Preface: Wetland ecosystems—functions and use in a changing climate

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Wetlands, both natural and constructed, provide a wide range of ecological benefits and ecosystem services that include water quality improvement, climate regulation, nutrient processing, carbon sequestration, as well as recreation and habitat improvement. Research in natural wetlands as well as constructed wetlands has increased exponentially in the past years, since wet ecosystems can serve as nature-based solutions against the threats posed by climate change. During the past decades, many wetland-based water treatment technologies have been developed and tested, and now several of these are being applied as ecotechnologies for sustainable water management. Wetlands are also being used for resource recovery and wet crop production. This Themed Issue contains seven research articles, which improve our understanding of the role wetlands perform in processing nutrients and contaminants and discuss and demonstrate how restored and constructed wetlands in the future, via their associated ecosystem services, can contribute to ensure sustainable water management

and resource recovery, while at the same time regulating and mitigating impacts of global climate change. The articles range from freshwater over brackish to saline wetland ecosystems, natural and anthropogenic systems in European areas and China. The research presented here deals with biogeochemical and eco-physiological processes, focusing on microbial and vegetation biology.

Wetland integrity and functioning is determined by a high soil moisture and intact hydrological regime. Coastal wetlands store large amounts of carbon and are thereby an important buffer against carbon release and greenhouse gas emissions to the atmosphere. Qu et al. (2020) investigated soil organic carbon (SOC) decomposition from the Yellow River Delta in China. In general, SOC is decomposed easily in aerated but not dry conditions, and the highly fluctuating conditions in deltas, which are situated at the land-ocean interface, complicate predictions of SOC release. The authors incubated soil from the Yellow River Delta under different soil moisture and flooding conditions and found that dry conditions resulted in the lowest CO₂ and CH₄ emissions, and high soil water content generally favored high C release. Soil pH was found to be a main factor to change with moisture and to control microbial activity, which, in turn, was controlling SOC decomposition through exoenzymes. However, excess water conditions and flooding also lowered SOC decomposition, although to a lesser degree than

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drought. Soil C sequestration in coastal soils can, therefore, be anticipated to be altered, if the climatic and hydrological conditions in salt marshes are exposed to climate change and sea level rise, especially under the prediction of more frequent weather extremes such as droughts and heavy precipitation.

Coastal wetlands and estuaries are not unique in their transitional position between land and water. Also, freshwater wetlands show the dynamics of temporary flooding and variable exposure to nutrient regimes. Specifically, wetlands located between agricultural land and adjacent rivers experience different nutrient loadings throughout the vegetation period. Sequestration of those nutrients in the wetland vegetation can protect surface waters and discharge to the river from nutrient pollution. Jablonska et al. (2020) investigated how vegetation harvesting affected the nutrient removal efficiency of such wetland buffer zones. Harvesting the vegetation at the end of the growing season can remove nutrients even further, by preventing them from re-entering the system due to decomposing plant tissues. The harvested plant material could also be used beneficially, for example as compost, potting substrate, or industrial raw biomass. Wetland buffer zones that are established by rewetting of formerly drained agricultural land do not have the ecological and hydrological functioning of natural riparian wetlands. Hence, the degraded soil poses a risk of nutrient fluxes, which can be removed by harvesting the established vegetation. The authors sampled mown and unmown sites along a small river in Poland for water and biomass nutrient concentrations. The vegetation was dominated by tall sedges, poor fen species, ruderals, reeds, and typical riverside tall herbs (e.g., *Carex* sp., *Phragmites australis* (Cav.) Trin. ex. Steud., *Phalaris arundinacea* L., *Juncus effusus* L., with sporadic occurrence of alder and willow). Unmown sites had the highest biomass production, with higher nitrogen concentration in the plant material. Up to 92% of nitrogen and up to 77% of phosphorus in the agricultural runoff was removed by the buffer zone, resulting in considerably lower nutrient content in the groundwater close to the river. However, harvesting also altered the quality and nutrient uptake of the plant biomass, but not its nutrient removal efficiency. The tissue of regularly harvested plants can be expected to become more decomposable than unmown vegetation. More nutrients will, therefore, be leaching into the soil, if the

mown biomass is left at the site. The authors conclude that harvesting results in biomass that can increase its nutrient uptake, but the mown biomass should be removed relatively fast, to prevent leaching of nutrients.

The capacity of natural wetlands, to remove nutrients and pollutants from water, is used in agricultural buffer zones and in constructed wetlands through phytoremediation. Multiple organic and inorganic pollutants, heavy metals, and also pharmaceutical compounds have been found to be removed by properly designed systems. The inefficient removal of unregulated substances of concern in wastewater treatment plants leads to damaging effects in the environment. Dias et al. (2020) evaluated the pollutant removal potential of *Phragmites australis* and its associated rhizospheric microorganisms in controlled laboratory experiments. The authors focused on the pharmaceutical substances paroxetine (an antidepressant) and bezafibrate (a cholesterol lowering drug), which are found in Portuguese rivers and estuaries. Since estuaries are particularly vulnerable to contaminated river discharge, estuarine reeds and their associated rhizospheric sediment were sampled and exposed to the substances in flasks. Bezafibrate was partially removed (42% of the added compound) in the presence of plants, probably due to adsorption to roots. The native estuarine microbial community alone removed up to 45% of the drug by degradation and sediment adsorption, and plants and sedimental microorganisms together most efficiently removed up to 70%. Plants removed 57% of paroxetine, probably mostly due to uptake in plant tissues. The microbial community alone removed up to 82% of paroxetine, and sediment and plants together removed up to 90% from the solution. Thus, the estuarine environment with its sediment and flora characteristics has a natural potential to remove certain pharmaceutical pollutants from the water, and other factors, such as nutrients, can even enhance the removal efficiency.

Another way of utilizing the beneficial effects of wetlands for human purposes is the construction of urban stormwater ponds. Those systems are important for flood protection against heavy rainfall in urban areas with sealed soil, for temperature regulation, biodiversity conservation, as sediment and nutrient traps, and for recreational purposes. Lenzewski et al. (2020) investigated the plant diversity of an urban stormwater pond in the northern German city of

Hamburg. While the hydrological functioning of stormwater ponds is well studied, little is known about their importance for wild plant biodiversity. Seed banks are paramount in dynamic ecosystems like wetlands, but when ponds are newly created, seeds are often sown for fast re-colonization, which can reduce the natural plant species diversity. The authors studied the herbaceous vegetation and seed bank of a stormwater pond over 3 years, to assess species richness. They found that sowing did not alter the species composition after the pond was established, as compared to before pond establishment. On the contrary, a higher plant species diversity was found after the reconstruction of the pond compared to before. Even threatened and in the city so-far unrecorded species were detected in the soil seed bank. Abundant wetland species like *Juncus* sp. or *Epilobium* sp. that produce large amounts of seeds granted a fast re-colonization, without suppressing the germination of other seeds over time. Since hydrological conditions in stormwater ponds vary, the different germination requirements of at least some species are fulfilled at different times, also following disturbances. The authors concluded that sowing or planting is unnecessary to re-establish the vegetation cover and achieve high plant biodiversity after an urban stormwater pond has been constructed, although the seed bank resilience also depends on the initial conditions of the wetland.

Humans have always altered wetland ecosystems to serve their needs, for the better, as in the examples of pollutant removal, or for the worse, as observed by the effects of river canalization and straightening. River modifications can affect the genetic diversity of the associated species, and Naugžemys et al. (2021) studied those effects on the dominant and abundant wetland grass *Phragmites australis*, common reed. The species is a typical tall wetland plant, which can serve as model species for studying evolutionary processes shaped by global environmental changes. High intraspecific diversity in reed stands is generally associated with higher resilience against environmental pressures and better seed viability. Reed diversity was compared from natural and formerly straightened rivers in Lithuania. Each investigated population had 1 to 10 different genotypes, and natural river sites had fewer different or unique genotypes in total than straightened sites. However, the genetic diversity was generally high, which demonstrates why reed is a

highly competitive species in aquatic ecosystems. Not only does the species propagate vegetatively, but also to a higher degree than often believed by seed dispersal. The authors concluded that higher reed diversity, derived from seedling establishment rather than clonal propagation, could be found shortly after disturbances—natural or anthropogenic, such as river modification. This will, however, only be observed if the disturbance has not completely disrupted the river hydrology. Also, disturbance or age were not the only sources of high genetic diversity. Distance to other reed populations, and the lack of geographic barriers, also determined the recruitment of seeds.

The importance of intraspecific diversity of wetland vegetation becomes obvious by the example of common reed. This dominant wetland species with its high genetic variability and global occurrence comprises both endemic subspecies and invasive lineages. Xie et al. (2020) investigated the invasive potential of reed populations from the Far East and Australia (FEAU) with native Chinese reed populations. Biological invasions are a part of global change that threatens wetlands, and climate change is one of the factors associated with successful invasions. Contrary to species invasions, cryptic invasions can arise from within an otherwise native species. In the case of *P. australis*, a European lineage has invaded North America and is threatening the native flora, including the native subspecies of *P. australis*. While invasive plants often are more vigorous, plastic and ecologically superior to native plants, Xie et al. (2020) found no differences between most physiological traits or number of shoots between Chinese and FEAU reeds. Where differences were found, such as biomass production or specific leaf area, the non-native FEAU reeds were inferior to the native Chinese populations. To investigate climate effects, the plants were also grown in two different environments, which affected almost all traits significantly, but to a similar degree across all populations. The study shows that, although there is no immediate concern of FEAU reeds becoming invasive in China, since no superior competitive traits were discovered, future climatic changes such as more frequent drought events, may well favor FEAU. Taking global change into account is therefore of utmost importance to predict future species distribution and range expansion.

Vegetation responses to the environment are shaped by the genetic diversity, but also the capacity

to acclimate by phenotypic plasticity. Plants that have high plasticity can be anticipated to cope well with environmental changes. Soil salinity is predicted to be a major driver in coastal wetlands affected by global environmental changes and anthropogenic hydrological alterations. Salinity has a major impact on the associated flora and fauna. Song et al. (2020) investigated, if the dominant ecosystem engineer *P. australis* is capable of acclimating to different soil salinities, or if the salt tolerance is shaped by local adaptation. Differences in salinity tolerance can ultimately lead to different distribution of genotypes of the same species, shaping their habitat according to the intraspecific variation. In the Yellow River Delta in China, large parts of the area are threatened by salinization, and restoration efforts need to take the salt tolerance of the vegetation into account. A freshwater and a salt marsh population of *P. australis* were grown in two different outdoor environments under fresh or saline conditions. In contrast to the authors' expectations, salt affected both populations similarly. Hence, local adaptation to soil salinity could be ruled out to as a reason for the salt tolerance of the investigated populations. Compatible ion accumulation and water loss were found to be crucial for salt tolerance and significantly affected by the surrounding climate. Salinity decreased biomass production of both populations to a similar degree, although with large intra-population differences, which could be ascribed to different genotypes. This study also emphasized the importance of high genetic diversity for functional integrity of the ecosystem-vegetation nexus. The authors also found that other environmental factors, such as air humidity, played a major role for the salt resistance.

Future global changes will enforce the interaction of several environmental pressures and thereby affect stress tolerance, species composition, and biogeochemical processes in wetland ecosystems, challenging their stress resistance. The research presented in this Themed Issue highlights the importance of wetlands for humanity. If we are to benefit from the exceptional capacity of wetlands to remove surplus nutrients or other pollutants from the groundwater, to

protect adjacent areas from flooding and inundation, and to sequester large amounts of carbon, we must protect the integrity of those versatile ecosystems. This includes protecting them from invasive species by securing their vegetation diversity—between as well as within species.

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