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# Impacts of Climate and Nutrients on Carbon Sequestration Rate by Wetlands: A Meta-analysis

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**Abstract:** Global numerous wetlands are the most productive ecosystem and have high carbon sequestration potential to mitigate increasing $CO_2$ in the atmosphere. However, few are available on estimating average carbon sequestration rates by global wetlands (Carbon$_{sq}$) at century timescale. In this article, Carbon$_{sq}$ data of 473 wetland soil/sediment cores from the literatures were collected in detail by the meta-analysis method. These cores were no more than 300 years old and spanned a latitudinal range from 33.6° S to 69.7° N. Globally, the average Carbon$_{sq}$ was 185.2 g/(m$^2$•yr) regardless of wetland types. Carbon$_{sq}$ varied remarkably between wetland types and ranked as an order of salt marsh (247.7 g/(m$^2$•yr)) > mangrove (229.8 g/(m$^2$•yr)) > freshwater marsh (196.7 g/(m$^2$•yr)) > peatland (76.9 g/(m$^2$•yr)). Carbon$_{sq}$ was positively related to mean annual temperature (AMT) and annual precipitation (Pre). Nitrogen was the most common and primary factor controlling Carbon$_{sq}$ regardless of wetland types.

**Keywords:** global wetlands; carbon sequestration; temperature and precipitation; nutrient; phosphorus

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## 1 Introduction

Wetlands, characterized by high productivity, waterlogged, and low pH soil conditions, and decomposition-resistant litter (Chmura et al., 2003; Bridgham et al., 2006; Wissing et al., 2014), play vital roles in mitigating global greenhouse effects because of their high carbon sequestration rates (Carbon$_{sq}$). Wetlands usually function as carbon sinks (Mitsch et al., 2013), and cover only 6% of the earth's land surface but account for a large proportion of the world's carbon stored in terrestrial soil reservoirs (Whiting and Chanton, 2001; Kayranli et al., 2010). Wetlands are believed to be effective in continuously sequestering $CO_2$ from the atmosphere into soil carbon pool, forming negative feedbacks (Sutfin et al., 2016), and so could mitigate climate warming effectively (Helbig et al., 2017). Carbon storage in global peatlands is estimated to 88.6 Gt (Page et al., 2011). Globally, tidal and saline wetlands store at least 44.6 Tg/yr carbon (Chmura et al., 2003). Up to now, there are many researches focusing on carbon sequestration rates by peatlands in Canada and America (Nakatsubo et al., 2015), a freshwater marsh in Northeast China (Zhang et al., 2016), and mangroves in south Asia (Bianchi et al., 2013). However, there is no data about carbon sequestration rates by global wetlands containing

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most wetland types on a global scale, which could provide basic values for assessing function change as the carbon sink when wetlands face environmental disturbance like climate change (Bertolucci et al., 2015).

Currently, carbon sequestration rates are usually estimated by two methods depending on a different timescale from annual to centurial years. Isotopes like $^{14}C$, $^{210}Pb$, and $^{137}Cs$ are usually employed to estimate chronology of soil cores to calculate soil accretion rate and $Carbon_{sq}$ (Wall et al., 2015). $^{14}C$ is appropriate for dating soil cores on millennium timescale, $^{210}Pb$ was suitable for dating soil cores on century timescale (Li et al., 2019). $^{137}Cs$ maxima had well-defined peaks, which represents the location of the soil surface in 1964, the year of peak deposition of atmospheric $^{137}Cs$ from aboveground weapons testing of thermonuclear weapons of mass destruction (Loomis and Craft, 2010). At a short timescale within one year, $Carbon_{sq}$ is estimated by monitoring carbon input and output. It is unreasonable to compare $Carbon_{sq}$ estimated by different methods because of the timescale difference. Usually, chronology dating by isotopes could provide more reasonable and accurate estimations on soil accretion rate on decadal to centennial timescales. $Carbon_{sq}$ is generally estimated based on soil organic carbon storage and chronology (Sackett et al., 2010), it is regarded as one inherent comparable property of wetlands when estimation was performed on a long temporal or large spatial scale.

Since the pre-industrial period, the climate has been becoming warmer and warmer, which has yielded positive feedbacks with carbon circulation of most terrestrial ecosystems, including wetlands. From 1850−1900 to 2006−2015, mean land surface air temperature has increased by 1.53℃, carbon circulation in wetlands is susceptible to thermal-hydrological variations (Fan et al., 2013; Sutfin et al., 2016). Climate and nutrient availability are proved to be as predominant drivers affecting carbon circulation in wetlands (Lang et al., 2014; Schuur et al., 2015). How $Carbon_{sq}$ in wetlands response to climate change in conjunction with increasing global nitrogen deposition receive more and more attention (Morris and Bradley, 1999; Hessen et al., 2004). However, facilitation or restriction effects of climate change and nitrogen input on $Carbon_{sq}$ by wetlands exist great arguments because of differences in research spatio-temporal scale, dating methods and wetland types. Most related works were carried out at the community, local or regional scale, but little work has been performed on the global scale (Sulman et al., 2013; Baldwin et al., 2014; Drake, 2014).

At the ten-thousand-year scale, peatland has been proved to effectively sequester carbon (O'Lear and Blair, 1999; Hågvar and Klanderud, 2009). However, more attention should be paid to decipher relations between $Carbon_{sq}$ and nutrient input and climate change within 300 years, since when the climate has become remarkably warm and nutrient deposition has been increasing greatly on a global scale (Reay et al., 2008; Zhang et al., 2016; Helbig et al., 2017). Still, few accurate estimations are performed to forecast how much carbon could be captured by wetlands annually because the average $Carbon_{sq}$ data on the global scale is lack. So, objectives of our study are to estimated $Carbon_{sq}$ by wetlands on a global scale using the meta-analysis, and to reveal impacts of temperature, precipitation and nutrient availability on $Carbon_{sq}$. It is hoped to provide a scientific estimation of potential carbon storage capacities by wetlands and to make predictions about carbon sequestration under future global climate change scenarios.

## 2 Materials and Methods

### 2.1 Data source

We searched the literatures, up to 31, Dec. 2017, by Google Scholar (https://scholar.google.com/) using carbon sequestration or carbon accumulation and wetland (including marsh, fen, tidal marsh, salt marsh, brackish, swamp, bog, fen, mire, peatland, moor) as keywords. Considering soil chronology was generally established by isotopes ($^{137}Cs$, $^{210}Pb$, and $^{14}C$), which were suitable for different timescale from decades to millennium years. To make data comparable on the century timescale, only the literatures dated by $^{137}Cs$ and $^{210}Pb$ were chosen, and finally, we got 121 valid literatures containing 473 soil/sediment cores from various wetlands for meta-analysis (Fig. 1). All wetlands were categrated into peatland ($n$ = 132), freshwater marsh ($n$ = 126), salt marsh ($n$ = 182) and mangrove ($n$ = 33) according to descriptions in literatures (Table 1). Detailed information about location, wetland types, annual temperature, and precipitation information was provided in the valid literature. These 473 soil/sediment cores spanned a

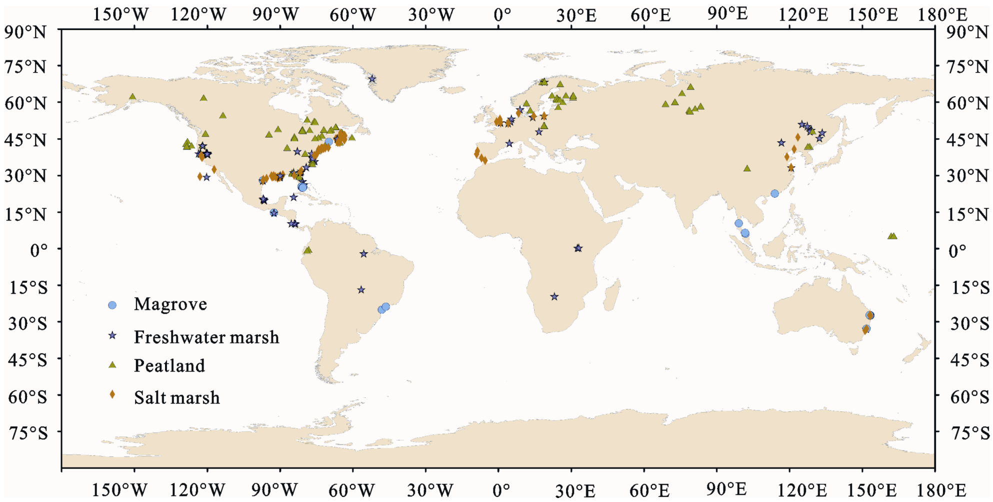


**Fig. 1** Location of selected soil/sediment cores. There were 33 mangrove points, 126 freshwater marsh points, 132 peatland points, and 182 salt marsh points. Not all cores were shown in this figure because of site overlap on the global scale

**Table 1** Range of $Carbon_{sq}$, nutrients accumulation rates and climate parameters of different wetlands types

| Wetland types | $Carbon_{sq}$ (g/(m$^2$•yr)) | $Nitrogen_{ac}$ (g/(m$^2$•yr)) | $Phosphorus_{ac}$ (g/(m$^2$•yr)) | AMT (℃) | Pre (mm) |
|---|---|---|---|---|---|
| Peatland (*n* = 132) | 2.96–407.00 | 0.05–12.80 | 0.06–0.64 | −7.6–27.4 | 361–5458 |
| Freshwater marsh (*n* = 126) | 12–1180.00 | 0.11–25.80 | 0.06–2.37 | −5.0–28.2 | 11–3975 |
| Salt marsh (*n* = 182) | 8.63–1713.00 | 1.63–55.00 | 0.23–13.00 | 4.6–21.9 | 270–1594 |
| Mangrove (*n* = 33) | 17.36–1085.00 | 0.31–33.00 | 0.13–12.58 | 7.8–28.2 | 878–2741 |

Notes：AMT, annual mean temperature; Pre, annual precipitation; $Carbon_{sq}$, carbon sequestration rates; $Nitrogen_{ac}$, accumulation rate; $Phosphorus_{ac}$, phosphorus accumulation rate

latitudinal range from 33.6 °S to 69.7 °N, and chronology of these cores were all dated by $^{210}$Pb. $Carbon_{sq}$, nitrogen accumulation rate ($Nitrogen_{ac}$), phosphorus accumulation rate ($Phosphorus_{ac}$), and relative climate annual parameters including annual mean temperature (AMT), annual precipitation (Pre), mean annual minimum temperature ($T_{min}$) and mean annual maximum temperature ($T_{max}$) were extracted and integrated to a dataset. All data were available at Renewable Resources and Environment National Earth System Science Data Center of World Data Center (WDC) (http://wdcrre.data.ac.cn/info/90fb9).

## 2.2 Climate data interpolation and verification

Climate data were collected from the WorldClim Version 2 (https://www.worldclim.org/), which included mean, minimum, and maximum temperature and mean annual precipitation from 1970 to 2000. Considering $Carbon_{sq}$ was also greatly regulated by seasonal climate parameters (Zhang et al., 2017), so some other seasonal climatic parameters were also introduced into this study (Table 2). In sum, 14 climatic parameters were used. Considering that many wetlands locate in remote areas usually without meteorological stations, the Kriging interpolation method was applied to obtain climate information of sites without climate data records. Accuracy of interpolation results was assessed by comparing interpolated climate data with corresponding values found in literature, which were considered as real values. Results indicated that interpolated data agreed well with actual values ($R^2$ = 0.994 for AMT and $R^2$ = 0.979 for Pre) (Fig. 2).

**Table 2** Climatic parameters used in the present work

| Abbreviation | Climatic parameters |
|---|---|
| AMT | Annual mean temperature |
| Pre | Annual precipitation |
| $T_{max}$ | Max temperature of the warmest month |
| $T_{min}$ | Min temperature of the coldest month |
| Bio8 | Mean temperature of the wettest quarter |
| Bio9 | Mean temperature of the driest quarter |
| Bio10 | Mean temperature of the warmest quarter |
| Bio11 | Mean temperature of the coldest quarter |
| Bio13 | Precipitation of the wettest quarter |
| Bio14 | Precipitation of the driest month |
| Bio16 | Precipitation of the wettest quarter |
| Bio17 | Precipitation of the driest quarter |
| Bio18 | Precipitation of the warmest quarter |
| Bio19 | Precipitation of the coldest quarter |

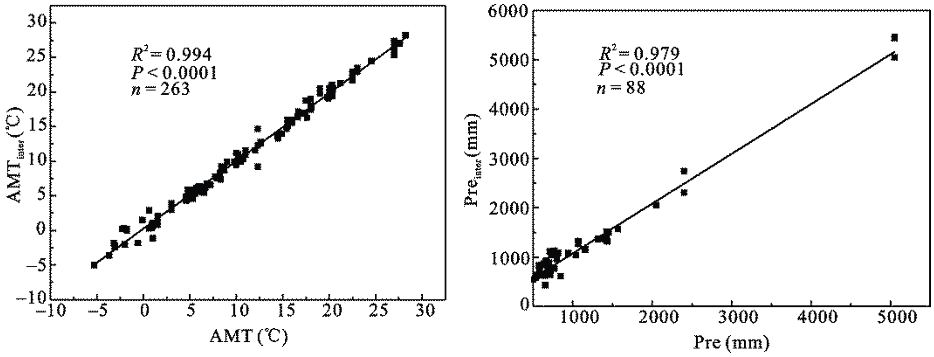


**Fig. 2** Validation of Kriging interpolation results of climate information. AMT$_{inter}$ and Pre$_{inter}$ are Kriging interpolation annual average temperature and annual precipitation in sites with actual meteorological information records in literatures

### 2.3 Statistical analysis

All statistical analyses were performed using the SPSS software version 13.0 (SPSS Inc., Chicago, Illinois). The analysis of variance (ANOVA) and the LSD (Least Square Difference) post hoc test of significance were used to compare Carbon$_{sq}$ within and across different wetland types, which were peatland ($n$ = 132), freshwater marsh ($n$ = 126), salt marsh ($n$ = 182) and mangrove ($n$ = 33) (Table 2). To find the predominant factors regulating Carbon$_{sq}$, a linear regression model was used and the step-wise method was employed to exclude factors without significant contributions to Carbon$_{sq}$. All 14 climate parameters, nitrogen accumulation rates, and phosphorus accumulation rates were introduced into the linear regression model. The mean values are reported within 95% confidence intervals.

## 3 Results

Summary information of different wetland types was shown in Table 2. Globally, the average Carbon$_{sq}$ is 185.2 g/(m$^2$·yr) regardless of wetland types. The average Carbon$_{sq}$ differed significantly among types, ordered as salt marsh (247.7 g/(m$^2$·yr)) > mangrove (229.8 g/(m$^2$·yr)) > freshwater marsh (196.7 g/(m$^2$·yr)) > peatland (76.9 g/(m$^2$·yr)) (Fig. 3).

In the Northern Hemisphere, Carbon$_{sq}$ decreased with latitude (Fig. 4). However, Carbon$_{sq}$ in the Southern Hemisphere showed no trend, which might be due to the scattered sites and inadequate samples. For different wetland types, Carbon$_{sq}$ in mangrove and freshwater marsh significantly and negatively related to latitude ($r$ = −0.403, $P$ = 0.020; $r$ = −0.259, $P$ = 0.004). However, there were no such relationships for peatlands and salt marsh.

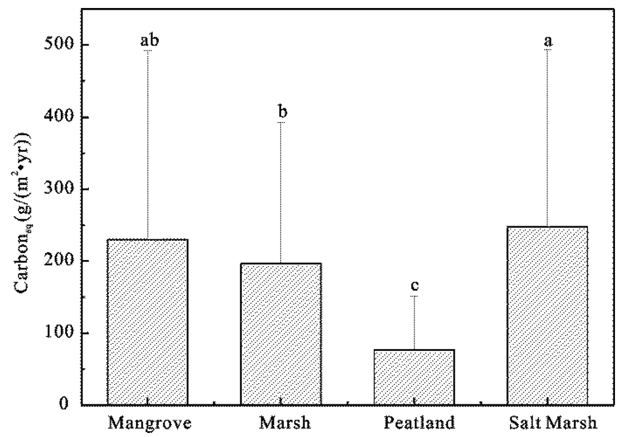


**Fig. 3** Carbon sequestration rates (Carbon$_{sq}$) of different wetland types. of selected soil/sediment cores Significant differences were represented by different letters

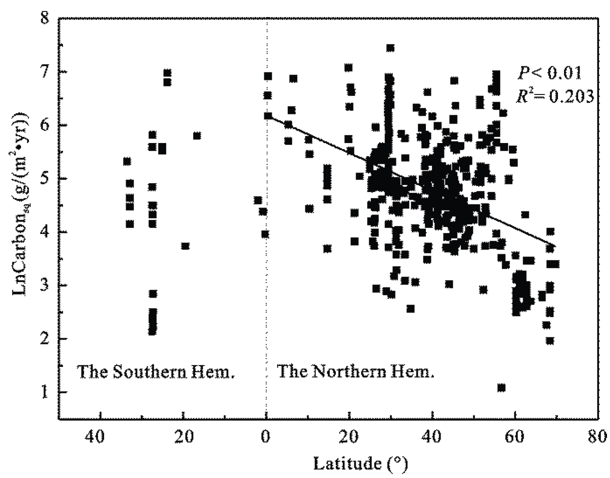


**Fig. 4** The relationship between Carbon$_{sq}$ of wetland and latitude. Hem., Hemisphere

## 4 Discussion

### 4.1 Impacts of climate on $Carbon_{sq}$

A significantly positive relationship was observed between $Carbon_{sq}$ and AMT (Table 3), which illustrated that higher temperatures could enhance $Carbon_{sq}$ because the higher temperature might facilitate to yield more biomass in wetlands (Feng et al., 2008). $T_{max}$ and $T_{min}$ were also significantly correlated with $Carbon_{sq}$, and the correlation coefficient between $Carbon_{sq}$ and $T_{min}$ was higher than that between $Carbon_{sq}$ and $T_{max}$. It indicated that the minimum temperature increase could more effectively promote $Carbon_{sq}$ than that by maximum temperature rise. Rapid warming during winter and spring induced earlier plant germination, prolonged the growing season and yielded more biomass, thereby triggering greater $Carbon_{sq}$ (Black et al., 2000; Sutfin et al., 2016). However, asymmetrical warming had an inconsistent effect on $Carbon_{sq}$ and was proved to promote carbon capture by grasslands due to the photosynthetic overcompensation under nocturnal warming enhancement (Wan et al., 2005). Moreover, asymmetrical diurnal warming leads to divergent responses of Northern Hemisphere vegetation growth (Peng et al., 2013), and asymmetrical warming in spring and summer would lessen $Carbon_{sq}$ and oppose wetland functions as carbon sinks (Zhang et al., 2017). Precipitation (Pre) also significantly promote $Carbon_{sq}$ in mangroves, freshwater marsh, and peatland but had little impact on $Carbon_{sq}$ in the salt marsh (Table 3). The highest correlation coefficient was observed between Pre and $Carbon_{sq}$ in peatland, and it implied that $Carbon_{sq}$ in peatland was the most sensitive to precipitation. The increase of $Carbon_{sq}$ with higher temperature and enhanced precipitation might reflect the self-adjustment capability and feedback mechanisms of wetlands facing climate change (Bridgham et al., 1995; Helbig et al., 2017).

$Carbon_{sq}$ is governed by both hydrological and thermal dynamics. Temperature increasing could potentially reduce $Carbon_{sq}$ by yielding greater $CO_2$ production (Boyero et al., 2011), but surface water table rising would also greatly facilitate $Carbon_{sq}$ by restricting decomposition or accelerating recalcitrant organic compounds generation (Macdonald et al., 1998; Kettunen et al., 1999; Turetsky et al., 2008; Li et al., 2019). In areas that become warming but also suffering drought, impacts of climate change on $Carbon_{sq}$ depends upon whether enhanced $Carbon_{sq}$ caused by warming could offset $Carbon_{sq}$ reduction caused by precipitation decreasing (Zhang et al., 2017). To explore the relationship between $Carbon_{sq}$ and climate change, the ratio of Pre to AMT, defined as PT, was used to proxy integrated impacts of temperature and precipitation (Bernal and Mitsch, 2013). PT was significantly and positively related to $Carbon_{sq}$ ($r$ = 0.317, $P$ < 0.0001), and the best fitting line exhibited a bell-shaped curve form with highest $R^2$ ($R^2$ = 0.132, $P$ < 0.0001) (Fig. 5), which agreed well with Bernal and Mitsch's report (Bernal and Mitsch, 2013). This implied that an intermediate PT value, approximately 12.7, was ideal to introduce the highest $Carbon_{sq}$.

**Table 3** Results of correlation coefficients between $Carbon_{sq}$ and nutrients and climate parameters

| Taxa | AMT | Pre | $T_{max}$ | $T_{min}$ |
|---|---|---|---|---|
| All sites | 0.417** | 0.325** | 0.386** | 0.484** |
| Mangrove | ns | 0.479* | 0.637* | 0.657* |
| Freshwater marsh | 0.315** | 0.208* | 0.245* | 0.272** |
| Peatland | 0.300** | 0.520** | 0.411** | 0.317** |
| Salt marsh | 0.279** | ns | ns | 0.334** |

Notes: AMT, annual mean temperature, ℃; Pre, annual precipitation, mm; $T_{max}$, the max temperature of the warmest month,℃; $T_{min}$, the min temperature of the coldest month,℃; * $P$ < 0.05; ** $P$ < 0.01; ns, $P$ > 0.05

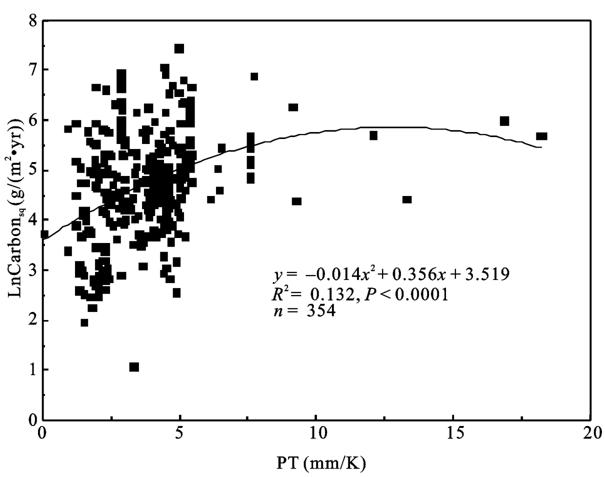


**Fig. 5** The fitting curve of PT (Pre/AMT, annual precipitation/annual mean temperature) and $Carbon_{sq}$. All sites, regardless of wetland type, were introduced into the figure. AMT used in the figure was converted from degrees centigrade to degrees Kelvin to avoid negative values. SPSS software was employed to perform a curve estimation

### 4.2 Impacts of nutrients on Carbon$_{sq}$

Effects of nitrogen and phosphorus loading on Carbon$_{sq}$ were generally explored based on in-situ experiments (Martina et al., 2016), and nitrogen availability was believed to be the dominant limitation factor on Carbon$_{sq}$ to most global terrestrial ecosystems (Vitousek and Howarth, 1991; LeBauer and Treseder, 2008). A significant positive correlation was observed between nitrogen accumulation rate (Nitrogen$_{ac}$) and Carbon$_{sq}$ ($r$ = 0.657, $P$ < 0.001, $n$ = 162), and the fitting curve was in a negative exponential form (Fig. 6). This meant that nitrogen input would facilitate Carbon$_{sq}$ in wetlands, which was consistent with other reports (Reay et al., 2008). The fitting curve implied that the effect of nitrogen input on promoting Carbon$_{sq}$ was the most effective when Nitrogen$_{ac}$ was lower than 20 g/(m$^2$·yr) (Fig. 6a). Currently, Nitrogen$_{ac}$ in the present work was below 20 g/(m$^2$·yr) in most sites (Ackerman et al., 2019), and so, it was reasonable to deduce that Carbon$_{sq}$ in most wetlands was limited by Nitrogen$_{ac}$ now, and increasing of global nitrogen deposition might cause more carbon to be captured by wetlands.

Among all four wetland types, Carbon$_{sq}$ was significantly positive with Nitrogen$_{ac}$, and slopes of fitting curves ordered by peatland > freshwater marsh > mangrove > salt marsh. This meant that nitrogen limitation was the most critical in peatland and of the least importance in salt marshes. This finding was almost identical to prior conclusions (Turunen et al., 2004). Nitrogen in peatland mainly originates from atmospheric deposition and is generally low enough in concentration that it induces nitrogen limitation (Waughman and Bellamy, 1980; Song et al., 2017). Additionally, it can be predicted that current nitrogen deposition would accelerate Carbon$_{sq}$ in peatland in high latitudes of the Northern Hemisphere. Most salt marshes are located in estuarine, coastal or tidal zones, where terrestrial and marine ecosystems converge. There are various nitrogen sources for the salt marsh, and nitrogen concentrations are generally enough high for plant growth (Burdige and Zheng, 1998; Valiela et al., 2000; Martina et al., 2016).

However, some research also reported a minor contribution of nitrogen deposition, at an input rate of 0.4−5.8 g/(m$^2$·yr), to Carbon$_{sq}$ in temperate forests (Nadelhoffer et al., 1999). High nitrogen input would yield high Carbon$_{sq}$ in agricultural fields because additional nitrogen would facilitate more carbon into the stable fine fraction pool irrespective of soil type (Kirkby et al., 2013). However, it was not the same case for wetlands. High Nitrogen$_{ac}$ provoked only a slight improvement of Carbon$_{sq}$, which was proved by the stable and unvarying fitting curve when Nitrogen$_{ac}$ was larger than 20 g/(m$^2$·yr) (Fig. 6a). It implied more carbon loss via soil and vegetation respiration stimulated by greater nitrogen input, and improvement of nitrogen on Carbon$_{sq}$ disappeared when carbon loss offset or even exhausted more carbon input from nitrogen fertilization (Yang et al., 2005; Tao et al., 2013). Though global nitrogen deposition has been increasing recently, current atmospheric nitrogen deposition fluxes to arctic ecosystems are still very low (< 0.20−0.33 g/(m$^2$·yr)). Nitrogen deposition to (sub)alpine ecosystems in central Europe is occasionally considerably high (1.00−2.00 g/(m$^2$·yr)) (Bobbink et al., 2010). However, global nitrogen deposition fluxes are still much lower than 20 g/(m$^2$·yr). Therefore, it is speculated that the current global nitrogen deposition increase would facilitate Carbon$_{sq}$ in wetlands.

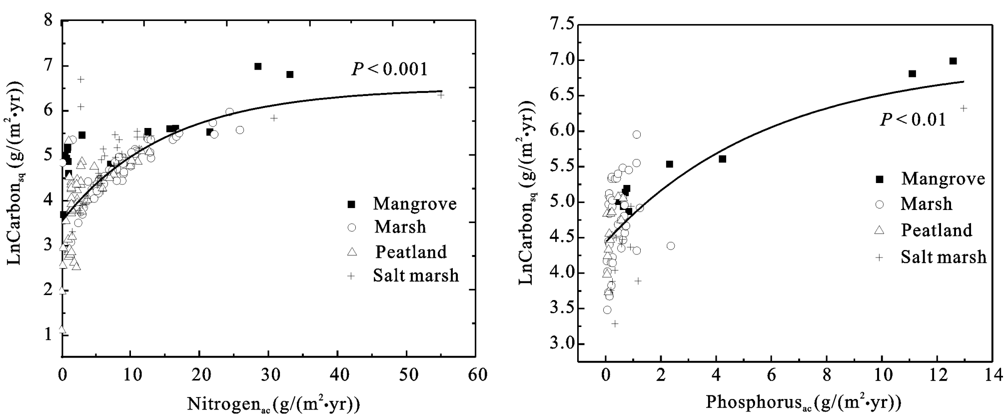


**Fig. 6** Relations between nitrogen accumulation rate (Nitrogen$_{ac}$, a), phosphorus accumulation rate (Phosphorus$_{ac}$, b) and carbon sequestration rates by global wetlands (Carbon$_{sq}$)

Though phosphorus is vital to $Carbon_{sq}$ in ecosystems (Hessen et al., 2004), phosphorus limitation in terrestrial ecosystems is often underestimated (Sundareshwar et al., 2003; Vitousek et al., 2010). Depletion, soil barriers, and low phosphorous parent material often provide the ultimate P limitation to ecosystems because they control the mass balance of phosphorus (Vitousek et al., 2010). Phosphorus accumulation rates ($Phosphorus_{ac}$) were significantly positive with $Carbon_{sq}$ in wetlands, and it implied that phosphorus limitation should not be neglected (Sundareshwar et al., 2003) (Fig. 6b). Correlations between $Phosphorus_{ac}$ and $Carbon_{sq}$ depended on wetland types, which was significant and positive in peatland and salt marsh, respectively ($r$ = 0.633, $P$ = 0.027, $n$ = 12; $r$ = 0.842, $P$ = 0.001, $n$ = 11) but weak in the freshwater marsh ($r$ = 0.191, $P$ > 0.05, $n$ = 49). Phosphorus usually tends to accumulate in wetland soils because there are no remarkable gaseous loss pathways like carbon or nitrogen (Noe and Hupp, 2005; Reddy and DeLaune, 2008). In our study, $Phosphorus_{ac}$ was much lower in peatland (0.235 g/($m^2$·yr)) than those in the salt marsh (0.530 g/($m^2$·yr)) and in the freshwater marsh (1.730 g/($m^2$·yr)). Low phosphorus availability may, at least in part, contribute to low biomass in peatland, and ultimately yield relatively small $Carbon_{sq}$ in peatland. However, it remains poorly understood why relationships between $Phosphorus_{ac}$ and $Carbon_{sq}$ are weak in the freshwater marsh.

### 4.3 Combined impacts of climate and nutrients on $Carbon_{sq}$

Climate and nutrient supply generally regulate $Carbon_{sq}$ together by complex positive or negative feedback. It is necessary to find the factor with the most important contribution to facilitate or restrict $Carbon_{sq}$. The multiple linear regression analysis implied that nitrogen was the common and primary factor controlling $Carbon_{sq}$ regardless of wetland types (Table 4), and this was in good agreement with other researches (Turunen et al., 2004). Another common factor affecting $Carbon_{sq}$ in wetlands was Bio17, the precipitation of the driest quarter. It mirrored the negative effects of drought on $Carbon_{sq}$. Zhang et al. (2017) have reported that warming in spring and summer would lessen $Carbon_{sq}$ and oppose wetland functions as carbon sinks.

For freshwater marsh, Bio8 was another factor affecting $Carbon_{sq}$ besides nitrogen. Litter decomposition in the marsh is restricted greatly by water-logged soil conditions. Bio8 represented temperature in the warmest season, which was often synchronous with the growth season of plants. Higher Bio8 would facilitate net primary production (NPP) and provide more leaf litters into the soil, and finally introduce high $Carbon_{sq}$. For peatlands, nitrogen was also the primary factor affecting $Carbon_{sq}$. Nitrogen limitation is common in peatlands, and high N deposition would yield more biomass of larger vascular plant leaf, which would facilitate $Carbon_{sq}$. Turnen et al. (2004) reported that there was a statistically significant positive relationship between N deposition alone and present-day C accumulation in both hummocks and hollows. Meanwhile, high Bio19 and Bio10 could also promote $Carbon_{sq}$ in peatlands. These two parameters represented precipitation and temperature respectively. More precipitation in the coldest season could greatly delay organic matter decomposition, and increasing temperature in the warmest season could yield more NPP, these two factors could finally promote $Carbon_{sq}$. For saltmarsh, nitrogen was the only factor that controlling $Carbon_{sq}$. It has been well established that nitrogen is a major nutrient that limits primary production in salt marsh ecosystems (Sundareshwar et al., 2003).

**Table 4** Models of multiple linear analysis for carbon sequestration rates by global wetlands ($Carbon_{sq}$) climatic parameters and nutrients

| Wetlands | Models | $R^2$ |
|---|---|---|
| All sites | $Carbon_{sq}$ = 9.660$Nitrogen_{ac}$ + 0.215Bio17 + 13.057 | 0.460 |
| Freshwater marsh | $Carbon_{sq}$ = 9.522$Nitrogen_{ac}$ + 0.152Bio8 + 19.530 | 0.818 |
| Peatland | $Carbon_{sq}$ = 12.854$Nitrogen_{ac}$ + 0.564Bio19 + 0.467Bio10 − 207.73 | 0.958 |
| Salt marsh | $Carbon_{sq}$ = 9.816$Nitrogen_{ac}$ + 24.336 | 0.994 |
| Mangrove | No enough cases | – |

Notes: $Nitrogen_{ac}$, nitrogen accumulation rate; $Phosphorus_{ac}$, Phosphorus accumulation rate; $Carbon_{sq}$, carbon sequestration rates by global wetlands; Bio14, Precipitation of the driest month; Bio17, precipitation of the driest quarter; Bio8, mean temperature of the wettest quarter; Bio19, precipitation of the coldest quarter; Bio10, mean temperature of the warmest quarter

## 5 Conclusions

Globally, the average $Carbon_{sq}$ is 185.2 g/($m^2$·yr) regardless of wetland types, of which salt marsh has the highest $Carbon_{sq}$. Positive relationships implied that higher temperatures could enhance $Carbon_{sq}$ because the higher temperature might facilitate to yield more biomass in wetlands. Precipitation also significantly promote $Carbon_{sq}$ in mangroves, freshwater marsh, and peatland but had little impact on $Carbon_{sq}$ in the salt marsh. Nitrogen and phosphorus accumulation also accelerate $Carbon_{sq}$ greatly. Nitrogen input on promoting $Carbon_{sq}$ was the most effective. However, improvement effects of nitrogen on $Carbon_{sq}$ depend on wetland types. Nitrogen and the precipitation of the driest quarter were the two common and primary factors controlling $Carbon_{sq}$ regardless of wetland types. Wetlands have degraded greatly owing to accessibility for utilization in the Northern Hemisphere, which greatly weakened wetland function as a carbon sink. Therefore, there is an urgent need to enact measures protecting wetlands.

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