Towards more sustainable hydrological management and land use of drained coastal peatlands - A biogeochemical balancing act

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SUMMARY

Worldwide, drainage-based water management is applied to facilitate agricultural use of coastal peatland areas, leading to large-scale peat oxidation and land subsidence. Meanwhile, there is a strong call for a more sustainable use and management of drained peatlands. Drainage severely enhances greenhouse gas emission and land subsidence, which can be counteracted by rewetting. However, this advocated alternative may also induce unwanted processes affecting ecosystem functioning. In this overview we discuss the complex biogeochemical responses related to drainage and rewetting in peatlands and compare the biogeochemical effects of deep drainage to those of rewetting in order to identify the most sustainable management strategy for drained coastal peatlands. Due to drainage, oxidation of the iron sulphide pool leads to a highly underestimated source of sulphate for adjacent surface waters, indirectly enhancing eutrophication. Although rewetting also enhances eutrophication by mobilisation and discharge of phosphorus to surface waters, we propose this effect may be mitigated by co-discharged iron, binding phosphorus. As rewetting is expected to reduce societal costs and maximises ecosystem services of peatlands, we suggest to rewet drained agricultural peatlands wherever feasible. We discuss several promising, more sustainable, land use alternatives for rewetted coastal peatlands.

KEY WORDS: drainage, eutrophication, restoration, review, rewetting, paludiculture

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INTRODUCTION

Peatlands are extensively being used for human purposes such as peat extraction and crop production, in both coastal and inland regions worldwide (e.g. Joosten *et al*. 2012, Zedler & Kercher 2005, Verhoeven & Setter 2009). Large parts of these landscapes have gradually been converted into managed grasslands on peat soil used for cattle grazing and hay-making (peat meadows; Bakker 1989), or into agricultural fields for the production of crops such as potato, oil palm or sugar cane (Fargione *et al*. 2008, Couwenberg *et al*. 2010, Koh *et al*. 2011). To enable this use of peatlands, continuous large-scale drainage is necessary, which generally requires an extended network of waterways and canals (Figure 1). The drainage-based, intensive land use has a huge impact on its local and regional environment, as it strongly affects hydrology and related biogeochemical processes resulting in rapid peatland subsidence (e.g. Laiho 2006, Joosten *et al*. 2012, Lamers *et al*. 2015). Drainage increases the oxygenation and subsequent aerobic decomposition of peat soils. Once important carbon (C) sinks, the cultivated and drained peatlands have been turned into strong C sources with net emission rates ranging from 80 to 880 g m^{-2} y^{-1} (Kasimir-Klemedtsson *et al*. 1997, Lamers *et al*. 2015, Tiemeyer *et al*. 2016). As a result of drainage and enhanced decomposition, severe land subsidence rates of 8–10 mm y^{-1} in Western Europe (Hoogland *et al*. 2012), 25–75 mm y^{-1} in the United States (Galloway *et al*. 1999) or up to 50–150 mm y^{-1} in Asia have been observed (Syvitski *et al*. 2009), requiring progressively lower water tables to enable the continuation of current land use practice. In addition, this generates high societal costs for the maintenance and restoration of subsiding levees, roads and residencies (van den Born *et al*. 2016).

Meanwhile, the global mean sea level is rising at an increasing rate (Hay *et al*. 2015). Due to ongoing subsidence, flooding risks have severely increased in drained peatlands, especially in coastal areas, compromising their flood protection service (Zedler & Kercher 2005, Verhoeven & Setter 2009, Herbert *et al.* 2015). To reduce the severe problems involved with drained peatlands, the re-establishment of higher water tables has been proposed as an alternative management option (Joosten *et al*. 2012, Grootjans *et al*. 2012, IPCC 2014). High water tables

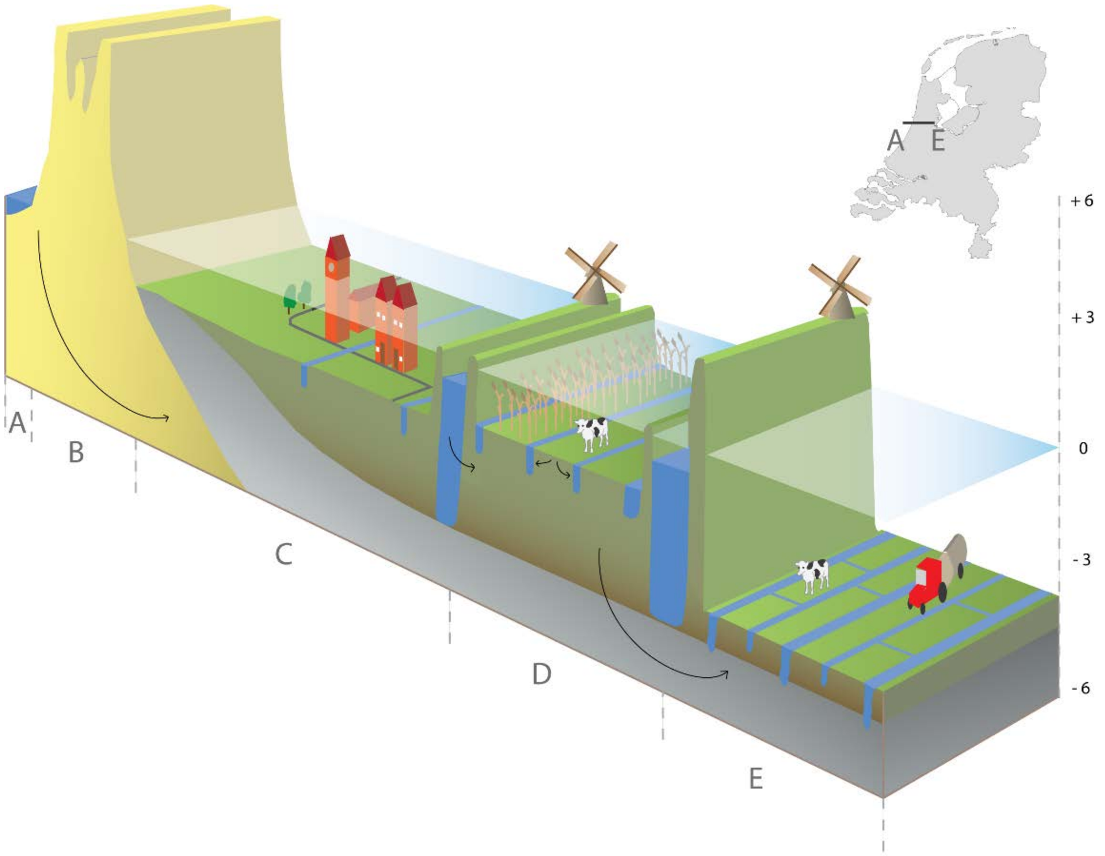

Figure 1. Schematic representation of a typical Dutch peatland area, drained for the purpose of urban and agricultural use, located several metres below seawater level. A) Sea level; B) Sand dunes, dikes and levees to prevent flooding; C) drained urban area; D) drained peatland predominantly used for agriculture, also called ‘peat meadow’ in The Netherlands. Small parts of these peatlands still comprise more natural marshes; E) drained polder with clay soil, where the peat soil has disappeared or almost disappeared due to excavation and peat oxidation (from: van Diggelen 2015, created by Gijs van Dijk).

will strongly decrease peat decomposition and carbon dioxide (CO_2) emission rates by limiting the availability of oxygen (O_2) as the thermodynamically most favourable terminal electron acceptor for the microbial breakdown of organic matter (Laiho 2006). In addition, phenol oxidase activities, regulating overall decomposition rates, are lower during anaerobic conditions (Freeman *et al*. 2004). On the other hand, rewetting of drained and fertilised peatlands may lead to high methane (CH_4) emission rates, compromising the advantage with respect to total greenhouse gas (GHG) emission (e.g. Moore & Knowles 1989, Hendriks *et al*. 2007, Harpenslager *et al*. 2015, Wen *et al*. 2018) although this has recently been debated by Günther *et al.* (2020).

As climate change is an important driver for proposed changes in water management nowadays, there is a strong focus on reducing land subsidence and GHG emission (Wichtmann *et al*. 2016, IPCC 2014, 2019). However, changes in water table management will also affect redox-related biogeochemical processes in peatland systems (Figure 2). Especially in coastal areas, peatlands are generally rich in reduced sulphur compounds (iron sulphides, FeS_x), and alterations in hydrology will strongly affect sulphur (S) and phosphorus (P) cycling (Smolders & Roelofs 1995, Corell, 1998, Lamers *et al*. 1998, 2002, Smolders *et al*. 2006a, Zak *et al*. 2010). Both ongoing drainage and rewetting of (formerly) drained peatlands may lead to indirect eutrophication in surrounding surface waters, which generates a serious dilemma for water table management. Therefore, we believe these eutrophication-related problems should be considered in future policy.

In this paper we will assess the complex biogeochemical interactions between S, iron (Fe), and P in drained and formerly drained coastal peatlands, under two different water management strategies: (1) the continuation of intensive agriculture on deeply drained peatland (mean water tables of 60 –90 cm below surface), (2) the raising of

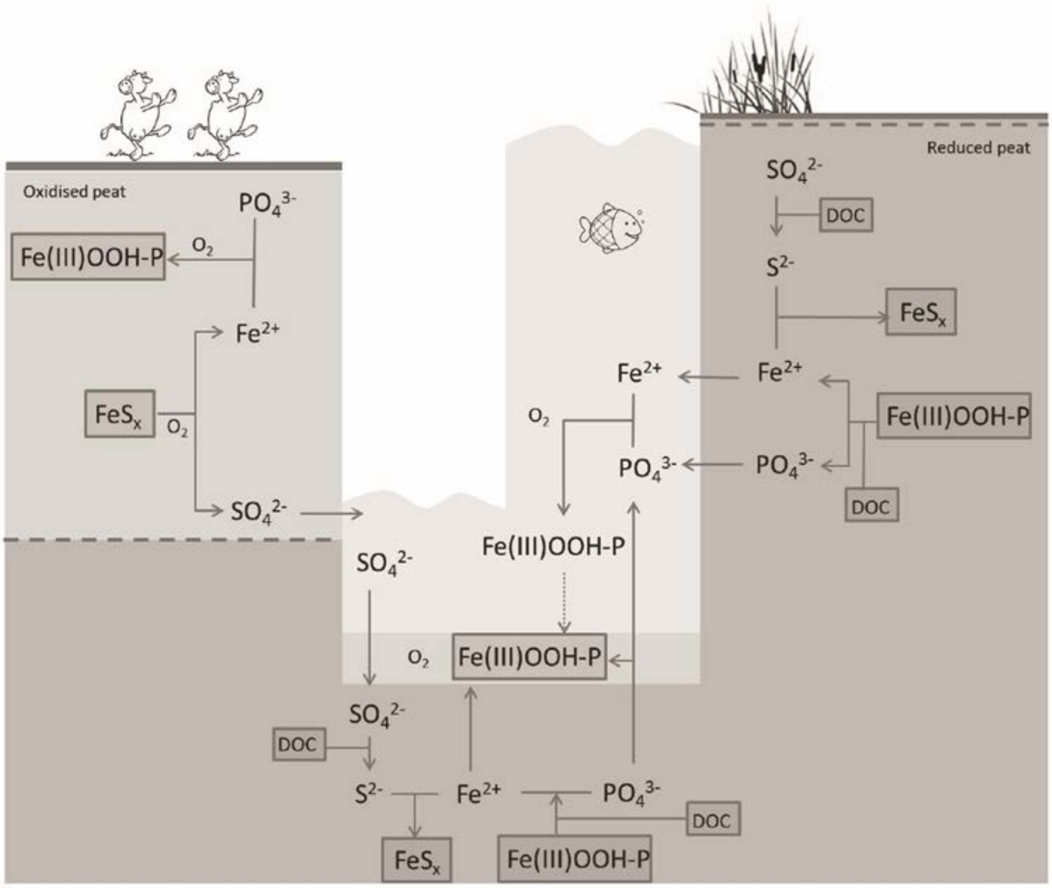

Figure 2. Schematic overview of interactions between P, Fe and S cycling for drained (left panel; low water tables) and rewetted (right panel; high water tables) coastal peatlands, and the resulting effects for adjacent surface water. See text for further explanation (from: van Diggelen 2015).

water tables (mean levels higher than 40 cm below surface). This assessment is based on an extensive database under these different water management strategies in the Netherlands. We will briefly discuss the biogeochemical effects of both deep drainage and strong rewetting, and then discuss the consequences for future water management and land use policy aimed at a more sustainable use of drained coastal peatlands.

BIOGEOCHEMICAL EFFECTS OF (DEEP) DRAINAGE IN PEAT SOILS.

Effects on peat soils

In the terrestrial soils of drained peatlands, an unsaturated top zone (vadose zone) and a saturated underlying zone (phreatic zone) can be distinguished. The saturated zone has a permanently high water table, while the unsaturated zone is exposed to O_2 whenever the water table drops. Even without drainage, water table fluctuations at the interface of the saturated and unsaturated peat zone are common due to seasonal variations in temperature, vegetation-mediated evapotranspiration, precipitation, wind, and humidity. Drainage, however, significantly lowers average water tables, subsequently increasing the depth of the unsaturated zone (frequently more than 50 cm below soil surface), while seasonal water table fluctuations still occur at the interface of the saturated and unsaturated zone. Consequently, drainage strongly increases the oxygenation of the peat soil. As a result of O_2 penetrating into the peat matrix, aerobic microbial communities that use organic C compounds as an electron donor are stimulated, leading to a net release of CO_2 and N_2O, and land subsidence (Kasimir-Klemedtsson *et al*. 1997, Berglund & Berglund 2011, Joosten *et al*. 2012, Lamers *et al*. 2015). In the Netherlands, for instance, soil surfaces in many agricultural areas with a peat depth of 1 –3 metres have dropped by more than 30 cm within the last 20 years (Figure 1; van den Akker *et al*. 2008). Long-term exposure to aerobic decomposition has led to irreversible changes in the peat characteristics of the unsaturated zone, including not only a strongly increased P content (van Diggelen

2015, Smolders *et al*. 2019) but also a decrease in cellulose and lignin (Laiho 2006), and decreased lignin:P ratios (Tomassen *et al*. 2004). It also affects porewater chemistry in the unsaturated soil, resulting in for example decreased phenolic compounds (Freeman *et al*. 2004) and higher dissolved organic carbon (DOC) concentrations (Zak *et al*. 2010). Ongoing land subsidence and increasingly lower water tables therefore will lead to the progressive exposure of deeper, formerly saturated, peat zones to oxygenation. Although nutrient contents are generally much lower in the saturated zone (van Diggelen 2015, Smolders *et al.* 2019), nutrient availability will be increased through mineralisation. This might create a positive feedback for decomposition, as long as acidification associated with aerobic oxidation and accumulation of organic acids is prevented by sufficient buffering (Bridgham & Richardson 2003). The latter is likely, as alternating aerobic and anaerobic episodes generate buffering capacity through increasing HCO_3^- concentrations (Smolders *et al.* 2006a). In addition, lime is added to drained peatlands in agricultural use to prevent acidification and promote crop production (Bertrand *et al*. 2007).

Drainage not only leads to changes in the unsaturated peat soil characteristics, but also to an increased content of mineral components (Zak *et al.* 2010, Aggenbach *et al*. 2013). In the western parts of the Netherlands, peatlands are S-rich and can be considered coastal systems as they were influenced in the past by the North Sea and the former ‘Zuider sea’ (Vermaat *et al*. 2016). In these peatlands, the total S pool in the unsaturated peat zone, with a relatively high bulk density, is only slightly higher compared to the saturated zone (van Diggelen 2015, Smolders *et al*. 2019). As a result of oxygenation in the unsaturated zone, aerobic oxidation of FeS_x primarily results in the formation of relatively mobile Fe^{2+} and SO_4^{2-} (Smolders *et al*. 2006b). Mobilised SO_4^{2-} can easily be transported by water flow, resulting in a net loss of S from the unsaturated zone, explaining the observed high sulphate concentrations in adjacent surface waters (Vermaat *et al*. 2016).

Mobilised Fe^{2+}, however, becomes oxidised in the unsaturated soil where it precipitates as poorly soluble amorphous ferric Fe oxides and hydroxides (FeOOH). This process leads to a large accumulation of Fe in this zone (van Diggelen 2015). As ferric Fe oxides and hydroxides have a high P sorption capacity, the mobility of P is limited in the unsaturated zone as long as aerobic conditions prevail (Lucassen *et al*. 2005, Griffioen 2006, Aggenbach *et al*. 2013). Consequently, a substantial accumulation of P is found in the unsaturated zone of the peat soil (van Diggelen 2015). This partly originates from P released during historic peat mineralisation, and partly from the (excessive) use of manure and fertiliser for decades, if not centuries (Sharpley *et al*. 1994, van Beek *et al*. 2004).

Effects on surface waters

Weather conditions and hydrological pathways in the peat strongly determine nutrient discharge towards surrounding surface water. Due to long-term drainage, large areas of peat meadows in the Netherlands have become infiltration areas. As a result of that there is hardly any groundwater movement towards adjacent canals during dry periods. Instead, surface water from these canals will infiltrate into the peat soil during dry periods, because surface water levels in the canals are maintained high by water management authorities. This external supply of surface water is crucial to limit further water stress on the meadows. Increased evapotranspiration in dry and warmer periods enhances desiccation of the topsoil during low water tables, also enhancing aerobic oxidation of FeS_x (Vermaat *et al*. 2016) and thus the formation of SO_4^{2-} and poorly soluble Fe(III)OOH. Consequently, P concentrations in the groundwater remain low due to P adsorption to Fe(III)OOH (Griffioen 2006, Smolders *et al*. 2006b), while SO_4^{2-} concentrations increase greatly (van Diggelen 2015).

After heavy rainfalls in autumn and winter, water levels in the drainage ditches are usually lowered and about 90 % of the surplus precipitation is discharged towards adjacent surface water channels (van Beek *et al*. 2004). Consequently, leaching of SO_4^{2-} will temporarily lead to a substantial increase in sulphate concentrations in adjacent canals or lakes (Figure 3), where it may indirectly lead to eutrophication through the mobilisation of P from the sediment. In this process, SO_4^{2-} is used in the sediment as an alternative electron acceptor during microbial decomposition of organic matter. Hydrogen sulphide (H_2S) is formed, which efficiently decouples Fe - P interactions at the sediment-water boundary, internally mobilising phosphate (PO_4^{3-}) and increasing pore water H_2S concentrations (Caraco *et al*. 1989, Smolders & Roelofs 1995, Smolders *et al.* 2006a). In aquatic systems P is often limiting for primary production, and its increased availability will strongly stimulate the growth of fast-growing primary producers, such as duckweed or algae (Roelofs 1991, Corell 1998, Smolders & Roelofs 1995). In conclusion, drained coastal peat soils appear to be very significant sources of SO_4^{2-}, enhancing the internal eutrophication of surrounding surface waters.

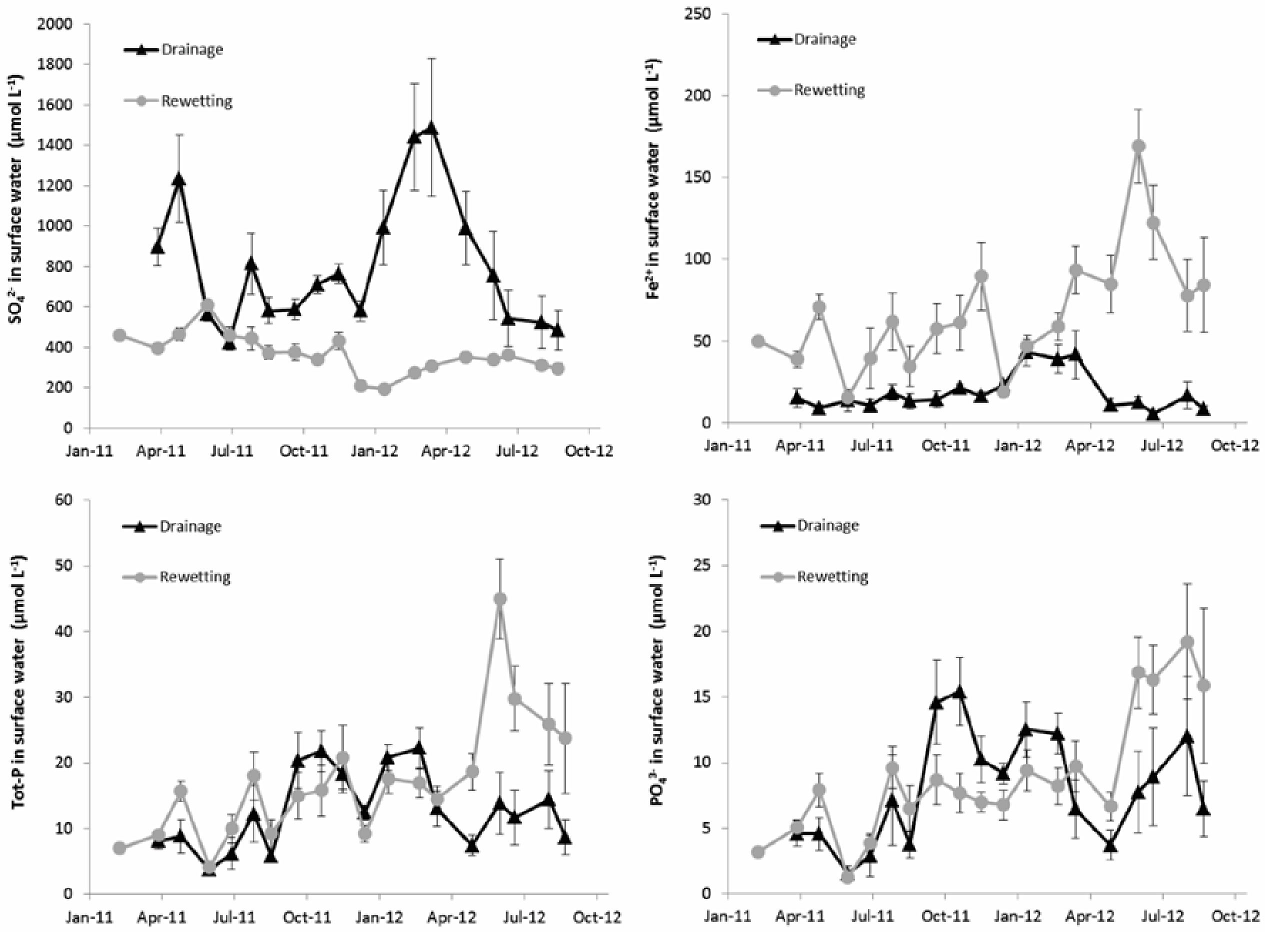

Figure 3. Average sulphate (SO_4^{2-}), iron (Fe^{2+}), phosphor (tot-P), and phosphate (PO_4^{3-}) concentrations monitored during 2 years in the surface water of canals, adjacent to rewetted (grey line; n=2) and still drained (black line; n=2) peatland meadows in Ronde Hoep, The Netherlands (from: van Diggelen 2015).

BIOGOCHEMICAL EFFECTS OF REWETTING DRAINED PEAT SOILS

Effects on peat soils

The maintenance of higher water tables has been advocated as an alternative management option in order to prevent further peat degradation. Raised water tables have been shown to strongly decrease CO_2 emission to the atmosphere (Couwenberg *et al*. 2010, Joosten *et al*. 2012, Evens *et al.* 2016), while CH_4 emissions may increase, partly counteracting the beneficial effect with respect to climate change (Moore & Knowles 1989, Hendriks *et al*. 2007, Harpenslager *et al.* 2015). Nevertheless, various studies have shown that total net GHG emissions are still reduced after rewetting, especially in the long term (van de Riet *et al*. 2013, Hendriks *et al*. 2007, Hendriks *et al*. 2008, Günther *et al*. 2020). Inhibited CH_4 production due to high SO_4^{2-} reduction rates may contribute to this effect (Gauci *et al*. 2004, Herbert *et al*., 2015).

Anaerobic conditions in the former unsaturated zone will strongly enhance SO_4^{2-} and Fe(III)OOH reduction rates of rewetted coastal peatlands. As a result, groundwater SO_4^{2-} concentrations will remain relatively low and dissolved Fe^{2+} concentrations will increase (Figure 2; van Diggelen 2015). Another important issue after rewetting the unsaturated peat zone, however, is the fact that P becomes mobilised to the pore water and groundwater (Aldous *et al*. 2007, Zak *et al*. 2010, van de Riet *et al*. 2013, Emsens *et al*. 2016). The release of inorganic P is a rapid process (within days) in which PO_4^{3-} is mobilised by anaerobic reduction of Fe(III)OOH to which it was bound under aerobic conditions (Lamers *et al*. 1998, Kinsman-Costello *et al*. 2014). During the processes following rewetting, both P and Fe will dissolve (Lucassen *et al*. 2005, van de Riet *et al*. 2013, Kinsman-Costello *et al*. 2014), although part of the Fe will become re-immobilised by precipitation as FeS_x (Figure 2). The rates of Fe and P mobilisation are expected to depend on the relative concentrations of Fe and P accumulated in the unsaturated zone before the water table increases (van Diggelen 2015, Smolders *et al*. 2019).

Effects on surface waters

The discharge of dissolved P towards adjacent surface waters becomes enhanced after rewetting of drained peatlands, which is an important cause of eutrophication (e.g. Zak *et al*. 2010, Kinsman-Costello *et al*. 2014). Co-discharge of dissolved Fe with P, however, might be an important and relatively underestimated process in the actual contribution to nutrient loading after rewetting (Figure 3; from van Diggelen 2015). Higher groundwater tables will enhance nutrient transport through shallow pathways in the former unsaturated zone and decrease the potentially high contribution from the saturated peat soil (van Beek *et al*. 2004). Additionally, as inundation of the peat soil is usually allowed with high water table management, this increases water storage capacity leading to enhanced rainwater retention and dilution of nutrients. In general, groundwater movement will be limited compared to drained systems, and transport of shallow P (and Fe)-rich groundwater towards adjacent surface waters will occur predominantly during heavy rainfall.

We suggest that the concomitant discharge of dissolved Fe^{2+} after rewetting induces co-precipitation of P in surface waters, due to Fe oxidation in the surface water, alleviating the effects of P discharge. So, once in the surface water, P may become (temporarily) immobilised in the sediment by co-precipitation with Fe^{3+} (Smolders *et al*. 2006a, Geurts *et al*. 2008, van der Grift *et al*. 2018). As a result, surface water P concentrations are not as high as would be expected based on the often high groundwater P concentrations, although eutrophic conditions usually still prevail (Figure 3). The actual extent of this effect will depend on the concentration of dissolved Fe in the phreatic groundwater, which may vary due to local soil characteristics in relation to past hydrological conditions. In general, we expect relatively high Fe:P ratios in the pore water of the unsaturated peat zone that (partly) prevent the accumulation of P in the surface water. Moreover, the transport of relatively Fe-rich peat particles from the unsaturated peat zone, directly entering adjacent water courses, is also expected to enhance immobilisation of P in the surface water. Co-transport of Fe from the peat soil is therefore proposed to act as a P scavenger, or ‘filter’, for surface water.

WATER MANAGEMENT DILEMMA

The choice between two options: (1) business as usual or (2) raising the water table

In this paper we focused on the shifts of dominant biogeochemical interactions among Fe, S and P in the unsaturated zone of coastal peatlands that, unlike changes in GHG emissions (Moore & Knowles 1989, Kasimir-Klemedtsson *et al*. 1997, Hendriks *et al*. 2007), received little attention in literature. As both regular drainage and rewetting directly or indirectly leads to eutrophication in agricultural coastal peatlands, this generates a challenge for water management authorities that have to comply with strict water quality targets. Therefore, the expected long-term effects should be considered for both water management options.

Especially in the light of climate change and sea level rise, current drainage-based water management is considered unsustainable with respect to GHG emissions and soil subsidence (e.g. Karki *et al.* 2016, Günther *et al.* 2020). In addition, drainage of peatlands results in adverse surface water quality in the long term, as it strongly stimulates Fe and S oxidation–reduction cycles at the interface of the saturated and unsaturated soil. This leads to alternating episodes of respectively high P and SO_4^{2-} release, and aerobic and anaerobic decomposition. Additionally, in iron depleted soil layers, it may lead to constant or periodical accumulation of highly toxic H_2S (Lamers *et al*. 2002). To determine the actual contribution of P loading from drained peat soils to the aquatic system (which is usually based on a modelled, general P flux; e.g. van Beek *et al*. 2004, Hendriks *et al*. 2008), the interactions with S and Fe during reduced and oxidised conditions (enhancing or inhibiting effect on P eutrophication), as well as groundwater movement in the saturated and unsaturated zones, should be taken into account.

Direct P mobilisation after rewetting of drained coastal peatlands, however, may be less harmful to adjacent water quality than previously thought. Due to the proposed alleviating co-mobilisation of dissolved Fe^{2+}, and also because of a more limited water movement towards the surface water (Aldous *et al*. 2007, Kinsman-Costello *et al*. 2014). In addition, with a stable high water table, mobilised P may be partially re-immobilised in the peat soil by the formation of reduced amorphous Fe(II)OOH in the longer term (Vepraskas & Faulkner 2001). Despite eutrophication risks after rewetting in the short term, it is expected to improve water quality prospects in the longer term. In addition, the predominantly anaerobic conditions will limit GHG emissions, enhance net C sequestration, reduce land subsidence, and improve flood protection of urban areas in the long term (Evans *et al*. 2016, Karki *et al.* 2016, Taft *et al*. 2018, Günther *et al*. 2020).

Maintenance of high water tables may be realised by filling up drainage ditches, by retaining rainwater if feasible, or even by external water supply (e.g. during extended dry periods). Depending on the water quality, the latter may form an additional source of eutrophication (Roelofs 1991, Smolders & Roelofs 1995, Burgin & Hamilton 2008). High rainwater retention, in turn, may lower the buffer capacity of the soil which affects vegetation composition in the meadows, and may additionally cause nutrient dilution in surface waters.

Future land use options for rewetted peatlands

Raising water tables in formerly drained agricultural peatlands will cause significant issues regarding land use. Traditional agricultural land use will be impossible after rewetting. Currently drained agricultural areas are often situated at lower altitudes in the landscape compared to present nature reserves as a result of progressive land subsidence, which may even enhance infiltration and associated acidification of the soil in the higher situated nature areas (van Duren *et al*. 1998). As drainage costs are increasing and agricultural use may become unprofitable, this unnatural situation may favour the transition of these lower agricultural lands towards eutrophic marshes. High soil P levels after rewetting, however, can become an environmental concern, in particular for nutrient poor ecosystems (Sharpley *et al*. 1994).

To limit the mobilisation of P in the case of wetland restoration, removal of the nutrient-rich topsoil before rewetting may be a good option (Smolders *et al*. 2007, Emsens *et al*. 2015). Topsoil removal leads directly to a higher water table, and these anaerobic conditions in combination with low P availability will strongly decrease decomposition and nutrient mineralisation rates, creating mesotrophic conditions. Although topsoil removal from an already subsiding system may appear undesirable, the remaining nutrient-poor subsoil will provide more suitable conditions for peat re-growth than the nutrient-rich topsoil (Emsens *et al*. 2015, Harpenslager *et al*. 2015). Although this may potentially result in the undesired elimination of the seed bank (that is already devoid of short-lived seeds), this can effectively be counteracted by hay transfer after topsoil removal (Patzelt *et al*. 2001, Hölzel & Otte 2003, Klimkowska *et al*. 2010). This will enhance the establishment and conservation of biodiverse peatland vegetation and re-growth of peat in the longer term, which will in turn re-create one of the societal services provided by peatlands.

The removed, nutrient-rich topsoil can subsequently be used to raise the soil surface of areas that are still being used for traditional agriculture (Figure 4). This will allow, at least temporarily, establishment of higher water tables in both higher-situated agricultural and lower-situated restored peatlands, possibly even without changing the actual water table (Smolders *et al*. 2019).

An alternative and much more sustainable agricultural use of peatlands is paludiculture (from *palus,* Latin for marshland*)*, which involves the rewetting of drained agricultural peat soils and cultivation of wetland crops for commercial use (Joosten *et al*. 2012, Wichtmann *et al*. 2016). This agricultural use of rewetted peatlands will strongly inhibit aerobic peat decomposition, and the cultivated wet crops may take up a large portion of the mobilised P limiting its discharge to adjacent surface waters.

Although many sustainable management options for drained coastal peatlands have been suggested before, the implementation of these ideas is found to be extremely slow and difficult (Joosten *et al* 2012, IPCC 2014, 2019). These options need support of land owners and other stakeholders, which has recently proved to be a delicate societal and political issue for the Dutch government. Where the protection and restoration of coastal peatlands can bring direct or indirect economic benefits to many people, it may negatively impact others. To prevent opposition, financial compensation of land owners when converting to alternative land use options may have to be incorporated in policy, as long as these alternative land use options are not yet economically viable.

A trade-off analysis for optimal decision-making should be based on the geohydrological setting of coastal peatlands, sustainable land use options, and profits (e.g. agricultural products). It should also include the optimisation of supporting and regulating ecosystem services (e.g. flood protection, sediment transport and water purification; Acreman *et al.* 2011) and the cost-benefit ratios of different hydrological scenarios. We conclude that rewetting of drained coastal peatlands may well be the most sustainable and cost-effective water management strategy in the long term (Günther *et al*. 2020), promoting a range of possible land use options in a changing climate.

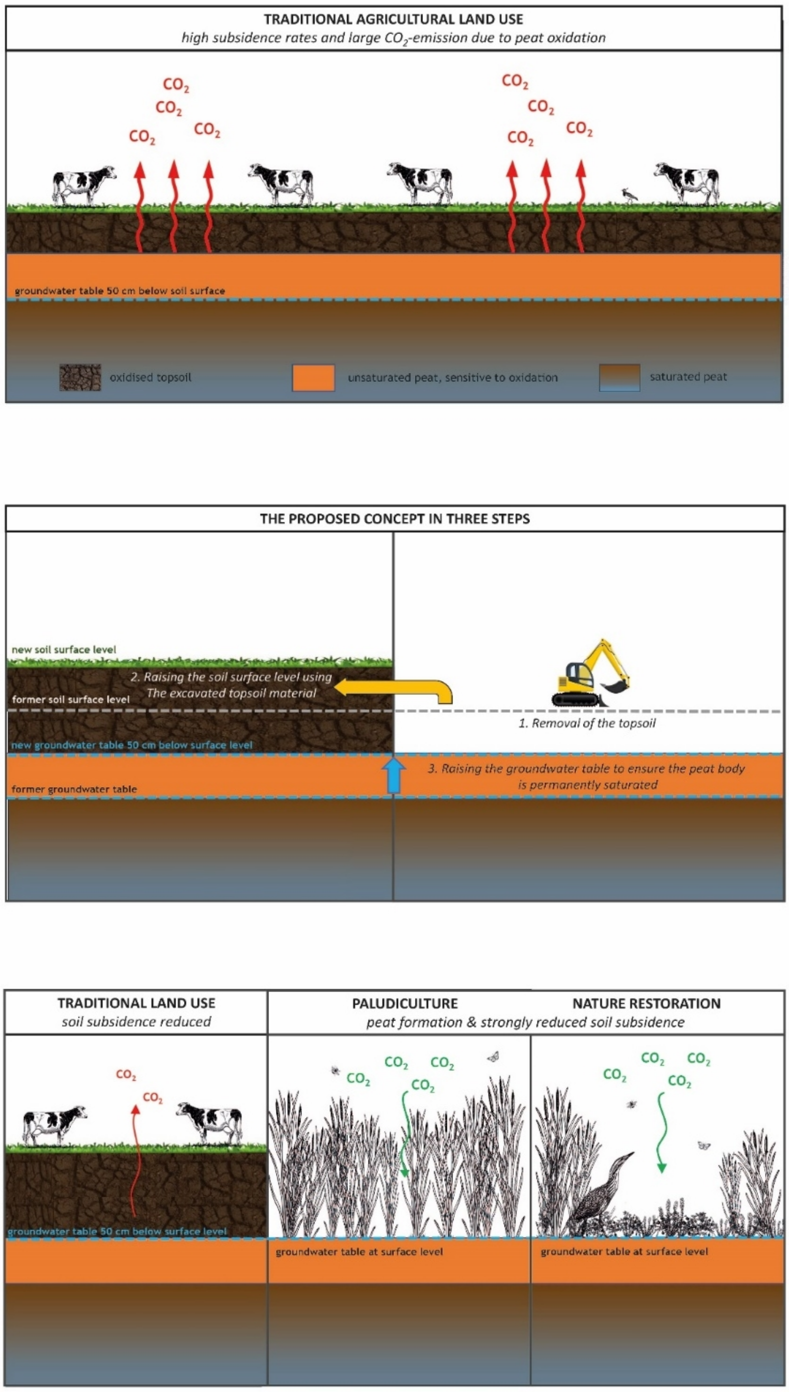

Figure 4. Schematic representation of the proposed concept of topsoil replacement before rewetting during the transition period towards a more sustainable use of coastal peat areas. Upper panel: traditional drainage-based agricultural land use in peat meadows. The groundwater table is usually situated below the intact peat soil which causes severe soil subsidence and high CO_2-emission. Middle panel: overview of three steps: (1) removal of the nutrient-rich topsoil in area X, (2) raising the soil surface level using the excavated topsoil material in area Y, and (3) raising the groundwater table to ensure the intact peat soil is permanently saturated in both area X and Y. Lower panel: in the new situation the higher groundwater table will facilitate the implementation of more sustainable measures such as nature restoration or paludiculture in area X, but area Y will also remain suitable for continuation of traditional agricultural land use. The thicker unsaturated topsoil in area Y mainly consists of recalcitrant, already oxidised material which has become insensitive to peat oxidation. As the sensitive, intact subsoil in area X will become permanently saturated, the overall expectation is that our proposed concept of topsoil replacement before rewetting will strongly reduce soil subsidence and CO_2-emissions (from: Smolders *et al*. 2019, created by Bas van de Riet).

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AUTHOR CONTRIBUTIONS

Hydrological field data were collected by JvD, JL, WR, and AS. JvD, LL and AS were the main authors of the manuscript.

REFERENCES

Acreman, M.C., Harding, R.J., Lloyd, C., McNamara, N.P., Mountford, J.O., Mould, D.J., Purse, B.V., Heard, M.S., Stratford, C.J., Dury, S.J. (2011) Trade-off in ecosystem services of the Somerset Levels and Moors wetlands. *Hydrological Sciences Journal*, 56(8), 1543–1565.

Aggenbach, C.J.S., Backx, H., Emsens, W.J., Grootjans, A.P., Lamers, L.P.M., Smolders, A.J.P., Stuyfzand, P.J., Wołejko, L., van Diggelen, R. (2013) Do high iron concentrations in rewetted rich fens hamper restoration? *Preslia*, 85, 405–420.

Aldous, A.R., Craft, C.B., Stevens, C.J., Barry, M.J., Bach, L.B. (2007) Soil phosphorus release from a restoration wetland, Upper Klamath Lake, Oregon. *Wetlands* 27(4), 1025–1035.

Bakker, J.P. (1989) *Nature Management by Grazing and Cutting. On the Ecological Significance of Grazing and Cutting Regimes Applied to Restore Former Species-Rich Grassland Communities in The Netherlands*. PhD thesis, University of Groningen, Kluwer Academic Publishers, Dordrecht, 400 pp.

Berglund, O., Berglund, K. (2011) Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. *Soil Biology and Biochemistry*, 43, 923–931.

Bertrand, I., Delfosse, O., Mary, B. (2007) Carbon and nitrogen mineralization in acidic, limed and calcareous agricultural soils: Apparent and actual effects. *Soil Biology & Biochemistry*, 39, 276–288.

Bridgham, S.D., Richardson, C.J. (2003) Endogenous versus exogenous nutrient control over decomposition and mineralization in North Carolina peatlands. *Biogeochemistry*, 65, 151–178.

Burgin, A.J., Hamilton, S.K. (2008) NO_3^-- driven SO_4^{2-} production in freshwater ecosystems: Implications for N and S cycling. *Ecosystems*, 11, 908–922.

Caraco, N.F., Cole, J.J., Likens, G.E. (1989) Evidence for sulphate-controlled phosphorus release from sediments of aquatic systems. *Nature*, 341, 316–317.

Corell, D.L. (1998) The role of phosphorus in the eutrophication of receiving waters: A review. *Journal of Environmental Quality*, 27(2), 261–266.

Couwenberg, J., Dommain, R., Joosten, H. (2010) Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, 16, 1715–1732.

Emsens, W-J, Aggenbach, C.J.S., Smolders, A.J.P., van Diggelen, R. (2015) Topsoil removal in degraded rich fens: Can we force an ecosystem reset? *Ecological Engineering*, 77, 225–232.

Emsens, W.-J., Aggenbach, C.J.S., Schoutens, K., Smolders, A.J.P., Zak, D., van Diggelen, R. (2016) Soil iron content as a predictor of carbon and nutrient mobilization in rewetted fens. *Plos One*, 11(4), 0153166, 17 pp.

Evans, C., Morrison, R., Burden, A., Williamson, J., and 31 others (2016) *Lowland Peatland Systems in England and Wales - Evaluating Greenhouse Gas Fluxes and Carbon Balances*. Final report on project SP1210, Centre for Ecology and Hydrology, Bangor, 170 pp.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P. (2008) Land clearing and the biofuel carbon debt. *Science*, 319, 1235–1238.

Freeman, C., Ostle, N.J., Fenner, N., Kang, H. (2004) A regulatory role for phenol oxidase during decomposition in peatlands. *Soil Biology & Biochemistry*, 36, 1663–1667.

Galloway, D., Jones, D.R., Ingebritsen, S.E. (1999) *Land Subsidence in the United States* (Part II: Drainage of organic soils). Circular 1182, Geological Survey, Denver CO, 79–106.

Gauci, V., Matthews, E., Dise, N., Walter, B., Koch, D., Granberg, G., Vile, M. (2004) Sulphur pollution suppression of the wetland methane source in the 20th and 21st centuries. *Proceedings of the National Academy of Sciences*, 101(34), 12583–12587.

Geurts, J.J.M., Smolders, A.J.P., Verhoeven, J.T.A., Roelofs, J.G.M., Lamers, L.P.M. (2008) Sediment Fe:PO_4 ratio as a diagnostic and prognostic tool for the restoration of macrophyte biodiversity in fen waters. *Freshwater Biology*, 53, 2101–2116.

Griffioen, J. (2006) Extent of immobilisation of phosphate during aeration of nutrient-rich, anoxic groundwater. *Journal of Hydrology*, 320, 359–369.

Grootjans, A.P., van Diggelen, R., Joosten, H., Smolders, A.J.P. (2012) Restoration of mires. In: Van Andel, J., Aronson, J. (eds.) *Restoration Ecology: The New Frontier*, Wiley-Blackwell, UK, 203–213.

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., Couwenberg, J. (2020) Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications*, 11, 1644, 5 pp. https://doi.org/10.1038/s41467-020-15499-z

Harpenslager, S.F., van den Elzen, E., Kox, M.A.R., Smolders, A.J.P., Ettwig, K.F., Lamers, L.P.M. (2015) Rewetting former agricultural peatlands: topsoil removal as a prerequisite to avoid strong eutrophication and reduce greenhouse gas emission. *Ecological Engineering*, 84, 159–168.

Hay, C.C., Morrow, E., Kopp, R.E., Mitrovica, J.X. (2015) Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, 517(7535), 481–484.

Hendriks, D.M.D., van Huissteden, J., Dolman, A.J., van der Molen, M.K. (2007) The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences*, 4, 411–424.

Hendriks, R.F.A., Wolleswinkel, R.J., van den Akker, J.J.H. (2008) Predicting greenhouse gas emission from peat soils depending on water management with the SWAP–ANIMO model. In: Farrell, C., Feehan, J. (eds.) *After Wise Use - The Future of Peatlands*, Proceedings of the 13th International Peat Congress, International Peat Society, Tullamore, Ireland, 583–586.

Herbert, E.R., Boon, P., Burgin, A.J., Neubauer, S.C., Franklin, R.B., Ardón, M., Hopfensperger, K.N., Lamers, L.P.M., Gell, P. (2015) A global perspective on wetland salinization: Ecological consequences of a growing threat to freshwater wetlands. *Ecosphere*, 6(10), 206, 43 pp.

Hoogland T., van den Akker, J.J.H., Brus, D.J. (2012) Modelling the subsidence of peat soils in the Dutch coastal area. *Geoderma*, 171–172, 92–97.

Hölzel, N., Otte, A. (2003) Restoration of a species-rich flood meadow by topsoil removal and diaspore transfer with plant material. *Applied Vegetation Science*, 6, 131–140.

IPCC (2014) Overview. In: *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (eds. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G.), IPCC, Switzerland, 10 pp.

IPCC (2019) 2019 *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (eds. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S.). IPCC, Switzerland, 15 pp.

Joosten, H., Tapio-Biström, M-L., Tol, S. (2012*) Peatlands - Guidance for Climate Change Mitigation through Conservation, Rehabilitation and Sustainable Use*. Second edition, FAO and Wetlands International, Rome, 100 pp.

Karki, S., Elsgaard, L., Kandel, T.P., Lærke, P.E. (2016) Carbon balance of rewetted and drained peat soils used for biomass production: a mesocosm study. *GCB Bioenergy*, 8, 969–980.

Kasimir-Klemedtsson, A., Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J., Oenema, O. (1997) Greenhouse gas emissions from farmed organic soils: a review. *Soil Use and Management*, 13, 245–250.

Kinsman-Costello, L.E., O'Brien, J., Hamilton, S.K. (2014) Re-flooding a historically drained wetland leads to rapid sediment phosphorus release. *Ecosystems*, 17, 641–656.

Klimkowska, A., Kotowski, W., van Diggelen, R., Grootjans, A.P., Dzierża, P., Brzezińska, K. (2010) Vegetation redevelopment after fen meadow restoration by topsoil removal and hay transfer. *Restoration Ecology*, 18(6), 924–933.

Koh, L.P., Miettinen, J., Liew, S.C., Ghazoul, J. (2011) Remotely sensed evidence of tropical peatland conversion to oil palm. *Proceedings of the National Academy of Sciences*, 108(12), 5127–5132.

Laiho, R. (2006) Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry*, 38, 2011–2024.

Lamers, L.P.M., Tomassen, H.M., Roelofs, J.G.M. (1998) Sulfate-induced eutrophication and phytotoxicity in freshwater wetlands. *Environmental Science & Technology*, 32, 199–205.

Lamers, L.P.M., Falla, S-J., Samborska, E.M., van Dulken, I.A.R., van Hengstum, G., Roelofs, J.G.M. (2002) Factors controlling the extent of eutrophication and toxicity in sulfate-polluted freshwater wetlands. *Limnology and*

Oceanography, 47(2), 585–593.

Lamers, L.P.M., Vile, M.A., Grootjans, A.P., Acreman, M.C., van Diggelen, R., Evans, M.G., Richardson, C.J., Rochefort, L., Kooijman A.M., Roelofs, J.G.M., Smolders, A.J.P. (2015) Ecological restoration of rich fens in Europe and North America: from trial and error to an evidence-based approach. *Biological Reviews*, 90(1), 182–203.

Lucassen, E.C.H.E.T., Smolders, A.J.P., Roelofs, J.G.M. (2005) Effects of temporary desiccation on the mobility of phosphorus and metals in sulphur-rich fens: differential responses of sediments and consequences for water table management. *Wetlands Ecology and Management*, 13, 135–148.

Moore, T.R., Knowles, R. (1989) The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science*, 9, 33–38.

Patzelt, A., Wild, U., Pfadenhauer, J. (2001) Restoration of wet fen meadows by topsoil removal: Vegetation development and germination biology of fen species. *Restoration Ecology*, 9(2), 127–136.

Roelofs, J.G.M. (1991) Inlet of alkaline river water into peaty lowlands: effects on water quality and Stratiotes aloides L. stands. *Aquatic Botany*, 39, 267–293.

Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims J.T., Daniel, T. C., Reddy, K.R. (1994) Managing agricultural phosphorus for protection of surface waters: Issues and options. *Journal of Environmental Quality*, 23(3), 437–451.

Smolders, A.J.P., Roelofs, J.G.M. (1995) Internal eutrophication, iron limitation and sulphide accumulation due to the inlet of river Rhine water in peaty shallow waters in The Netherlands. *Archiv für Hydrobiologie*, 133, 349–365.

Smolders, A.J.P., Lamers, L.P.M., Lucassen, E.C.H.E.T., van der Velde, G., Roelofs, J.G.M. (2006a) Internal eutrophication: How it works and what to do about it - a review. *Chemistry and Ecology*, 22(2), 93–111.

Smolders, A.J.P., Moonen, M., Zwaga, K., Lucassen, E.C.H.E.T., Lamers, L.P.M., Roelofs, J.G.M. (2006b). Changes in pore water chemistry of desiccating freshwater sediments with different sulphur contents. *Geoderma*, 132, 372–383.

Smolders, A.J.P., Lucassen, E.C.H.E.T., van der Aalst, M., Lamers, L.P.M., Roelofs, J.G.M. (2007) Decreasing the abundance of *Juncus effusus* on former agricultural lands with noncalcareous sandy soils: possible effects of liming and soil removal. *Restoration Ecology*, 16(2), 240–248.

Smolders, A.J.P., van de Riet, B.P., van Diggelen, J.M.H., van Dijk, G., Geurts, J.J.M., Lamers, L.P.M. (2019) The future of our peat meadow landscape. About rewetting, 'optoppen' ('layering up') and peat moss cultivation (*Sphagnum* farming). *Landschap*, 36,133–141 (in Dutch with English summary).

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls R.J. (2009) Sinking deltas due to human activities. *Nature Geoscience*, 2, 681–686.

Taft, H.E., Cross, P.A., Jones, D.L. (2018) Efficacy of mitigation measures for reducing greenhouse gas emissions from intensively cultivated peatlands. *Soil Biology and Biochemistry*, 127, 10–21.

Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Drösler, M., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Freibauer, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Leiber-Sauheitl, K., Peichl-Brak, M., Roßkopf, N., Sommer, M., Zeitz, J. (2016) High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biology*, 22, 4134–4149.

Tomassen, H.B.M., Smolders, A.J.P., Lamers, L.P.M., Roelofs, J.G.M. (2004) Development of floating rafts after the rewetting of cut-over bogs: the importance of peat quality. *Biogeochemistry*, 71(1), 69–87.

van Beek, C.L., van den Eertwegh, G.A.P.H., van Schaik, F.H., Velthof, G.L., Oenema, O. (2004) The contribution of dairy farming on peat soil to N and P loading of surface water. *Nutrient Cycling in Agroecosystems*, 70(1), 85–95.

van den Akker, J.J.H. , Kuikman, P.J., de Vries, F., Hoving, I., Pleijter, M., Hendriks, R.F.A., Wolleswinken, R.J., Simões, R.T.L., Kwakernaak, C. (2008) Emission of CO_2 from agricultural peat soils in the Netherlands and ways to limit this emission. In: Farrell, C., Feehan, J. (eds.) *After Wise Use - The Future of Peatlands*, Proceedings of the 13th International Peat Congress, Volume 1 Oral Presentations, International Peat Society, Tullamore, Ireland, 645–648.

van den Born, G.J., Kragt, F., Henkens, D., Rijken, B., van Bemmel, B., van der Sluis, S. (2016) *Dalende bodems, stijgende kosten. Mogelijke maatregelen tegen veenbodemdaling in het landelijk en stedelijk gebied* (*Subsiding Soils, Rising Costs. Possible Measures against Peat Soil Subsidence in Rural and Urban Areas*).

Publication Number 1064PBL, Netherlands Environmental Assessment Agency, The Hague, 92 pp. (in Dutch with English Summary).

van der Grift, B., Osté, L., Schot, P., Kratz, A., van Popta, E., Wassen, M., Griffioen, J. (2018) Forms of phosphorus in suspended particulate matter in agriculture-dominated lowland catchments: Iron as phosphorus carrier. *Science of the Total Environment*, 631–632, 115–129.

van de Riet, B.P., Hefting, M.M., Verhoeven, J.T.A. (2013) Rewetting drained peat meadows: risks and benefits in terms of nutrient release and greenhouse gas exchange. *Water Air and Soil Pollution*, 224, 1440, 12 pp.

van Diggelen, J.M.H. (2015) *Human Impact on Peatlands: From Biogeochemical Issues Towards Sustainable Land Use Options*. PhD thesis, Radboud University Nijmegen, 139 pp. ISBN 978-94-6259-818-8.

van Duren, I.C., Strykstra, R.J., Grootjans, A.P., Ter Heerdt, G.N.J., Pegtel, D.M. (1998) A multidisciplinary evaluation of restoration measures in a degraded *Cirsio-Molinietum* fen meadow. *Applied Vegetation Science*, 1, 115–130.

Vepraskas, M.J., Faulkner, S.P. (2001) Redox chemistry of hydric soils. In: Richardson, L.J., Craft, C.B., Vepraskas, M.J. (eds.) *Wetland Soils: Genesis, Hydrology, Landscapes, and Classification*. CRC Press, Florida (USA), 432 pp.

Verhoeven, J.T.A., Setter T.L. (2009) Agricultural use of wetlands: opportunities and limitations. *Annals of Botany*, 105(1), 155–163.

Vermaat, J.E., Harmsen, J., Hellmann, F.A., van der Geest, H.G., de Klein, J.J., Kosten, S., Smolders, A.J.P., Verhoeven, J.T.A., Mes, R.G., Ouboter, M. (2016) Annual sulphate budgets for Dutch lowland peat polders: The soil is a major sulphate source through peat and pyrite oxidation. *Journal of Hydrology*, 533, 515–522.

Wen, X., Unger, V., Jurasinski, G., Koebsch, F., Horn, F., Rehder, G., Sachs, T., Zak, D., Lischeid, G., Knorr, K-H., Böttcher, M.E., Winkel, M., Bodelier, P.L.E., Liebner, S. (2018) Predominance of methanogens over methanotrophs in rewetted fens characterized by high methane emissions. *Biogeosciences*, 15, 6519–6536.

Wichtmann, W., Schröder, C., Joosten, H. (eds.) (2016) *Paludiculture - Productive Use of Wet Peatlands*. Schweizerbart Science Publishers, Stuttgart, 272 pp.

Zak D., Wagner, C., Payer, B., Augustin, J., Gelbrecht, J. (2010) Phosphorus mobilization in rewetted fens: the effect of altered peat properties and implications for their restoration. *Ecological Applications*, 20(5), 1336–1349.

Zedler, J.B., Kercher, S. (2005) Wetland resources: Status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources*, 30, 39–74.

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