

## Refining soil organic carbon stock estimates for China's palustrine wetlands

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2015 Environ. Res. Lett. 10 124016

(<http://iopscience.iop.org/1748-9326/10/12/124016>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 129.11.22.19

This content was downloaded on 20/01/2016 at 11:24

Please note that [terms and conditions apply](#).

## Environmental Research Letters



## LETTER

## Refining soil organic carbon stock estimates for China's palustrine wetlands

## OPEN ACCESS

RECEIVED  
16 July 2015REVISED  
11 November 2015ACCEPTED FOR PUBLICATION  
1 December 2015PUBLISHED  
15 December 2015

Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Kun Ma<sup>1</sup>, Junguo Liu<sup>1</sup>, Ying Zhang<sup>1</sup>, Lauren E Parry<sup>2</sup>, Joseph Holden<sup>2</sup> and Philippe Ciais<sup>3</sup><sup>1</sup> School of Nature Conservation, Beijing Forestry University, Qinghua East Road 35, Haidian District, 100083, Beijing, People's Republic of China<sup>2</sup> water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK<sup>3</sup> Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, F-91191, Gif sur Yvette, FranceE-mail: [junguo.liu@gmail.com](mailto:junguo.liu@gmail.com)**Keywords:** ecosystem services, climate change, China, peatland, swamp, marshSupplementary material for this article is available [online](#)**Abstract**

Palustrine wetlands (PWs) include all bogs, fens, swamps and marshes that are non-saline and which are not lakes or rivers. They therefore form a highly important group of wetlands which hold large carbon stocks. If these wetlands are not protected properly they could become a net carbon source in the future. Compilation of spatially explicit wetland databases, national inventory data and *in situ* measurement of soil organic carbon (SOC) could be useful to better quantify SOC and formulate long-term strategies for mitigating global climate change. In this study, a synergistic mapping approach was used to create a hybrid map for PWs for China and to estimate their SOC content. Total SOC storage in PWs was estimated to be  $4.3 \pm 1.4$  Pg C, with a SOC density of  $31.17 (\pm 10.55)$  kg C m<sup>-2</sup> in the upper 1 m of the soil layer. This carbon stock is concentrated in Northeast China (49%) and the Qinghai-Tibet Plateau (41%). Given the large pool of carbon stored in PWs compared to other soil types, we suggest that urgent monitoring programmes on SOC should be established in regions with very few datasets, but where PWs appear to be common such as the Tibet region and Northwest China.

**1. Introduction**

Palustrine wetlands (PWs) cover the majority of wetland types in the world (Lehner and Döll 2004). PWs refer to non-tidal marshes, swamps, bogs, and fens (Ramsar Convention Secretariat 2013). Only lakes, rivers and saline wetlands are not included as wetland types within the PW classification. PWs are important in the global carbon (C) cycle because of their large soil carbon pools held under largely anaerobic conditions, their high methane emissions, and their potential for considerable future carbon sequestration (Page *et al* 2011, Vicari *et al* 2011, Carlson *et al* 2012, Kleinen *et al* 2012, Sapart *et al* 2012, Charman *et al* 2013). Undisturbed PWs are usually observed to be small sinks of C annually, but large sinks over many years (Gorham 1991, Thormann *et al* 1999, Bellamy *et al* 2005, Huang *et al* 2010, Vicari *et al* 2011, van der Valk 2013, Maltchik *et al* 2014).

However, if there is warming-induced acceleration of organic matter decomposition then net C release could occur. Alternatively, if climate change enhances plant productivity over decomposition then there may be an enhanced net C uptake. There is large uncertainty as to how different types of PWs will respond in different regions to climate change but it is clear that as a starting point there is an urgent need to map and quantify the existing extent of PWs and their C stock so that better estimates of potential feedbacks to climate change may be developed.

Human activities such as drainage and prescribed burning threaten PWs and may enhance C release. Protection of PWs has been considered as an important component of climate change mitigation (Holden 2005, Davidson and Janssens 2006, Song *et al* 2006, Smith *et al* 2007, Vicari *et al* 2011), but without good maps or reliable soil organic carbon (SOC) stock estimates, organizing such protection by

national and international agencies becomes more difficult (Post *et al* 1982, Sigua *et al* 2009, Charman *et al* 2013, Lu and Xu 2014).

In China there are a number of soil maps and databases on SOC. However, the maps vary in spatial resolution and detailed estimates of SOC storage for PWs in China are only available for some wetland-rich regions (Tian *et al* 2003, Peng *et al* 2005a, 2005b, Kang *et al* 2009, Li 2009, Bai *et al* 2010). The lack of spatially explicit wetland area databases combined with a lack of representative *in situ* data on SOC is a major constraint for accurate estimation of SOC storage in China's wetlands. Thus previous estimates of wetland SOC storage in China are highly uncertain (Wang *et al* 2003, 2014, Mitra *et al* 2005, Wang 2009, Liu *et al* 2012, Zheng *et al* 2013). Many of the earlier SOC studies have predominantly focused on the Northeast of China (NEC), Zoige plateau and the middle and lower reaches of the Yangtze River, and do not provide a representative estimate of country-wide SOC stocks. In addition, the method of quantification of SOC stock for each region differs between studies, resulting in difficulties with comparisons between regions.

High-resolution remote sensing (RS) data, geographical information systems (GIS) and global positioning systems have made the mapping of PWs feasible. Maps of national and global PWs are now becoming available (Lehner and Döll 2004, Niu *et al* 2009, BFU 2011, Chen and Jessel 2011) but considerable discrepancies remain between these datasets, due to both different wetland classification systems and the methods used for mapping wetlands (table S1). Comparisons of these spatially explicit wetland area datasets with the Chinese first wetland census (National Bureau of Statistics of China 2007), showed large disagreements between the maps and national and provincial wetland census data. For example, the first Chinese wetland census suggested the total PW area was 137 002 km<sup>2</sup> around the year 2000, while Niu *et al* (2009) reported the total PW area to be only 90 885 km<sup>2</sup> in 2000. Based on the first Chinese wetland census database, PWs accounted for 35.6% of the total wetland area in China (National Bureau of Statistics of China 2007). However, there is no map focused on the spatial distribution of PWs in China. The SOC stock in the PWs of China is also not clear. In this study, we establish the first standardised map of PWs for China, evaluated against ground-based data. In a second step, we combined this dataset with *in situ* SOC measurements to provide a spatially explicit estimate of the SOC storage distribution across Chinese PWs.

## 2. Materials and methods

### 2.1. Materials

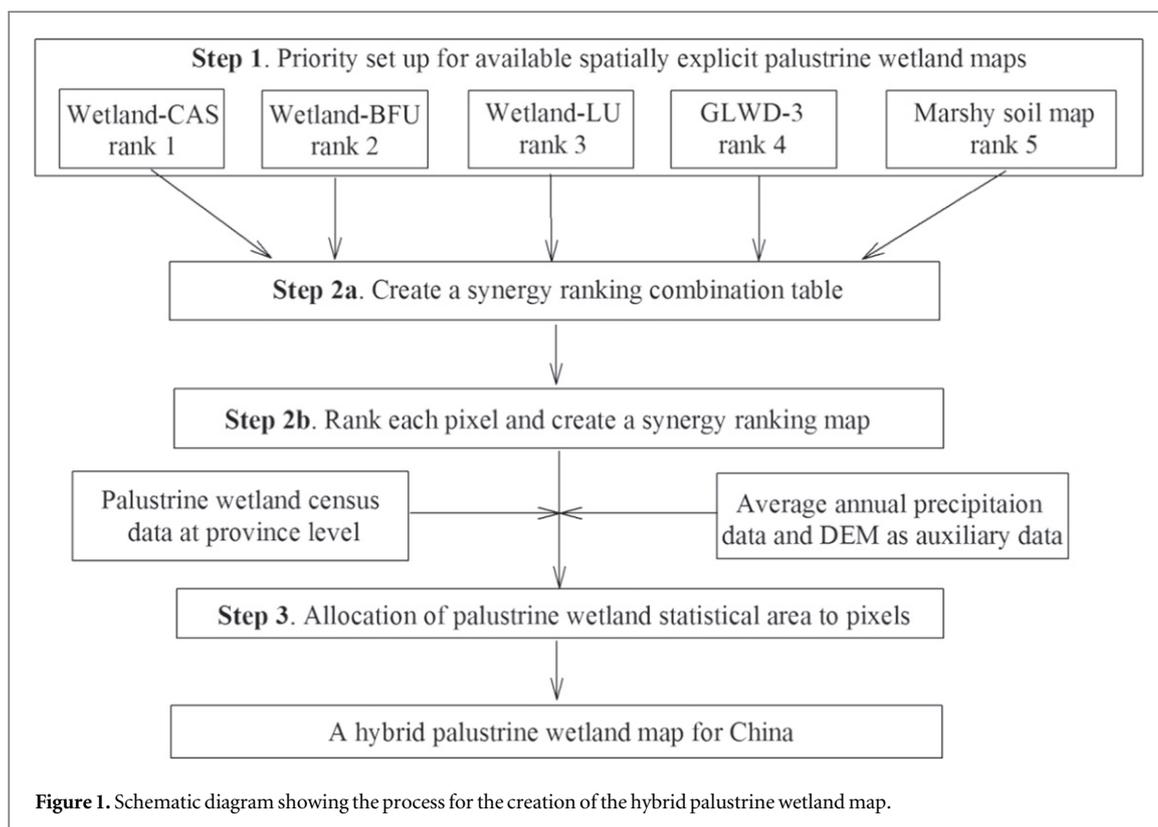
We adopt the classification of wetlands used by the Ramsar Convention on Wetlands. The treaty was adopted in 1971 with 168 contracting parties and the

Chinese government is one contracting party of the Ramsar Convention and the classification of wetland in China is officially based on that from the Ramsar Convention (State Forestry Administration, P. C. R 2004, Ramsar Convention Secretariat 2013). In the national wetland census in China, PWs were investigated and their areas were reported to the public for each province in mainland China (State Forestry Administration, P. C. R 2004). PWs include eight types in the census: moss bog, herbaceous marsh, swamp meadow, shrub marsh, forest swamp, inland marsh, geothermal wetland and freshwater spring or oasis wetland.

The landmass of China is large, with a very wide range of topographical conditions. As a result, a wide range of climatic regimes exists, which in turn may cause spatial variability in the amount and characteristics of PW across the nation. We carried out SOC mapping and quantification in each of China's eight eco-regions (Chen and Jessel 2011): NEC, Northwest of China (NWC), Qinghai–Tibet Plateau (QTP), Middle temperate humid zone (MTH), North subtropical humid zone (NSH), Middle subtropical humid zone (MSH), South subtropical humid zone (SSH), and Tropical humid zone (TH).

Six existing datasets which map wetlands in China were used to develop a standardised hybrid PWs map (see table S1). Each of these datasets provides the distribution and area for different kinds of PWs. These include: the wetland database of the Chinese Academy of Science (Wetland-CAS) which provides the distribution and area of swamp, inland marsh and coastal marshes; the wetland database of Beijing Forestry University (Wetland-BFU) which provides the distribution and area of marsh, swamp, bog, fen, mire, and forest wetland; the wetland database of Chinese Land Use (Wetland-LU) which provides land use and cover information for China including the distribution and area of marsh and peatland; the Global Lake and Wetlands database (GLWD-3) which provides the distribution and area of marsh, swamp, bog, fen, mire, and forest or flooded forest, marshland soil data extracted from 1:4million China soil data ([www.geodata.cn](http://www.geodata.cn)); and the Chinese wetland census dataset, which reports PW area by province. The formal five datasets provided spatially explicit wetland distribution, while the census reported wetland areas by province. To further refine the hybrid PWs map, we used historical temperature and precipitation datasets available from the Chinese Academy of Agricultural Science's weather station network (<http://geodata.cn>) as auxiliary data (see section 2.2). We also used a 1 km resolution Digital Elevation Model (DEM) (available from <http://westdc.westgis.ac.cn>) as auxiliary data (see section 2.2).

A soil physical property database was generated using existing literature. Soil data for PWs, including carbon content, carbon density, bulk density, geographical coordinates, and soil layering, were



compiled from data within peer reviewed literature and postgraduate theses. A database consisting of 4996 samples across 297 sites from 73 individual literature sources was created (table S2). In order for these data to be comparable with other global and national SOC stock estimates (Sjörs 1980, Mitra *et al* 2005) and Chinese wetland or peatland SOC stocks (Wang *et al* 2003, Zheng *et al* 2013), we gathered data from the upper 1 m of the soil profile, divided into two layers, topsoil (0–30 cm) and subsoil (30–100 cm). For the TH zone, we used data from the Harmonized World Soil Database (HWSD) because no other suitable data were available in the literature. The HWSD is a global soil database compiled from a number of different data sources (Nachtergaele *et al* 2008). In China, the 1:1million soil map, based on the second national soil census, is used in HWSD. This was provided by the Institute of Soil Science, Chinese Academy of Science (<http://westdc.westgis.ac.cn>). The HWSD gives the distribution of internationally recognized soil associations, which are defined by their SOC content (%), volume of stones (%), and bulk density ( $\text{kg dm}^{-3}$ ) by standard layers (0–30 cm and 30–100 cm).

## 2.2. Synergy mapping of PWs

A synergistic approach, which gives each mapping pixel a score based on the agreement among different wetland databases, was used to combine census and spatially explicit datasets. In this study, we collected four spatially explicit wetland distribution datasets, plus one marshland soil dataset and one national wetland census dataset. The spatial resolution of these

five datasets was different as summarised in table S1. Wetland-CAS is 1 km, Wetland-LU is 2 km (but was created based on 1 km land use data), and GLWD-3 is 30 arc seconds (equivalent to approximately 1 km). Wetland-BFU and Marshland soil map are not in raster data format. Hence, we standardized all datasets into the raster data format with the same spatial resolution of 1 km. We performed three processing steps to combine each dataset and create a single inventory of PW spatial extent in China, following the procedures from Ma *et al* (2012) (figure 1). These three processing steps are described below in sections 2.2.1–2.2.3.

### 2.2.1. Ranking available datasets

First, the datasets were ranked based on their data quality. As a general rule, a dataset was given a higher rank if it was created specifically for mapping PWs in China. The Wetland-CAS map, 1 km resolution, was created using RS data (Landsat ETM+) and was specifically calibrated to China's PWs and as a result was given the highest rank. The Wetland-BFU map was created based on directly surveyed Chinese wetland data, but this dataset was originally not in a raster format. Hence it was not given a rank as high as the Wetland-CAS, but a second rank. The Wetland-LU dataset, 2 km resolution, was specifically developed for land-use mapping (not wetland mapping) and it contains a specific land type of PWs. Therefore, it was classed as the third rank. The GLWD-3, 30 s resolution, is a global map of wetlands including PWs. It was produced based on various data sources and is not

specific to China. It is difficult to confirm the consistence and reliability of this dataset, and as a result we assigned it as the fourth rank. The marshland soil map was given the lowest rank, as it was extracted from the 1:4 million China soil map and was developed to specifically consider only marshland soils.

### 2.2.2. Ranking pixels

The second step in the synergy mapping process was to create a priority table and to rank each 1 km pixel. Since five different PW datasets were used in order of rank of confidence, there are 31 different possible combinations of confidence from 1 to 31 (table S3). When all five maps indicated a pixel as a PW, then we gave it the highest rank of 1. If four maps showed a pixel as a PW (four yes [Y] combinations), then we created the rank based on the priority orders of these four maps. For example, when the marshland soil map (the map with lowest priority) is the only map indicating no PW present on that pixel we gave the highest rank for the 4Y combination (or 2, table S3). However, when Wetland-CAS (the map with the highest priority) was the only map not indicating a PW for a pixel then we assigned that situation the lowest rank for a 4Y combination (a score of 6, table S3). A similar approach was applied for 3Y, 2Y and 1Y combinations. Rank 1 implies that a pixel is associated with the highest confidence that a PW exists on the pixel, while rank 31 means the pixel is associated with the lowest confidence of a PW existing on that pixel. The synergy map was then created after implementing the ranking (figure S1).

### 2.2.3. Allocating the PW area to pixels

The third step in the mapping process was to allocate the statistics of PW area for each province reported in the Chinese wetland census database to pixels. We here considered the census data for each province to be the most accurate source of PW area because this wetland inventory was produced with greatest rigour (State Forestry Administration, P. C. R 2004). While a more recent survey has been completed (2009–2013), the results of wetland area in each province are not accessible. Hence, in our study, we selected the first national survey of wetlands as our benchmark. Thus, the results of SOC presented in this paper represent the situation for the years around 2000.

To create a raster map, the census of the PW area for each province was allocated into different pixels of the synergy map. There were two situations in the allocation process. The first case was when the total area of pixels with a rank from 1 to 31 was higher than the total census PW area. In this case, PW areas were first allocated to the pixels with a higher rank. We then added the area of pixels in a province with a rank of 1. If this area was smaller than the total PW area in this province, we assume all these pixels with rank 1 are PWs. Then we added the area of pixels in this province

with rank of 1 and 2. This process was repeated until the total area of pixels with a rank of 1 to  $i$  (where  $i$  will be an integer from 1 to 31) was larger than the census PW area. At this point a decision was required as to how to allocate PWs in pixels with the rank of  $i$ . Since all of these pixels have the same rank, we used the 1960–2000 average annual precipitation data and DEM data as a secondary criterion to reorder these pixels, and assumed the pixels with higher precipitation and lower relative elevation have a higher probability of PWs. For example, suppose the census area of PWs for a province is 100 km<sup>2</sup>, the sum of areas with rank from 1 to 3 is 90 km<sup>2</sup>, and the sum of areas with rank from 1 to 4 is 110 km<sup>2</sup>. In this case, we need to reorder the pixels that are rank 4 with precipitation and DEM information and allocate the remaining 10 km<sup>2</sup> of PWs according to the criterion of precipitation and DEM. The second allocation situation was when the total area of pixels with a rank from 1 to 31 in a province was lower than the province's census PWs area. In this case, we assumed all these pixels with ranks 1–31 are PW, and other pixels were excluded.

### 2.3. Calculation of SOC stock using literature data

Using the geographical coordinates of directly measured soil parameters from our soil physical properties database (table S2), the Thiessen polygon method was applied within each eco-region using ArcGIS to divide each eco-region into several subareas where geographically relevant soil physical property values could be applied in SOC stock calculations (figure 3). For each subarea, SOC stock was calculated as follows:

$$SSOC_{ji} = SOCC_{ji} \times BD_{ji} \times A_{ji} \times H \times R, \quad (1)$$

where,  $SSOC_{ji}$  is the SOC stock of subarea  $j$  in eco-region  $i$  (kg C),  $SOCC_{ji}$  is the SOC content of subarea  $j$  in eco-region  $i$  (% weight or g kg<sup>-1</sup>),  $BD_{ji}$  is the bulk density (g cm<sup>-3</sup>),  $A_{ji}$  is the total PW area of subarea  $j$  in eco-region  $i$  (m<sup>2</sup>),  $H$  is the depth (m) of soil layer. Because the units of the measured soil parameters (i.e. SOC content, bulk density) were not consistent, we used the transfer coefficient  $R$  to standardize the SOC stock into the same unit (i.e. kg C). The volume of stones was omitted due to lack of data. In this study, we calculated the SOC stock of 1 m depth of soil in the area of PWs. The SOC density was calculated by SOC content multiplied by the bulk density. However, in 41% of the PW area, we could only obtain *in situ* experimental data from the literature for soil layers shallower than 1 m. For these areas, we assumed the soil had the same SOC density values from the deepest point for which experimental data were available down to 1 m depth. A total of 28% of PW area lacked bulk density data. These areas were gap-filled using the mean carbon density and standard error for the given eco-region. Then, the  $SSOC_{ji}$  was calculated for the topsoil (0–30 cm) and subsoil (30–100 cm).

The SOC stock of each eco-region and China as a whole was calculated as below

$$\text{SSOC}_i = \sum_{j=1}^n \text{SSOC}_{ji}, \quad (2)$$

$$\text{SSOC}_t = \sum_{i=1}^i \text{SSOC}_i, \quad (3)$$

where,  $\text{SSOC}_i$  is the total SOC stock of PWs in eco-region  $i$  (kg C),  $n$  is the number of subareas in eco-region  $i$ ,  $i$  is the code of the eco-regions while  $\text{SSOC}_t$  the total SOC stock of PWs in China (kg C).

Based on the total SOC stock and PW area, we calculated the mean SOC density for each eco-region and the whole country as below

$$\text{SOCD}_{\text{mean},i} = \frac{\text{SSOC}_i}{A_i}, \quad (4)$$

$$\text{SOCD}_{\text{mean}} = \frac{\text{SSOC}_t}{A_t}, \quad (5)$$

where,  $\text{SOCD}_{\text{mean},i}$  is the mean SOC density (kg C  $\text{m}^{-2}$ ) of eco-region  $i$ ,  $A_i$  is the total PW area ( $\text{m}^2$ ) of eco-region  $i$ ,  $\text{SOC}_{\text{mean}}$  is the mean SOC density (kg C  $\text{m}^{-2}$ ) of China's PWs and  $A_t$  is total PW area ( $\text{m}^2$ ) of China.

### 3. Results

#### 3.1. Distribution of PWs

A new hybrid PW map for China (Hybrid Palustrine Wetland Map of China, HPWMC) is shown in figure 2. The total PW area of China is 136 963  $\text{km}^2$ , 1% of the total national land surface area (National Bureau of Statistics of China 2007). The final results from the hybrid map are close to the areas for PW from the census provided for each province with a range of relative error of  $-0.8\%$ – $1.0\%$ , except for Guizhou, Guangdong and Zhejiang provinces (table S4). The Heilongjiang province has the highest PW area, with 24% of China's total PW area. The highest PW fractional coverage is also found in Heilongjiang, Inner Mongolia, Qinghai and Tibet. These four provinces altogether have 85% of China's total PW area. At eco-region scale, most PWs are distributed in the NEC, QTP, and NWC. These three ecological regions possess 97% of the PWs in China.

#### 3.2. PW SOC stock

Our study indicates that the total SOC stock in the upper 1 m of China's PWs is  $4.3 \pm 1.4$  Pg C with an average SOC density of  $31.2 \pm 10.1$  kg C  $\text{m}^{-2}$ . The NEC has the highest SOC storage with  $2.1 \pm 0.6$  Pg C, and this area accounts for 49% of the total national SOC storage in PWs. The second largest store of SOC is found in the QTP with 41% ( $1.8 \pm 0.8$  Pg C) of the total national SOC storage in PWs. Even though Northwest China contains 22% of the total PW area of China, its SOC storage is low due to a lower SOC density with a value of  $0.4 \pm 0.1$  Pg C, only 8% of the total national PW SOC pool. The SOC pools of other eco-regions are much lower than for the three

dominant PW eco-regions (figures 3(A) and (B1), table 1).

The total SOC stock stored in China's PW topsoil (0–30 cm) (figure 3(B2), table 1) was  $1.6 \pm 0.6$  Pg C with an average SOC density of  $11.9 \pm 4$  kg C  $\text{m}^{-2}$ . The NEC contains approximately  $0.8 \pm 0.3$  Pg C and 51% of the national PW total SOC topsoil stock. The NEC has the highest topsoil SOC stock, due to both a large spatial coverage of PWs and a high carbon density. The second highest topsoil SOC stock can be found in the QTP which contains  $0.6 \pm 0.2$  Pg C or 39% of the national PWs total SOC stock. The SSH zone contains the lowest topsoil SOC due to the lower carbon density and scarce PW distribution.

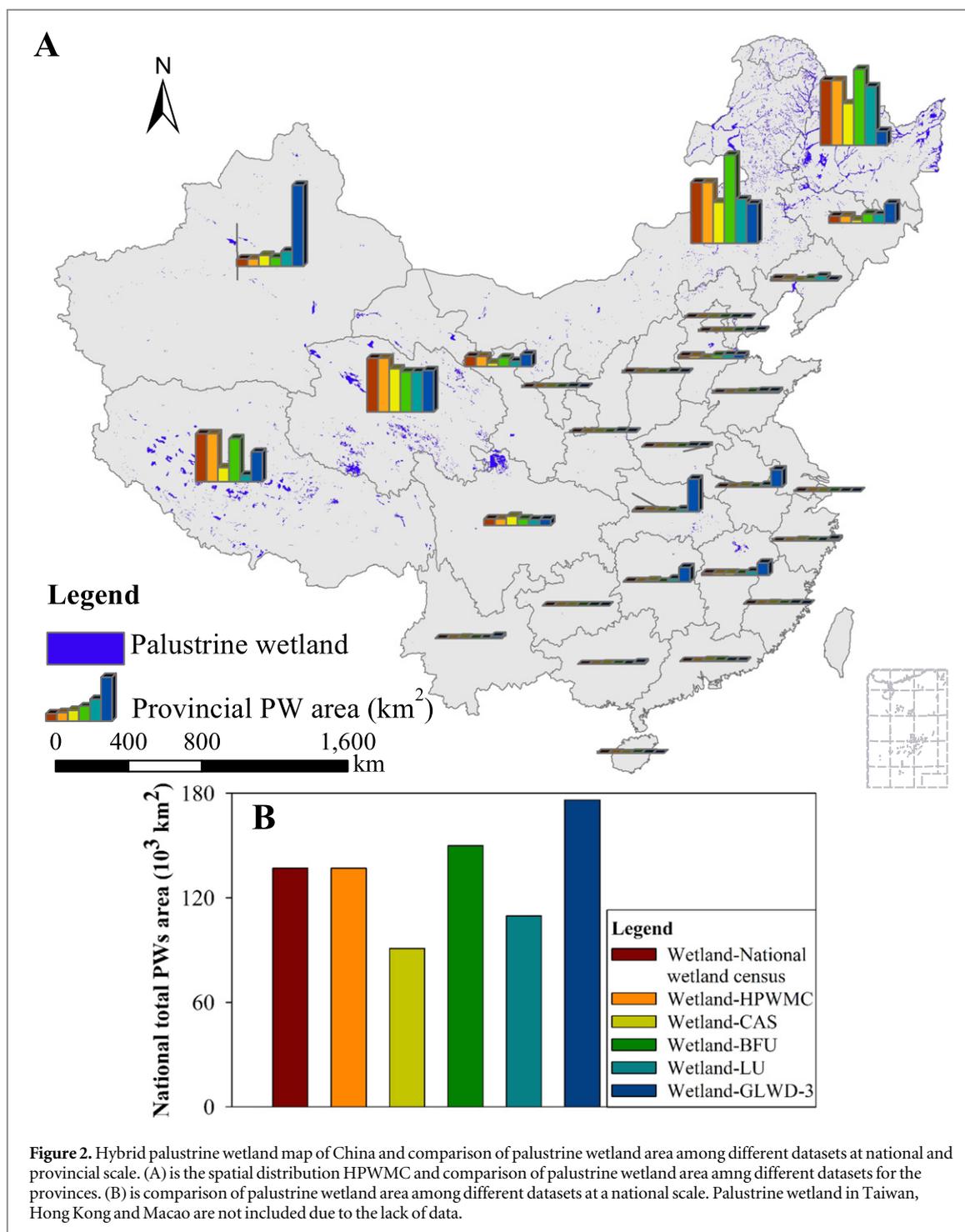
For the subsoil (30–100 cm), the average SOC density was  $19.3 \pm 6.6$  kg C  $\text{m}^{-2}$ , and the total SOC stock was  $2.6 \pm 0.9$  Pg C. The NEC contains approximately  $1.3 \pm 0.2$  Pg C or 48% of the national total subsoil SOC stock for all PWs (figure 3(B3), table 1). QTP contains the second highest subsoil SOC stock with a value of  $1.1 \pm 0.6$  Pg C, or 42% of the national total subsoil SOC stock for all PWs. The SSH zone has the lowest PW subsoil SOC stock among all of the eco-regions of China.

### 4. Discussion

#### 4.1. Comparison between hybrid PW map and other data-sets

Our approach helps reduce uncertainties in mapping PWs but it is clear that there are still some locations where uncertainties are great. The available datasets were given different priorities based on their authority, geographical focus, and spatial resolution. Allocation of PW area based on the rank of each pixel was estimated by considering the agreements between, and ranking of, existing datasets.

The area of the HPWMC shows some consistency with the national PW census (figure 2(B)). At a provincial scale, the PW area of HPWMC also has a good consistency with the provincial PW census (figure 2(A)). However, in some areas there are inconsistencies particularly in terms of reporting presence or absence of PWs. Our results suggest that the position of existing mapped PWs do not correspond between the four datasets. For Guangxi, Jiangsu and Anhui, the original four maps all indicated that some PWs exist there. However, the hybrid map suggests that no PW is present. This is because the first wetland census reported no PWs in these provinces. Therefore, in order to provide better estimates of PW distribution, surveys with improved spatial accuracy are needed in these regions. The HPWMC provides a reference of PW distribution and quantification in China, but also indicates that better directly surveyed datasets are required.

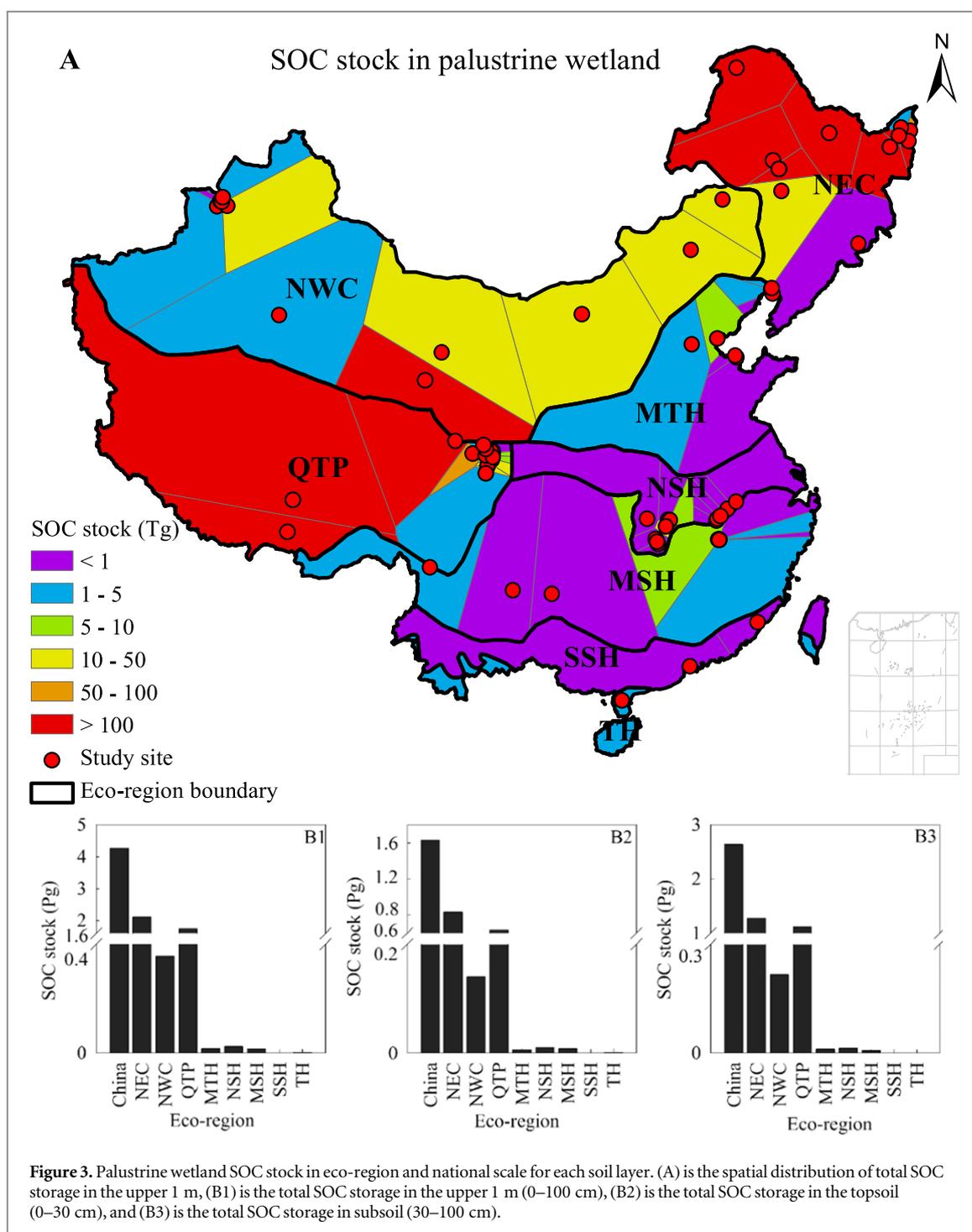


#### 4.2. Comparisons of SOC density

In this study, the mean SOC density of PWs calculated with data from the literature is  $31.2 \pm 10.6 \text{ kg C m}^{-2}$  in the upper 1 m. And the value we calculated for China is more than three times the national average SOC density (Yu *et al* 2007). The mean SOC density for PWs in China is lower than that Northern peatlands such as the peatlands in Russian ( $81.2 \text{ kg C m}^{-2}$ , Stoblovoi 2002). Tarmocai *et al* (2009) reported that the average SOC density to a depth of 1 m for peatlands in the Northern permafrost region was  $66.6 \text{ kg C m}^{-2}$  for Histels and  $69.6 \text{ kg C m}^{-2}$  for Histosols. The lower

mean SOC density of PWs was driven by PWs in some eco-regions which have a lower C content, such as those of inland marshes in NWC. Xu *et al* (2010) reported the SOC density ranged from 0.08 to  $1.77 \text{ kg C m}^{-2}$  in the PWs around Ebinur Lake.

On a national scale, based on the Chinese wetland RS map and the 1:1million soil map, Zheng *et al* (2013) reported the SOC density of wetland soils in China to vary from 2.4 to  $101 \text{ kg C m}^{-2}$  while Yu *et al* (2007) estimated a mean value for China's wetland soils of  $16.8 \text{ kg C m}^{-2}$  based on the 1:1million soil map. Liu *et al* (2012) found that the average SOC density in



Chinese peatlands was  $143.8 \text{ kg C m}^{-2}$ . There is clearly considerable variability in SOC density between wetland types. Comparisons with non-wetland ecosystems suggest, as expected, that the SOC density of PWs is greater. Based on the Chinese national soil census database, Yu *et al* (2007) suggested that the SOC density of forestland was  $14.3 \text{ kg C m}^{-2}$ , with shrub ( $11.5 \text{ kg C m}^{-2}$ ), grassland ( $8.2 \text{ kg C m}^{-2}$ ), farmland ( $9.2 \text{ kg C m}^{-2}$ ), desert ( $2.9 \text{ kg C m}^{-2}$ ) and urban areas ( $8.17 \text{ kg C m}^{-2}$ ) all having lower SOC density.

SOC densities in China's PWs are highly variable between the eight eco-regions. The highest SOC densities were found in the QTP, NEC and the NSH zone.

The SOC density is dependent on plant productivity and the mineralization intensity of organic matter, which are both strongly controlled by hydrology, climate conditions and soil texture (Duchaufour 1982, Paul 1984, National Soil Survey Office 1998, Wu *et al* 2003). The NWC has 22% of the total PW area, but SOC density is much lower than the national mean wetland SOC density. In the NWC, the climate is arid due to the moisture barrier effect of the QTP and the long distance from the ocean. The arid climate patterns and coarse soil textures (Wu *et al* 2003) result in lower SOC density and carbon storage in this eco-region.

**Table 1.** SOC stock and density (mean  $\pm$  standard error of the mean) in palustrine wetlands calculated with data from literature. The location of regions are shown in figure 3.

Region	Area (km <sup>2</sup> )	Top soil (0–30 cm)		Subsoil (30–100 cm)		Total over upper 100 cm	
		SOC stock (Pg C)	SOC density (kg C m <sup>-2</sup> )	SOC stock (Pg C)	SOC density (kg C m <sup>-2</sup> )	SOC stock (Pg C)	SOC density (kg C m <sup>-2</sup> )
NEC	58 890	0.83 $\pm$ 0.32	14.13 $\pm$ 5.43	1.28 $\pm$ 0.23	21.67 $\pm$ 3.96	2.11 $\pm$ 0.55	35.80 $\pm$ 9.39
NWC	30 170	0.14 $\pm$ 0.01	4.63 $\pm$ 0.24	0.22 $\pm$ 0.04	7.16 $\pm$ 1.27	0.36 $\pm$ 0.05	11.79 $\pm$ 1.50
QTP	44 128	0.63 $\pm$ 0.21	14.39 $\pm$ 4.83	1.11 $\pm$ 0.62	25.24 $\pm$ 14.06	1.75 $\pm$ 0.83	39.63 $\pm$ 18.88
MTH	1659	0.01 $\pm$ 0.00	3.40 $\pm$ 0.46	0.01 $\pm$ 0.00	6.22 $\pm$ 0.98	0.02 $\pm$ 0.00	9.62 $\pm$ 1.44
NSH	717	0.01 $\pm$ 0.00	14.28 $\pm$ 2.77	0.01 $\pm$ 0.00	18.86 $\pm$ 4.52	0.02 $\pm$ 0.01	33.14 $\pm$ 7.29
MSH	1242	0.01 $\pm$ 0.00	6.45 $\pm$ 2.42	0.01 $\pm$ 0.01	5.86 $\pm$ 1.55	0.02 $\pm$ 0.00	12.31 $\pm$ 3.98
SSH	35	0.00 $\pm$ 0.00	2.60 $\pm$ 2.02	0.00 $\pm$ 0.00	5.74 $\pm$ 4.48	0.00 $\pm$ 0.00	8.35 $\pm$ 6.50
TH	122	0.00 $\pm$ 0.00	4.94 $\pm$ 0.98	0.00 $\pm$ 0.00	4.43 $\pm$ 1.46	0.00 $\pm$ 0.00	9.37 $\pm$ 2.44
China	13 6963	1.62 $\pm$ 0.54	11.91 $\pm$ 3.98	2.64 $\pm$ 0.90	19.26 $\pm$ 6.56	4.27 $\pm$ 1.44	31.17 $\pm$ 10.55

**Table 2.** Comparisons SOC stock and density of palustrine wetlands with peatlands, wetlands and country-wide soils within China.

Scale	SOC density (kg C m <sup>-2</sup> )	SOC stock (Pg C)	Depth (m)	Reference
China's palustrine wetland	31.17 $\pm$ 10.55	4.27 $\pm$ 1.44	1	This study
	155.25	2.09	1.11	(Wang <i>et al</i> 2003)
China peatland	91.35	0.95	NA	(Wang 2009)
	143.97	1.50	NA	(Liu <i>et al</i> 2012)
	193	2.17	NA	(Wang <i>et al</i> 2014)
China wetland	15.0	3.67	1	(Niu <i>et al</i> 2009)
	22.4–27.5	5.04–6.19	1	(Zheng <i>et al</i> 2013)
	20.81–26.01	8–10	1	(Zhang <i>et al</i> 2008)
All China soil	8.01	70.31	NA	(Wu <i>et al</i> 2003)
	9.17	82.65	NA	(Li <i>et al</i> 2004)
	9.6	89.14	1	(Yu <i>et al</i> 2007)

### 4.3. SOC stock at different spatial scales

Estimates of national and global terrestrial SOC stock vary greatly (Mitra *et al* 2005). For example, the SOC stock in China's wetlands has previously been estimated to be somewhere between 3.7 and 12.2 Pg C (Yu *et al* 2007, Zhang *et al* 2008, Niu *et al* 2009, Zheng *et al* 2013). Our study indicates that the SOC stock in China's PWs is  $4.3 \pm 1.4$  Pg C. This is the first such estimate for PWs alone. For Chinese peatlands (a subset of PWs), the total SOC stock has previously been estimated to range from 1 to 2.2 Pg C (Wang *et al* 2003, 2014, Wang 2009, Liu *et al* 2012). The SOC stock of PWs calculated with data from literature in the upper 1 m of the soil layer was found to be 2–4 times larger than the SOC stock previously reported for 'peatlands' (note that bog and fen peatlands belong to the PW class), and 1–3 times smaller than SOC stock previously reported for wetlands as whole (table 2). This comparison implies that SOC storage in PWs is large not only in China's peatlands, but also in other types of PWs. There is therefore a need to conduct further in-depth analysis of SOC storage in these ecosystems.

At a national scale, Yu *et al* (2007) reported that China's soil contains 89 Pg C in the top 1 m with an average SOC density of  $9.6 \text{ kg C m}^{-2}$  based on the second national soil survey. Other estimates showed that the total SOC stock in China's soil are 92 Pg C (Wang

*et al* 2001), 70 Pg C (Wu *et al* 2003), and 83 Pg C (Li *et al* 2004). In the meeting of the 236th Xiangshan, Chinese soil experts accepted 90 Pg as the total SOC stock in China's soil (Zhang *et al* 2008). Our result shows that 5% of China's total SOC is held in PWs even though these ecosystems only occupy 1% of the total national land surface area. The SOC density of PWs is three times larger than the national average soil carbon density. In addition, the C sequestration rate of other ecosystems (such as forest, shrub, grassland and cropland) is  $0.075 \pm 0.025 \text{ Pg C yr}^{-1}$  (Piao *et al* 2009). Hence these other ecosystems combined may take more than 50 years to capture the same amount of carbon currently stored by the PWs in China.

At a global scale, Lehner and Döll (2004) reported that the total area of global wetland is about 11–13 million km<sup>2</sup>, and Mitra *et al* (2005) showed that estimates of carbon in global wetlands ranged from 202 to 535 Pg. PWs cover a broad class of wetlands, and our results show that Chinese PWs occupy 1% of global total wetland area, but hold 1%–2% of global wetland SOC in the upper 1 m of soil.

## 5. Conclusions

The hybrid map produced in this study provides a new reference for PW distribution and quantification in

China which will be valuable for wetland planning and management. However, considerable differences exist when comparing the hybrid map with other available datasets, especially in Guangxi, Jiangsu, Anhui. For these provinces our results indicate that careful PW investigation is urgently needed to improve the accuracy of the PW maps and SOC estimates.

PWs in China are widespread. Our results show that Chinese PWs occupied 1% of global total wetland area, but hold 1%–2% of global wetland SOC in the upper 1 m of soil. However, the existing research on these Chinese systems is most concentrated in the Sanjiang plain, Zoige plateau, and the middle and lower reaches of Yangtze River. There is therefore a clear need to both broaden the studies across different regions and for regional co-operation in collecting data and building databases based on such systems. Given the global significance of the response of SOC to environmental change and the very large pool of carbon stored in PWs, we suggest that regions with very limited datasets such as the PWs of the Tibet region and the NWC require an urgent monitoring programme and inventory effort. International co-operation is also required to ensure that consistent and comparable datasets on wetland carbon content are developed to support the protection and enhancement of these systems. Given the difficulty in compiling data on the spatial extent and carbon content of wetland systems, this makes understanding whether these systems are currently net sinks or sources for carbon even more challenging. Regional and international co-operation must be developed to ensure that the current and future carbon response of wetlands to global environmental change is understood and factored in to international and national policy and the IPCC wetland supplement (Agrawala *et al* 2014, Stavins *et al* 2014).

### Acknowledgments

This study was supported by the International Science & Technology Cooperation Program of China (2012DFA91530), the National Natural Science Foundation of China (41161140353, 91325302), the 1st Youth Excellent Talents Program of the Organization Department of the Central Committee, and the Fundamental Research Funds for the Central Universities (TD-JC-2013-2). The research was also supported by a Cheney Fellowship awarded to Professor Junguo Liu by the University of Leeds as part of the water@leeds research programme. We also want to thank Prof. Changhui Peng (Institute of Environmental Sciences, Department of Biological Science, University of Quebec at Montreal, Canada) for useful discussions on an earlier version of this manuscript. The data used in the paper can be requested from Professor Junguo Liu ([junguo.liu@gmail.com](mailto:junguo.liu@gmail.com)).

### References

- Agrawala S *et al* 2014 Regional development and cooperation *Climate Change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- Bai J, Ouyang H, Xiao R, Gao J Q, Gao H F, Cui B S and Huang L B 2010 Spatial variability of soil carbon, nitrogen, and phosphorus content and storage in an alpine wetland in the Qinghai–Tibet Plateau, China *Aust. J. Soil Res.* **48** 730–6
- Bellamy P H, Loveland P J, Bradley R I, Lark R M and Kirk G J D 2005 Carbon losses from all soils across England and Wales 1978–2003 *Nature* **437** 245–8
- BFU 2011 *Mapping China's Wetland Based on the First National Wetland Census* Beijing Forestry University
- Carlson K M, Curran L M, Ratnasari D, Pittman A M, Soares-Filho B S, Asner G P, Trigg S N, Gaveau D A, Lawrence D and Rodrigues H O 2012 Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia *Proc. Natl Acad. Sci. USA* **109** 7559–64
- Charman D, Beilman D W, Blaauw M, Booth R K, Brewer S, Chambers F M, Christen J A, Gallego-Sala A, Harrison S P and Hughes P D M 2013 Climate-related changes in peatland carbon accumulation during the last millennium *Biogeosciences* **10** 929–44
- Chen Y and Jessel B 2011 *Ecosystem Services and Management Strategy in China* (Beijing: China Environmental Science Press) (in Chinese)
- Davidson E A and Janssens I A 2006 Temperature sensitivity of soil carbon decomposition and feedbacks to climate change *Nature* **440** 165–73
- Duchaufour P 1982 *Pedology* (London: George Allen and Unwin)
- Gorham E 1991 Northern peatlands: role in the carbon cycle and probable responses to climatic warming *Ecol. Appl.* **1** 182–95
- Holden J 2005 Peatland hydrology and carbon release: why small-scale process matters *Phil. Tran. R. Soc. A* **363** 2891–913
- Huang Y, Sun W J, Zhang W, Yu D S, Su Y H and Song C C 2010 Marshland conversion to cropland in Northeast China from 1950 to 2000 reduced the greenhouse effect *Glob. Change Biol.* **16** 680–95
- Kang W, Tian H, He J N, Xi H Z, Cui S S and Hu Y P 2009 Carbon storage of the wetland vegetation ecosystem and its distribution in dongting lake *J. Soil Water Conserv.* **23** 129–33 (in Chinese)
- Kleinen T, Brovkin V and Schuldt R J 2012 A dynamic model of wetland extent and peat accumulation: results for the Holocene *Biogeosciences* **9** 235–48
- Lehner B and Döll P 2004 Development and validation of a global database of lakes, reservoirs and wetlands *J. Hydrol.* **296** 1–22
- Li H 2009 *Studies on Changes of Landscape Pattern and Soil Organic Carbon Storage in Rorergai Wetland* Sichuan Agricultural University (in Chinese)
- Li K R, Wang S Q and Cao M K 2004 Vegetation and soil carbon storage in China *Sci. China D* **47** 49–57
- Liu Z, Wang M and Ma X H 2012 Analysis of organic carbon storage and characteristics of China's peatlands *China Environ. Sci.* **32** 1814–9 (in Chinese)
- Lu Y and Xu H 2014 Distribution characteristic of soil organic carbon fraction in different types of wetland in hongze lake of China *Sci. World. J.* **3** 246–61
- Ma K, You L Z, Liu J G and Zhang M X 2012 A hybrid wetland map for China: a synergistic approach using census and spatially explicit datasets *PLoS One* **7** e47814
- Maltchik L, Lanés L E K, Keppeler F W, Rolon A S and Stenert C 2014 Landscape and habitat characteristics associated with fish occurrence and richness in Southern Brazil palustrine wetland systems *Environ. Biol. Fish.* **97** 297–308
- Mitra S, Wassmann R and Vlek P L G 2005 An appraisal of global wetland area and its organic carbon stock *Curr. Sci. India* **88** 25–35

- Nachtergaele F, van Velthuisen H and Verelst L 2008 *Harmonized World Soil Database* FAO
- National Bureau of Statistics of China 2007 *China Statistical Yearbook (2007)* (Beijing: China Statistics Press) (in Chinese)
- National Soil Survey Office 1998 *Soil of China* (Beijing: China Agriculture Press) (in Chinese)
- Niu Z G *et al* 2009 Geographical characteristics of China's wetlands derived from remotely sensed data *Sci. China D* **52** 723–38
- Page S E, Rieley J O and Banks C J 2011 Global and regional importance of the tropical peatland carbon pool *Glob. Change Biol.* **17** 798–818
- Paul E 1984 Dynamics of organic matter in soils *Plant Soil* **76** 275–85
- Peng P Q, Zhang W J, Tong C L, Qiu S J and Zhang W C 2005a Soil C, N and P contents and their relationships with soil physical properties in wetlands of Dongting lake floodplain *Chin. J. Appl. Ecol.* **16** 1872–8 (in Chinese)
- Peng P Q, Zhang W J, Tong C L, Wang X L and Cai C G 2005b Vertical distribution of soil organic carbon, nitrogen and microbial biomass C, N at soil profiles in wetlands of dongting lake floodplain *J. Soil Water Conserv.* **19** 49–53 (in Chinese)
- Piao S L, Fang J Y, Philippe C, Philippe P, Huang Y, Stephen S and Wang T 2009 The carbon balance of terrestrial ecosystems in China *Nature* **458** 1009–13
- Post W M, Emanuel W R, Zinke P J and Stangenberger A G 1982 Soil carbon pools and world life zones *Nature* **298** 156–9
- Ramsar Convention Secretariat 2013 *The Ramsar Convention Manual: A Guide to the Convention on Wetlands* 6th edn (*Ramsar, Iran, 1971*) (Gland, Switzerland: Ramsar Convention Secretariat)
- Sapart C, Monteil G, Prokopiou M, Van De Wal R S W, Kaplan J O, Sperlich P, Krumhardt K M, Van Der Veen C, Houweling S and Krol M C 2012 Natural and anthropogenic variations in methane sources during the past two millennia *Nature* **490** 85–8
- Sigua G C, Coleman S W and Albano J 2009 Beef cattle pasture to wetland reversion: impact on soil organic carbon and phosphorus dynamics *Ecol. Eng.* **35** 1231–6
- Sjörs H 1980 Peat on earth: multiple use or conservation? *Ambio* **9** 303–8
- Smith P, Chapman S J, Scott W, Black H I J, Wattenbach M, Milne R, Campbell C D, Lilly A, Ostle N and Levy P E 2007 Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978–2003 *Glob. Change Biol.* **13** 2605–9
- Song C, Wang Y Y, Wang Y S and Zhao Z C 2006 Character of the greenhouse gas emission in the freshwater mire under human activities *Sci. Geogr. Sin.* **26** 82–6 (in Chinese)
- State Forestry Administration, P. R. C 2004 *The National Wetland Resources Census—Report* (in Chinese)
- Stavins R *et al* 2014 International cooperation: agreements and instruments *Climate Change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- Stoblovoi V 2002 Carbon in Russian Soils *Clim. Change* **55** 131–56
- Tarmocai C, Canadell J, Schuur E, Kuhry P, Mazhitova G and Zimov S 2009 Soil organic carbon pools in the Northern circumpolar permafrost region *Glob. Biogeochem. Cycles* **23** GB023
- Thormann M N, Szumigalski A R and Bayley S E 1999 Aboveground peat and carbon accumulation potentials along a bog-fen-marsh wetland gradient in Southern boreal Alberta, Canada *Wetlands* **19** 305–17
- Tian Y B, Xiong M B, Xiong X S and Song G Y 2003 The organic carbon distribution and flow in wetland soil-plant system in Ruogegai plateau *Chin. J. Plant Ecol.* **27** 490–5 (in Chinese)
- van der Valk A G 2013 Seed banks of drained floodplain, drained palustrine, and undrained wetlands in Iowa, USA *Wetlands* **33** 183–90
- Vicari R, Kandus P, Pratalongo P and Burghi M 2011 Carbon budget alteration due to landcover-landuse change in wetlands: the case of afforestation in the lower delta of the paraná river marshes (Argentina) *Water Environ. J.* **25** 378–86
- Wang C 2009 *A Dynamic Research on Carbon Storage and Carbon Budget in Peatlands in China* Northeast Normal University (in Chinese)
- Wang M *et al* 2014 Carbon dynamics of peatlands in China during the Holocene *Quat. Sci. Rev.* **99** 34–41
- Wang S Q, Liu J Y and Yu G R 2003 Error analysis of estimating terrestrial soil organic carbon storage in China *Chin. J. Appl. Ecol.* **14** 797–802 (in Chinese)
- Wang S Q, Zhou C H, Li K R, Zhu S L and Huang F H 2001 Estimation of soil organic carbon reservoir in China *J. Geogr. Sci.* **11** 3–13
- Wu H B, Guo Z T and Peng C H 2003 Distribution and storage of soil organic carbon in China *Glob. Biogeochem. Cycles* **17** 1048
- Xu H H, Zeng C S, Wang W Q and Zhai J H 2010 Study on vertical distribution and the influencing factors of soil organic carbon in Ebinur Lake wetland *J. Fujian Norm. Univ.* **26** 86–91 (in Chinese)
- Yu D S, Shi X Z, Wang H J, Sun W X, Chen J M, Liu Q H and Zhao Y C 2007 Regional patterns of soil organic carbon stocks in China *J. Environ. Manage.* **85** 680–9
- Zhang W J, Xiao H A, Tong C L, Su Y R, Xiang W S, Huang D Y, Syers J K and Wu J S 2008 Estimating organic carbon storage in temperate wetland profiles in Northeast China *Geoderma* **146** 311–6
- Zhang X H, Li D Y, Pan G X, Li L Q, Lin F and Wu X W 2008 Conservation of wetland soil C stock and climate change of China *Adv. Clim. Change. Res.* **4** 202–8 (in Chinese)
- Zheng Y M, Niu Z G, Gong P, Dai Y J and Shangguan W 2013 Preliminary estimation of the organic carbon pool in China's wetlands *Chin. Sci. Bull.* **58** 662–70