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Soil hydromorphy and soil carbon: A global data analysis

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ABSTRACT

Wetland soils are an important component of the Global Carbon Cycle because they store about 20–25% of the terrestrial soil organic carbon (SOC). Wetlands occupy about 6% of the global land surface and any change in their use or management has potentially dramatic consequences on greenhouse gases emissions. However, the capacity of wetland soils to store carbon (C) differs from place to place due to reasons still not well understood. The objective of this review was to evaluate the global variations in wetlands SOC content (SOC_C) and to relate it to key soil and environmental factors such as soil texture, intensity of soil hydromorphy, metallic element content and climate. A comprehensive data analysis was performed using 122 soil profiles from 29 studies performed under temperate, humid, sub-humid, tropical and sub-arctic conditions. The results point to average SOC_C of 53.5 ± 15.8 g C kg^{-1} with a maximum of 540 g C kg^{-1}. SOC_C increased with increase in intensity of soil hydromorphy ($r = -0.52$), Al ($r = 0.19$) and Fe content ($r = 0.21$), and decreased with soil pH ($r = -0.24$). There was also a surprising tendency for intensity of soil hydromorphy, and thus SOC_C, to decrease with increasing mean annual precipitation and soil clay content. These results contribute to a better understanding of the impact of soil hydromorphy in wetlands on organic C stabilization in the soils. However, further studies with additional information on soil bulk density to assess carbon C stocks, still need to be performed.

1. Introduction

Wetlands are transitions from aquatic to dry land (upland) habitats and they occur in areas where soils are inundated/saturated by water due to high groundwater or ponding surface water during a part or all of the year (Neue et al., 1997). Globally, wetlands cover over 2.1 million km^2 (Ramsar Convention, 2016), representing about 6% of the earth's surface (Zhang et al., 2016). Even though wetlands provide a wide range of ecosystem services of great social and economic values, their rate of deterioration is faster than that of any other ecosystem (Davidson and Finlayson, 2007). For example, US wetland area was reported to have declined by about 25,200 ha between 2004 and 2009 (US Fish and Wildlife Services, 2011). Wetlands are also a highly threatened ecosystem type in New Zealand with only < 10% of their original extent remaining nowadays (Myers et al., 2013).

All wetland soils are characterized by excess water on momentary to permanent bases (EPA, 2017). The excess water induces reduction processes (Vepraskas and Guertal, 1992) resulting in generally low soil chroma and value (< 2). Additionally, the lack of oxygen lessens organic matter mineralization with subsequent accumulation of organic carbon (C) in the soils (Vaughan et al., 2008). Gorham (1995) and Zhang et al. (2016) estimated worldwide wetlands' C storage to range from 150 to 535 Gt C, which makes wetlands a key component of the global C cycle. The capability of wetlands to accumulate organic C varies with climate, soil properties and hydrological regime (Zhang et al., 2011; Wang et al., 2016). Accumulation of C in wetlands is a balance between net primary productivity and decomposition mediated by microbial processes (Stemmler and Berthelin, 2003; Zerva and Mencuccuni, 2005), decomposer community, environmental conditions and substrate litter quality (Werker et al., 2002; Koide et al., 2005; Urakawa and Bernhard, 2017).

Wetlands of cold regions have the greatest C accumulation potential due to low temperatures, high humidity and weak microbial activities (Tockner and Stanford, 2002) with, for example, boreal peatlands containing 270–370 Gt C (Fan et al., 2013), compared to tropical wetlands which stock only 89 Gt C (Page et al., 2011) because of higher temperatures and microbial activities. The boreal and temperate wetlands are C sinks (Moore and Bellamy, 1974) and they accumulate peat layers at rates regulated by climate, vegetation and topography (Armentano and Menges, 1986). The total organic C pool in the

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permafrost zone is composed of C frozen at depth in peatlands and C intermixed with mineral soils (Schuur et al., 2008). The northern permafrost zone alone is estimated to store 1672 Pg C; 277 Pg C of that in peatlands and 1024 Pg C in the 0–3 m permafrost-zone, representing a large fraction of global soil C stocks (Schuur et al., 2008). Thawing of the permafrost, which results in decomposition of previously frozen organic C, constitutes a significant feedback from terrestrial ecosystems to the atmosphere (Schuur et al., 2008) with approximately 100 Pg C set to be released from thawing permafrost by 2100 if temperature increases by 4 °C (Gruber et al., 2004). The collapsing permafrost generates fens in hydromorphic zones and bogs in the drier zones. Trumbore et al. (1999) showed that different decomposition rates give rise to the greatest C accumulation in the intermediate zone. Accumulation of C in the bogs and fens is low due to low inputs matched by low outputs and high productivity matched by high respiration, respectively. The collapse of permafrost wetlands also changes plant and microorganism communities with, for example, increasing organic C degraders in Alaska (Chapman et al., 2017).

On the other hand, tropical wetlands are the largest natural source of atmospheric C with organic substrate quality the main control of decomposition (Miyajima et al., 1997). Substrate quality is important in both anaerobic decomposition and methanogenesis, and correlate strongly with lignin content (Miyajima et al., 1997; Hoyos-Santillan et al., 2016). Hoyos-Santillan et al. (2016) reported high CO_2 and CH_4 emissions under anoxic conditions in tropical peatlands, which strongly correlated to lignin content, long chain fatty acids and polysaccharides concentrations. Unlike temperate and boreal peatlands which come from more degradable sphagnum mosses and sedges (Yavitt and Williams, 2015a), tropical peatlands come from high lignin tree litter. Although decomposition rates are generally faster in lower C:N ratio substrates, C:N ratio had no limit on mineralization in tropical wetlands (Yavitt and Williams, 2015b). However, Sjogersten et al. (2016) showed no link between organic chemistry of arctic and subarctic peatlands and CH_4 emission under flooded and non-flooded conditions. The emission was limited by availability of specific substrates i.e. sugars and low molecular weight organic acids, which ferment to acetate, a precursor for CH_4 production. Unlike high latitude wetlands with relatively stable water levels (Junk et al., 2014), neotropic peatland C losses follow water level drawdown and litter quality (Bridgham and Richardson, 1992; Laiho, 2006). The neotropic wetland hydrology, characterized by river flooding and groundwater table fluctuations (Junk et al., 1989), modifies the chemical and physical properties, degree of anoxia, sediment properties and soil pH, which subsequently reflect in the decomposition rates of organic materials (Webster and Benfield, 1986).

However, there are discrepancies in wetland C storage for any given region because decomposition in the wetlands is a complex aerobic-anaerobic process regulated by physical, chemical, and biological processes (Kayranli et al., 2010). Landscape diversity also contrasts wetlands by influencing vegetation growth and C storage capacity (Heinselman, 1970). In similar Brazilian climatic conditions, for example, Martins (2014) pointed to maximum SOC content (SOC_C) of 41 g C kg^{-1}, while Bardy et al. (2008) and Rosolen et al. (2015) estimated maximum values of 455 and 537 g C kg^{-1}, respectively. Chaplot et al. (2001) and Rosolen et al. (2015), amongst others, also reported on large differences in SOC_C of a single wetland, which may be associated with differences in soil saturation by water and hydromorphy. The results of Chaplot et al. (2001) showed the highest SOC_C of 460 g C kg^{-1} at the valley bottom and a lowest of 100 g C kg^{-1} at the footslope in the Armorican Massif of western France.

Relationships between flooding duration and frequency and decomposition rates in wetlands are still not well understood due to great variability in wetland types (Brinson et al., 1981; Neiff et al., 2006). The present study aimed at (i) reviewing existing works that assessed SOC_C levels in wetland soils at a global scale and (ii) investigating the links between SOC_C and soil hydromorphy and the main soil and environmental factors of control. These objectives were achieved by gathering quantitative data from various natural wetlands in different environments worldwide. Such quantitative analysis is important for land managers concerned with understanding the potential impact of change in wetland hydromorphy through, for instance drainage, on C losses from the soils. It might also help in estimating the C sequestration potential of degraded wetland soils in the framework of international programs such as the ‘4 per mille Soils for Food Security and Climate’, which was launched at the COP21 with an aspiration to increase global soil organic matter stocks. The results could in particular inform on ways to render certain wetlands more efficient in sequestrating atmospheric C. Finally, quantitative information on the links between, for instance, climate or soil clay content and wetland SOC_C could constitute an important tool for the spatial prediction of wetland soil C.

2. Materials and methods

2.1. Study setup

The study was based on data collected from electronic reserves and databases containing field experiment reports performed on wetlands or waterlogged sites. The literature data search targeted information from soil profiles developed under different wetland types e.g. floodplains, swamps and peatlands. The search used key words and phrases such as “water-logged soil”, “soil hydromorphy”, “hydromorphic features”, “*Gleysols*”, and “SOC”. A number of electronic databases such as Google, Google Scholar, Web of Science and Science Direct were searched for the data. The methods used in organizing the database and statistical treatments of the data were according to Mutema et al. (2015).

Many papers were downloaded but gaps in data on SOC_C and/or information on the intensity of soil hydromorphy led to omission of some papers from the current analysis. Other important soil parameters sought included iron (Fe), aluminum (Al), clay content and Munsell soil color (Hue, Value and Chroma). In addition to these parameters, the data sources also needed to provide site locational and climatic information. Boreal and temperate wetlands were not included the current study because they accumulate very large amounts of C and would behave as outliers when put together with other environments. Outliers are values that shift the median and mean up. The final database consisted of 27 published ISI papers and two masters' theses, totalizing 122 soil profiles from different sites across the world. Amongst these accepted data sources, 12 came from Brazil, 3 from Germany, two from China and USA, and one from each of Switzerland, Bangladesh, Italy, India, Mexico, Bolivia, Russia, South Africa, and France (Fig. 1) with sites spanning a latitudinal range from 30° 15′ S to 47° 57′ N.

The database captured information on author name(s), years the papers were published, paper titles, experimental site characteristics such as geographical location, climatic parameters, dominant land use, number and descriptions of the studied soil profiles. The data on SOC_C, Clay, Fe and Al, collected from the data sources, were in different units but mainly presented in terms of mass (e.g. g kg^{-1}, mg g^{-1} and percentage %). The data were normalized to g C kg^{-1} for SOC_C and % for Fe, Al and Clay. Other site characteristics recorded include longitude (LONG), latitude (LAT) in degrees, 30-year mean annual precipitation (MAP) and temperature (MAT). Table 1 presents a summarized version of the database.

2.2. Definitions of variables

2.2.1. Climatic factors

The climatic factors considered in the present study were MAP and MAT. They were grouped into categories (Table 2) following Mutema et al. (2015). MAP was categorized into 120–800, 800–1200 and 1200–2200 mm year^{-1}, while MAT was grouped into 6–15, 15–22 and 22–30 °C year^{-1}.

2.2 Soil properties.