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Editorial

Properties, processes and ecological functions of floodplain, peatland, and paddy soils

Wetlands are complex and diverse semi-terrestrial ecosystems that function as important links between terrestrial and aquatic systems (Reddy and Patrick, 1993). They comprise one hand natural or restored ecosystems such as marshes, bogs, fens, swamps, peatlands and floodplains, and on the other hand flooded lowland rice fields, which are anthropogenic wetlands of paramount importance for human nutrition worldwide (Kögel-Knabner et al., 2010; Neue, 1991). Anthropogenically unaltered and restored wetlands are important natural resources (Mitra et al., 2005) and fulfill a large range of ecosystem services including drinking water production, flood protection, climate regulation and habitat provision (Tockner and Stanford, 2002; Verhoeven et al., 2006). In particular, they are hotspots of biogeochemical cycling and as such they play an important role in regulating greenhouse gas emissions (e.g., Yu et al., 2007). As a consequence, policies and laws have been established worldwide attempting to protect wetlands against human degradation (Megonigal, 2008). Recent years have witnessed a dramatic increase in our knowledge of wetland biogeochemistry and its contribution to element cycling (Megonigal, 2008; Reddy and DeLaune, 2008) as well as in our understanding of soil hydraulic and physical properties (Janssen and Lennartz, 2008; Janssen et al., 2010). Nevertheless, in comparison to terrestrial environments, our understanding of the linked chemical, physical, and biological processes in wetland soils is still poor. Due to permanent or temporary water saturation, the processes are dramatically different from soils in upland ecosystems. This is mainly for two reasons, both as a consequence of the restricted oxygen supply during water saturation, i.e. (i) the permanent or temporary occurrence of reducing conditions, and (ii) potentially high contents of soil organic matter (SOM; Rinklebe et al., 2007). Similar physical and geo-chemical properties occur in soils of flooded lowland rice fields (paddy soils), but here they are the consequence of the mechanical preparation of the soil for rice planting, the so-called puddling (Lennartz et al., 2009), and the distinct management (Kögel-Knabner et al., 2010; Neue, 1991).

Development, properties, processes, and functions of these soils are strongly influenced by their hydrological connectivity with ground- and/or surface water. The hydrological and hydraulic characteristics determine the level, frequency, and duration of water saturation and the related dynamics of redox conditions as well as the linked matter fluxes (Du Laing et al., 2009; Frohne et al., 2011; Hefting et al., 2004; Kögel-Knabner et al., 2010).

Despite the common characteristics of the various types of wetland soils, research communities have evolved dealing with individual soil types and/or single aspects such as nutrient dynamics, carbon cycling, metal solubility, biological or physical properties. The different communities met at the EUROSOIL 2012 conference in Bari, Italy, during several sessions. This special issue brings together the knowledge developed in the different communities in order to foster cross-disciplinary exchange. It combines contributions mainly from river floodplains and paddy soils. In both systems there is a large variation of hydrological regimes in terms of frequency and duration of saturation and dry phases. In addition, two manuscripts deal with the use of degraded peat as constructed treatment wetlands to purify nutrient-rich run-off water, which can be considered as a single extreme dry–saturation cycle. In the following, the individual contributions are summarized and discussed mainly with respect to the effects of different hydrological regimes. This discussion is subdivided into processes during individual saturation events or saturation/drying sequences on one hand, and long-term effects of specific hydrological regimes on soil chemical and physical parameters on the other hand.

1. Processes during individual flooding events or flooding/drying sequences

The behavior of trace metals in estuarine and floodplain soils and how it depends on controlling factors such as redox potential has been studied in great detail (Du Laing et al., 2009; Rinklebe and Du Laing, 2011), however there have not been many attempts to characterize processes within different flood–dry-cycles so far. In a lysimeter study using large undisturbed soil columns originating from the Elbe River floodplain (NE Germany), Shaheen et al. (2014-in this issue) studied the mobilization of trace elements during sequences of long and short flooding and drying phases. While the long-term cycling mainly revealed expected relations between trace element mobilization on one hand and changes in redox potential and the dissolution of potential metal carriers such as oxides and dissolved organic matter (DOM) on the other hand, these conditions and processes were partly temporally de-coupled in the short-term cyclings. This de-coupling might be attributed to slow kinetics of some of the processes involved. In contrast to large rivers such as the Elbe River, where short-term flooding still means water saturation of a few weeks, small rivers (e.g. peri-alpine) without dams and reservoirs are characterized by a flashy-flow regime with water-saturated conditions even after major floods of not more than 1 to 2 days. Shrestha et al. (2014-in this issue) studied nitrogen cycling in the restored section of the Thur River (NE Switzerland) and how it was affected by a major flood event. In floodplain zones, where water-saturation was coupled with the fast over-flow of water, the flooding initiated a strong stimulation of the entire N cycle. Temporary input of available organic matter during the inundation led to a strong increase of N mineralization. During the drying phase also nitrification and denitrification were enhanced with close coupling of the two processes

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supported by different redox conditions at the inside and outside of soil aggregates. This study is among the rather few of the numerous studies of nitrogen transformations in wetlands considering all major processes within the nitrogen cycle (Shrestha et al., 2012).

Artificial drainage of peatlands for agriculture, forestry and peat extraction has been performed worldwide for centuries (Holden et al., 2004). Recently, interest has arisen to use drained peatland for purification of agricultural run-off, e.g. in constructed wetlands (Vymazal, 2011). Kleimeier et al. (2014-in this issue) performed a mesocosm study designed to delineate the conditions to use formerly drained fens as constructed wetlands for the purification of run-off from agricultural fields. While the peat material performed effectively after anoxic operating conditions were established, the authors observed a large initial flush of mineralized nitrogen upon rewetting. This initial nitrate flux compromised the treatment efficiency and a recycling of the first water on the constructed wetland is recommended. These findings were corroborated during field measurements by Postila et al. (2014-in this issue) who found significant leaching of nitrogen and phosphorus from treatment wetlands that were recently established on formerly drained peatlands in order to purify the run-off from peat extraction operation.

Since in paddy rice agriculture the flooding regime is under direct control of the farmer, experimental studies to elucidate the effects of different regimes can be directly transferred into management recommendations. One important aspect is the efficient use of fertilizers (Kögel-Knabner et al., 2010). Said-Pullicino et al. (2014-in this issue) incubated topsoil from a field under 30 years of continuous rice cultivation and compared the application of nitrogen fertilizer under flooded and non-flooded conditions, both with and without incorporation of rice straw. Using an innovative approach involving physical and chemical soil fractionation and isotopic analyses, they could show that both flooded conditions and litter incorporation helped to immobilize N in the soil. Xinqiang et al. (2014-in this issue) performed a field experiment to test the effectiveness of different applications of manure as N fertilizer in paddy rice cultivation. They were able to predict plant uptake, volatilization, and leaching of the fertilizer N successfully using a dedicated model. Despite the large fluxes of DOM from paddy topsoils to subsoils and the potentially important role in the organic carbon budget of paddy fields, studies of DOM dynamics in these soils are rare (Kögel-Knabner et al., 2010). In a laboratory experiment, Hanke et al. (2014-in this issue) looked into the effect of redox conditions during the initial residence time of rice straw leachates in the topsoil on the sorption of DOM to potential binding sites upon leaching into the oxic subsoil. Sorption of anoxically incubated DOM was clearly weaker than of oxically incubated DOM. This could only be explained by differences in the molecular composition of the DOM.

2. Long-term effects of specific hydrological regimes

Although it is well known that properties of paddy soils change continuously with increasing duration of cultivation (Kögel-Knabner et al., 2010), details of the underlying processes are still insufficiently known. Kölbl et al. (2014-in this issue) compared soil formation in a chronosequence of paddy soils characterized by a yearly cropping sequence of rice under flooded conditions alternated with a non-inundated crop, with the soil formation in a chronosequence of fields with exclusively non-inundated crop production. The land-use history was established based on the analysis of lipid biomarkers. Overall, soil formation was accelerated in paddy soils. This was mainly explained by processes during flooded rice cultivation, specifically accelerated leaching (desalinization, decalcification), formation and redistribution of oxides in the subsoil, and increased SOM accumulation in the topsoil. In a further study by Wissing et al. (2014-in this issue), the latter phenomenon could be explained by the increase in the relative content of oxides after decalcification. Furthermore the authors could show that SOM and iron oxides protect each other in organo-mineral associations under the alternating oxic and anoxic conditions.

The soil structural dynamic as induced by drying and wetting cycles in paddy fields may foster the development of a crack network operating as preferential pathways for water and compounds (Sander and Gerke, 2007). However, a regular mechanical soil treatment over decades and centuries and the resulting plough pan may reduce infiltration losses (Janssen and Lennartz, 2007). Two studies in this special issue provided further insight into crack formation in paddy soils. Yoshida et al. (2014-in this issue) determined the water retention capacity of undisturbed samples from monoculture rice paddies and rotationally cropped fields in the laboratory. The decrease in water retention due to pore shrinkage during drying was smaller in the rotationally cropped field. Similarly, Zhang et al. (2014-in this issue) found larger – but fewer – cracks after 100 years than after 20 years of alternating flooding/drying cultivation. Comparison with continuously flooded fields demonstrated the significance of the large cracks for water infiltration.

Long-term effects of different flooding regimes are also manifest in riverine floodplain soils. In contrast to paddy soils, where often a good documentation of land-use history allows a quite precise determination of type and duration of a flooding regime, in floodplains this often can be determined only rather vaguely based on soil type or by a comparison of topographic position relative to hydrograph recordings (Du Laing et al., 2009; Hefting et al., 2004; Rinklebe et al., 2007). Despite the recognized important role that wetlands play in the global carbon cycle (Mitra et al., 2005), investigations of carbon budgets in non-peat wetlands are rare. In a study on carbon storage and SOM stabilization in floodplains differing in human influence (near natural, restored, channelized), Bullinger-Weber et al. (2014-in this issue) showed that the long-term flooding regime – including effects of human activities – is reflected in the overall morphology of the alluvial soil profiles. Furthermore, within a floodplain carbon storage and SOM stabilization differed among morphologically defined soil groups. Thus, morphological characterization may prove a means to a more precise determination of hydrological regimes. The long-term effects on trace element mobilization in riverine floodplains were investigated in two studies. Martin et al. (2014-in this issue) compared floodplain soils along the Ganges and the Meghna Rivers in Bangladesh that were irrigated using As containing groundwater. There are large differences between the flooding regimes of the two rivers, based on rather vaguely defined “inundation land types”. The relatively long water saturation of the Meghna River floodplain soils resulted in high leaching losses of As. In the Ganges River floodplain soils, which were subjected to shorter inundation, more As persisted but to a higher degree in potentially mobile form than the remaining As in the Meghna soils. Similar results were obtained by Shaheen and Rinklebe (2014-in this issue) for Cr, Cu, and Zn mobilities in Fluvisols and Gleysols at the Elbe River. Using a sequential extraction scheme, they found that the Fluvisols, characteristic for relatively short inundations, exhibited higher total and “potentially mobile” contents of the investigated trace metals than the Gleysols which indicated longer periods of water saturation. These results were further corroborated by the finding that the “potentially mobile” metal contents were higher in the Gleysol layers above the average groundwater level than below. Mihajlovic et al. (2014-in this issue) provide one of the – to date – rare systematic reports on geochemical forms of rare earth elements (REE) in wetland soils. Their results for Fluvisols along the Wupper River suggest that similar dependencies on the flooding regime may be true for REE as observed for Cr, Cu and Zn in the aforementioned study.

Considering the large amounts of money spent on river restoration activities in the last few decades, it is important to develop suitable indicators to assess the success of the restoration efforts (Pereira and Cooper, 2006). Among others, a good understanding of long-term effects of different hydrological regimes may help to develop such indicators. Bullinger-Weber et al. (2014-in this issue) proposed the definition of morphologically defined soil groups that are characteristic for natural fluvial dynamics. Based on a systematic determination of spatial variability across different scales, Hale et al. (2014-in this issue) advocated the use of soil parameters with an inherently small variability. This