Seasonal and inter-annual variations of CO2 fluxes over 10 years in an alpine wetland on the Qinghai-Tibetan Plateau

Jingbin Zhu[1], Fawei Zhang[2], Hongqin Li[3], Huidan He[1], Yingnian Li[2], Yongsheng Yang[2], Guangru Zhang[2], Chunyu Wang[2], and Fanglin Luo[2]

[1]Zaozhuang University
[2]Northwest Institute of Plateau Biology Chinese Academy of Sciences
[3]Luoyang Normal University

August 11, 2020

Abstract

Alpine wetlands play a sensitive function in global carbon cycle during the ongoing climate warming, yet the temporal patterns of carbon dynamics from in situ ground-based long-term observations remains unclear. Here, we analyzed the continuous net ecosystem CO2 exchange (NEE) measured with the eddy covariance technique over an alpine peatland on the northeastern Qinghai-Tibetan Plateau from 2007 to 2016. The wetland acted as a net CO2 source with a positive NEE (120.4 ± 34.8 gCm-2year-1, Mean ± S.D.), with the mean annual gross primary productivity (GPP) of 500.3 ± 59.4 gCm-2year-1 and annual ecosystem respiration (RES) of 620.7 ± 74.2 gCm-2year-1. At the seasonal scale, the classification and regression trees (CART) analysis showed that aggregated growing season degree days (GDD) was the predominant determinant on variations in monthly NEE and monthly GPP. Variations in monthly RES were determined by soil temperature (Ts). Furthermore, non-growing season Ts had a significant positive correlation with the following year annual GPP ($p<0.05$). Non-growing season RES only accounted for about 25% of annual RES, but had significant correlation with annual RES and annual NEE ($p<0.05$). The further partial correlation analysis showed that non-growing season air temperature (Ta, $p = 0.05$), rather than precipitation (PPT, $p = 0.25$) was a predominant determinant on variations in annual NEE. Our results highlighted the importance in carbon dynamics of climate fluctuations and CO2 emission from the non-growing season in alpine wetlands. We speculated that the vast peadlands would positively feedback to climate change on the Tibetan plateau where the non-growing season warming was significant.

1. INTRODUCTION

The ongoing global warming have caused wide spread changes the carbon cycle in terrestrial ecosystems (Ganjurjav et al., 2015). The wetland accounts for only 5%–8% of land surface area, but it accounts for 25%–30% soil organic carbon (SOC) in terrestrial ecosystem, which is crucial for global carbon balance (Mitsch et al., 2007). The Qinghai-Tibetan Plateau (QTP) contains approximately 33% of wetland area in China, which accounts for 30%–40% soil organic matter of Chinese wetland (Zheng et al., 2013), where is experiencing an intense increase in surface temperature (IPCC, 2013). Due to the special environment of high altitude and low temperature in QTP, the carbon dynamics in alpine wetland are sensitive to global climate change (Barichivich et al., 2013). Therefore, understanding the carbon budgets from alpine wetland ecosystems has become increasingly important in accurately projecting global carbon cycling in future climatic change (Hirota et al., 2006; Shen et al., 2015).

Past studies have not reached a consistent conclusion about the wetland ecosystem is carbon sink or carbon source. Due to the difference of environmental factors, the CO_2 fluxes of wetland ecosystem have large inter-annual variability (Griffis et al., 2000; Heinsch et al., 2004; Lafleur et al., 1999; Liikannen et al., 2005;). Many investigations indicated that wetland CO_2 fluxes are affected by a variety of ecological factors, such as air and soil temperature, PPFD, precipitation, and average water depth, which are usually non-linear associations (Hao et al., 2011; Hirota et al., 2006). Furthermore, changes in hydrothermal conditions and other key environmental factors, along with the increased concentrations of CO_2, will influence plant community characteristics and photosynthetic productivity (Song et al., 2018). Therefore, due to different environmental factors in different wetland ecosystem, the carbon source or sink of wetland ecosystems are not consistent (Heinsch et al., 2004; Song et al., 2018). However, the studies of carbon balance on the QTP were mainly focused on alpine shrub and alpine meadow (Kang et al., 2014; Saito et al., 2009; Zhao et al., 2010; Zhu et al., 2015). In recent, there are few studies on the carbon sources/sinks and their influencing mechanisms in alpine wetland ecosystems (Kato et al., 2006; Zhao et al., 2005; Zhang et al., 2008). There is still no unified result about the source or sink of alpine wetland in QTP (Hao et al., 2011; Zhao et al., 2005). Furthermore, previous studies on carbon balance of wetland ecosystem were limited to short time series data, which was difficult to fully explain the dynamics of carbon balance and its influence mechanism (Kang et al. 2014; Zhang et al., 2011). Therefore, the study based on the field measurement for many years could more accurately understand the CO_2 fluxes of the alpine wetland ecosystems (Chen et al., 2016; Griffis et al., 2000; Marcolla et al., 2011; Song et al., 2018).

Under the background of global climate change, a large number of studies have shown that the increase of temperature promotes the extension of growing season and the early greening of vegetation (Li et al., 2015), and promote alpine ecosystem to absorb carbon and improve the vegetation productivity (Zhang et al., 2013; Shen et al., 2015). In addition, the increase of temperature is beneficial to the activity of microorganisms and would accelerate the decomposition of soil organic matter, thus stimulating soil C emission (Chen et al., 2016). However, the in situ observational response of carbon balance in alpine wetland under the current climate change remains limited (Hao et al., 2011). As permafrost melts and glaciers recede, the area of wetlands on the QTP might increase, which will have an important impact on the carbon dynamic of the alpine ecosystem (Sturm et al., 2005; Zhang et al., 2011). Therefore, we used ten consecutive years of flux data from January 2007 to December 2016 to study an alpine wetland in QTP. The purposes of the research are to (1) investigate the variation patterns of the seasonal and inter-annual CO_2 fluxes (gross primary production (GPP), ecosystem respiration (RES) and net ecosystem CO_2exchange (NEE)); and (2) clarify the environmental drivers for the change of seasonal and annual CO_2 fluxes. We proposed the following hypotheses: (1) the hydrothermal condition is the dominant factor controlling the change of seasonal CO_2 fluxes; and (2) CO_2 emission during the non-growing season are crucial to annual CO_2 fluxes in alpine wetland (Hao et al., 2011; Song et al., 2018; Zhao et al., 2005).

2. MATERIALS AND METHODS

2.1. Study area

The study site was located in the Luanhaizi wetland (37°35'N, 101deg20'E, 3250m a.s.l.), which was adjacent to the Haibei Research Station, Chinese Academy of Sciences, in Qinghai Province, China. The region was controlled by the continental monsoon climate of the plateau, with cool summers and cold winters. Based on past monitoring data, the annual average temperature was -1.1 and the average minimum (-18.3) and maximum (12.6) temperature occurred in January and July, respectively. The mean annual precipitation is about 490mm, and precipitation in the growing period accounts for more than 80% of the annual total precipitation. The grass began to photosynthesize and sequester carbon at the end of April. The soil in this study site is a silty clay loam of Mat-Cryic Cambisols, which was rich in organic matter content. The study site has many scattered mounds due to the seasonal freeze-thaw process. The constructive species of the alpine wetland was *Carex pamirensis* , and the other common species including *Carex alrofusca* , *Hippuris vulgaris* , *Triglochin palustre* , and*Heleocharis spp* (Song et al., 2015; Wang et al., 2016; Zhao et al., 2010; Zhang et al., 2008).

2.2. Flux and abiotic measurements

The eddy covariance sensor array included a three-dimensional ultrasound anemometer (CSAT3, Campbell, Scientific Inc., Logan, Utah, United States), open-path infrared CO_2/H_2O analyzer (CS7500, Campbell Scientific Inc.). The data collector records the raw data at a frequency of 10 Hz. The mean, variance, and covariance values of the raw data were calculated and logged every 30 min with a data logger (CR5000, Campbell Scientific Inc., Logan, Utah, United States). The collected data were adjusted by WPL (Webb, Pearman and Leuning) density adjustment. The microclimate observation system includes wind direction and wind speed (150 cm and 250 cm), air temperature and humidity (150 cm and 250 cm), net radiation (150 cm), soil temperature (0, 5, 10, 20, 40 cm) and rainfall sensor (50 cm) and photosynthetic photon flux density (LI-190SB, LI-Cor, USA). Due to there are much water on the wetland surface, so soil moisture and soil heat flux were not measured

2.3. Data processing

After data collection, we performed quality control on all flux and meteorological data. Since small deviations can be ignored with low canopy height in flat study sites, axial rotation and trend elimination for raw eddy data were not performed (Zhao et al. 2006, Fu et al. 2009). We use the data processing method of flux from ChinaFLUX (Yu et al. 2008). The data quality was improved by spike screening and night-time filtering. The spike was defined as the beyond 4.5 standard deviations of a 10-day moving window. The night-time flux data collected under low atmospheric turbulence conditions were screened using thresholds of friction velocity (u_*), and flux data were rejected when $u_* < 0.15$ m*s^{-1}. Then, the missing CO_2 flux data were filled by empirical non-linear regression of valid data with environmental variables (Ma et al., 2007; Li et al., 2016). Daily GPP was obtained by subtracting NEE from RES (Eq. (1)), and daily RES was the sum of nocturnal respiration (RES_n) and daytime respiration (RES_d), which was extrapolated the exponential regressions of RES_n with nighttime soil temperature to the daytime periods. Negative and positive NEE represent the ecosystem to absorb and release CO_2 (Yu et al. 2008).

GPP = RES - NEE = (RES_d + RES_n) - NEE (1)

2.4. Statistical analysis

Classification and regression tree (CART) analysis is a machine learning algorithm, which is able to identify relatively important variables. CART is a non-parametric model based on graphics, which is easier to understand than traditional statistical techniques. Use CART to judge what the environment factors (air temperature (Ta), soil temperature (Ts), aggregated growing season degree day (GDD), photosynthetic photon flux density (PPFD), precipitation (PPT), air relative humidity (RH) and vapor pressure deficit (VPD)) played a major control role on variations of CO_2 fluxes. The maximum number of split was 5, and the minimum Proportional Reduction in Error (PRE) was 0.01. The growing season is from May to October, and the other months belong to the non-growing season (Zhang et al. 2008). Linear regression and correlation analysis were used to explore the inter-annual variation characteristics of CO_2 fluxes and its response mechanism to environmental factors. We used SYSTAT 13.0 (Systatsoftware Inc, USA) for the CART and linear regression analyses.

3. RESULTS

3.1. Seasonal and inter-annual variations of meteorological

Environmental factors varied greatly in different seasons from January 2007 to December 2016 (Fig. 1). The peaks of monthly environmental factors (Ta, Ts, GDD, PPFD, PPT, RH and VPD) were not consistent (Fig. 1). The maximum value of monthly GDD occurs in July (Fig. 1a). The average annual air temperature (Ta) and soil temperature (Ts) were -1.0 +- 0.5 and 3.0 +- 0.8degC, respectively. Only in April, May and June, the average monthly Ta is higher than monthly Ts (Fig. 1a). This may be caused by melting of snow and ice, which absorbed heat from the soil. Based on a threshold deviation from average annual Ta of 20%, the years 2014 and 2015 were classified as warmer years (>0.8 Ta), the years 2007, 2010, 2013, 2016 were considered normal years, and the years 2008, 2009, 2011, 2012 were defined as cooler years (<1.2 Ta) (Fig. 1). The average annual precipitation (PPT) was 456.5 +- 86.2 mm. The minimum annual rainfall was 323.1 mm occurred in 2012 year, and the maximum annual rainfall was 578.1 mm occurred in 2013. The years

2007, 2013, 2014 were classified as wetter years (>1.1 PPT) and 2012, 2015, 2016 were classified as drier years (<0.9 PPT) (Fig. 1).

3.2. Seasonal and inter-annual variations of GPP, RES and NEE

Both monthly GPP (162.7 +- 8.4 g C $m^{-2}month^{-1}$, mean +- S.E., with the same notation hereon in) and monthly NEE (-61.1 +- 6.3 g C $m^{-2}month^{-1}$) peaked in July, while the maximum monthly RES (109.4 +- 8.8 g C $m^{-2}month^{-1}$) appeared in August (Fig. 2a). The wetland ecosystem is a carbon sink from June to August with a negative NEE (Fig. 2a). During the growing season, linear regression analysis indicated that compared to monthly RES (r^2= 0.44, $p < 0.001$), monthly GPP (r^2= 0.88, $p < 0.001$) played a more important role in controlling the change of monthly NEE.

Annual GPP was 500.3 +- 59.4g C $m^{-2}year^{-1}$ and annual RES was 620.7 +- 74.2g C $m^{-2}year^{-1}$, respectively (Fig. 2b). Both monthly GPP (r^2= 0.11, p =0.33) and monthly RES (r^2= 0.28, p = 0.12) in the peak growing season (July and August) were not predominantly determined for variations of annual GPP and annual RES. The10-year mean NEE was 120.4+-34.8 g C $m^{-2}year^{-1}$ and a range of 76.3 g C $m^{-2}year^{-1}$ in 2010 to 184.8 g C $m^{-2}year^{-1}$ in 2014 (Fig. 2b). The change of annual NEE was neither directly controlled by annual RES (p = 0.06) nor directly controlled by annual GPP (p = 0.61), which was controlled more strong by annual RES to a certain extent compared to annual GPP. The sum of monthly NEE of July and August was also not predominantly determined for variations of annual NEE (r^2= 0.12, p =0.32). The non-growing season RES accounts for a small proportion of annual RES, but it is significantly positively correlated with annual NEE (r^2= 0.50, $p < 0.05$) and annual RES (r^2= 0.45, $p < 0.05$). This finding suggested that CO_2fluxes in alpine wetland during the non-growing season were crucial for annual carbon balance of alpine wetland.

3.3. Influence of environmental factors on seasonal variations of GPP, RES and NEE

The value of proportional reduction in error is more than 0.92, indicating that the analysis results of CART on monthly CO_2 fluxes (GPP, RES and NEE) are acceptable. The results of CART indicated that GDD was the main control factor that affecting the change of monthly GPP and NEE. GDD accounted for 78% and 79% change of monthly GPP (Fig. 3a) and NEE (Fig. 3c), respectively. Furthermore, the splitting values of GDD were all around 230d, and appeared at the beginning of July or the end of August, indicating that thermal condition was the main control factor that determined the change of monthly GPP and NEE during the peak of plant growth stage. The factor of the second right root node of GPP is Ta, suggesting that Ta was crucial to the photosynthetic and carbon fixation capacity of plants in wetland ecosystem during the peak growth period. Variability in monthly RES was predominantly determined by Ts in the whole year (Fig. 3b). The factor of the second right root node of NEE was Ts, suggesting that the carbon dynamics of wetland ecosystem to some extend was controlled by RES more than GPP in non-peak growth period. In addition, during the growing season, the influence of GDD on variations of monthly GPP was stronger than the change of monthly RES ($p < 0.001$) (Fig. 4). Furthermore, the growing season NEE had no significant correlation with growing season Ta (r^2=0.06, p=0.48) and PPT (r^2= 0.15, p=0.27). However, the non-growing season NEE significantly correlated with non-growing season Ta (Fig. 5a) and PPT (Fig. 5b).

3.4. Influence of environmental factors on annual GPP, RES and NEE

Annual GPP and RES had no significant correlation with annual environmental factors ($p > 0.05$, Table.1). The correlation analysis showed annual GPP had significant positive and negative correlation with the growing season Ta ($p<0.05$) and PPT ($p<0.05$), respectively, suggesting that the increase of temperature and decrease of precipitation in growing season was beneficial to the improvement of GPP. The result was noteworthy that the Ts during the non-growing season had significant impact on annual GPP of the following year ($p<0.05$), indicating that the warmer Ts during the non-growing season promoted the activities of microorganisms and accelerates the decomposition of litters and soil organic matter. Therefore, the soil of wetland contained a lot of nutrients and promoted the photosynthesis and carbon sequestration of vegetation in the following year. The further partial correlation analysis showed that annual RES had significant positive correlation with the Ta and Ts ($p<0.05$) of the non-growing season. Annual PPT exhibited significant impact on variation of annual NEE (Table 1), and linear regression analysis indicated that the non-growing season

Ta (Fig. 5c) and PPT (Fig. 5d) had a major impact on the change of annual NEE. However, the further partial correlation analysis showed that non-growing season air temperature (Ta, $p = 0.05$), rather than precipitation (PPT, $p = 0.25$) was a predominant determinant on the change of annual NEE. Overall, hydrothermal condition especially in non-growing season was the most important variable for describing variation on annual carbon fluxes.

4. DISCUSSIONS

4.1. Seasonal variations of GPP, RES and NEE

The result showed that GDD was the primary control factor affecting the change of monthly NEE and GPP in the alpine wetland (Figs. 3 and 4). In addition, to a certain extent, Ts had a relatively strong control over monthly GPP and monthly NEE in the alpine wetland (Figs. 3). In the alpine ecosystem of the QTP, photosynthetic radiation is relatively strong, and vegetation contains a large amount of aboveground biomass. As a result, temperature in the growing season has a strong impact on photosynthesis and carbon sequestration of vegetation in alpine wetland ecosystem (Marcolla et al., 2011; Shen et al., 2015). Furthermore, the accumulation effect of temperature had important effects on dormancy, leaf phenology and late growth of plants (Kato et al., 2006; Ueyama et al., 2013). Therefore, the metabolism of alpine plants, especially in response to temperature, had rich phenotypic plasticity (Korner, 1999). In addition, temperature could affect microbial activity, enzyme activity and decomposition of soil organic matter, so that the thermal condition was indirectly positively correlated with the supply of available nutrients in the soil of the ecosystem, thus making temperature a key control factor for the photosynthetic and carbon fixation capacity of alpine vegetation in the wetland of QTP (Street et al., 2007).

Ts played the most important role in the change of monthly RES in the alpine wetland of QTP (Fig. 3b). Many studies have shown that low soil temperature limits the soil enzyme activity and soil microbial biomass, and had an important impact on soil respiration and carbon balance in the alpine ecosystem (Van den Bos., 2003). This might be because the alpine wetland contained a large amount of soil organic matter, which was extremely sensitive to the change of soil temperature. Higher soil temperature could stimulate the activity of microorganisms and the decomposition of soil organic matter, so that soil temperature was the dominant control factor of RES (Moore et al., 1997; Updegraff et al., 2001). Furthermore, during the growing season, monthly NEE had significant correlation with monthly GPP ($r^2= 0.88$, $p < 0.001$) and monthly RES ($r^2= 0.44$, $p < 0.001$). Therefore, GPP played a more controlling role on the variation of NEE compared with RES during the growing season, which was consistent with other studies on temperature-restricted ecosystems (Groendahl et al., 2007; Ueyama et al., 2013).

4.2. Inter-annual variations of GPP, RES and NEE

There was a significant positive correlation between Ts of the non-growing season and annual GPP of the following year ($p <0.05$). This might be because the higher Ts in the non-growing season stimulated the activities of microorganisms, enhanced the soil enzyme activity, accelerated the decomposition of litters and soil organic matter, and thus produced rich nutrients in the soil, promoted the growth of vegetation in the following year, and improved the photosynthesis and carbon fixation capacity of vegetation in alpine wetland (Yu et al., 2003; Shen et al., 2011). In addition, the increase of Ts in the non-growing period promoted the melting of snow and ice, thus reducing the surface albedo, which was conducive to the early re-greening of vegetation and ultimately improved the photosynthetic productivity of vegetation in alpine wetland (Li et al., 2014; Reverter et al., 2010; Yu et al., 2003; Zhang et al., 2013). Meanwhile, the findings suggested that annual GPP had significant negative correlation with the growing season PPT ($p <0.05$). One possible was that PPT raised the water level of the wetland, thereby limiting the diffusion of oxygen in the atmosphere to the soil, thus inhibiting the activity of microorganisms and reducing the decomposition rate of soil organic matter, thus reducing the nutrients in the soil, and consequently reducing the photosynthetic and carbon fixation capacity of vegetation in alpine wetland (Chimner and Cooper., 2003).

Annual RES had a significant positive correlation with the non-growing season Ts ($r^2 = 0.44$, $p = 0.037$), which had no significant correlation with growing season Ts ($r^2 = 0.006$, $p = 0.83$) and annual Ts ($r^2 =$

0.01, p = 0.74). Furthermore, the non-growing RES had significant correlation with non-growing season Ts (r^2 = 0.45, p = 0.034). This might due to the long cold weather, the wetland contained a large amount of soil carbon that was extremely sensitive to temperature changes (Hao et al., 2011; Kang et al., 2014). The higher temperature during the non-growing season was conducive to the decomposition of soil organic matter and the improvement of soil respiration (Zhao et al., 2005; Kang et al., 2014). These results also suggested that the non-growing RES was crucial for annual RES. In addition, the non-growing RES had significant correlation with non-growing season PPT (r^2 = 0.54, p = 0.015). This might due to rainfall and snowfall cause snow and ice cover on the surface of wetland, which had a certain insulation effect on soil temperature and was conducive to promoting soil respiration (Hao et al., 2011; Song et al., 2018; Zhang et al., 2008).

Annual PPT was significant positive correlated with annual NEE (Table 1). This might be due to the increase of PPT in the growing season would reduce GPP, while the increase of PPT in the non-growing season would increase RES. As a result, the increase of inter-annual PPT leaded to accelerate the carbon loss in wetland ecosystem. The increase of the non-growing season temperature promotes soil respiration, lead to have significant positive correlation with annual NEE. In this study, the non-growing season RES was significantly correlated with annual RES and NEE ($p < 0.05$), which might be because the alpine wetland ecosystem on the QTP had a long non-growing period due to high altitude and low temperature, and the alpine wetland was covered by snow and ice for nearly half one year, so CO_2 emission in the non-growing season had a crucial impact on the variations of annual CO_2 fluxes (Hao et al., 2011; Song et al., 2018; Zhao et al., 2005). Our results also suggested that under the context of global warming, especially the increase of temperature in the non-growing season of the QTP, thus alpine wetland will might have a positive feedback on carbon loss caused by climate warming. In addition, the water table depth in the alpine wetland could also affect the soil thermal conductivity, thus impact on the change of soil temperature. In the context of climate change with increasing temperature and precipitation on the QTP, which is likely to through the interactive effects of Ts and water table depth on CO_2 production (Gao et al., 2012; Zhu et al., 2013). Further research is needed to make this clearly.

5. CONCLUSIONS

Our results indicated that the alpine wetland in this study was a weak carbon source. Our findings indicate that aggregated growing season degree day and soil temperature were the most important controlling factors for the seasonal variations of CO_2 fluxes. The hydrothermal conditions especially during the non-growing season played an important role in determining inter-annual variations of CO_2 fluxes. The results of our study highlighted the importance of the non-growing season CO_2 emissions for the variation of CO_2 dynamics, which was few focused by previous studies. According to our study results, we speculate that under the context of global warming, especially in the non-growing seasons, which will exacerbate carbon loss in the alpine wetlands of the QTP.

Our alpine wetland was a carbon source, which agrees well with the earlier reports. However, the swamps in Northern Tibetan Plateau (NTP) and Qinghai Lake (QL) are strong carbon sink (Cao et al., 2017; Niu et al., 2017). The stronger GPP in NTP and lower RES in QL accounted for the discrepancy, respectively. Our results showed that the estimation of carbon sequestration capacity of alpine wetland should be more cautious.

ACKNOWLEDGMENTS

This work was financially supported by the National Key R&D Program of China (2017YFA0604801), Qinghai R&D Infrastructure and Facility Development Program (2018-ZJ-T09), and the National Natural Science Foundation of China (41877547).

CONFLI CT OF INTEREST

None declared

AUTH ORS CONTRI BUTION

Jingbin Zhu and Fawei Zhang performed the research, analyzed data, and wrote the paper; Hongqin Li, Yongsheng Yang, Chunyu Wang , Guangru Zhang and Fanglin Luo analyzed data and wrote the paper, Huidan He and Yingnian Li conceived the study.

DATA AVAILABILITY STATEMENT

We had uploaded our data to the OSF.

https://mfr.osf.io/render?url=https%3A%2F%2Fosf.io%2F3aybs%2Fdownload

REFERENCES

Barichivich, J., Briffa, K.R., Myneni, R.B., Osborn, T.J., Melvin, T.M., Ciais, P., Piao, S., Tucker, C. (2013). Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO_2 at high northern latitudes from 1950 to 2011.*Global Change Biology* , 19(10): 3167-3183.

Cao, S., Cao, G., Feng, Q., Han, G., Lin, Y., Yuan, J. (2017). Alpine wetland ecosystem carbon sink and its controls at the Qinghai Lake.*Environmental Earth Sciences* , 76(5): 210.

Chen, J., Luo, Y., Xia, J., Shi, Z., Jiang, L., Niu, S., Zhou, X., Cao, J. (2016). Differential responses of ecosystem respiration components to experimental warming in a meadow grassland on the Tibetan Plateau.*Agricultural & Forest Meteorology* , 220(220): 21-29.

Chimner, R.A., Cooper, D.J. (2003). Influence of water table levels on CO_2 emissions in a Colorado subalpine fen: an in situ microcosm study. *Soil Biology & Biochemistry* , 35(3): 345-351.

Fu, Y.L., Zheng, Z.M., Yu, G.R., Hu, Z.M., Sun, X.M., Shi, P.L., Wang, Y.S., Zhao, X.Q. (2009). Environmental influences on carbon dioxide fluxes over three grassland ecosystems in China. *Biogeosciences* , 6(12), 2879–2893.

Ganjurjav, H., Gao, Q., Zhang, W. (2015). Effects of Warming on CO_2 Fluxes in an Alpine Meadow Ecosystem on the Central Qinghai-Tibetan Plateau. *Plos One* , 10(7): e0132044.

Gao, X., Shi, D., Zhang, F. (2012). Climate change in China in the 21st century as simulated by a high resolution regional climate model,*Chinese Science Bulletin* , 57(10), 1188–1195.

Griffis, T.J., Rouse, W.R., Waddington, J.M. (2000). Scaling net ecosystem CO_2 exchange from the community to landscape-level at a subarctic fen. *Global Change Biology* , 6:459–473

Groendahl, L., Friborg, T., Soegaard, H. (2007). Temperature and snow-melt controls on inter-annual variability in carbon exchange in the high Arctic. *Theoretical & Applied Climatology* , 88(1-2): 111-125.

Hao, Y.B., Cui, X.Y., Wang, Y.F. (2011). Predominance of Precipitation and Temperature Controls on Ecosystem CO_2 Exchange in Zoige Alpine Wetlands of Southwest China. *Wetlands* , 31(2): 413-422.

Heinsch, F.A., Heilman, J.L., McInnes, K.J. (2004). Carbon dioxide exchange in a high marsh on the Texas Gulf Coast: effects of fresh water availability. *Agriculture and Forest Meteorology* , 125: 159–172.

Hirota, M., Tang, Y., Hu, Q. 2006. Carbon Dioxide Dynamics and Controls in a Deep-water Wetland on the Qinghai-Tibetan Plateau.*Ecosystems* , 9(4):673-688.

IPCC. (2013). Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Kato, T., Tang, Y.H., Gu, S., Hirota, M., Du, M.Y., Li, Y.N., Zhao, X.Q. (2006). Temperature and biomass influences on interannual changes in CO_2 exchange in an alpine meadow on the Qinghai-Tibetan Plateau. *Global Change Biology* , 12 (7), 1285–1298.

Kang, X.M., Wang, Y.F., Chen, H., Tian, J.Q., Cui, X.Y., Rui, Y.C. (2014). Modeling carbon fluxes using multitemporal MODIS imagery and CO_2 eddy flux tower data in Zoige alpine wetland, south-west China. *Wetlands* 34(3):603–618

Korner, C. (1999). Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems. Springer-Verlag, Berlin & Heidelberg.

Lafleur P. (1999). Annual net ecosystem exchange of CO_2at a boreal bog. Symposium 43. Carbon balance of peatlands sponsor, International Peat Society.

Li, H., Zhang, F., Li, Y., Zhao, X., Cao, G. (2015). Thirty-year variations of above-ground net primary production and precipitation-use efficiency of an alpine meadow in the north-eastern Qinghai-Tibetan Plateau. *Grass Forage Science* ,71 (2), 208–218.

Li, H., Zhang, F., Li, Y., Wang, J., Zhang, L., Zhao, L., Cao, G., Zhao, X., Du, M. (2016). Seasonal and inter-annual variations in CO_2 fluxes over 10 years in an alpine shrubland on the Qinghai-Tibetan Plateau, China. *Agricultural & Forest Meteorology* . 228–229, 95–103.

Li, H., Zhang, F., Li, Y., Cao, G., Zhao, L., Zhao, X. (2014). Seasonal and interannual variations of ecosystem photosynthetic features in an alpine dwarf shrubland on the Qinghai-Tibetan Plateau, China.*Photosynthetica* 52 (3), 321–331.

Liikannen, A., Huttunen, J.T., Karjalainen, S.M. (2005). Temporal and seasonal changes in greenhouse gas emissions from a constructed wetland purifying peat mining runoff waters. *Ecological Engine* , 26: 241–251.

Marcolla, B., Cescatti, A., Manca, G., Zorer, R., Cavagna, M., Fiora, A., Gianelle, D., Rodeghiero, M., Sottocornola, M., Zampedri, R. (2011). Climatic controls and ecosystem responses drive the inter-annual variability of the net ecosystem exchange of an alpine meadow.*Agricultural & Forest Meteorology* . 151 (9), 1233–1243.

Ma, S., Baldocchi, D., Xu, L., Hehn, T. (2007). Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. *Agricultural & Forest Meteorology* . 147, 157–171.

Mitsch, W.J., Gosselink, J.G. (2007). Wetlands (4th edition). New York: John Wiley & Sons, Inc.

Moore, T.R. and Dalva, M. (1997). Methane and carbon dioxide exchange potentials of peat soils in aerobic and anaerobic laboratory incubations. *Soil Biology & Biochemistry* , 29: 1 157–1 164.

Niu, B., He, Y., Zhang, X., Du, M., Shi, P., Sun, W. (2017). CO_2 exchange in an alpine swamp meadow on the central Tibetan plateau. *Wetlands* , 37(3), 525-543.

Reverter, B.R., Sanchez-Ca nete, E.P., Resco, V., Serrano-Ortiz, P., Oyonarte, C., Kowalski, A.S. (2010). Analyzing the major drivers of NEE in a Mediterrane an alpine shrubland. *Biogeosciences* 7 (9), 2601–2611.

Saito, M., Kato, T., Tang, Y. (2009). Temperature controls ecosystem CO2 exchange of an alpine meadow on the northeastern Tibetan Plateau.*Global Change Biology* , 15(1):221–228

Shen, M., Tang, Y., Chen, J., Zhu, X., Zheng, Y. (2011). Influences of temperature and precipitation before the growing season on spring phenology in grasslands of the central and eastern Qinghai-Tibetan Plateau. *Agricultural & Forest Meteorology.* 151, 1711–1722.

Shen, M., Piao, S., Jeong, S., Zhoue, L., Zeng, Z., Ciais, P., Chen, D., Huang, M., Jin, C.,Li, L.Z.X., Li, Y., Myneni, R.B., Yang, K., Zhang, G., Zhang, Y., Yao, T. (2015). Evaporative cooling over the Tibetan Plateau induced by vegetation growth. *Proceedings of the National Academy of Sciences of the United States of America* , 112 (30), 9299–9304.

Song, Y., Jin, L., Wang, H. (2018). Vegetation changes along the Qinghai-Tibet Plateau engineering corridor since 2000 induced by climate change and human activities. *Remote Sens.* 10, 95.

Song, W., Wang, H., Wang, G. (2015). Methane emissions from an alpine wetland on the Tibetan Plateau: Neglected but vital contribution of the non-growing season. *Journal of Geophysical Research: Biogeoences* , 120(8):1475-1490.

Street, L.E., Shaver, G.R., Williams, M., Van Wijk, M.T. (2007). What is the relationship between changes in canopy leaf area and changes in photosynthetic CO_2 flux in arctic ecosystems?*Journal of Ecological* , 95, 139–150.

Sturm, M., Schimel, J., Michaelson, G., Welker, J.M., Oberbauer, S.F., Liston, G.E., Fahnestock, J., Romanovsky, V.E. (2005). Winter biological processes could help convert arctic tundra to shrubland.*Bioscience* 55 (1), 17–26.

Ueyama, M., Iwata, H., Harazono, Y., Euskirchen, E.S., Oechel, W.C., Zona, D. (2013).Growing season and spatial variations of carbon fluxes of Arctic and boreal ecosystems in Alaska (USA). *Ecological Appl* ications, 23 (8), 1798–1816.

Updegraff, K., Bridgham, S.D., Pastor, J., Weishampel, P., Harth, C. (2001). Response of CO_2 and CH_4emissions from peatlands to warming and water table manipulation.*Ecological Appl* ications, 11: 311–326.

Van den Bos, R. M. (2003). Human influence on carbon fluxes in coastal peatlands: process analysis, quantification and prediction. Ph. D. Thesis, Vrije Universiteit.

Wang, H., Yu, L., Zhang, Z. (2016). Molecular mechanisms of water table lowering and nitrogen deposition in affecting greenhouse gas emissions from a Tibetan alpine wetland. *Global Change Biology* , 23(2): 815-829.

Yu, F., Price, K.P., Ellis, J., Shi, P. (2003). Response of seasonal vegetation development to climatic variations in eastern central Asia.*Remote Sensing of Environment* , 87 (1), 42–54.

Yu, G., Zhang, L., Sun, X., Fu, Y., Wen, X., Wang, Q., Li, S., Ren, C., Song, X., Liu, Y. (2008). Environmental controls over carbon exchange of three forest ecosystems in eastern China. *Global Change Biology* , 14 (11), 2555–2571.

Zhang, F.W., Liu, A.H., Ying-Nian, L.I., Liang, Z. and Wang, Q.X. (2008). CO_2 flux in alpine wetland ecosystem on the Qinghai-Tibetan Plateau. *Acta Ecologica Sinica* , 28(2): 453-462.

Zhang, G., Zhang, Y., Dong, J., Xiao, X. (2013). Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011.*Proceedings of the National Academy of Sciences of the United States of America* , 110, 4309–4314.

Zhang, Y., Wang, G., Wang, Y. (2011). Changes in alpine wetland ecosystems of the Qinghai–Tibetan plateau from 1967 to 2004.*Environmental Monitoring and Assessment* ,180, 189–199.

Zhao, L., Li, Y., Xu, S., Zhou, H., Gu, S., Yu, G., Zhao, X. (2006). Diurnal, seasonal and annual variation in net ecosystem CO_2 exchange of an alpine shrubland on Qinghai-Tibetan plateau. *Global Change Biology* , 12 (10), 1940–1953.

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

Zhao, L., Li, Y.N., Zhao, X.Q., Xu, S.X., Tang, Y.H., Yu, G.R., Gu, S., Du, M.Y., Wang, Q.X. (2005). Comparative study of the net exchange of CO_2 in 3 types of vegetation ecosystems on the Qinghai-Tibetan Plateau. *Chinese Science Bulletin* , 50(16):1767–1774

Zheng, Y., Niu, Z., Gong, P., Dai, Y., Shangguan,W. (2013). Preliminary estimation of the organic carbon pool in China's wetlands. *Chinese Science Bulletin* , 58, 662–670.

Zhu, X., Wang, K., Fraedrich. (2013). Future climate in the Tibetan Plateau from a statistical regional climate model, *Journal of Climate* , 26(24), 10,125–10,138.

Zhu, Z., Ma, Y., Li, M., Hu, Z., Xu, C., Zhang, L., Han, C., Wang, Y. (2015). Carbon dioxide exchange between an alpine steppe ecosystem and the atmosphere on the Nam Co area of the Tibetan Plateau. *Agricultural & Forest Meteorology* , 203(S1):169–179.

Hosted file

`Figures.docx` available at https://authorea.com/users/349939/articles/474907-seasonal-and-inter-annual-variations-of-co2-fluxes-over-10-years-in-an-alpine-wetland-on-the-qinghai-tibetan-plateau