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Interactive comment on “Effects of soil water content on carbon sink strength in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau”

Junqi Wei, Xiaoyan Li, Lei Liu, Torben Røjle Christensen, Zhiyun Jiang, Yujun Ma,
Xiuchen Wu, Hongyun Yao, Efrén López-Blanco

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We appreciate you and reviewers for the valuable and constructive comments. We have carefully considered them all and changed our manuscript accordingly. In the following, we include a point-by-point response to the reviewers #1 and #2, and attached a marked-up manuscript version showing the differences to the initially submitted version. Please note that the line numbers point to the non-marked manuscript.

Interactive comment on “Effects of soil water content on carbon sink strength in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau” by Wei et al.

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Response to Comments of Referee #1

Wei et al. reports that “Effects of soil water content on carbon sink strength in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau”. This study investigated the diurnal, seasonal and annual variability of CO_2 fluxes and their drivers in an alpine swamp on the northeastern Tibetan Plateau. This helps to more clearly understand the role of alpine swamp in alpine ecosystem carbon (C) cycling in Tibetan Plateau, because alpine swamp cycling in Tibetan Plateau is less focused at regional scale, compared with alpine steppe and alpine meadow. The text is well-written and clear. Nevertheless, I have reservations about the innovation of scientific questions and the reliability of some results that need to be addressed before the publication of this manuscript.

We thank Reviewer #1 for taking the time to assess our manuscript and for providing general positive comments and main concerns. We believe the comments have helped to improve the manuscript and we carefully considered them. Here specifically we clarify the innovation of our scientific questions addressed in this study. As REF#1 pointed out, alpine swamps in Tibetan Plateau are less focused at regional scale than alpine steppes and alpine meadows. This study highlights among other things the importance of soil water availability regulating carbon sink strength of an alpine swamp, which is characterized by saturated water condition and high soil water content (SWC). The role of soil water has often been neglected or assumed to be less important relative to other factors for carbon (C) cycling. This study provides a four-year field observation dataset to characterize and quantify the importance of soil water controlling the C sink strength of an alpine swamp – one key finding is that a 15% decrease in soil water can induce 25% higher respiration and therefore weaken C sink strength by 20%, and an additional 44% increase of temperature at annual scale can also weaken the C sink strength by about 50% (see answer to comment number 4). These new insights will help us to better understand, model and predict the complex C cycle dynamics in the Tibetan Plateau driven by the almost certain future intensified climate warming.

1. The experimental site is located at Haibei in the northeastern Tibetan Plateau. According to Wei et. al (2021), there are at least six eddy covariance sites at Haibei, including alpine swamp CO2 fluxes monitoring site. Haibei is the most densely distributed area of eddy covariance sites on the Tibetan Plateau. The strength of CO_2 sink and its diurnal, seasonal and interannual characteristics in alpine swamp at Haibei have been reported in previous publications, such as Zhao et al. (2005) and Zhao et al. (2010), yet it is also the first objective of this study. Thus, the innovation of the objective is not clear to me.

We appreciate REF#1 for sharing this very useful information about other existing eddy covariance sites and related references. We have now cited these previous studies in the revised manuscript see L76 and L77. According to Wei et al. (2021), there are six observational studies about C fluxes at Haibei. However, only three of them focused on alpine swamp meadows (or wetland in Wei et. al (2021)). Among them, one study only focused on a 1-year dataset (Zhang et al., 2008), and the other two characterized the same location (Zhao et al., 2005, 2010). Moreover, these alpine swamp meadows were reported as a net C source while we our site showed a consistent C sink. The different directions of C exchange suggest that there are still uncertainties in our understanding of C exchange in this alpine swamp meadows, and further insights are obtained from studying multiple years of observations. Therefore, further efforts are still needed to improve our projection of C balance change of this ecosystem under changing climate.

Additionally, as mentioned before, previous studies focusing on C fluxes in alpine swamp meadows did not give enough consideration to the effects of soil water content on C fluxes given their nearly saturated nature. A number of previous studies have shown that temperature is an important driver of ecosystem respiration in similar alpine swamp meadows. For example, in the papers from Zhao et al. (2010) and Zhao et al. (2005), the authors showed that ecosystem respiration follows the exponential variation of soil temperature without considering soil water content. Zhu et al. (2020) also suggested that soil temperature plays the most important role in the change of monthly ecosystem respiration in the alpine wetland at Luanhaizi, northeastern Qinghai-Tibet Plateau. Therefore, in this study, we wanted to characterize and estimate the terrestrial C exchange while considering the potential effects of soil moisture. Meanwhile, it should be noted that Zhao et al. (2010) also noticed that the CO_2 emission rates decrease notably after rain events, and Zhu et al. (2020) confirmed that annual precipitation exhibits significant impact on variation of annual net C uptake. All these existing studies have suggested that C fluxes are related to water availability condition, but few studies have found that soil moisture explicitly affects respiration, and its decrease further reduces net C uptake in alpine swamp meadows, this finding could be an important factor for carbon modelling in the future.

Finally, the addition and further analysis of multiple years of data from new sites is always very important also in a more regional/global context - there is a generalized sparsity of in situ observations where their temporal and spatial coverage is very limited. We believe that any effort and addition to this generalized lack of in situ data will be useful for both flux communities such as FLUXNET and ASIAFLUX and modelling community in general.

2. The main drivers of NEE variation based on the different approaches are contradictory in this study. Net radiation is the leading factor affecting seasonal and annual variability of NEE based on machine learning approach (Fig. 5, Lines 231-250). However, the combined

effect of temperature and soil moisture change is the main factor influencing the annual variation of NEE in Section 4.3 and Table 2. The title of this manuscript only emphasizes the effect of soil moisture. Therefore, there are three different descriptions of the dominant factor of CO_2 sink in this manuscript. The mechanism underlying NEE variation needs to be more rigorously analyzed.

Thank you for this insightful comment. Our first draft didn't present the findings clearly and it was somewhat misleading. First of all, we should acknowledge that the original title did not fully reflect our conclusions, therefore we revised it as follows:

> *"Radiation, soil water content, and temperature interactions with carbon cycling in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau".*

In the S4.3, we intend to put our results into a broader context by comparing with other surrounding alpine swamp meadow sites to highlight the effects of the complex interactions between temperature and soil water content on carbon fluxes. In this section, we did not intend to explicitly disentangle the most important drivers for the NEE at annual scales among these different sites, given that detailed observations for net radiation are lacking for other sites. Such comparison highlights the importance of SWC (precipitation as a proxy for SWC as explicit SWC is not present in these either) in controlling NEE. This further validates our Random Forest (RF) findings regarding the drivers for the Re in our site (Figure 5). We should keep in mind that NEE is the difference between Re and GPP, environmental variables affecting Re and GPP could affect NEE indirectly (Song et al. 2011). We revealed that the main drivers for the GPP, Re and NEE are remarkably different. Net radiation is a key driver of seasonal and annual NEE and GPP, while soil water content is most important for Re at diurnal, seasonal and annual scales. Therefore, our findings from the RF analyses are not contradictory to the discussions regarding the difference in NEE and the potential influence factors among different sites.

However, your constructive comments point out an interesting scientific issue regarding the divergent drivers for the NEE dynamics at different time scales across different alpine swamp meadow sites. This will be an excellent point to be addressed in our future study.

3. A key conclusion of this study is that ecosystem respiration (Re) increases with decreasing soil water content (SWC). This is based on the comparisons of Re and SWC observations in the late growing seasons of 2014 and 2015 (Section 4.1). However, both SWC and Re in the late growing season are largest in 2017 during the observational period (2014-2017) (Figs. 2 and 4). Thus, the conclusion of "Section 4.1 Low soil moisture is associated with enhanced ecosystem respiration" (Lines 262-312) is likely to be unreliable. All observational years (2014, 2015, 2017 and 2018) are recommended to be considered in the analyses, rather than only two years (2014 and 2015).

Many thanks for this comment - we have not clearly described the comparisons in S4.1 between years in the text. Since C fluxes are affected by plant phenology and climate factors including temperature, soil moisture, and radiation simultaneously (Figure 5), in order to analyze the effects of single factor, ideally, other factors need to be identical or at least close (no significant differences). Based on this theory, we made our comparisons of specific time periods other than all the observation time. We now explicitly implemented the following text in S4.1, L293-298:

> *"Since C fluxes are affected by plant phenology and climate factors, including temperature, soil moisture, and radiation simultaneously (Fig. 5), to analyze the effect of a single factor, ideally, other factors need to be identical or at least close (no significant differences). Based on this theory and to better understand the underlying mechanisms around how SWC interacts with the C fluxes in the studied alpine swamp meadow ecosystem, we selected a specific group of data for further evaluation other than the entire observation time. "*

As described in S2.4, L177-185, we chose explicitly 2014 and 2015 for comparison in S4.1 because there was not a significant change in temperature (<1%) between these two periods, while soil water content decreased significantly more (15.4%) in 2015 (see Table S2). Therefore, within this set of conditions we can compare the influence of soil water content reduction on Re, and its influence further over NEE. Similarly, in S4.2, we also chose 2014 and 2018 for comparison, because the temperature difference between these two periods was greatest (25%) while there was no significant difference in soil water content (0.1%) (see again Table S2), so we could isolate and study the impact of temperature increase over the C fluxes.

Although the soil water content and ecosystem respiration in 2017 were at their highest, the temperature was also higher than in 2015, so we cannot compare it with 2015 to study separately the influence of soil water content change on ecosystem respiration and further net C uptake. To clarify this, we included a more detailed explanation about this comparison in the revision, see S2.4, L177-185:

> *"To further analyse the effect of soil moisture, radiation, and temperature on C fluxes, we selected two groups of time stamps with a significant difference in SWC but almost identical Ta and Rn (i.e. late growing season of 2014 vs 2015) and a significant difference in Ta but almost identical SWC and Rn (i.e. late growing season of 2014 vs 2018). Additionally, in order to analyse the effect of annual temperature on C fluxes, we selected a group of time stamps with significant differences in Ta but almost identical SWC and Rn (i.e. 2017 vs 2014, and 2018 vs 2014). We made the comparison in each group to exclude the influence of plant phenology, which can influence C fluxes significantly. The magnitude of the differences between C fluxes in the same group were analysed by the independent-sample T-test method."*

Please note also that we included a new column with net radiation to complement the comparison and expand the discussion in order to improve the manuscript's clarity and align better with RF findings, this is including also radiation as suggested by REF#1 indirectly in the earlier point but also explicitly suggested by REF#2 later on.

Table S2. Seasonally aggregated environmental drivers and C fluxes in the late growing season of 2014, 2015, and 2018 and their relative difference between years.

Period	Ta (°C)	Rn (W m^{-2})	SWC (%)	NEE (g C m^{-2})	Re (g C m^{-2})	GPP (g C m^{-2})
2014 Late GS	6.8±2.6	93.2±49.4	80.7±4.1	-175.6	152.7	328.3
2015 Late GS	6.8±2.5	93.2±43.6	68.3±4.3	-141.6	191.9	333.5
2018 Late GS	8.5±3.4	97.7±47.6	80.8±3.8	-134.3	225.4	359.7
2015 - 2014	0.8%	-0.1%	-15.4%	-19.4%	25.7%	1.6%
2018 - 2014	25%	4.8%	0.1%	-23.5%	47.6%	9.6%

Note: late GS represents late (Aug. - Sep.) growing season.

4. Another key conclusion of this study is that warming leads to higher C losses rather than enhanced C uptake. This is based on the comparisons of Re and GPP observations in the late growing seasons of 2014 and 2018 (Section 4.2). Warming decreases NEE in late growing season but this does not indicate that warming decreases annual NEE. Recently, Wei et al. (2021) found that "plant uptake of CO2 outpaces losses from permafrost and plant respiration on the Tibetan Plateau" at annual scale based on 32 eddy covariance sites in the Tibetan Plateau. Thus, the authors should more rigorously examine whether warming decreases net C sink of alpine swamp on the Tibetan Plateau.

This is a great point, thanks for bringing this up. In the revised manuscript, we added a new Table S4 to characterize the effect of temperature increase on net C uptake at annual basis and added more discussion accordingly. Based on a new variance analysis, soil water content in 2015 was significantly lower than in 2014, 2017, and 2018 ($p < 0.05$), while there was no significant difference in soil water content between 2014, 2017, and 2018, and there was also no significant difference in net radiation between these four years either. Therefore, we chose 2014, 2017, and 2018, when there was no significant difference in moisture conditions, to study the impact of temperature increase on C fluxes at an annual scale in the alpine swamp meadow. In fact, according to our data there was a reduction of net C uptake in warmer 2017 and 2018, and an increase of GPP and Re in 2017 and 2018 compared with 2014 (the increase of GPP is relatively lower than Re in warmer 2017 and 2018). Therefore, these extended results indicate that a temperature increase can decrease the net C uptake on an annual scale in this site. We added a new Table S4 in the supplement material:

Table S4. Daily aggregated environmental drivers and C fluxes in 2014, 2017, and 2018.

Year	Ta (°C)	Rn (W m^{-2})	SWC (%)	NEE (g C m^{-2})	Re (g C m^{-2})	GPP (g C m^{-2})
2014	-0.9 ± 8.2	72.2 ± 52.9	47.8 ± 32.0	-240.3	561.1	801.4
2017	-0.5 ± 8.3	73.4 ± 53.7	50.2 ± 32.8	-117.6	959.3	1076.9
2018	-0.5 ± 9.1	74.7 ± 54.9	49.8 ± 31.6	-113.4	788.4	901.8
2017-2014	44.4%	1.7%	5.0%	-51.1%	71.0%	34.4%
2018-2014	44.4%	3.5%	4.1%	-52.8%	40.5%	12.5%

We further added the following text in Section 4.2, L337-343:

> *"To evaluate if this finding is also consistent at an annual scale, we further analyzed annual aggregated data. An annual comparison was made between 2014, 2017, and 2018 when SWC were found insignificantly different while temperatures in 2017 and 2018 were 44.4% higher than in 2014 (Table S4). Additionally, this 44.4% increase in Ta in 2017 and 2018 both led to stronger GPP and Re (Table S4). Although both GPP and Re increased, the intensity in Re was greater than GPP, indicating that warmer temperatures have a stronger impact on ecosystem respiration in this site, resulting in an approximately 50% decrease of the net C uptake (Table S4). "*

We thank REF#1 for pointing us towards this nice paper by Wei et al., 2021 *"Plant uptake of CO_2 outpaces losses from permafrost and plant respiration on the Tibetan Plateau"*. We benefited a lot from this paper. The conclusion from Wei et al. (2021) are based on data of 32 eddy covariance sites during 2002 to 2020, while our study only covers 4-years of year-round observations. Differences in time and space scales may help to explain the differences we found. In fact, in the figure 4 from Wei et al. (2021) there are specific sites from Haibei where RR_{NEP} (Response ratio of NEP to the warming rate) is smaller than 1.0, indicating a negative effect of warming on the NEP. Potential site-specific differences together with the particularity of water condition in of alpine swamp ecosystem could be the possible reason. We have added more text in the discussion section S4.2, L354-360.

> *"Wei et al. (2021) also found that the uptake of C by plants will exceed the amount of C release under warmer and wetter climate conditions at an annual scale based on manipulative experiments and model simulations focused on the Tibetan Plateau. Their study is based on a longer-term trend while our study only covers 4-years of year-round observations thus site-specific differences in time and space scales may explain this variability. Nevertheless, such results indicating inconsistent ecosystem responses suggest that there are still large uncertainties regulating the responses of C fluxes to temperature variation and further work is still crucial. "*

Specific comments

1. Line 26, "-168.0 ±-62.5" may should be "-168.0 ± 62.5".

Typo, thanks for picking it up. Changed accordingly.

2. Lines 75-76, "only a few experiments have been conducted to specifically characterise alpine swamp meadow ecosystem C dynamics.", but no study focusing on alpine swamp C cycling is mentioned at here. The previous studies focusing on alpine swamp CO2 fluxes in the Tibetan Plateau are recommended to be mentioned, such as alpine swamp CO2 fluxes observations at Haibei (Zhao et al., 2005, 2010), Shenzha (Qi et al., 2021), Nam Co (Liu et al., 2020), and Huanhaizi (Zhu et al., 2020).

References

Liu, Y., Geng, X., Tenzintarchen, Wei, D., Dai, D. and Xu, R., 2020. Divergence in ecosystem carbon fluxes and soil nitrogen characteristics across alpine steppe, alpine meadow and alpine swamp ecosystems in a biome transition zone. Science of the Total Environment, 748. 10.1016/j.scitotenv.2020.142453.

Qi, Y., Wei, D., Zhao, H. and Wang, X., 2021. Carbon sink of a very high marshland on the Tibetan Plateau. Journal of Geophysical Research-Biogeosciences, 126 (4). 10.1029/2020jg006235.

Wei, D., Qi, Y., Ma, Y., Wang, X., Ma, W., Gao, T., Huang, L., Zhao, H., Zhang, J. and Wang, X., 2021. Plant uptake of CO2 outpaces losses from permafrost and plant respiration on the Tibetan Plateau. Proceedings of the National Academy of Sciences of the United States of America, 118 (33). 10.1073/pnas.2015283118.

Zhao, L., Li, J., Xu, S., Zhou, H., Li, Y., Gu, S. and Zhao, X., 2010. Seasonal variations in carbon dioxide exchange in an alpine wetland meadow on the Qinghai-Tibetan Plateau. Biogeosciences, 7 (4): 1207-1221. 10.5194/bg-7-1207-2010.

Zhao, L., Li, Y.N., Zhao, X.Q., Xu, S.X., Tang, Y.H., Yu, G.R., Gu, S., Du, M.Y. and Wang, Q.X., 2005. Comparative study of the net exchange of CO2 in 3 types of vegetation ecosystems on the Qinghai-Tibetan Plateau. Chinese Science Bulletin, 50 (16): 1767-1774. 10.1360/04wd0316.

Zhu, J., Zhang, F., Li, H., He, H., Li, Y., Yang, Y., Zhang, G., Wang, C. and Luo, F., 2020. Seasonal and interannual variations of CO2 fluxes over 10 years in an alpine wetland on the Qinghai-Tibetan Plateau. Journal of Geophysical Research-Biogeosciences, 125 (11). 10.1029/2020jg006011.

Thank you very much for this very useful information concerning previous studies including sites focusing on alpine swamp CO_2 fluxes. Following the recommendation from REF#1 we have cited these previous studies and updated the description in the revised manuscript to further highlight the novelty of this study, S1, L75-78:

> *"Although many studies concerning ecosystem C dynamics on the QTP have focused on alpine meadow ecosystems (Saito et al., 2009; Zhao et al., 2005, 2010; Zhu et al., 2015b) and alpine swamp meadow ecosystems (Zhao et al., 2005, 2010; Qi et al., 2021; Liu et al., 2020; Zhu et al., 2020), the effect of SWC on the C uptake is still unclear as compared to that of temperature for alpine swamp meadow ecosystems. "*

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Interactive comment on "Effects of soil water content on carbon sink strength in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau" by Wei et al.

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Response to Comments of Referee #2

Wei et al. did an interesting job about carbon balance of an alpine swamp meadow on the Qinghai-Tibet plateau, enriching the dataset of carbon fluxes in alpine wetland. This study highlights that decreasing in soil water content in this wetland ecosystem can stimulate ecosystem respiration significantly and weaken ecosystem carbon sink strength as a result. The writing is good and data processing is reasonable. Some major concerns in data interpretation should be addressed.

We are thankful for the reviewer's insightful comments that have improved the manuscript. We have carefully considered the reviewer's remarks and clarified our manuscript accordingly.

Major Comments:

1. In section 3.3, radiation has been identified as the main driver for the variation of GPP and NEE, and air temperature as the second force. However, in section 4.2 and 4.3, only the role of air temperature is discussed through the comparison of different study periods and different studies. This may confuse the reader because the main driver for NEE seems inconsistent in the Result and Discussion section. The authors may want to highlight the role of warming on carbon fluxes, but a statement or discussion on radiation is necessary to make the manuscript with good clarity.

Thanks for your useful comments. We therefore added the following text accordingly at the beginning of the Discussion section, L265-275:

> "*Since NEE is the difference between Re and GPP, environmental variables affecting Re and GPP could affect NEE indirectly (Song et al., 2011). Radiation affects the magnitude of plant*

photosynthesis and controls temperature, one of the key factors related to C fluxes. This suggests that abundant radiation benefits photosynthesis and respiration and thus directly affects the C sink strength in the alpine wetland ecosystem of the Qinghai Lake (Cao et al., 2017). Niu et al. (2017) show that 99% of the interannual variation of NEE in an alpine swamp meadow can be well explained by temperature conditions, precipitation and radiation. The results of this study demonstrate that ecosystem C sequestration is regulated not only by radiation and temperature but also by soil moisture in the alpine swamp meadow site studied herein. Given there is no significant difference in net radiation between the four years we studied, the effects of soil water content and temperature on C fluxes on diurnal, seasonal, and annual scales are therefore discussed in detail below."

Please note that further implementations including radiation numbers and discussion were made in the following points. But please also note that also the original title has been revised to reflect REFS#2 and #1 points:

> *"Radiation, soil water content, and temperature interactions with carbon cycling in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau".*

2. In section 4.1, two groups of data (the late growing season of 2014 and 2015) were used to analyze the effects of soil moisture on carbon fluxes. Although the authors declared that air temperature and phenology of these two periods were comparable, I could not find information about radiation of these two periods. As radiation has already been concluded as a main driver for the variation of GPP and NEE in the Result section, it is critical to build the comparison based on comparable radiation, or the results can be pointless. The same issue goes for the comparison between the late growing season of 2014 and 2018 in section 4.2 (L322-324).

We appreciate this comment about the comparisons in S4.1 and S4.2. The REF#2 is right, we did not present the values of net radiation (Rn) in the original comparison because there was no significant difference in Rn between these compared periods. However, following the referees' advice, we have now added radiation number to Table S2 that are addressed and discussed in S4.1 and S4.2.

Table S2. Seasonally aggregated environmental drivers and C fluxes in the late growing season of 2014, 2015, and 2018 and their relative difference between years.

Period	Ta (℃)	Rn (W m^{-2})	SWC (%)	NEE (g C m^{-2})	Re (g C m^{-2})	GPP (g C m^{-2})
2014 Late GS	6.8±2.6	93.2±49.4	80.7±4.1	-175.6	152.7	328.3
2015 Late GS	6.8±2.5	93.2±43.6	68.3±4.3	-141.6	191.9	333.5
2018 Late GS	8.5±3.4	97.7±47.6	80.8±3.8	-134.3	225.4	359.7
2015 - 2014	0.8%	-0.1%	-15.4%	-19.4%	25.7%	1.6%
2018 - 2014	25%	4.8%	0.1%	-23.5%	47.6%	9.6%

Note: late GS represents late (Aug. - Sep.) growing season.

We further edited the text in S2.4, L177-185 to include radiation not only in this comparison, but also in an additional test looking specifically at annual data following REF#1 comment, number 4 (covered above). REF#1 was not convinced about the conclusion addressed in S4.2 regarding *"Temperature increase leads to higher C losses rather than enhanced C uptake"* - the referee suspected that our claim about warming decreasing NEE in late growing season do not necessarily indicate that warming can decrease annual NEE. Therefore, in order to address this point, we also added a new test to confirm our previous finding (S2.4, L177-185):

> *"To further analyse the effect of soil moisture, radiation, and temperature on C fluxes, we selected two groups of time stamps with a significant difference in SWC but almost identical Ta and Rn (i.e. late growing season of 2014 vs 2015) and a significant difference in Ta but almost identical SWC and Rn (i.e. late growing season of 2014 vs 2018). Additionally, in order to analyse the effect of annual temperature on C fluxes, we selected a group of time stamps with significant differences in Ta but almost identical SWC and Rn (i.e. 2017 vs 2014, and 2018 vs 2014). We made the comparison in each group to exclude the influence of plant phenology, which can influence C fluxes significantly. The magnitude of the differences between C fluxes in the same group were analysed by the independent-sample T-test method."*

And in S4.2, L337-343:

> *"To evaluate if this finding is also consistent at an annual scale, we further analyzed annual aggregated data. An annual comparison was made between 2014, 2017, and 2018 when SWC were found insignificantly different while temperatures in 2017 and 2018 were 44.4% higher than in 2014 (Table S4). Additionally, this 44.4% increase in Ta in 2017 and 2018 both led to stronger GPP and Re (Table S4). Although both GPP and Re increased, the intensity in Re was greater than GPP, indicating that warmer temperatures have a stronger impact on ecosystem respiration in this site, resulting in an approximately 50% decrease of the net C uptake (Table S4). "*

3. The comparison between the late growing season of 2014 and 2015 shows that drought in 2015 stimulated Re noticeably (L279-282). However, the differences in GPP between these two periods are not significant (L290), the authors should be more careful to make the statement that high soil water content would suppress GPP (L287-295). Figure 5 shows that the contribution of soil water content to the variation of GPP is small on all the time scales.

The referee is fully right, thanks for pointing to this issue. We agree that our data do not support the potential suppressing effect of SWC on GPP, as since this paragraph is not central to the overall storyline, we have removed the text below as well as the references from the revised manuscript to improve clarity:

> *"There is evidence that excessive soil water can negatively affect plant physiological and ecological processes by, for example, insufficient supply of metabolic substrates and the production of toxic substances (Jackson and Colmer, 2005), which may reduce the overall plant photosynthetic efficiency (Xu and Zhou, 2011). Although there was no significant difference between the late growing season GPP of 2015 and 2014 in terms of both daily accumulated GPP and diurnal rates of GPP, the decline observed in SWC during September 2015 (the driest month with 65.1% SWC) led to a 11% increase of daily accumulated GPP (Fig. S1; Table S3). The excess of SWC in 2014 caused an inundation of the aboveground plant domain, which also likely contributed to the lower value in GPP by reducing plant photosynthetic efficiency (Cronk et al., 2001; Hirota et al., 2006). Since the increase of GPP*

> *could not offset the increase in Re, September 2015 and the late growing season of 2015 experienced a lower C sink strength."*

4. The authors concluded that warming would weaken carbon sink strength in this alpine swamp meadow ecosystem because it would increase Re more than GPP. The authors also pointed out that other studies have reported opposite results that warming would stimulate GPP more than Re. However, these studies were conducted in different ecosystems, such as Arctic marshlands and Arctic tundra (L334-341). A discussion that focuses on alpine swamp meadow would be more worthwhile for understanding the effects of climate warming on carbon balance of alpine wetland ecosystem.

Thank you very much for comment. Now we have now removed the discussion around different ecosystems and replaced it with the following paragraph in S4.2, L352-360:

> " *Liu et al. (2018) concluded that warming has a significant inhibitory effect on GPP and minor effect on Re, resulting in a weaker carbon sequestration capacity of their studied alpine wetland ecosystem. Wei et al. (2021) also found that the uptake of C by plants will exceed the amount of C release under warmer and wetter climate conditions at an annual scale based on manipulative experiments and model simulations focused on the Tibetan Plateau. Their study is based on a longer-term trend while our study only covers 4-years of year-round observations thus site-specific differences in time and space scales may explain this variability. Nevertheless, such results indicating inconsistent ecosystem responses suggest that there are still large uncertainties regulating the responses of C fluxes to temperature variation and further work is still crucial. "*

Specific Comments:

1. The font of 'CO2' in the draft should be the same as others.

Corrected accordingly.

2. Potentilla in Line 96 and Kobresia in L121 should be italic.

Thanks! Corrected accordingly.

3. **L174-175: what do you mean by 'this is one random forest per hour of the day, day of the year and *year, respectively'?***

We apologize for not been clear. In order to run random forest (RF) diurnally, seasonally and annually, we needed to aggregate the data as revised below in S2.4, L175-176:

> *"we ran multiple random forests with growing season data binned per hour of the day, day of the year and year, respectively (Table S1). "*

4. Figure 4 and Figure 5 should have tags.

Changed accordingly.

5. L373-379: The stronger C sink strength is first attribute to saturated soil condition rather than lower temperature, but then to higher precipitation and lower temperature.

Thank you very much for pointing this out. As the rest of sites included in Table 2 do not have all available SWC data, in S4.3 we used precipitation as a proxy for soil moisture (see L378-379: "*we examined the temperature and precipitation (as a proxy for SWC) impacts on NEE (Liu et al., 2016).*"). This reasoning is consistent with our data; for example, in Figure 2b it is clear that when precipitation is low in 2014 in e.g. August and October compared to other years, SWC decreased significantly.

We further clarified in the text S4.3, L393-398:

> "*This is likely a result of the inhibiting effects of the nearly-saturated soil condition over soil respiration rather than by the lower temperatures (Sun et al., 2021). Therefore, in permanently or seasonally inundated swamp meadows, high SWC may have triggered lower C loss rates further benefiting C preservation. At our site, the higher C sink strength was likely attributed to higher precipitation (and therefore higher SWC) and lower temperature, which created colder and more humid conditions than other sites (Table 2).* "

6. The data supports the opinion that soil water content is a key control on ecosystem respiration, but soil water content does not affect the overall C sink strength (i.e., NEE) directly.

Agreed, we deleted the words "*and the overall C sink strength*" from the conclusion. Now the sentence was changed to *"Soil moisture, however, has the largest influence over Re variability on diurnal, seasonal, and interannual scales, suggesting that soil water content is a key control on ecosystem respiration. "*.

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Radiation, soil water content, and temperature interactions with carbon cycling in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau~~Effects of soil water content on carbon sink strength in an alpine swamp meadow of the northeastern Qinghai-Tibet Plateau~~

Junqi Wei[1,2], Xiaoyan Li[1,2,3,4], Lei Liu[5,6], Torben Røjle Christensen[7,8], Zhiyun Jiang[9~~8~~], Yujun Ma[10~~9~~], Xiuchen Wu[1,2], Hongyun Yao[1,2], Efrén López-Blanco[11~~0~~, 7]

1 State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

2 School of Natural Resources, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

3 Academy of Plateau Science and Sustainability, People's Government of Qinghai Province & Beijing Normal University, Qinghai Normal University, Xining 810008, China

4 Key Laboratory of Tibetan Plateau Land Surface Processes and Ecological Conservation, Ministry of Education, Qinghai Normal University, Xining 810016, China

5 Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

6 College of Resources and Environment, University of Chinese Academy of Sciences, Yuquanlu, Beijing 100049, China

7 Department of Bioscience, Arctic Research Center, Aarhus University, Roskilde 4000, Denmark

8 Oulanka Research Station, Oulu University, Finland

9~~8~~ School of Geography, South China Normal University, Guangzhou 510631, China

10~~9~~ School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China

11~~0~~ Greenland Institute of Natural Resources, Department of Environment and Minerals, Nuuk 3900, Greenland

Corresponding to: Xiao-Yan Li (xyli@bnu.edu.cn)

Abstract. Predicted intensified climate warming will likely alter the ecosystem net carbon (C) uptake of the Qinghai-Tibet Plateau (QTP). Variations in C sink/source responses to climate warming have been linked to water availability; however, the mechanisms by which net C uptake responds to soil water content in ~~water-~~saturated swamp meadow ecosystems remain unclear. To explore how soil moisture and other environmental drivers modulate net C uptake in the QTP, field measurements were conducted using the eddy covariance technique in 2014, 2015, 2017, and 2018. The alpine swamp meadow presented in this study was a consistent and strong C sink of CO_2 (-168.0 ± ~~-~~62.5 gC m^{-2} y^{-1}, average ± standard deviation) across the entire 4-year study period. A random forest machine-learning analysis suggests that the diurnal, seasonal, and annual variations of net ecosystem exchange (NEE) and gross primary productivity (GPP) were controlled by temperature and net~~solar~~ radiation. Ecosystem respiration (Re), however, was found mainly regulated by the variability of soil water content (SWC) at different temporal aggregations followed by temperature, the second contributing driver. We further explored how Re is controlled by nearly saturated soil moisture and temperature comparing two different periods featuring almost identical temperatures and significant~~ly~~ differences on SWC and vice versa. Our data suggest that, despite the relatively abundant water supply, periods with a substantial decrease of SWC or increase of temperature produced higher Re and therefore weakened~~lowering~~ the C sink strength. Our results reveal that nearly saturated soil conditions during the ~~warm~~growing seasons can help~~ to~~ maintain lower ecosystem respiration rates and thus enhance the overall C sequestration capacity in this alpine swamp meadow. We argue that climate warming in the future could change soil hydrological conditions of alpine swamp meadow through degrading permafrost or accelerating thawing-freezing cycling, therefore, having a direct effect on soil respiration and subsequent effect on ecosystem C sink magnitude.~~e.changes in soil hydrological conditions induced by a warming climate near permafrost (or seasonal frozen layers) may affect the C sink magnitude of wet and cold ecosystems through changes in soil hydrology and the subsequent effect on respiration losses~~

1. Introduction

Wetlands play a significant role in the global carbon (C) cycle due to ~~the~~a large amount of C stored in their soils. The Qinghai-Tibet Plateau (QTP), with an average altitude of over 4,000 m a.s.l., has approximately 10×10^4 km^2 of natural wetlands, of which ~ 50% (4.9×10^4 km^2) are alpine swamp meadows. These ecosystems are predominantly located in permafrost areas and are typically soil nutrient-rich and water-logged (Bai et al., 2019; Zhao et al., 2005). Climate change and human disturbance can have profound consequences on permafrost regions (Biskaborn et al., 2019) and significantly impact their hydrological regimes (Lafrenière and Lamoureux, 2019). Hydrological regimes have an important role in controlling wetland functioning (Bohn et al., 2007; Christensen et al., 2003), and the changes of hydrological regimes may put the wetland functioning of the QTP under pressure (Hruby, 1999; Woodward and Wui, 2001; Foti et al., 2013).

The QTP is forecasted to be warmer and wetter in the future (Chen et al., 2015; Cheng et al., 2011). Warming may accelerate the microbial breakdown of alpine soil organic C and subsequently increase CO_2 emissions (Zhu et al., 2015a). Warming could also improve C sequestration capacity by enhancing the photosynthetic inputs and growth rates of alpine plants (Fu et al., 2015). Therefore, the potential increase of CO_2 emissions due to warming in alpine regions could be partially offset by enhanced C uptake (Schuur et al., 2009), triggering different net C uptake responses to climate warming. For example, an increase in temperature in the QTP has been associated with net C sinks in the Zoige alpine wetlands (Kang et al., 2014) but also with net C sources in the Damxung alpine swamp meadow (Niu et al., 2017).

According to recent studies in QTP alpine grasslands, water conditions such as soil water content (SWC) can be a key factor that changes water-use patterns and ecophysiological characteristics of alpine plants (Wu et al., 2019) and modulate the warming-mediated increase of ecosystem C uptake (Ganjurjav et al. 2016; Peng et al. 2014). Ecosystem C processes such as net C uptake and soil respiration may increase with SWC in dry environments, and decrease in water-logged environments (Quan et al., 2019; Taylor et al., 2017). Warming in conjunction with increased precipitation can turn an ecosystem from net source to a sink of C (Zhao et al., 2019), increasing both photosynthesis and respiration rates during warmer and wetter years (López-Blanco et al., 2017, 2018). However, when warming occurs in soils associated with low moisture, soil drought can change ecosystems from C sinks to sources (Ganjurjav et al., 2017). Studies in QTP alpine meadows have indicated that warming significantly stimulates ecosystem net C uptake in wet years but does not affect ecosystem net C uptake in dry years because the positive effects of warming on net C uptake are compensated by the negative effects of lower soil moisture (Peng et al., 2014).

Although many studies concerning ecosystem C dynamics on the QTP have focused on~~ the~~ alpine meadow ecosystems (Saito et al., 2009; Zhao et al., 2005, 2010; Zhu et al., 2015b)~~,~~ and~~only a few experiments have been conducted to specifically characterise ~~ alpine swamp meadow ecosystems (Zhao et al., 2005, 2010; Qi et al., 2021; Liu et al., 2020; Zhu et al., 2020)~~C dynamics~~, the effect of SWC on the C uptake is still unclear as compared to that of temperature for alpine swamp meadow ecosystems. Alpine swamp meadow ecosystems are characterised by high SWC, and it remains unclear whether a decrease in SWC would alleviate the stress from saturated water on net C uptake or aggravate drought effects. Given that these ecosystems have high soil moisture compared to typical alpine meadows, the effects of warming and water availability~~drying~~ on the future C sink strength of the QTP ecosystem remain uncertain~~unknown~~. These questions and uncertainties require a detailed investigation to understand wetland C source/sink processes and their future C sink strength variations (sign and magnitude). Therefore, the objectives of this study are to (i) quantify the diurnal, seasonal, and annual variations of net ecosystem exchange (NEE), gross primary productivity (GPP), and ecosystem respiration (Re), (ii) identify and quantify the relative importance of different key environmental drivers contributing to the variability observed of NEE, Re, and GPP, and (iii) analyse how these C fluxes respond to soil water availability, ~~key environmental drivers such as~~ temperature, and radiation~~or soil moisture~~ variation in a QTP alpine swamp meadow.

2. Materials and methods

2.1 Site description

The study site (37°35.75′ N, 100°00.47′ E, 3,571 m a.s.l.) is located in Gangcha County, Qinghai Province, in the north-eastern part of the QTP (Fig. 1(a)). The mean annual temperature and precipitation measured at the Gangcha National Weather Station were 0.1 °C and 389.4 mm between 1982 and 2011, respectively (Zhang et al., 2016). The site area has seasonal permafrost featuring frozen soils between January–March and November–December for a total of about 125–135 days (Zhang et al., 2014). The dominant species of the alpine swamp meadow ecosystem is~~are~~ *Kobresia pygmaea*, companied by~~along with~~ *Saussurea pulchra*, *Polygonum viviparum*, and *Potentilla saundersiana.* The average plant height at the experimental site is 7.4 ± 1.5 cm, with a 97 ± 2% coverage. Our study defined the growing season as the period between June and September. The early (June–July) and late (August–September) growing seasons, as they will be henceforth referred to, correspond with the early growing season and late growing seasons, respectively.

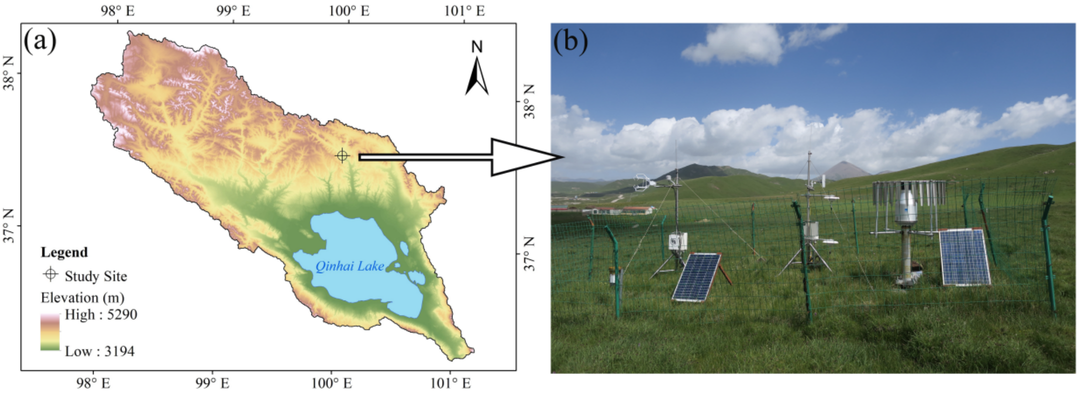


Figure 1. (a) Location of the study site in the Qinghai Lake basin in the northeastern part of the QTP. (b) Eddy covariance system measuring water and CO_2 fluxes between the land surface and the atmosphere in the alpine swamp meadow.

2.2 Field measurements

An Eddy Covariance (EC) system was installed at the study site (Fig. 1b) to measure the CO_2 fluxes at a sampling frequency of 10 Hz from 2014 to 2018. Data for 2016 was missing due to equipment malfunction. The EC system included an open-path CO_2/H_2O infrared gas analyser, which quantified fluctuations in water vapour and CO_2 fluxes. A 3-D sonic anemometer was ~~also~~ installed at a 2.0 m height above ground to directly measure horizontal and vertical wind velocity components (u, v, and w). C flux data were recorded with a data logger (Campbell Scientific Inc.). An automated meteorological station was installed near the EC station to measure meteorological variables such as air temperature (Ta; °C), precipitation (P; mm), net radiation (Rn; W m^{-2}), wind speed (WS; m s^{-1}), wind direction (WD; °), relative humidity (RH; %), and vapour pressure deficit (VPD; hPa). The meteorological data were collected at one-minute intervals and subsequently resampled at 30-minute timesteps to keep pace with the EC data. More details on the in-situ instrument specifications are summarised in Table 1.

Table 1 Information about the sensors installed in the alpine swamp meadow.

	Sensor Names	Sensor type	Installation height/depth	Manufacturer
Eddy Covariance	Open-path CO_2/H_2O infrared gas analyser	EC150	2.0 m	Campbell, US
	Three-dimensional sonic anemometer	CSAT3	2.0 m	Campbell, US
Meteorological observation	Net radiation	NR Lite	1.8 m	Kipp&Zonen, Netherlands
	Wind speed/direction	034B	2m	
	Air temperature/humidity	083E-1-6	0.5 m, 1.5 m	MetOne, US
	Atmosphere pressure	PTB110	In data acquisition box	Vaisala, Finland
	Rain-gauge	7852M-AB	0.7 m	Davis, US

Soil water content (SWC; %) were measured at depths of 10, 20, 40, 60, and 100 cm from the soil surface with EC-H_2O sensors (Decagon Devices, USA) at a 10-minute frequency. The precision of the EC-H_2O sensors for soil moisture measurements was ± 0.03 m^3 m^{-3}. As the roots of *Kobresia* meadows are mainly distributed within the top 20 cm of soil, we focused only on the variation of SWC in the top 20 cm of the soil.

2.3 Eddy Covariance data processing

The half-hourly NEE ~~of CO_2~~ data was calculated using the EddyPro software (version 5.2, LI-COR) from the 10-Hz raw data. During the calculation, three-dimensional rotation was used to correct the data by removing the effects of instrument tilt irregularity on airflow (Wilczak et al., 2001). Webb, Pearman, and Leuning (WPL) (Webb et al., 1980) correction was applied to calculate the averages of CO_2 covariance, rectifying the air density variations induced by heat and water vapour. The half-hourly flux data were quality-checked based on several filtering algorithms, including: (1) the rejection of outliers in sonic temperature, water vapour density, and CO_2 density (Li et al. 2008; Liu et al., 2011), (2) the elimination of data one hour before and after precipitation events (Li et al. 2008; Liu et al., 2011), (3) the removal of negative NEE during the non-growing season (from November to March) (Cao et al., 2017; Qi et al., 2021) attributed to the self-heating effect from EC instruments (Cao et al., 2017), and (4) the exclusion of measurements with weak turbulence conditions at night time. The weak turbulence periods were identified by bootstrapping friction velocity (u∗) thresholds, as described by Papale et al. (2006). This approach effectively divided the data into 4-year and 7-temperature subsets with similar micro-meteorological conditions (except for u*). The u* thresholds (5%, 50%, and 95% of bootstrapping) were calculated specifically per year and temperature subset.

Based on those different subsets, we gap-filled and partitioned NEE (into GPP and Re) to spread the uncertainty variability that emerged from the different u* thresholds, similar to López-Blanco et al. (2017). All missing data were marked as -9999 (no data). Negative and positive NEE values represent sink and source of C, respectively. Additionally, a standardised mechanism to fill NEE gaps is needed for adequate data processing (Moffat et al., 2007). Therefore, this study adopted the method described by López-Blanco et al. (2020) using the marginal distribution sampling (MDS) algorithm in the REddyProc gap-filling tool (Reichstein et al., 2016), which was readapted from Reichstein et al. (2005). Finally, NEE was separated into GPP and Re applying the REddyProc partitioning algorithm (Reichstein et al., 2016) for further analyses. This partitioning method is based on the exponential regression of night-time respiration with temperature using the Lloyd-Taylor-Function (Lloyd and Taylor, 1994). Night-time periods were selected via current combined solar radiation and potential radiation thresholds based on the exact solar time, latitude, and longitude. REddyProc estimates the temperature sensitivity from a short-term period~~,~~ and based on this short-term temperature sensitivity. ~~,~~ I~~i~~t estimates the reference temperature in the continuous period of the entire dataset. These estimates were then used to calculate Re for day-time and night-time, while GPP was estimated based on the difference between NEE and Re.

2.4 Identifying the importance of environmental drivers

In order to characterize how environmental conditions impact diurnal, seasonal, and interannual variability of NEE, GPP and Re at this alpine swamp meadow, we used a novel method based on machine learning.

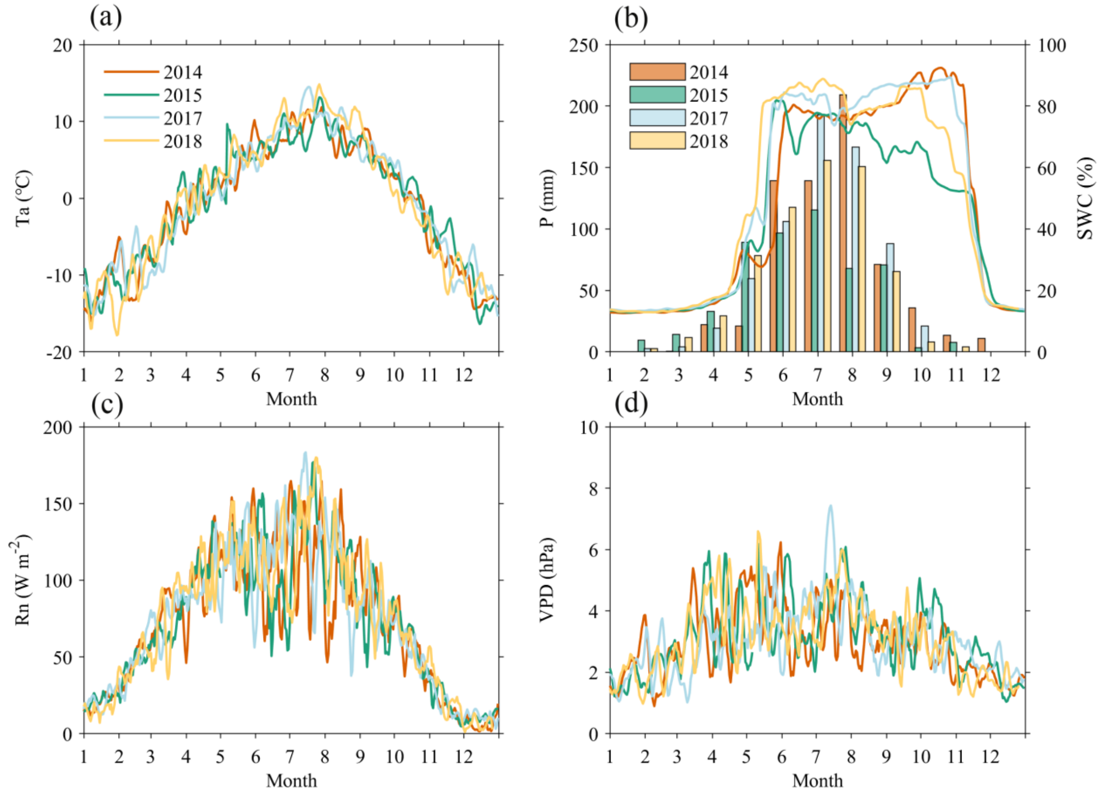
Random forest (Breiman, 2001) is a machine learning technique that can be used to quantify and interpret the contribution of environmental drivers (covariates) to the variability of different C fluxes (response variables) by combining multiple individual regression trees. This technique has been increasingly utilized to upscale global C fluxes from eddy covariance data (Zeng et al., 2020) but also to evaluate controls on C cycle processes (Zhang et al., 2017; López-Blanco et al., 2017, 2020). Here, we calculate the relative importance of air temperature (Ta), net radiation (Rn), soil water content (SWC) and vapour pressure deficit (VPD) controlling the C sink strength, photosynthesis, and respiration variability. This random forest algorithm constructs multiple (1000 in this analysis) decision trees during training time with different random subsamples (with replacement) from the same input training dataset. In each cluster classified by random forest, the algorithm generates a multiple linear regression to characterize different C fluxes as a function of environmental drivers (López-Blanco et al., 2017, 2020). This algorithm version (Pedregosa et al., 2011) estimates the relative importance of each covariate between 0 and 100%, which correspond to the fraction of decision participating during data clustering. We used the random forest algorithm to evaluate the diurnal, seasonal, and annual patterns of the relative importance of Ta, Rn, SWC, and VPD responsible for the variability of C fluxes. We used data from the June-September period aggregated per hour, and we ra~~u~~n multiple random forests with growing season data binned per hour of the day, day of the year and year, respectively (Table S1). ~~per hour of the day, day of the year, and year, respectively (Table S1).~~

~~In order to~~To further analyse the effect of soil moisture, radiation, and temperature~~SWC~~ on C fluxes, we selected two groups of time stamps with a significant difference in SWC but almost identical Ta and Rn~~same Ta~~ (i.e. late growing season of 2014 vs 2015) and a significant difference in Ta but almost identical SWC and Rn (i.e. late growing season of 2014 vs 2018). Additionally, in order to analyse the effect of annual temperature on C fluxes, we selected a group of time stamps with significant differences in Ta but almost identical SWC and Rn (i.e. 2017 vs 2014, and 2018 vs 2014). We made the comparison in each group to exclude the influence of plant phenology, which can influence C fluxes significantly. The magnitude of the differences between C fluxes in the same group~~during the same periods from different years~~ were analysed by the independent-sample T-test method.

3. Results

3.1 Meteorological variability

Mean daily meteorological variables including Ta, P, SWC, and Rn exhibited evident seasonal variability except for VPD; these variables increased progressively in the early growing seasons, reached their maximum in July and decreased gradually afterwards (Fig. 2(a), (b), (c), (d)). Air temperature during the growing season was 7.7 ± 2.6, 7.4 ± 2.6, 8.5 ± 2.9, and 9.2 ± 3.3 °C in 2014, 2015, 2017, and 2018, respectively while precipitation totalled 662.8, 521.4, 661.2, and 624.3 mm for the same years, falling primarily during the growing season. The precipitation measured during the late growing season of 2015 was only half of the amount measured in 2014, 2017, and 2018. The lower precipitation regime led to a marked decline in SWC, making the late growing season of 2015 the driest period among all growing seasons during the study period. The greatest difference in SWC occurred in the late growing season of 2014 and 2015, when Ta was the same at 6.8 ± 2.6 and 6.8 ± 2.5°C, respectively. Compared to 2014, SWC decreased by 15.4% in the late growing season of 2015 (Fig. 2(b); Table S2). Meanwhile, SWC in the late growing season of~~during the same period, the SWC in~~ 2014 and 2018 was almost identical (80.7 ± 4.1 and 80.8 ± 3.8, respectively), but the temperature difference was the largest (25%) compared to any other year (Fig. 2(a); Table S2).



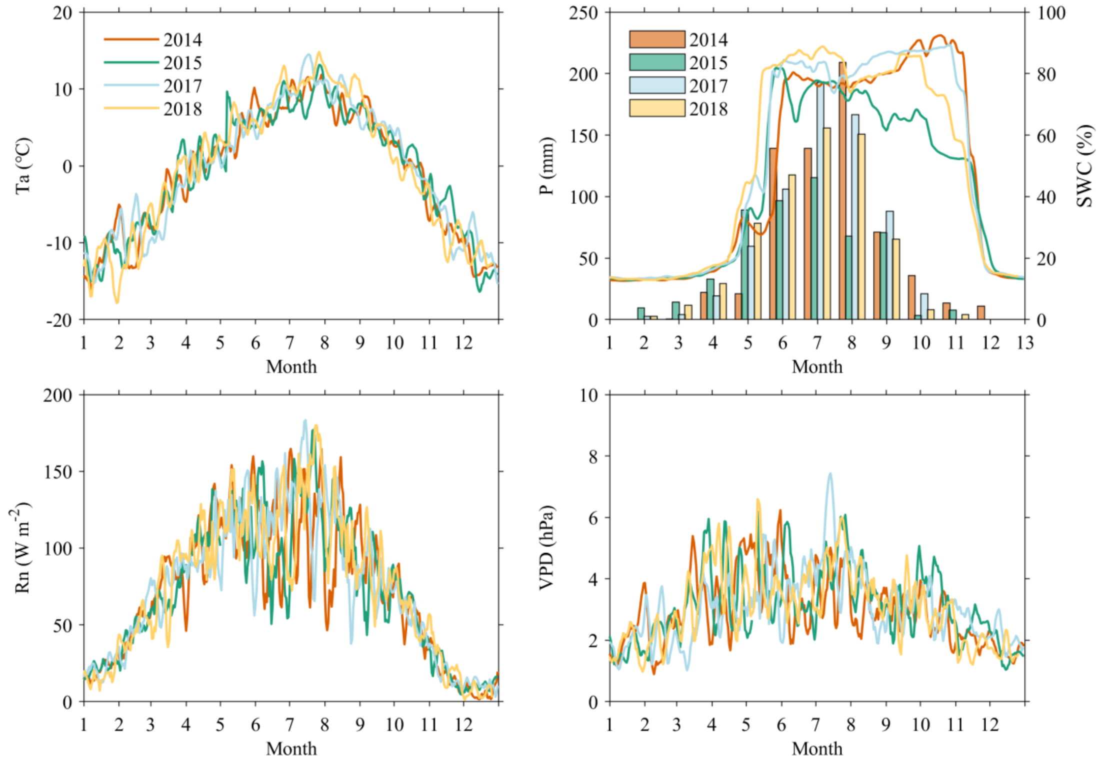


Figure 2. Five-day moving average meteorological variables (Ta, P, SWC, Rn, VPD) in the studied swamp alpine meadow.

3.2 Diurnal, seasonal, and annual variability of CO_2 fluxes

During the growing season, NEE (Fig. 3, (a1)–(d1)) and GPP (Fig. 3, (a3)–(d3)) featured a clear peak of the diurnal variations; both fluxes reached their summit between 12:00 and 14:00 local time. Re, however, presented a lower daily variability. The rates of NEE, Re, and GPP during the growing season averaged -2.3 ± 0.3, 3.2 ± 1.0, and 5.5 ± 0.9 µmol m^{-2} s^{-1}, respectively, for the entire study period (2014, 2015, 2017 and 2018). For the late growing season, the lowest rate of net C uptake was measured in 2015 (-10.0 µmol m^{-2} s^{-1}), whereas 2014 (-12.4 µmol m^{-2} s^{-1}), 2017 (-12.2 µmol m^{-2} s^{-1}), and 2018 (-12.5 µmol m^{-2} s^{-1}) exhibited more negative NEE values (i.e. stronger net C uptake rate). Between the late growing season in 2015 and the late growing seasons in 2014, 2017 and 2018, there was a significant difference in the rates of Re ($p<0.01$) while no significant difference was found in GPP variability ($p>0.05$), suggesting that Re may be the component causing the difference observed in NEE. Specifically, the rates of Re in the late growing season of 2014 and 2015 were 2.4 ± 0.2 and 3.0 ± 0.2 µmol m^{-2} s^{-1}, respectively, which indicated that during 2015 drier conditions generated a 25% higher Re compared to 2014. For the same periods, the rate of Re in warmer 2018 was~~ere~~ 3.5 ± 0.2 µmol m^{-2} s^{-1}, which was also significantly higher than in 2014 (2.4 ± 0.2 µmol m^{-2} s^{-1}).

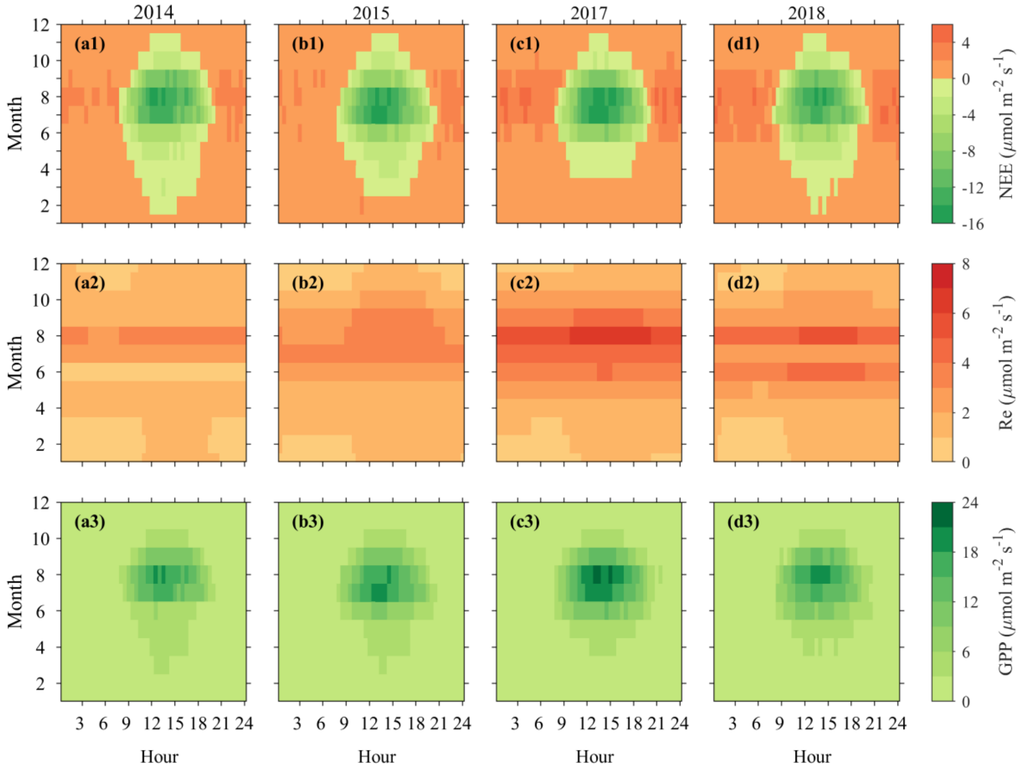
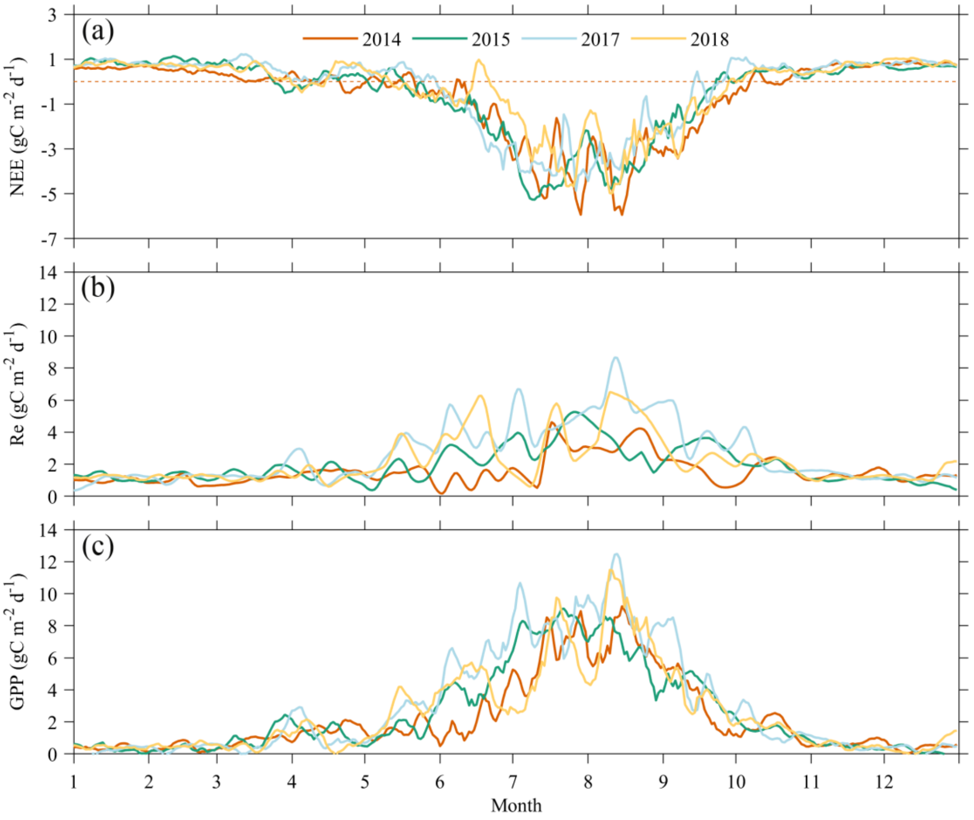


Figure 3. Diurnal variability of gap-filled NEE and partitioned Re and GPP in 2014, 2015, 2017 and 2018.

NEE, Re, and GPP also exhibited a strong seasonal variability; the C fluxes gradually increased from low values in early June to maximum values in the middle of the growing season (late July to early August on average), followed by a decrease towards the end of the growing season (Fig. 4(a), (b), (c)). The C sink strength across the growing season was found lowest in 2018, followed by 2017, whereas 2014 and 2015 exhibited relatively higher values (Fig. 4(a)). Notably, the accumulated Re in the late growing season was significantly higher in 2015 compared to 2014 ($P<0.05$), when there was no significant difference in GPP (Fig. 4(b); Table S2). Moreover, the late growing season of 2015 witnessed the lowest SWC while keeping the same Ta compared to the same period in 2014 (Fig. 2(b); Table S2). The substantial decline of SWC observed in 2015 appeared to be responsible for the weaker observed C sink strength. On the other hand, Ta in the late growing season of 2018 was the highest for the same period among all the years while the SWC remained the same as 2014 (Fig. 2(a)). The late growing season of 2018 showed overall higher GPP, Re, and lower net C uptake than 2014. Significantly higher Re in 2018 caused by higher ~~warmer~~ temperatures eventually led to a decrease of the C sink capacity (Fig. 4(a), (b), (c); Table S2).



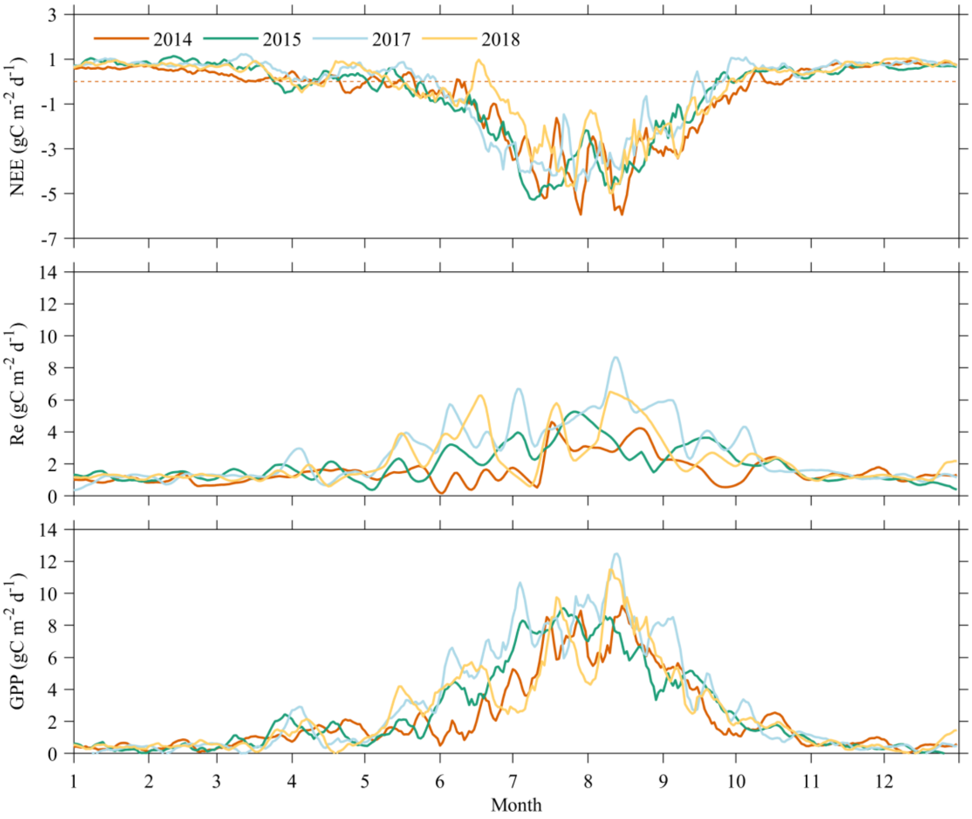
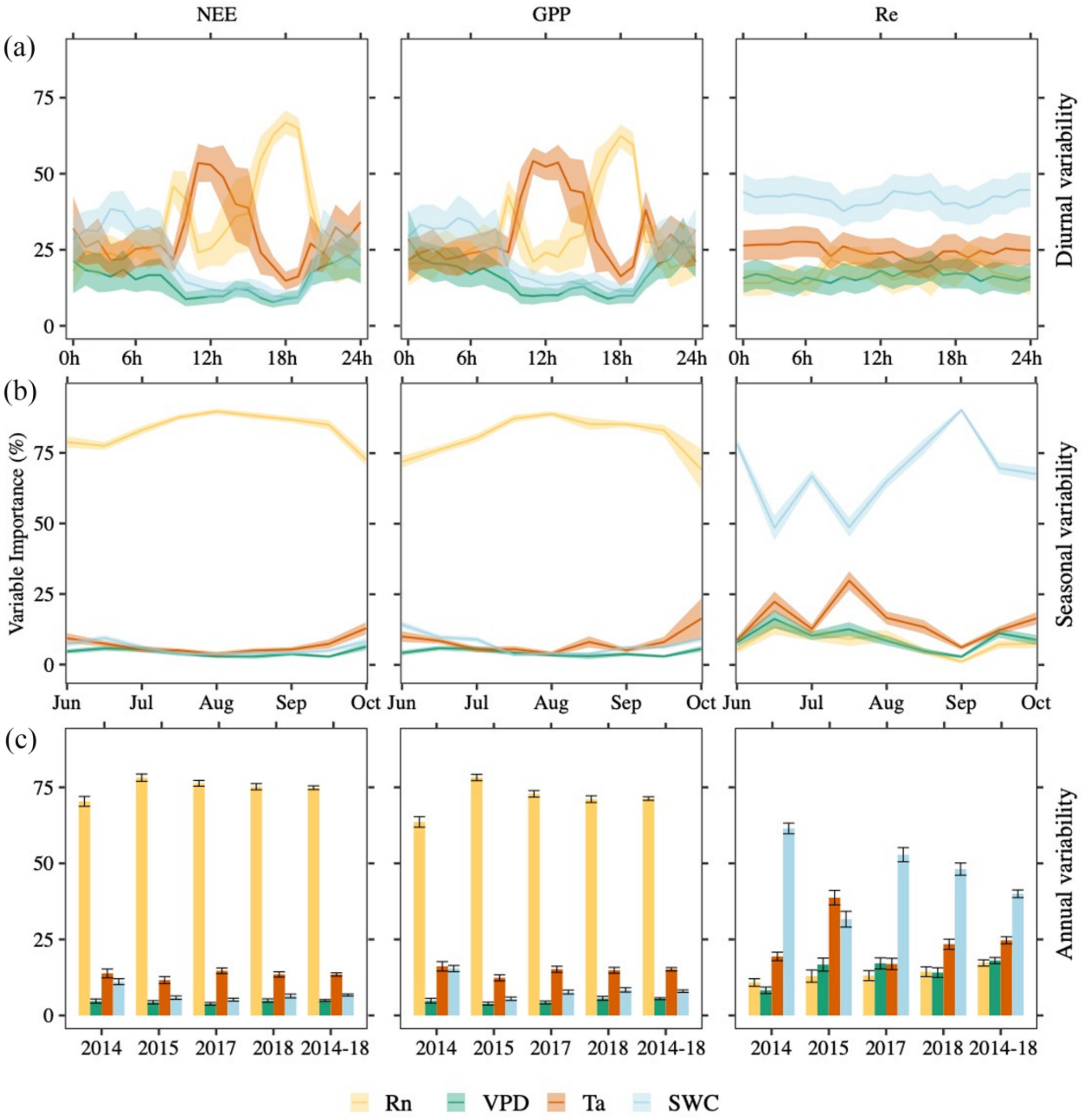


Figure 4. Seasonal variability of daily 5-day moving average daily NEE, Re, and GPP in the swamp alpine meadow.

3.3 The importance of environmental forcing controlling C fluxes

Our data processed by a machine learning technique suggest that the relative importance of the primary environmental drivers (Rn, Ta, VPD, and SWC) regulating terrestrial C fluxes varies on different time scales (i.e., diurnal~~ly~~, seasonal~~ly~~, and interannual scales~~ly~~) in this swamp meadow of QTP (Fig. 5(a), (b), (c)). The diurnal variability of NEE and GPP was mostly driven by Ta (Fig. 5(a)), especially in the central hours of the day between 11:00 and 15:00 while Re showed a fairly lower temperature dependence compared to NEE and GPP (Fig. 5(a)). SWC was~~ a~~ relatively more important than air temperature controlling the diurnal variability of respiration (Fig. 5(a)). The seasonal variability shaping the terrestrial C fluxes are regulated not only by meteorological variables but also by plant phenology. To separate the role of meteorological variables from phenology, we ~~also~~ carried out a random forest analysis every fortnight and assumed that plant phenology changed little during this time span (Fig. 5(b); seasonal variability). The analyses based on random forest revealed a distinct seasonal pattern from June to September, pointing to a marked contribution of net radiation over NEE and GPP (Fig. 5(b)).

Interestingly, Re was found mostly regulated by SWC. On an annual scale, the contribution patterns of each environmental driver to the variations of C fluxes are similar to the ones found at the seasonal scale. The interannual variability of NEE and GPP were controlled more clearly by Rn~~incoming radiation~~ while SWC~~soil moisture~~ revealed a stronger relative importance over Re (Fig. 5(a), (b), (c)). Overall, SWC dynamics seem to be the most important variable explaining the variability observed in the Re data (Fig. 5), suggesting that soil moisture plays an essential role on diurnal, seasonal, and interannual basis in this cold swamp meadow ecosystem. Note also that Ta played a secondary role controlling the Re at all assessed time scales (Fig. 5(a), (b), (c)).


NEE
GPP
Re
(a)
(b)
(c)
Diurnal variability
Seasonal variability
Annual variability
Variable Importance (%)
0
25
50
75
0h
6h
12h
18h
24h
Jun
Jul
Aug
Sep
Oct
2014
2015
2017
2018
2014-18
Rn
VPD
Ta
SWC

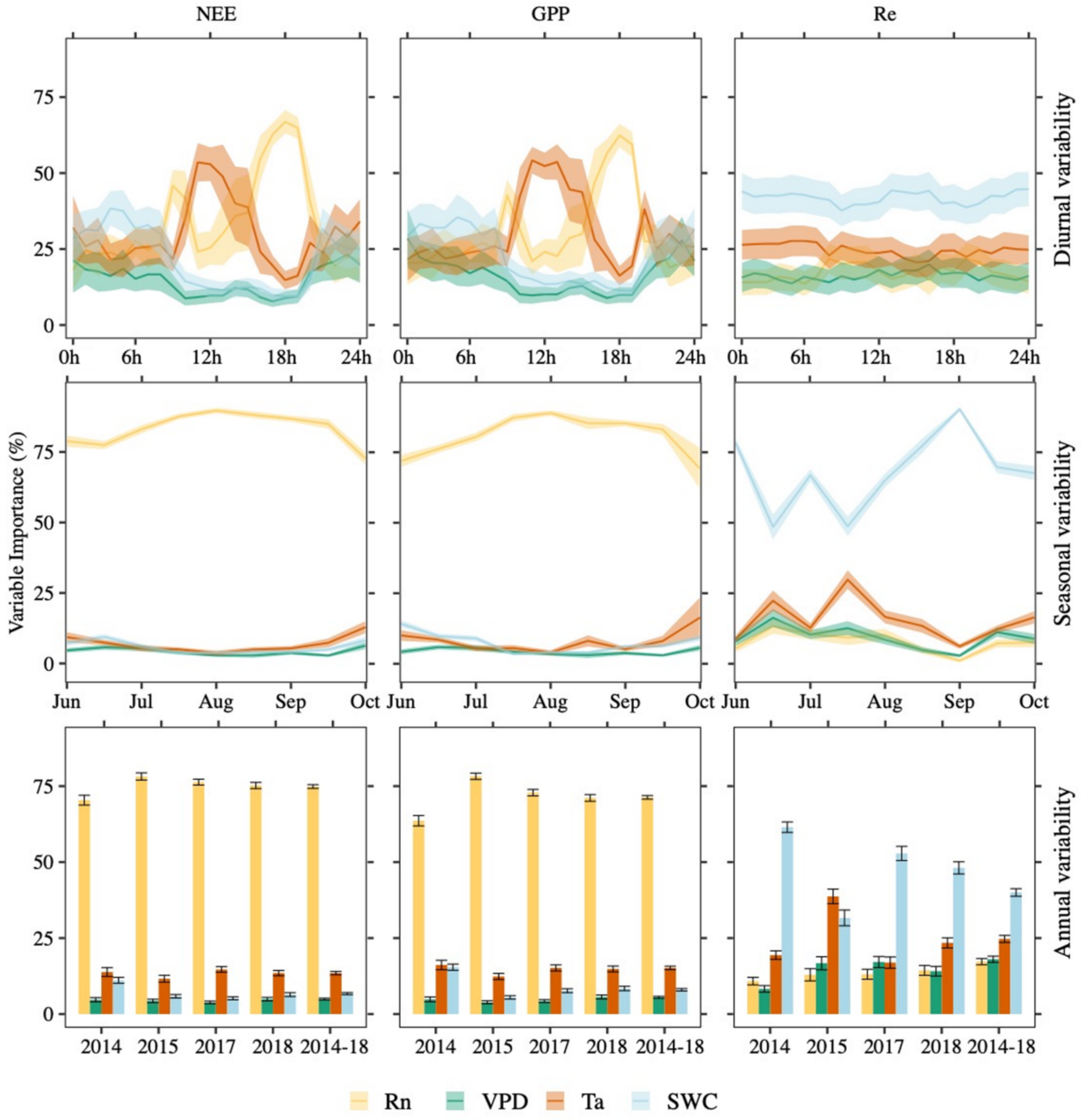


Figure 5. Contribution to diurnal, seasonal, and annual variation of NEE, GPP, and Re from different environmental drivers (Rn (yellow), Ta (orange), SWC (blue), and VPD (green)). Solid lines (diurnal and seasonal variability) and bars with error bars (annual variability) both illustrate the average ± standard deviation of the importance across 1000 decision trees. Annual variability refers to the variability of the integrated growing season of 2014, 2015, 2017, and 2018.

4. Discussion

Since NEE is the difference between Re and GPP, environmental variables affecting Re and GPP could affect NEE indirectly (Song et al., 2011). Radiation affects the magnitude of plant photosynthesis and controls temperature, one of the key factors related to C fluxes. This suggests that abundant radiation benefits photosynthesis and respiration and thus directly affects the C sink strength in the alpine wetland ecosystem of the Qinghai Lake (Cao et al., 2017). Niu et al. (2017) show that 99% of the interannual variation of NEE in an alpine swamp meadow can be well explained by temperature conditions, precipitation and radiation. The results of this study demonstrate that ecosystem C sequestration is regulated not only by radiation and temperature but also by soil moisture in the alpine swamp meadow site studied herein. Given there is no significant difference in net radiation between the four years we studied, t~~T~~he effects of soil water content and temperature on C fluxes on diurnal, seasonal, and annual scales are therefore discussed in detail below.

4.1 Low soil moisture is associated with enhanced ecosystem respiration

A previous study in alpine swamp meadow ecosystems found that water stress may be the key limiting factor leading to a decline in the photosynthetic rate at noon with a low SWC of 6–21% (Zhang et al., 2018). In this alpine swamp, the soil layer maintained a relatively high~~er~~ SWC due to the frequent precipitation during the growing season. SWC was always greater than 70% during the entire study period (Fig. 2(b)). Therefore, microbial activity, and thus heterotrophic respiration were likely suppressed by the anaerobic environment due to saturated soil water condition. At this site, SWC was found to be a more important variable than temperature controlling the variability of ecosystem respiration at different time aggregations (Fig. 5(a), (b), (c)). Our results suggest that even under water-saturated conditions, the C dynamics of this alpine swamp meadow are still highly sensitive to changes in soil moisture and could therefore be significantly influenced by future changes in water supply (Li et al., 2015). In fact, previous studies have stressed that soil moisture will likely interact with temperature to affect ecosystem respiration (Han et al., 2013) and therefore modify the overall C sink strength. Moreover, Zhao et al. (2010) also noticed that the CO_2 emission rates decrease notably after rain events, and Zhu et al. (2020) confirmed that annual precipitation exhibits significant impact on variation of annual net C uptake. All these existing studies have suggested that C fluxes are related to water availability condition, but few studies have found that soil moisture explicitly affects respiration.

Since C fluxes are affected by plant phenology and climate factors, ~~–~~including temperature, soil moisture, and radiation simultaneously (Fig. 5), to analyze the effect~~s~~ of a single factor, ideally, other factors need to be identical or at least close (no significant differences). Based on this theory and to~~To~~ better understand the underlying mechanisms around how SWC interacts with the C fluxes in the studied alpine swamp meadow ecosystem, we selected a specific group of data for further evaluation other than the entire observation time. The group contains two late growing season periods, ~~–~~which have significant differences in SWC but no significant difference in Ta (Fig. 6(a); Table S2).

The most significant difference in C fluxes between the late growing season of 2014 and 2015 was observed in Re (p<0.05). Additionally, on both diurnal and seasonal scales, a 15.4% decrease of SWC in the late growing season of 2015 resulted in a 25.7% increase of Re and a 19.4% decrease in net C uptake compared to 2014 (Figs. 6(a), (~~-~~b); Table S2). This finding suggests that drier conditions likely prevented this alpine swamp meadow from water-logged states, thereby strengthening soil respiration due to improved soil aeration (Wang et al., 2014). According to the literature, the intensification of anaerobic conditions due to water saturated soil can be responsible for weaker respiratory losses (Jansson and Hofmockel, 2020).

~~There is evidence that excessive soil water can negatively affect plant physiological and ecological processes by, for example, insufficient supply of metabolic substrates and the production of toxic substances (Jackson and Colmer, 2005), which may reduce the overall plant photosynthetic efficiency (Xu and Zhou, 2011). Although there was no significant difference between the late growing season GPP of 2015 and 2014 in terms of both daily accumulated GPP and diurnal rates of GPP, the decline observed in SWC during September 2015 (the driest month with 65.1% SWC) led to a 11% increase of daily accumulated GPP (Fig. S1; Table S3). The excess of SWC in 2014 caused an inundation of the aboveground plant domain, which also likely contributed to the lower value in GPP by reducing plant photosynthetic efficiency (Cronk et al., 2001; Hirota et al., 2006).~~

~~Since the increase of GPP could not offset the increase in Re, September 2015 and the late growing season of 2015 experienced a lower C sink strength.~~ Although the SWC in September 2015 was much greater than the 6–21% range reported by Zhang et al. (2018), our data suggest that a 22.2% reduction in SWC in September 2015 resulted in a 51.6% decline in net C uptake~~ rate~~ compared to September 2014 (Fig. S1; Table S3). There is evidence from the literature that the rates of net C uptake in alpine wetlands during the growing season can be lower under drier conditions (Hao et al., 2011), indicating that this alpine swamp meadow ecosystem may be adapted to high levels of SWC (Li et al., 2015)~~, but also that drier conditions may not always favour net C uptake in the cold-adapted alpine swamp meadow ecosystems~~. Higher SWC may limit the diffusion of oxygen from the atmosphere to the soil, inhibiting the activity of microorganisms and reducing the decomposition rate of soil organic matter, decreasing the nutrients in the soil, and consequently reducing the photosynthetic in alpine wetlands (Chimner and Cooper, 2003). Our comparisons suggest that drying can weaken the overall C sink strength in this alpine swamp meadow ecosystem. ~~Therefore, we conclude that the large C sink strength observed in this alpine swamp meadow of the QTP is largely attributed to the inhibiting effects of the nearly-saturated soil condition on C release.~~ Wetlands are predicted to experience lower water tables due to permafrost degradation in the Tibetan Plateau and, therefore, permafrost thaw-induced wetland drying could enhance the response of C emissions to climate warming (Yu et al., 2020).

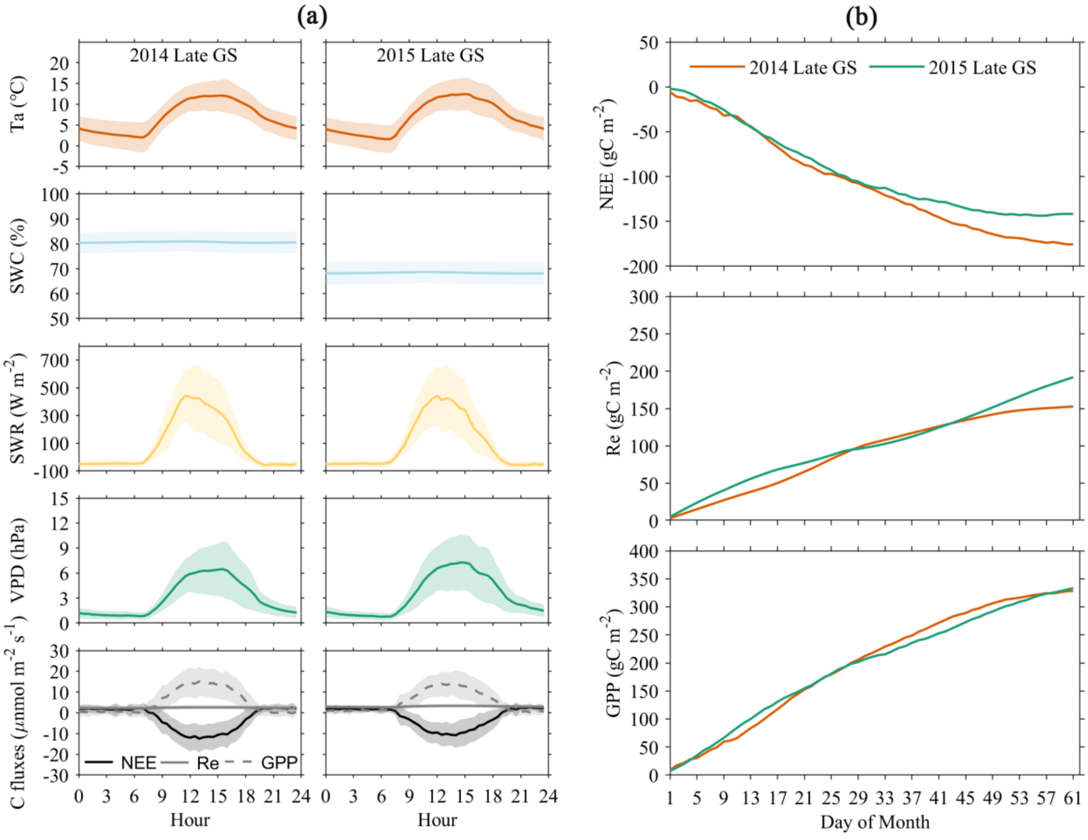


Figure 6. (a) Comparisons of the diurnal variations of environmental drivers (Ta, SWC, Rn, and VPD) and C fluxes (NEE, Re, and GPP) between the late growing season of 2014 and 2015. The shading represents the mean ± standard deviation of the presented variables. (b) Comparisons of the daily accumulated C fluxes (NEE, Re, and GPP) between the late growing season of 2014 and 2015. Note: late GS represents late (Aug.–Sep.) growing season.

4.2 Temperature increase leads to higher C losses rather than enhanced C uptake

The important role played by temperature controlling C exchange has been extensively found in alpine marshland~~ not only~~ across the QTP (Qi et al., 2021).~~,~~ For example, Zhao et al. (2010) and Zhao et al. (2005) show that ecosystem respiration follows the exponential variation of soil temperature. Zhu et al. (2020) also suggested that soil temperature plays the most important role in the change of monthly ecosystem respiration in the alpine wetland at Luanhaizi, northeastern Qinghai-Tibet Plateau.~~butand also in other ecosystems such as low and high Arctic tundra (López-Blanco et al., 2017, 2020) and northern marshlands (Watson and Byrne, 2009)~~.We therefore explored another ~~an additional ~~comparison between the late growing season of 2014 and 2018 (Fig. 7(a), (b); Table S2) where SWC was almost identical at both periods while temperature differed. Compared to 2014, a 25~~.2~~% increase in Ta in the late growing season of 2018 led to joint larger GPP and Re fluxes (Fig. 7a, b; Table S2). Although both GPP and Re increased, the intensification in Re was greater than~~ the one found in~~ GPP, indicating that warmer temperatures had a stronger impact on ecosystem respiration, resulting in a decrease of the net C uptake (Fig. 7(b); Table S2). To evaluate if this finding is also consistent at an annual scale, we further analyzed annual aggregated data. An annual comparison was made between~~ the~~ –2014, 2017, and 2018 when SWC were found insignificantly different while temperatures in 2017 and 2018 were 44.4% higher than in 2014 (Table S4). Additionally, this 44.4% increase in Ta in 2017 and 2018 both led to stronger GPP and Re (Table S4). Although both GPP and Re increased, the intensity in Re was greater than GPP, indicating that warmer temperatures have a stronger impact on ecosystem respiration in this site, resulting in an approximately 50% decrease of the net C uptake (Table S4).

This comparison suggests that future warming could weaken the overall C sink strength in this alpine swamp meadow ecosystem. Similar climate sensitivities have also been found in recent studies. For example, a study performed by Niu et al. (2017) in an alpine swamp meadow on the central Tibet Plateau suggests Re was more sensitive to increased temperature than GPP. This suggests that global warming may exacerbate future C releases in the alpine wetlands of the QTP (Gao et al., 2019; Niu et al., 2017; Zhu et al., 2020). However, other researchers have also reached different conclusions; for instance, Qi et al. (2021) found that GPP is consistently more sensitive than Re to changes of temperature at daily, seasonal, and annual scales, suggesting that cold condition~~s~~ can act as strong constraint on C uptake in alpine marshlands. Liu et al. (2018) concluded that warming has a significant inhibitory effect on GPP and minor effect on Re, resulting in a weaker carbon sequestration capacity of their studied alpine wetland ecosystem. Wei et al. (2021) also found that the uptake of C by plants will exceed the amount of C release under warmer and wetter climate conditions at an annual scale based on manipulative experiments and model simulations focused on the Tibetan Plateau. Their study is based on a longer-term trend while our study only covers 4-years of year-round observations thus site-specific differences in time and space scales may explain this variability. Nevertheless, such~~Additionally, an analysis based on a twenty-year warming experiment manipulated by Sistla et al. (2013) in an Arctic tundra ecosystem showed that the insensitive response of net C uptake to warming-induced conditions can be balanced by long-term variations in vegetation structure and composition together with soil thermodynamics, revealing a similar sensitivity to temperature triggered by a compensatory effect between photosynthesis and C losses. Similar correlated responses between GPP and Re balancing each other have also been found in low and high Arctic tundra sites (López-Blanco et al., 2017, 2020), a grassland in northeast China (Jiang et al., 2012), and an alpine meadow of the Qinghai-Tibet Plateau (Liu et al., 2018). Certainly, all these comparison~~ results indicating inconsistent ecosystem responses~~effects~~ suggest that there are still large uncertainties regulating the responses of C fluxes to temperature variation and further work is still crucial.

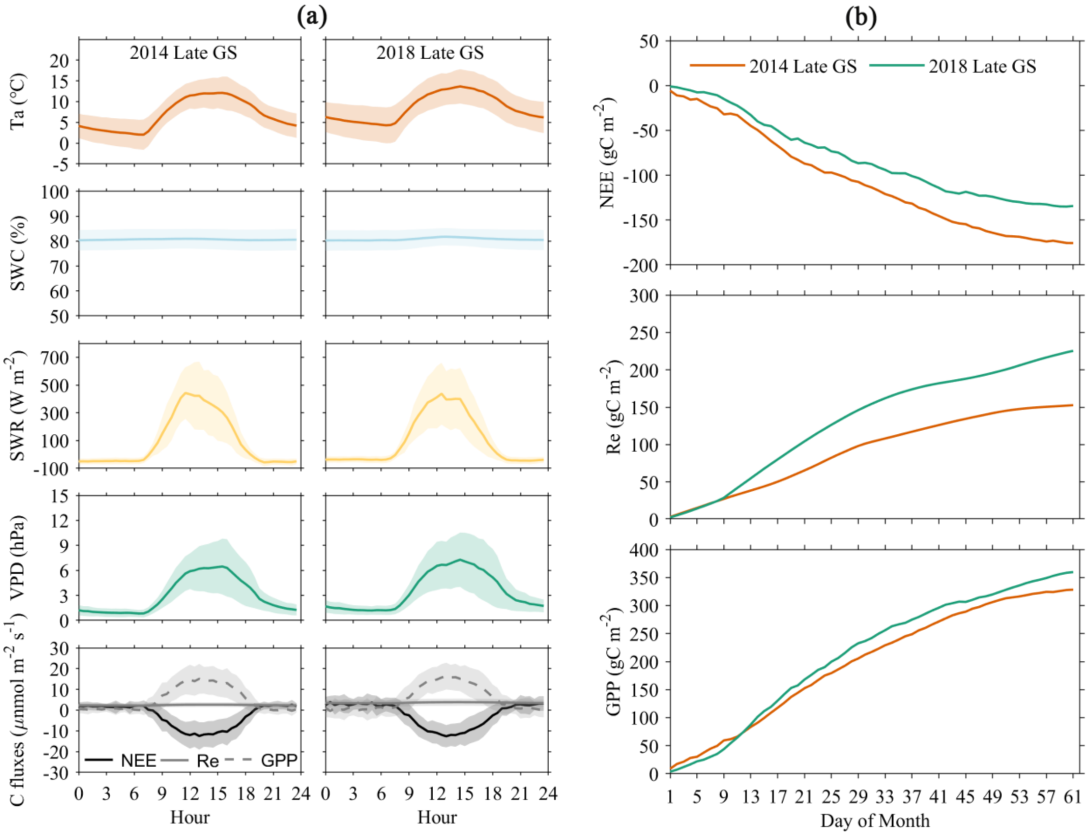


Figure 7. (a) Comparisons of the diurnal variations of environmental drivers (Ta, SWC, Rn, and VPD) and C fluxes (NEE, Re, and GPP) between the late growing season of 2014 and 2018. The shading represents the mean ± standard deviation of the presented variables. (b) Comparisons of the daily accumulated C fluxes (NEE, Re, and GPP) between the late growing season of 2014 and 2018. Note: late GS represents late (Aug.–Sep.) growing season.

4.3 ~~Impacts from the c~~Combined effects of ~~warming~~ temperature and soil moisture ~~changes~~ on C exchange dynamics ~~dynamics~~

The QTP experienced a higher rate~~s~~ of temperature increase than that of the Northern Hemisphere average (Zhang et al., 2013). The effects triggered by climate-induced warming over NEE in this area have been argued to either increase or decrease the net C balance NEE, or even have no effect whatsoever (Ganjurjav et al., 2018; Li et al., 2020; Wu et al., 2011; Zhu et al., 2017). These inconsistent responses could be due to water limitations offsetting the C balance or even reversing the effect of elevated temperatures, which change the decomposition and photosynthetic processes (Wu et al., 2011; Yu et al., 2013; Zhao et al., 2019). Alpine swamp meadows of the QTP have recently attracted much attention because they hold 5.9% (~ 1.98 Pg C) of the total grassland soil organic C (~ 33.52 Pg C). Such ecosystems have the highest organic C density (~ 50 kg C m^{-2}) and play an important role in the global C cycle (Niu et al., 2017). To test whether the observed SWC effects in this study were representative of other sites in the QTP and put it into a broader~~wider~~ perspective, we examined the temperature and precipitation (as a proxy for SWC)~~warming~~ impacts on NEE ~~in relation to ambient precipitation as a proxy for SWC~~ (Liu et al., 2016).

Our 4-year dataset revealed that this alpine swamp meadow functioned as a net C sink of -168.0 ± 62.5 gC m^{-2} y^{-1} at a 3571m asl. According to Wei et. al (2021), there are six observational studies about C fluxes at Haibei, three of which focused on alpine swamp meadows or wetland. These alpine swamp meadows were reported as a net C source while we our site showed a consistent C sink. The different directions of C exchange suggest that there are still uncertainties in our understanding of C exchange in this alpine swamp meadows, and further insights are obtained from studying multiple years of observations. Therefore, further efforts are still needed to improve our projection of C balance change of this ecosystem under changing climate.

The NEE observations from this study were within the NEE ranges of previous~~ly~~ studies in ~~the~~ similar alpine swamp meadows located across the QTP (-255.5 – 173.2 gC m^{-2} y^{-1}) (Table 2). In addition, the NEE estimates of this alpine swamp meadow show a stronger C sink strength than those from alpine meadows (-161.3 – 85.4 gC m^{-2} y^{-1}) (Chai et al., 2017; Wang et al., 2017; Wu et al., 2020), alpine steppes (-30 – 21.8 gC m^{-2} y^{-1}) (Wang et al., 2018; Wang et al., 2020a; Wang et al., 2020b; Wu et al., 2010), and alpine shrublands (-14 – -67 gC m^{-2} y^{-1}) (Zhao et al., 2005, 2006). This is likely a result of the inhibiting effects of the nearly-saturated soil condition over soil respiration rather than by the lower temperatures (Sun et al., 2021). Therefore, in permanently or seasonally inundated swamp meadows, high SWC ~~caused by relatively sufficient water supply~~ may have triggered lower C loss rates further benefiting C preservation. At our site, the higher C sink strength was likely attributed to higher precipitation (and therefore higher SWC) and lower temperature, which created colder and more humid conditions than other sites (Table 2).~~.The higher C sink strength at our site was likely attributed to higher precipitation and lower temperature, which created colder and more humid conditions than other sites (Table 2).~~ It has been demonstrated in the literature that cold and humid conditions favour stronger C sinks in alpine meadow ecosystems (Fu et al., 2009).

The interannual comparison of the sites presented in Table 2 shows that under low annual precipitation conditions (~ 300 mm), the joint effects of warming and reduced precipitation weakened the net C uptake at Damxung (Niu et al., 2017), and even turned the C sink of Xiaobo Lake wetland into a C source when comparing 2015 with 2012 and 2013 (Cao et al., 2017; Wu et al., 2018). Under relatively high annual precipitation (~ 500 mm), the joint effects of warming and increased precipitation~~also~~ ~~-~~enhanced C release in Haibei[a] ~~Haibei~~ site when comparing 2006 to 2004 and 2005 (Zhao et al., 2010). This indicates that net C uptake under warming conditions can be weakened even under high annual precipitation rates.

Table 2 Comparison of annual NEE (gC m^{-2} y^{-1}) at different sites in the QTP.

Site	Altitude (m)	Ecosystem	Year	Ta (°C)	P (mm)	Annual NEE	Reference
Haibei[a] ~~–~~(37º35′N, 101º20′E)	3200	AWM	2004	2.3	493.5	101.1	Zhao et al., 2010
			2005	2.2	475.2	44.0	
			2006	3.6	562.4	173.2	
Xiaopo Lake (36°42′N, 100°46′E)	3228	AWM	2015	2.8	304.3	54.6	Wu et al., 2018
			2012	1.2	357.0	-225.6	Cao et al., 2017
			2013	1.2	357.0	-255.5	
Damxung (30°28′N, 91°4′E)	4285	ASM	2009	3.4	208.9	-148.5	Niu et al., 2017
			2011	2.6	393.3	-190.8	
Haibei[b] (37º35′N, 100º00′E)	3571	ASM	2014	-0.9	662.8	-240.3	This study
			2015	-0.6	521.4	-200.1	
			2017	-0.5	661.2	-118.1	
			2018	-0.3	624.3	-113.4	

Note: P denotes precipitation, AWM denotes Alpine Wetland Meadow and ASM represents Alpine Swamp Meadow, Haibei[a] and Haibei[b] denotes different sites.

5. Conclusions

The alpine swamp meadow from the QTP presented in this study has been found to act as a consistent and strong sink of CO_2 (-168.0 ± 62.5 g C m^{-2} y^{-1}). The results from a novel machine learning technique revealed that air temperature is the most important variable driving NEE and GPP on~~at~~ a diurnal scale, while ~~incoming~~net radiation has a stronger importance controlling the seasonal and interannual variability of the same fluxes. Soil moisture, however, has the largest influence over Re variability on~~at~~ diurnal, seasonal, and interannual scales, suggesting that soil water content is a key control on ecosystem respiration~~ and overall C sink strength~~. In addition, air temperature plays a less important role in regulating the C exchange variability. This study reveals that both drying and warming can suppress net C uptake in water-saturated alpine swamp meadow ecosystems by enhancing ecosystem respiration. The response of net C uptake to climate warming further indicates that the forecasted warming in the QTP will not always increase the net C sink strength. Our results not only highlight the contributions of soil moisture in regulating C sequestration under high water conditions but also support future process-based modelling initiatives focusing on alpine swamp meadow ecosystem C dynamics.

Data availability. Post-processed data and scripts used in this paper are available from the authors upon request (xyli@bnu.edu.cn).

Author contribution

JQ, XL, LL, TRC, XW, and ELB designed the research. JQ, LL, and ELB processed the data and performed the analyses. YJ and HY helped collect the data. JQ and ELB created the visualization of the outputs. JQ, XL, and ELB prepared the manuscript with contributions (writing, review, and edition) from LL, TRC, and ZJ.

Competing interests. The authors declare that they have no conflict of interest.

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References

Bai, W., Xi, J., and Wang, G.: Effects of short-term warming and nitrogen addition on CO_2 emission during growing season in an alpine swamp meadow ecosystem of Qinghai-Tibetan Plateau, Chin. J. Ecol., 38, 927-936, https://doi.org/10.13292/j.1000-4890.201904.001, 2019.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmuller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kroger, T., Lambiel, C., Lanckman, J. P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M., and Lantuit, H.: Permafrost is warming at a global scale, Nat. Commun., https://doi.org/10, 264, 10.1038/s41467-018-08240-4, 2019.

Bohn, T. J., Lettenmaier, D. P., Sathulur, K., Bowling, L. C., Podest, E., McDonald, K. C., and Friborg, T.: Methane emissions from western Siberian wetlands: heterogeneity and sensitivity to climate change, Environ. Res. Lett., 2, https://doi.org/10.1088/1748-9326/2/4/045015, 2007.

Breiman, L.: Random forests, Mach. Learn., 45, 5-32, https://doi.org/10.1023/a:1010933404324, 2001.

Cao, S. K., Cao, G. C., Feng, Q., Han, G. Z., Lin, Y. Y., Yuan, J., Wu, F. T., and Cheng, S. Y.: Alpine wetland ecosystem carbon sink and its controls at the Qinghai Lake, Environ. Earth Sci., 76, https://doi.org/10.1007/s12665-017-6529-5, 2017.

Chai, X., Shi, P. L., Zong, N., Niu, B., He, Y. T., Zhang, X. Z.: Biophysical regulation of carbon flux in different rainfall regime in a northern Tibetan alpine meadow, J. Resour. Ecol., 8, 30-41, https://doi.org/10.5814/j.issn.1674-764x.2017.01.005, 2017.

Chen, D., Xu, B., Yao, T., Guo, Z., Cui, P., Chen, F., Zhang, R., Zhang, X., Zhang, Y., Fan, J., Hou, Z., and Zhang, T.: Assessment of past, present and future environmental changes on the Tibetan Plateau, Chin. Sci. Bull., 60, 3025-3035, https://doi.org/10.1360/n972014-01370, 2015.

Chen, N., Zhu, J., Zhang, Y., Liu, Y., Li, J., Zu, J., and Huang, K.: Nonlinear response of ecosystem respiration to multiple levels of temperature increases, Ecol. Evol., 9, 925-937, https://doi.org/10.1002/ece3.4658, 2019.

Cheng, Z., Liu, X., Fan, G., Bai, A., and Wang, B.: Spatiotemporal Distribution of Climate Change over the Qinghai-Tibetan Plateau in 21st Century, Arid Zone Res., 28, 669-676, 2011.

Chimner, R. A. and Cooper, D. J.: Influence of water table levels on CO_2 emissions in a Colorado subalpine fen: an in-situ microcosm study, Soil Biol. Biochem., 35, 345-351, https://doi.org/10.1016/s0038-0717(02)00284-5, 2003.

Christensen, T. R., Ekberg, A., Strom, L., Mastepanov, M., Panikov, N., Oquist, M., Svensson, B. H., Nykanen, H., Martikainen, P. J., and Oskarsson, H.: Factors controlling large scale variations in methane emissions from wetlands, Geophys. Res. Lett., 30, https://doi.org/10.1029/2002gl016848, 2003.

~~Cronk, J.K., 2001. Adaptations to growth conditions in wetland. Wetland plants: biology and ecology, Boca Raton (FL), Lewis Publishers, 87-110.~~

Foti, R., del Jesus, M., Rinaldo, A., and Rodriguez-Iturbe, I.: Signs of critical transition in the Everglades wetlands in response to climate and anthropogenic changes, Proc. Natl. Acad. Sci. U. S. A., 110, 6296-6300, https://doi.org/10.1073/pnas.1302558110, 2013.

Fu, G., Shen, Z.-X., Sun, W., Zhong, Z.-M., Zhang, X.-Z., and Zhou, Y.-T.: A Meta-analysis of the Effects of Experimental Warming on Plant Physiology and Growth on the Tibetan Plateau, J. Plant Growth Regul., 34, 57-65, https://doi.org/10.1007/s00344-014-9442-0, 2015.

Fu, Y., Zheng, Z., Yu, G., Hu, Z., Sun, X., Shi, P., Wang, Y., and Zhao, X.: Environmental influences on carbon dioxide fluxes over three grassland ecosystems in China, Biogeosciences, 6, 2879-2893, https://doi.org/10.5194/bg-6-2879-2009, 2009.

Ganjurjav, H., Gao, Q., Gornish, E. S., Schwartz, M. W., Liang, Y., Cao, X., Zhang, W., Zhang, Y., Li, W., Wan, Y., Li, Y., Danjiu, L., Guo, H., and Lin, E.: Differential response of alpine steppe and alpine meadow to climate warming in the central Qinghai-Tibetan Plateau, Agr. Forest Meteorol., 223, 233-240, https://doi.org/10.1016/j.agrformet.2016.03.017, 2016.

Ganjurjav, H., Hu, G., Wan, Y., Li, Y., Danjiu, L., and Gao, Q.: Different responses of ecosystem carbon exchange to warming in three types of alpine grassland on the central Qinghai-Tibetan Plateau, Ecol. Evol., 8, 1507-1520, https://doi.org/10.1002/ece3.3741, 2018.

Gao. Y., Quan, M. Y., Shen, W. D., Ren, X. D.: Research on experimental warming effects of CO_2 emissions and environmental response mechanisms in an alpine swamp meadow ecosystem on the Qinghai-Tibet Plateau, J. Guangxi Uni. (Nat. Sci. Ed.), 44, 580-586, https//doi:10.13624/j.cnki.issn.1001-7445.2019.0580, 2019.

Han, G., Yang, L., Yu, J., Wang, G., Mao, P., and Gao, Y.: Environmental Controls on Net Ecosystem CO_2 Exchange Over a Reed (Phragmites australis) Wetland in the Yellow River Delta, China, Estuar. Coast, 36, 401-413, https://doi.org/10.1007/s12237-012-9572-1, 2013.

Hao, Y. B., Cui, X. Y., Wang, Y. F., Mei, X. R., Kang, X. M., Wu, N., Luo, P., and Zhu, D.: Predominance of Precipitation and Temperature Controls on Ecosystem CO_2 Exchange in Zoige Alpine Wetlands of Southwest China, Wetlands, 31, 413-422, 10.1007/s13157-011-0151-1, 2011.

~~Hirota, M., Tang, Y., Hu, Q., Hirata, S., Kato, T., Mo, W., Cao, G., and Mariko, S.: Carbon dioxide dynamics and controls in a deep-water wetland on the Qinghai-Tibetan Plateau, Ecosystems, 9, 673-688, https://doi.org/10.1007/s10021-006-0029-x, 2006.~~

Hruby, T.: Assessments of Wetland Functions: What They Are and What They Are Not, Environ. Manage., 23, 75-85, https://doi.org/10.1007/s002679900168, 1999.

Hu, Z., Yu, G., Fu, Y., Sun, X., Li, Y., Shi, P., Wangw, Y., and Zheng, Z.: Effects of vegetation control on ecosystem water use efficiency within and among four grassland ecosystems in China, Glob. Change Biol., 14, 1609-1619, https://doi.org/10.1111/j.1365-2486.2008.01582.x, 2008.

~~Jackson, M. B. and Colmer, T. D.: Response and adaptation by plants to flooding stress - Preface, Annals of Botany, 96, 501-505, https://doi.org/10.1093/aob/mci205, 2005.~~

Jansson, J. K. and Hofmockel, K. S.: Soil microbiomes and climate change, Nat. Rev. Microbiol., 18, 35-46, https://doi.org/10.1038/s41579-019-0265-7, 2020.

Jiang, L., Guo, R., Zhu, T., Niu, X., Guo, J., and Sun, W.: Water- and Plant-Mediated Responses of Ecosystem Carbon Fluxes to Warming and Nitrogen Addition on the Songnen Grassland in Northeast China, Plos One, 7, https://doi.org/10.1371/journal.pone.0045205, 2012.

Kang, X., Wang, Y., Chen, H., Tian, J., Cui, X., Rui, Y., Zhong, L., Kardol, P., Hao, Y., and Xiao, X.: Modeling Carbon Fluxes Using Multi-Temporal MODIS Imagery and CO_2 Eddy Flux Tower Data in Zoige Alpine Wetland, South-West China, Wetlands, 34, 603-618, https://doi.org/10.1007/s13157-014-0529-y, 2014.

Kang, X., Yan, L., Cui, L., Zhang, X., Hao, Y., Wu, H., Zhang, Y., Li, W., Zhang, K., Yan, Z., Li, Y., and Wang, J.: Reduced Carbon Dioxide Sink and Methane Source under Extreme Drought Condition in an Alpine Peatland, Sustainability-Basel, 10, https://doi.org/10.3390/su10114285, 2018.

Lafreniere, M. J. and Lamoureux, S. F.: Effects of changing permafrost conditions on hydrological processes and fluvial fluxes, Earth-Sci. Rev., 191, 212-223, https://doi.org/10.1016/j.earscirev.2019.02.018, 2019.

Li, C., He, H., Liu, M., Su, W., Fu, Y., Zhang, L., Wen, X., and Yu, G.: The design and application of CO_2 flux data processing system at ChinaFLUX, Geo-Info. Sci., 10, 557-565, https://doi.org/10.3969/j.issn.1560-8999.2008.05.002, 2008.

Li, C., Yang, Y., Li, X., Chen, Q., and Zhou, H.: Effects of Simulated Climate Warming and Grazing on Photosynthesis and Respiration of Permafrost Meadow Plant Community, Russ J Ecol+, 51, 224-232, https://doi.org/10.1134/s1067413620030042, 2020.

Li, H., Nicotra, A. B., Xu, D., and Du, G.: Habitat-specific responses of leaf traits to soil water conditions in species from a novel alpine swamp meadow community, Conserv. Physiol., 3, cov046, https://doi.org/10.1093/conphys/cov046, 2015.

Liu, D., Li, Y., Wang, T., Peylin, P., MacBean, N., Ciais, P., Jia, G., Ma, M., Ma, Y., Shen, M., Zhang, X., and Piao, S.: Contrasting responses of grassland water and carbon exchanges to climate change between Tibetan Plateau and Inner Mongolia, Agr. Forest Meteorol., 249, 163-175, https://doi.org/10.1016/j.agrformet.2017.11.034, 2018.

Liu, J., Chen, K. L., Zhang, L. L.: Response of ecosystem carbon exchange to warming during the growing season of alpine lake wetland. Qinghai Prataculture, 27, 2-8, CNKI:SUN:QHCY.0.2018-04-002.

Liu, L., Wang, X., Lajeunesse, M. J., Miao, G., Piao, S., Wan, S., Wu, Y., Wang, Z., Yang, S., Li, P., and Deng, M.: A cross-biome synthesis of soil respiration and its determinants under simulated precipitation changes, Glob. Change Biol., 22, 1394-1405, https://doi.org/10.1111/gcb.13156, 2016.

Liu, S. M., Xu, Z. W., Wang, W. Z., Jia, Z. Z., Zhu, M. J., Bai, J., and Wang, J. M.: A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem, Hydrol. Earth Syst. Sc., 15, 1291-1306, https://doi.org/10.5194/hess-15-1291-2011, 2011.

Liu, Y., Geng, X., Tenzintarchen, Wei, D., Dai, D. and Xu, R.: Divergence in ecosystem carbon fluxes and soil nitrogen characteristics across alpine steppe, alpine meadow and alpine swamp ecosystems in a biome transition zone, Sci. Total Environ., https://doi.org/10.1016/j.scitotenv.2020.142453, 2020.

Lloyd, J. and Taylor, J. A.: On the Temperature-Dependence of Soil Respiration, Funct. Ecol., 8, 315-323, https://doi.org/10.2307/2389824, 1994.

López-Blanco, E., Lund, M., Williams, M., Tamstorf, M. P., Westergaard-Nielsen, A., Exbrayat, J.-F., Hansen, B. U., and Christensen, T. R.: Exchange of CO_2 in Arctic tundra: impacts of meteorological variations and biological disturbance, Biogeosciences, 14, 4467-4483, https://doi.org/10.5194/bg-14-4467-2017, 2017.

López-Blanco, E., Lund, M., Christensen, T. R., Tamstorf, M. P., Smallman, T. L., Slevin, D., Westergaard-Nielsen, A., Hansen, B. U., Abermann, J., and Williams, M.: Plant Traits are Key Determinants in Buffering the Meteorological Sensitivity of Net Carbon Exchanges of Arctic Tundra, J. Geophys. Res-Biogeo., 123, 2675-2694, https://doi.org/10.1029/2018jg004386, 2018.

López-Blanco, E., Jackowicz-Korczynski, M., Mastepanov, M., Skov, K., Westergaard-Nielsen, A., Williams, M., and Christensen, T. R.: Multi-year data-model evaluation reveals the importance of nutrient availability over climate in arctic ecosystem C dynamics, Environ. Res. Lett., 15, https://doi.org/10.1088/1748-9326/ab865b, 2020.

Moffat, A. M., Papale, D., Reichstein, M., Hollinger, D. Y., Richardson, A. D., Barr, A. G., Beckstein, C., Braswell, B. H., Churkina, G., Desai, A. R., Falge, E., Gove, J. H., Heimann, M., Hui, D., Jarvis, A. J., Kattge, J., Noormets, A., and Stauch, V. J.: Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes, Agr. Forest Meteorol., 147, 209-232, https://doi.org/10.1016/j.agrformet.2007.08.011, 2007.

Niu, B., He, Y., Zhang, X., Du, M., Shi, P., Sun, W., and Zhang, L.: CO_2 Exchange in an Alpine Swamp Meadow on the Central Tibetan Plateau, Wetlands, 37, 525-543, https://doi.org/10.1007/s13157-017-0888-2, 2017.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, Biogeosciences, 3, 571-583, https://doi.org/10.5194/bg-3-571-2006, 2006.

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, E.: Scikit-learn: Machine Learning in Python, J. Mach. Learn. Res., 12, 2825-2830, 2011.

Peng, F., You, Q., Xu, M., Guo, J., Wang, T., and Xue, X.: Effects of Warming and Clipping on Ecosystem Carbon Fluxes across Two Hydrologically Contrasting Years in an Alpine Meadow of the Qinghai-Tibet Plateau, Plos One, 9, https://doi.org/10.1371/journal.pone.0109319, 2014.

Qi, Y., Wei, D., Zhao, H., and Wang, X.: Carbon Sink of a Very High Marshland on the Tibetan Plateau, J. Geophys. Res-Biogeo., 126, https://doi.org/10.1029/2020jg006235, 2021.

Quan, Q., Tian, D., Luo, Y., Zhang, F., Crowther, T. W., Zhu, K., Chen, H. Y. H., Zhou, Q., and Niu, S.: Water scaling of ecosystem carbon cycle feedback to climate warming, Sci. Adv., 5, eaav1131, https://doi.org/10.1126/sciadv.aav1131, 2019.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J. M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Glob. Change Biol., 11, 1424-1439, https://doi.org/10.1111/j.1365-2486.2005.001002.x, 2005.

Reichstein, M., Moffat, A. M., Wutzler, T., and Sickel, K.: REddyProc: Data processing and plotting utilities of (half-)hourly eddy-covariance measurements, R package version 0.8-2/r14, 2016.

Saito, M., Kato, T., and Tang, Y.: Temperature controls ecosystem CO_2 exchange of an alpine meadow on the northeastern Tibetan Plateau, Glob. Change Biol., 15, 221-228, https://doi.org/10.1111/j.1365-2486.2008.01713.x, 2009.

Schuur, E. A. G., Vogel, J. G., Crummer, K. G., Lee, H., Sickman, J. O., and Osterkamp, T. E.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459, 556-559, https://doi.org/10.1038/nature08031, 2009.

Sistla, S. A., Moore, J. C., Simpson, R. T., Gough, L., Shaver, G. R., and Schimel, J. P.: Long-term warming restructures Arctic tundra without changing net soil carbon storage, Nature, 497, 615-618, https://doi.org/10.1038/nature12129, 2013.

Song, C. C., Sun, L., Huang, Y., Wang, Y. S., Wan, Z. M.: Carbon exchange in a freshwater marsh in the Sanjiang Plain, northeastern China. Agr. For. Meteorol., 151, 1131 – 1138, https://doi.org/10.1016/j.agrformet.2011.04.001, 2011.

Sun, S., Che, T., Gentine, P., Chen, Q., Wang, L., Yan, Z., Chen, B., and Song, Z.: Shallow groundwater inhibits soil respiration and favors carbon uptake in a wet alpine meadow ecosystem, Agr. Forest Meteorol., 297, https://doi.org/10.1016/j.agrformet.2020.108254, 2021.

Taylor, P. G., Cleveland, C. C., Wieder, W. R., Sullivan, B. W., Doughty, C. E., Dobrowski, S. Z., and Townsend, A. R.: Temperature and rainfall interact to control carbon cycling in tropical forests, Ecol. Lett., 20, 779-788, https://doi.org/10.1111/ele.12765, 2017.

Wang, D., Wang, K., Zheng, X., Butterbach-Bahl, K., Diaz-Pines, E., and Chen, H.: Applicability of a gas analyzer with dual quantum cascade lasers for simultaneous measurements of N2O, CH4 and CO_2 fluxes from cropland using the eddy covariance technique, Sci. Total Environ., 729, 138784, https://doi.org/10.1016/j.scitotenv.2020.138784, 2020a.

Wang, H., Yu, L., Chen, L., Wang, C., and He, J.: Responses of soil respiration to reduced water table and nitrogen addition in an alpine wetland on the Qinghai-Xizang Plateau, Chin. J. Plant Ecol., 38, 619-625, https://doi.org/10.3724/SP.J.1258.2014.00057, 2014.

Wang, L., Liu, H., Sun, J., and Shao, Y.: Biophysical effects on the interannual variation in carbon dioxide exchange of an alpine meadow on the Tibetan Plateau, Atmos. Chem. Phys., 17, 5119-5129, https://doi.org/10.5194/acp-17-5119-2017, 2017.

Wang, L., Liu, H., Shao, Y., Liu, Y., and Sun, J.: Water and CO_2 fluxes over semiarid alpine steppe and humid alpine meadow ecosystems on the Tibetan Plateau, Theor. Appl. Climatol., 131, 547-556, https://doi.org/10.1007/s00704-016-1997-1, 2018.

Wang, Y., Zhu, Z., Ma, Y., and Yuan, L.: Carbon and water fluxes in an alpine steppe ecosystem in the Nam Co area of the Tibetan Plateau during two years with contrasting amounts of precipitation, Int. J. Biometeorol., 64, 1183-1196, https://doi.org/10.1007/s00484-020-01892-2, 2020b.

~~Watson, E. B. and Byrne, R.: Abundance and diversity of tidal marsh plants along the salinity gradient of the San Francisco Estuary: implications for global change ecology, Plant. Ecol., 205, 113-128, https://doi.org/10.1007/s11258-009-9602-7, 2009.~~

Webb, E. K., Pearman, G. I., and Leuning, R.: Correction of Flux Measurements for Density Effects Due to Heat and Water-Vapor Transfer, Q. J. Roy. Meteor. Soc., 106, 85-100, https://doi.org/10.1002/qj.49710644707, 1980.

Wilczak, J. M., Oncley, S. P., and Stage, S. A.: Sonic anemometer tilt correction algorithms, Bound-Lay. Meteorol., 99, 127-150, https://doi.org/10.1023/a:1018966204465, 2001.

Woodward, R. T. and Wui, Y. S.: The economic value of wetland services: a meta-analysis, Ecol. Econ., 37, 257-270, https://doi.org/10.1016/s0921-8009(00)00276-7, 2001.

Wu, F., Cao, S., Cao, G., Han, G., Lin, Y., and Cheng, S.: Variation of CO_2 Flux of Alpine Wetland Ecosystem of Kobresia tibetica Wet Meadow in Lake Qinghai, J. Ecol. Rural Environ., 34, 124-131, https://doi.org/10.11934/j.issn.1673-4831.2018.02.004, 2018.

Wu, H., Zhao, G., Li, X. Y., Wang, Y., He, B., Jiang, Z., Zhang, S., and Sun, W.: Identifying water sources used by alpine riparian plants in a restoration zone on the Qinghai-Tibet Plateau: Evidence from stable isotopes, Sci. Total Environ., 697, 134092, https://doi.org/10.1016/j.scitotenv.2019.134092, 2019.

Wu, J., Wu, H., Ding, Y., Qin, J. and Zeng, D.: Interannual and seasonal variations in carbon exchanges over an alpine meadow in the northeastern edge of the Qinghai-Tibet Plateau, China. PloS one 15, https://doi.org/10.1371/journal.pone.0228470, 2020.

Wu, L., Gu, S., Zhao, L., Xu, S., Zhou, H., Feng, C., Xu, W.-X., Li, Y., Zhao, X., and Tang, Y.: Variation in net CO_2 exchange, gross primary production and its affecting factors in the planted pasture ecosystem in Sanjiangyuan Region of the Qinghai-Tibetan Plateau of China, Chin. J. Plant Ecol., 34, 770, https://doi.org/10.3724/SP.J.1142.2010.40521, 2010.

Wu, Z., Dijkstra, P., Koch, G. W., Penuelas, J., and Hungate, B. A.: Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation, Glob. Change Biol., 17, 927-942, https://doi.org/10.1111/j.1365-2486.2010.02302.x, 2011.

Xu, Z. and Zhou, G.: Responses of photosynthetic capacity to soil moisture gradient in perennial rhizome grass and perennial bunchgrass, BMC Plant Biol., 11, 21, https://doi.org/10.1186/1471-2229-11-21, 2011.

Yu, G.-R., Zhu, X.-J., Fu, Y.-L., He, H.-L., Wang, Q.-F., Wen, X.-F., Li, X.-R., Zhang, L.-M., Zhang, L., Su, W., Li, S.-G., Sun, X.-M., Zhang, Y.-P., Zhang, J.-H., Yan, J.-H., Wang, H.-M., Zhou, G.-S., Jia, B.-R., Xiang, W.-H., Li, Y.-N., Zhao, L., Wang, Y.-F., Shi, P.-L., Chen, S.-P., Xin, X.-P., Zhao, F.-H., Wang, Y.-Y., and Tong, C.-L.: Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China, Glob. Change Biol., 19, 798-810, https://doi.org/10.1111/gcb.12079, 2013.

Yu, L., Wang, H., Wang, Y., Zhang, Z., Chen, L., Liang, N., and He, J.-S.: Temporal variation in soil respiration and its sensitivity to temperature along a hydrological gradient in an alpine wetland of the Tibetan Plateau, Agr. Forest Meteorol., 282, https://doi.org/10.1016/j.agrformet.2019.107854, 2020.

Zeng, J., Matsunaga, T., Tan, Z. H., Saigusa, N., Shirai, T., Tang, Y., Peng, S., and Fukuda, Y.: Global terrestrial carbon fluxes of 1999-2019 estimated by upscaling eddy covariance data with a random forest, Sci. Data, 7, 313, https://doi.org/10.1038/s41597-020-00653-5, 2020.

Zhang, G., Zhang, Y., Dong, J., and Xiao, X.: Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011, Proc. Natl. Acad. Sci. U. S. A., 110, 4309-4314, https://doi.org/10.1073/pnas.1210423110, 2013.

Zhang, H., Wu, P., Yin, A., Yang, X., Zhang, M., and Gao, C.: Prediction of soil organic carbon in an intensively managed reclamation zone of eastern China: A comparison of multiple linear regressions and the random forest model, Sci. Total Environ., 592, 704-713, https://doi.org/10.1016/j.scitotenv.2017.02.146, 2017.

Zhang, S. Y.: Energy partitioning and evapotranspiration over the typical ecosystems in the Qinghai Lake watershed, Ph.D. thesis, College of Resources Science and Technology, Beijing Normal University, China, 115 pp., 2014.

Zhang, S.-Y., Li, X.-Y., Zhao, G.-Q., and Huang, Y.-M.: Surface energy fluxes and controls of evapotranspiration in three alpine ecosystems of Qinghai Lake watershed, NE Qinghai-Tibet Plateau, Ecohydrology, 9, 267-279, https://doi.org/10.1002/eco.1633, 2016.

Zhang, T., Zhang, Y., Xu, M., Zhu, J., Chen, N., Jiang, Y., Huang, K., Zu, J., Liu, Y., and Yu, G.: Water availability is more important than temperature in driving the carbon fluxes of an alpine meadow on the Tibetan Plateau, Agr. Forest Meteorol., 256, 22-31, https://doi.org/10.1016/j.agrformet.2018.02.027, 2018.

Zhao, J., Luo, T., Wei, H., Deng, Z., Li, X., Li, R., and Tang, Y.: Increased precipitation offsets the negative effect of warming on plant biomass and ecosystem respiration in a Tibetan alpine steppe, Agr. Forest Meteorol., 279, https://doi.org/10.1016/j.agrformet.2019.107761, 2019.

Zhao, L., Li, Y. N., Zhao, X. Q., Xu, S. X., Tang, Y. H., Yu, G. R., Gu, S., Du, M. Y., and Wang, Q. X.: Comparative study of the net exchange of CO_2 in 3 types of vegetation ecosystems on the Qinghai-Tibetan Plateau, Chin. Sci. Bull., 50, 1767-1774, https://doi.org/10.1360/04wd0316, 2005.

Zhao, L., Li, Y., Xu, S., Zhou, H., Gu, S., Yu, G., and Zhao, X.: Diurnal, seasonal and annual variation in net ecosystem CO_2 exchange of an alpine shrubland on Qinghai-Tibetan plateau, Glob. Change Biol., 12, 1940-1953, https://doi.org/10.1111/j.1365-2486.2006.01197.x, 2006.

Zhao, L., Li, J., Xu, S., Zhou, H., Li, Y., Gu, S., and Zhao, X.: Seasonal variations in carbon dioxide exchange in an alpine wetland meadow on the Qinghai-Tibetan Plateau, Biogeosciences, 7, 1207-1221, https://doi.org/10.5194/bg-7-1207-2010, 2010.

Zhu, J., Zhang, Y., and Jiang, L.: Experimental warming drives a seasonal shift of ecosystem carbon exchange in Tibetan alpine meadow, Agr. Forest Meteorol., 233, 242-249, https://doi.org/10.1016/j.agrformet.2016.12.005, 2017.

Zhu, J., Zhang, F., Li, H., He, H., Li, Y., Yang, Y., Zhang, G., Wang, C., and Luo, F.: Seasonal and Interannual Variations of CO_2 Fluxes Over 10 Years in an Alpine Wetland on the Qinghai-Tibetan Plateau, J. Geophys. Res-Biogeo., 125, https://doi.org/10.1029/2020jg006011, 2020.

Zhu, X., Song, C., Swarzenski, C. M., Guo, Y., Zhang, X., and Wang, J.: Ecosystem-atmosphere exchange of CO_2 in a temperate herbaceous peatland in the Sanjiang Plain of northeast China, Ecol. Eng., 75, 16-23, https://doi.org/10.1016/j.ecoleng.2014.11.035, 2015a.

Zhu, Z., Ma, Y., Li, M., Hu, Z., Xu, C., Zhang, L., Han, C., Wang, Y., and Ichiro, T.: Carbon dioxide exchange between an alpine steppe ecosystem and the atmosphere on the Nam Co area of the Tibetan Plateau, Agr. Forest Meteorol., 203, 169-179, https://doi.org/10.1016/j.agrformet.2014.12.013, 2015b.