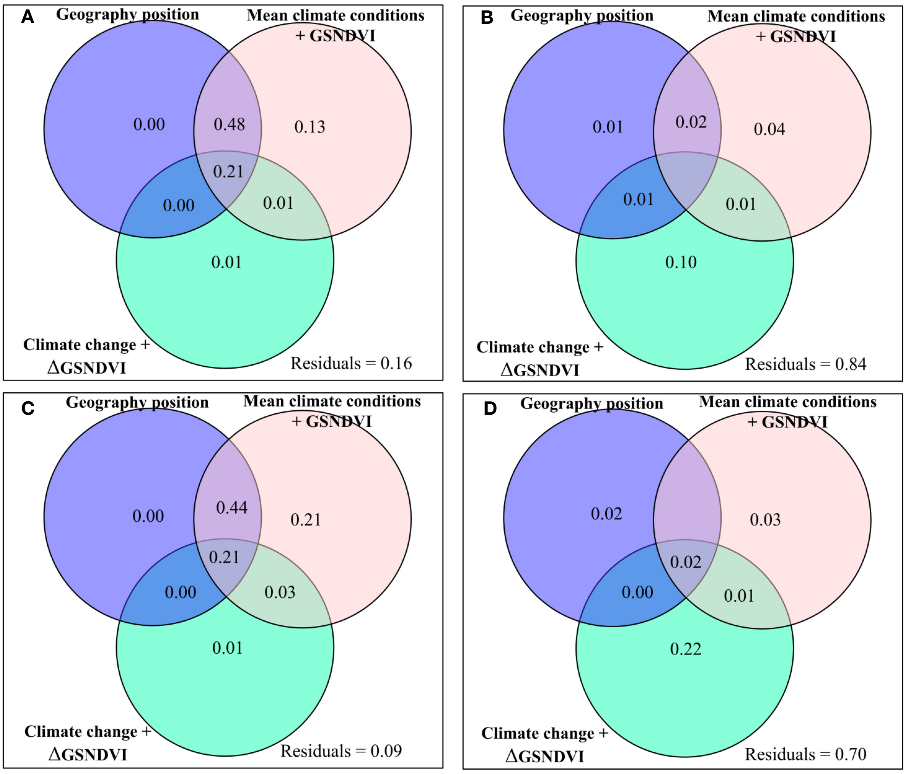

FIGURE 4
Relative influences of geographical position, mean climate conditions + GSNDVI, and climate change + slope_GSNDVI to **(A)** R_{SM_0-10}, **(B)** ΔR_{SM_0-10}, **(C)** R_{SM_10-20}, and **(D)** ΔR_{SM_10-20}.

characteristics, forage nutritional quality, and storage on the TP (Fu et al., 2016; Fu et al., 2022; Li and Fu, 2023).

This study shows that climate change had non-linear effects on SM in the TP grassland areas. This aligns with previous studies (Shen et al., 2015; Fu et al., 2018) and can be attributed to several underlying mechanisms. First, it is essential to consider that SM holding capacity is not infinite and that there exists a state of soil saturation where the soil cannot hold more water. Although increased precipitation can initially lead to an increase in SM, the point of saturation will eventually be reached, and further increases in precipitation will not result in additional gains in SM (Shen et al., 2015; Fu et al., 2018). The level of soil saturation is largely influenced by soil porosity, which, in turn, can be altered by factors such as plant growth and soil organic matter decomposition. These processes are directly or indirectly influenced by climate change (Fu et al., 2018; Zhang et al., 2022). Second, the influences of climate change on SM can be closely associated with the magnitude of climate change (Xu et al., 2013), local climate conditions (Fu and Sun, 2022), and geographical location (Zhang et al., 2021). Third, the influences of climate change on SM depend on their relative intensity of the influences of climate warming, increased/decreased precipitation, and dimming/brightening on SM. However, it is crucial to note that the influences of these factors on SM are not simply additive or subtractive effects in nature (Yu et al., 2019; Xiao et al., 2023).

This study shows that climate change had stronger negative effects on ΔSM_{p_10-20} than ΔSM_{p_0-10}. This is similar to previous studies (Rui et al., 2011; Berg et al., 2017; Dai et al., 2022), and several potential reasons contribute to this phenomenon. First, the dominant climate change factors affecting SM were different between soil depths under climate change scenarios (Figure S7). Second, the influences of climate change on SM were related to local water availability and warming magnitude (Rui et al., 2011; Xu et al., 2013). Both local SM and increase in soil temperature generally decrease with the increasing soil depth (Rui et al., 2011). Third, plant roots interspersed in soil pores draw water from water-bearing soil pores and generally decline with increasing soil depth (Berg et al., 2017). Although climate warming generally stimulates plant root growth and increases root biomass, such a boosting effect varies with soil depth (Fu et al., 2015).

This study shows that climate change resulted in the spatial relocation of SM across the TP grassland areas. This finding is consistent with previous studies (Wang et al., 2021a; Fu and Sun, 2022) and can be explained by one or more of the following reasons. First, significant spatial variations in the direction and amplitude of climate change have directly led to the spatial relocation of air temperature, precipitation, radiation, and wind (Huang and Fu, 2023). Moreover, because of such spatial heterogeneity of climate change, soil temperature and vapor pressure deficit can indirectly be relocated (Wang et al., 2021b; Han et al., 2022). Increases in wind speed, soil temperature, and vapor pressure deficit can generally elevate evapotranspiration, leading to a reduction in SM (Xu et al., 2013; Fu et al., 2018). Second, different species or function groups of plants may have diverse physiological water requirements, root growth depths, and phyllosphere microbes, indicating the change in plant growth, α-diversity, and community composition can also affect SM (Lian et al., 2020; Huang et al., 2023). Climate change can result in spatial relocation of plant growth and community structure (Wang et al., 2021a; Fu and Sun, 2022; Huang and Fu, 2023).

4.2 Human activity

In line with the hypothesis, this study shows that human activity strengthened the sensitivities of SM at 0–10 cm but weakened the sensitivities of SM at 10–20 cm to climate change. This is similar to previous studies (Rui et al., 2011; Zhang et al., 2020), and the underlying mechanism for this phenomenon is likely rooted in the fact human activity may have the capacity to either amplify or attenuate the influences of climate change on critical factors, including soil temperature, vapor pressure deficit, plant growth, and community structure (Wang et al., 2012; Fu and Shen, 2016; Li and Fu, 2023).

Furthermore, this study demonstrated that the influence of human activity on SM was related to soil depth. This is in agreement with previous studies (Sun et al., 2019). Several factors may account for this relationship. First, the growth of the human population has led to an increasing demand for groundwater, which serves as a vital supply of SM and is more proximate to the 10–20 cm soil layer. Second, the effects of human activity on soil temperature, bulk density, and root density are dependent on soil depth (Rui et al., 2011; Sun et al., 2019; Lai and Kumar, 2020).

In addition to soil depth, our study also indicated that the influence of human activity on SM varied from year to year (Figure 3), which aligned with findings from some previous studies (Sun et al., 2021; Zhang and Fu, 2021). This variability is likely attributable to at least one of the following factors. First, human activity can have cumulative influences on plant growth and community structure, etc. (Fu and Shen, 2016; Zhao et al., 2016; Gao and Carmel, 2020). Second, climate conditions can regulate the influence of human activity on SM (Figure S11), and climate conditions vary from year to year. Third, the intensity and extent of human activity also varied from year to year.

This study shows that human activity resulted in the spatial relocation of SM across the TP grassland ecological systems. This is in agreement with some previous studies (Zhang et al., 2020; Zhang and Fu, 2021). The underlying mechanisms for this phenomenon are likely rooted in at least one of the next causes. First, both the scope and intensity of human activity are spatiotemporal heterogeneous (Sun et al., 2019; Zha et al., 2022). For example, warm- and cold-season grazing may have diverse influences on SM (Sun et al., 2021; Zhang and Fu, 2021), and they exhibit spatial heterogeneity. Second, human activity may result in the spatial relocation of vapor pressure deficit, soil temperature, porosity, and compactness (Fu et al., 2012; Fu and Shen, 2016). Third, influences of human activity on SM were related to plant growth (Figures S11, S12), and human activity may result in spatial relocation of plant growth (Fu et al., 2022; Zha et al., 2022; Li and Fu, 2023). Moreover, human activity can also result in spatial relocation of plant α-diversity and community composition in TP grassland ecological systems (Sun et al., 2021; Zha et al., 2022).

5 Conclusions

This study represents the earliest investigation into the influences of both human activity and climate change on SM at 0–10 and 10–20 cm across the entire grasslands on the TP over the past 20 years. Our findings suggest that the impacts of human activity and climate change on SM were dynamic, varying with soil depth and geographical position. Notably, climate change resulted in topsoil drying of grassland areas on the TP as a whole, a phenomenon that previous research greatly underestimated. The effects of climate change on soil moisture are non-linear, with a stronger negative impact on SM at 10–20 cm than at 0–10 cm. Importantly, when compared to climate warming and precipitation change, radiation change exhibited significant exclusionary effects on SM, emphasizing the need for serious consideration of radiation change influences on SM. Additionally, human activity can modify the sensitivity of SM to climate change. Both human activity and climate change can contribute to the spatial relocation of SM.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

JX: Writing – original draft. CY: Writing – original draft. GF: Writing – original draft, Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1264870/full#supplementary-material

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