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TOPICAL REVIEW

Phosphorus fate, transport and management on subsurface drained agricultural organic soils: a review

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Abstract

Large quantities of mineral phosphorus (P) fertilizer are often applied to intensively cultivated organic soils. Although erosion and runoff can contribute to loss of P, the large amount of fertilizer applied causes a rapid build-up of this nutrient, resulting in the downward movement of excess P in the soil profile and subsequent loss through tile drainage water. For arable organic soils, these losses often occur through subsurface tile drains, a common requirement to maintain a favorable air–water balance in the crop root zone, as well as to prevent soil subsidence. As such, subsurface drainage is a major pathway for agricultural P loss, contributing to persistent eutrophication of rivers, lakes, and estuaries globally. Although studies have been conducted on P mitigation within organic soils, application of drainage water management (DWM) as a P mitigation strategy in these soils, has not been extensively studied. The objective of this paper is to address this gap in knowledge by reviewing previous studies on P losses from subsurface drained agricultural organic soils while evaluating potential mitigation strategies. Specifically, this paper assesses the unique properties of organic soils that could influence P fate and transport, such as the distribution of P pools within the soil pools; variable pore geometry, hydrophobicity, and shrinkage; P loads exiting tile drains; and DWM practices in mitigating P losses. It is concluded that P retention is affected by the dynamic nature of soil water movement in organic soils and that substantial P loads enter surrounding water bodies via subsurface drainage effluent. There is evidence that DWM is an effective best management practice in the abatement of subsurface P losses.

Abbreviations:

BMP Beneficial management practice
DOM Dissolved organic matter
DRP Dissolved reactive phosphorus
DWM Drainage water management
OM Organic matter
\( P_i \) Inorganic phosphorus
\( P_o \) Organic phosphorus
TDP Total dissolved phosphorus
TP Total phosphorus.

1. Introduction

Histosols, also known as organic, muck or peat soils are defined as having 40 cm of organic material within the top 80 cm of the soil profile (Kolka et al 2016). These soils are composed of at least 20%–35% organic matter (OM) (Kroetsch et al 2011, Silva 2012; Staff 2014, Mukherjee and Lal 2015) and account globally for approximately 4.23 million km² (Xu et al 2018), covering nearly 3% of the global land area (Joosten et al 2012, Tubiello et al 2016, Xu et al 2018). Of the global peatlands converted for agricultural use, Tubiello et al (2016) estimates that 60% are in cool temperate/boreal climates, 34% are in tropical regions and 5% are in warm temperate areas. Arable organic soils are peatlands that were artificially drained and cleared of vegetation for agricultural purposes (Keller and Medvedeff 2016). In contrast, arable mineral soils have on average less
than 2% OM and have higher fractions of sand, silt and clay. In regions of North and South America, Europe and South Asia, organic soils are favorable for the production of high value vegetable crops. There is a large economic return on crop production in these soils, as demonstrated in the Everglades, Florida, USA, with an agricultural industry worth $1.5 billion annually (Aillery et al 2001), the San Joaquin Delta, California, USA, with $702 million in crop revenue (Delta Protection Commission 2012), and the Holland Marsh, Ontario, Canada, with $58 million annual gross domestic product (Township of King 2012). There is an impetus to expand food production on organic soils to meet the nutritional diversity and food security of a growing world population. However, there are concerns as to how this can be achieved while maintaining the environmental safeguards of these ecologically significant land areas.

Organic soils, although high in OM and therefore rich in carbon (C), oxygen and hydrogen, have a low intrinsic soil phosphorus (P) content, which requires frequent P fertilization due to the high P demand of intensive vegetable production (Czuba and Hutchinson 1980, Parent and Khiari 2003, Litaor et al 2004, Guérin et al 2007). P fertilizer is regularly lost through export pathways to the surrounding environment, including runoff and agricultural tile drainage (Gentry et al 2007, Chikhaoui et al 2008). The tile drainage discharge, as a source of nutrient pollution, is a major factor in the growing eutrophication of lakes and rivers (Rockwell et al 2005, Schindler et al 2008, King et al 2015). Eutrophication is the enrichment of water bodies with superfluous nutrients, mostly nitrogen (N) and P, resulting in increased algal blooms, and subsequently leading to the removal of dissolved oxygen upon their decomposition (Spivakov et al 1999). Cultivation of organic soils within the watersheds of Lake Okeechobee (Daroub et al 2011), Lake Ontario (Longabucco and Rafferty 1989) and Lake Simcoe (Winter et al 2007) have been linked to the excessive eutrophication of their respective water bodies.

Studies into the effects of subsurface drainage P transport in organic soils are limited (Miller 1979, Robinson 1986). Many studies concentrate on soil P tests in organic soils and their link to P within the drainage water, rather than the actual P exported in drainage effluent (Zheng et al 2014, 2015). Additionally, studies rarely analyze both soil P and drainage dynamics in organic soils, as well as their combined effects on P pollution, although some studies have demonstrated that soil P was positively correlated to dissolved P concentrations in drainage waters (Miller 1979). In general, agricultural P export studies have primarily concentrated on surface run-off as the major pathway of P transport, compared to subsurface tile drainage, however, the flat topography and high water holding capacity of organic soils decrease their runoff potential (Skaggs et al 1994, Sims et al 1998, Algoazzny et al 2007, Eastman et al 2010, Christianson et al 2016). Subsurface drainage, also known as tile or artificial drainage, is used in the humid regions of northwestern Europe, the USA and Canada to lower the water table in the crop root zone (Madramootoo 1990, Blann et al 2009, Gramlich et al 2018). Recently, there has been an increased interest in better understanding the effects of subsurface drainage in relation to P pollution of water bodies. Sims et al (1998) concluded that subsurface drainage can be a significant P export pathway in tile drained fields, especially when soils are P-saturated and thereby reducing the P sorption capacity. King et al (2015) concluded that the hydrology of subsurface drained lands needs further study to better understand P losses under improved drainage and water table control.

Extensive reviews have been conducted on P pollution from arable mineral soils for many decades (Sims et al 1998, Kleinman et al 2015, Radcliffe et al 2015, Christianson et al 2016). However, to our knowledge no review has been conducted on drainage impacts of P in organic soils specifically; rather they have only been studied in combination with mineral soils (Thomas et al 1995, Haygarth and Jarvis 1999, King et al 2015, Gramlich et al 2018). This review focuses exclusively on farmed Histosols where there is fertilizer addition, soil tillage, installation of subsurface tile drainage, and other agronomic practices, all of which affect the movement of P within these soils. The effects of these fertilizer and water management practices are not fully known, as pointed out in the paper, and call for further research.

Increased understanding of nutrient movement in organic soils due to intensive agriculture can contribute to enhanced environmental practices required for sustainable crop production. The objectives of this review are to (a) critically review P losses from subsurface drained organic soils, with a focus on P in the soil-water continuum; (b) determine the effectiveness of drainage water management (DWM) strategies to reduce P leaching; and (c) identify gaps in knowledge regarding subsurface drainage and P dynamics in peat soils. The review will assess these objectives through the collation of published literature found to be pertaining to P on tile drained organic soils.

2. Methods

 Relevant research for this review was identified by searching the literature in databases including Web of Science (1975–2020: 160 references), Scopus (1823–2020: 195 references), Google Scholar (2004–2020: 118 references), Science Direct (1997–2020: 38 references), and WorldCat (1998–2020: 136 references). Articles in the databases overlapped by approximately 12%. Key words searched can be found in table 1. In total there were approximately 130 words used in combination or alone in the search. Multiple
combinations of the key words were used to find relevant articles in all five databases. Furthermore, the search used not only specific words to identify both the soil and drainage water P characteristics but also location specific terms, either countries or regions, such as Germany, Everglades or Kalimantan, to gain articles on specific locations known for crop production on organic soils. Searches were also done with various combinations of ‘drainage’, ‘water management’, and ‘mitigation practices’ to identify what has been done on these soils. The searched literature was considered relevant, if theory, principles and research results on cropping systems from organic soils and P dynamics in these soils were discussed. The research was inclusive of all studies, irrespective of the date of the article (Boelter and Blake 1964, Hill and Parlange 1972), as long as the information was pertinent to the review.

Following the search in the five databases, each article was reviewed and analyzed in terms of the objectives, results, discussion of the data and findings, and appropriateness to the review. The articles were screened for information and data on subsurface tile drainage, then classified into soil hydrology characteristics (22 references), soil P pools (55 references), subsurface tile drainage flows from arable organic soils (25 references), and DWM strategies (16 references). Each article within these four categories was evaluated to understand the underlying hydrology, agricultural management, soil chemical and physical properties, and how P was affected by these interactions. This comprehensive analysis of the literature revealed a paucity of the discussion of the underlying principles regarding P components in subsurface tile drainage flows, and their contribution to the overall P dynamics of organic soils. We have highlighted shortcomings in the knowledge base and have identified recommendations for research investigation.

3. Organic soils and its cultivation

Organic soils are highly productive cropping systems throughout the world, in particular for vegetable production. In Europe, a total of about 125 000 km² of peatland are used for agriculture, which represents about 14% of the total peatland area with the largest agricultural areas located in Russia (70 400 km²) and Germany (12 000 km²: Lucas 1982, Lappalainen 1996, Parent et al 2002, Röfköpfl et al 2015). In the United States, the Florida Everglades is the largest organic soil agricultural area at over 2300 km² (Kolka et al 2016), while in Canada 170 000 km² of organic soils are used for agriculture (Oleszczuk et al 2008). Subtropical and tropical areas can be found in Asia where in China 2610 km² of peatland are used for agriculture (Laine et al 2009), and in Indonesia there is a total of 42 000 km² of peatland used for agriculture (Oleszczuk et al 2008, Jauhiainen et al 2014, Konecny et al 2016, Dommair et al 2018). To date, only a small percentage have been converted for agricultural use. In Indonesia, 20% of organic soils have been converted for agricultural purposes, while in China, the U.S.A., Europe and Canada, 25%, 10%, 14% and 15% have been converted, respectively (Oleszczuk et al 2008). The potential for expansion of these agricultural organic areas could increase in the future, given the northward shift of the agricultural climate zone due to climate warming in countries such as Canada, Russia, Sweden and Finland (Rosenzweig and Parry 1994, King et al 2018).

The movement of water is a key driver of the biogeochemical processes in drained lands and a thorough understanding of the effects of improved drainage on field and landscape hydrology is essential for the determination of its effects on drainage water quality (Skaggs et al 1994). Over the past decade, the use of subsurface tile drainage has expanded rapidly in agriculture, yet its potential effect on nutrient loss from agricultural peatlands is not well understood (Kennedy et al 2018). Even though the nexus between water flow and solute transport properties in peat soils have been identified, little attention has been given towards investigating this link and few documented studies exist, in particular regarding P (Gharedaghloo et al 2018).

Peat is classified as a dual-porosity medium, which includes a ‘mobile region’ through which water and nutrients move relatively easily, and an ‘immobile region’, where fluid flow velocity is negligible (Rezazehad et al 2016). The immobile pores largely regulate microbial biogeochemical cycling in organic soils (McCartney et al 2020). Another consideration in estimating the movement of water in the unsaturated zone within organic soils is associated with changing pathways as a consequence of drying and shrinkage. Wang et al (2020) found that the structure of the peat, and the orientation of the undecomposed plant material can direct water flow in soils.

3.1. Organic soil hydraulic characteristics

Water retention capacity for organic soils has been extensively reported (Schwärzel et al 2002, Hallem et al 2015, Behctold et al 2018, Kennedy et al 2018, Wallor et al 2018a, 2018b). However, these results may not be applicable to field scale cultivated organic soils (Hallem et al 2015), as agricultural practices accelerate the soil-forming processes, leading to changes in soil physical, chemical and hydraulic properties (Kechavarzi et al 2010, Kroetsch et al 2011).

Managed peat soils exhibit different physical and hydraulic properties, in comparison to other types of soil. The saturated hydraulic conductivity (Ksat) in peat soils has been observed to increase with pore water pressure, in contrast with the Darcian behavior on mineral soils (Lafond et al 2014). The unsaturated hydraulic conductivity, K(h), in peat soils is also dependent on pore water pressure (Hemond and Goldman 1985, Wain et al 1985). Further,
previous studies have confirmed significant anisotropy in organic soil profiles. This was observed by Schlotzhauer and Price (1999) in a cutover peat soil, where the horizontal \( K_{sat} \) was more than four times greater than vertical conductivities at the surface horizon and at a depth of ~30 cm. Similar trends in hydraulic conductivities were also observed by Kechavarzi et al (2010) in managed peat soils.

Water repellency or hydrophobicity, which is common in peat soils, significantly influences the hydrologic processes within the soil profile; and is particularly related to the degree of decomposition of the material, as well as the initial wetting (Caron et al 2015). Preferential flow in peat soils is also a significant hydraulic factor influencing the fate and transport of P. Preferential flow is common in non-structured soils, owing to the development of unstable wetting fronts. Such factors like increasing hydraulic conductivity with depth and strong water repellency in the soil profile, have been found to result in fingers or preferential flow paths in peat soils (Dekker and Ritsema 2000).

### 3.2. Agricultural production effects

As organic soils vary considerably in their nutrient status and other physico-chemical properties, farmers employ various strategies to transform the organic soils into suitable substrate for horticultural production. Growers can amend the organic soils with substantial amounts of lime and fertilizer to adjust

| Organic soils | Phosphorous or P - soil | Methodologies |
|---------------|-------------------------|--------------|
| Histosols     | Soil phosphorus         | Hedley sequential fraction |
| Muck soils    | Soil phosphorus management | Phosphorus sequential extraction |
| Peat soils    | Microbial phosphorus biomass | Phosphorus sequential fractionation |
| Peatlands     | Organic phosphorus      | Phosphorus fractionation |
| Swamp         | Mineral phosphorus      | Soil phosphorus x-ray adsorption near edge spectroscopy |
| Marsh         | Available soil phosphorus | Soil P XANES |
| Bog           | Soil phosphorus cycle   | 31 phosphorus nuclear magnetic resonance |
| Wetland       | Soil phosphorus availability | 31P NMR |
| Pocosin       | Inorganic phosphorus    | Phosphorus isotope tracing |
| Minerotrophic | Labile organic phosphorus | 32P isotope tracing |
| Oligotrophic peatland | Organic phosphorus compounds | 33P isotope tracing |
| Everglades    | Organophosphorus classes | Soil P tests |
| San Joaquin Delta | Enzyme labile phosphorus | Mehlich P |
| Hula Valley   | Phosphatases            | Olsen P |
| Holland Marsh | Organic phosphorus species | Bray-1 P test |
| Agriculture   | Organic phosphorus speciation | Phosphorus enzyme hydrolysis |
| Arable        |                          | Phosphorus characterization |
| Cropping      |                          | Hydrological soil properties |
| Agricultural  |                          | Soil hydrology |
| Agricultural area |                      | Soil properties affecting water movement |
| Cropland      |                          | Water movement in porous media |
| Tile agriculture |                      | Non Darcian/Darcian flow |
| Subsurface tile |                      | Unstable flow |
| Tile-drawn    |                          | Physical properties |
| Cultivated    |                          | Water repellency |
| Crop production |                      | Hysteresis |
| Drainage management |                  | Macroporosity |
| Drainage      |                          | Solute transport |
| Subsurface tile |                      | Pore structure |
| Water management |                      | Water movement and humification in organic soil |
| Mitigation practices |                | Water movement and decomposition in organic soil |
| Phosphorus transport |                  |                       |
| Phosphorus fate |                          |                       |
| Phosphorus behavior |                      |                       |
| Phosphorus or P - Water |          |                       |
| Water quality phosphorus |                  |                       |
| Total phosphorus |                          |                       |
| Dissolved reactive phosphorus |              |                       |
| Particulate phosphorus |                      |                       |
| Total dissolved phosphorus |                |                       |
| Dissolved organic phosphorus |            |                       |
| Drainage phosphorus |                          |                       |
| \( \text{PO}_4-P \) |                          |                       |
| Others         | Global distribution     |                       |
| Land coverage  | Nutritional value       |                       |
| Beneficial effects of organic soil |       |                       |
| Indonesia      | Asia organic soil       |                       |
| Europe         | Eastern Canada          |                       |
| Sherrington    | Poland                  |                       |
| Germany        |                         |                       |

### Table 1. Key words identified to search for articles on multiple databases in relation to P dynamics, pollution and management from organic soil agricultural lands.
Table 2. Mean $P_i$ and $P_o$ concentrations in available, moderately labile, Al/Fe-bound non-labile and Ca-bound non-labile pools of arable organic soils from Canada, Germany, Israel, and the United States. Crop type and P fertilizer inputs are provided.

| Study                  | Crop          | Crop type | $P_i$ | $P_o$ | $P_i$ | $P_o$ | $P_i$ | $P_o$ | $P_i$ | $P_o$ | $P_i$ | $P_o$ | Total P |
|------------------------|---------------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|
| Ontario, Canada        | Carrot        | 50        | 25    | 2.9   | 50    | 5.4   | 190   | 92    | 480   | 50    | 890   |       |          |
| De Sena (2017)         | Carrot        | 25        | 37    | 4.5   | 100   | 7.6   | 460   | 130   | 980   | 62    | 1800  |       |          |
| Audette et al (2018)   | Arable        | 50        | 25$^b$| NA$^e$| 14$^d$| NA$^e$| 67    | NA$^e$| 86$^k$| NA$^e$| 450$^l$|       |          |
| Québec, Canada         | Vegetables    | NA$^e$    | 70$^g$| NA$^e$| 44    | 59    | 71    | 96    | NA$^e$| NA$^e$| 340   |       |          |
| Parent et al (1992)    | Arable        | 50$^i$    | 25$^h$| NA$^e$| 14$^i$| NA$^e$| 67    | NA$^e$| 86$^k$| NA$^e$| 450$^l$|       |          |
| Parent et al (2014)    | Arable        | 50$^i$    | 25$^h$| NA$^e$| 14$^i$| NA$^e$| 67    | NA$^e$| 86$^k$| NA$^e$| 450$^l$|       |          |
| Florida, USA           | Sugarcane     | 20–50$^f$| 0.80  | NA$^e$| NA$^e$| NA$^e$| 88    | 170   | 280$^k$| NA$^e$| 540   |       |          |
| Saxony-Anhalt, Germany | Arable        | 15.2      | 400$^f$| NA$^e$| 130   | 180   | 120   | 500   | 680$^j$| NA$^e$| 2000  |       |          |
| Hula Valley, Israel    | Arable        | 20–50$^f$| 0.12  | NA$^e$| 58    | 6.2   | 180   | 59    | 420   | NA$^e$| 720   |       |          |

$^a$ Sequentially extracted with deionized water.
$^b$ Sequentially extracted with 0.5 M NaHCO$_3$ (pH 8.5).
$^c$ Sequentially extracted with 0.1 M NaOH solution.
$^d$ Sequentially extracted with 1 M HCl solution.
$^e$ NA = not available.
$^f$ Conventional fertilizer application rates for the region.
$^g$ Sequentially extracted with resin
$^h$ Sequentially extracted with 1 M NH$_4$Cl
$^i$ Sequentially extracted with 0.11 M borate dithionite.
$^j$ Sequentially extracted with 1 M H$_2$SO$_4$ solution.
$^k$ Sequentially extracted with 0.5 M HCl solution.
$^l$ $P_o$ was only listed as a total, and not its distribution in individual pools.
pH and nutrient availability to appropriate levels (Castillo and Wright 2008, Ewing et al 2012).

The use of P fertilizer on organic soils is required to support intensive horticulture production (Hoffman et al 1962). However, P fertilization efficiency depends on the amount of precipitation or irrigation, which may lead to a loss of P via surface runoff (Carpenter et al 1998, Mbonimpa et al 2014). Miller (1979) found that up to 37 kg ha$^{-1}$ of dissolved orthophosphate (PO$_4^-$-P) was lost annually from cultivated organic soil through subsurface tile drainage in Ontario, attributed to over-fertilization. Present P application rates are often excessive, and can lead to increased water pollution (Asselin 1997, Parent and Khiaari 2003). High P build-up in the soil, known as legacy P (Reddy et al 2011, Sharpley et al 2015, Withers et al 2017), has global implications. In Florida, approximately 61% of stored P in the Southern Everglades Ecosystem is from the Everglades Agricultural Area (Reddy et al 2011).

One of the major issues with intensive cultivation of organic soils is increased microbial and chemical oxidation of OM and concomitant losses of carbon dioxide to the atmosphere. This loss of OM is accelerated by drainage and leads over time to subsidence (Castillo and Wright 2008). Millette et al (1982) found that in organic soils, subsidence occurs at a rate between 1 and 7 cm per year in Quebec. Subsidence can be minimized in drained organic soils through drainage infrastructure of subsurface tiles, ditches, pumping stations and levees (Ilnek, 2003, Gambolati et al 2006). Decomposition of peat soils is accelerated by tillage, fertilization, and drainage practices (Hallema et al 2015). Kechavarzi et al (2010) reported that decomposition and humification result in degradation of the soil structure and shrinkage, which can lead to a decrease in water storage, water transmission and water retention.

4. P dynamics in agricultural organic soils

P is a major nutrient required for crop production but is only available in limited quantities in nature. P is a rock-derived nutrient which enters the soil solution through the dissolution of primary and secondary minerals. The P cycle includes only a negligible gaseous phase and consequently nature depends on the continuing input of P through the weathering of soils (Filippelli 2008, 2017). Soils in tropical ecosystems are often highly weathered which leads to the fixation and occlusion of P impeding biological uptake. These systems sustain their primary production by efficient recycling mechanisms and by the utilization of P from atmospheric deposition of dust (Chadwick et al 1999, Bristow et al 2010).

P exists in a variety of forms, either as P$_o$ or P$_i$. Plants and microorganisms usually take up P from the soil solution as inorganic orthophosphate (PO$_4^{3-}$). Orthophosphate enters the soil solution via dissolution and desorption from soil particles and primary and secondary minerals or via the hydrolysis of P$_o$ by extracellular enzymes known as phosphatases. These processes operate on different timescales from seconds to millennia and therefore the supply of available P is often limited in natural ecosystems.

Anthropogenic activities have had a severe impact on the environmental P cycle such as increased use of P fertilizer, land-use change and sewage waste containment. This has led to the global environmental problems of eutrophication, algal blooms, hypoxia and coastal dead zones (Filippelli 2017). Intensive cropping relies on the application of P fertilizers so that P is available for immediate uptake by crops (Mbonimpa et al 2014). Without the application of this essential nutrient, available P in agricultural soils can be as low as 3–25 mg P kg$^{-1}$ (Nagassa and Leinweber 2009). This is due to the reactivity of the negatively charged oxygen moieties in a phosphate molecule, which are prone to adsorbing to soil particle surfaces via anion exchange (moderately labile P), unless these sites are P-saturated (Whalen and Sampedro 2010, Doolette and Smernik 2011). This moderately labile P is in equilibrium with the available P pool, replenishing the depleted pool when kinetically favorable (Whalen and Sampedro 2010, Doolette and Smernik 2011, Stutter et al 2015).

The microbiome’s function is crucial in driving agricultural P dynamics. Just as P is available to plants in the soil solution, the same is true for microorganisms, competing directly with plants and crops for limited P (Jones and Oburger 2011, Wasaki and Maruyama 2011, Dodd and Sharpley 2015). Microbes can immobilize, both, P$_o$ and some P$_i$ compounds (Oberson et al 2001, Jansa et al 2011, Jones and Oburger 2011). While immobilized, P undergoes modifications and transformations within the membranes of the microbes (Oberson et al 2011). Sudden fluctuations in the environment, such as decreases in organic C availability, increased P concentrations, drying and rewetting and lysis of microorganisms, can lead to the release of microbial P into the environment (Turner and Haygarth 2001). Upon release, much of this microbial P is P$_o$ (Bünnemann et al 2011).

Depending on the mineral composition of the agricultural soil, P can also form recalcitrant ionic complexes with aluminum (Al) and iron (Fe), known as sesquisoxides (Al/Fe-bound non-labile P) as well as precipitate with calcium (Ca) (Ca-bound non-labile P). The initial formation of these Al, Fe, and Ca phosphate complexes are amorphous, but can become crystalline structures such as variscite, strengite, and hydroxyapatite, respectively (Nagassa and Leinweber 2009, Doolette and Smernik 2011, George et al 2011). However, these reactions are pH dependent. When soil pH is more acidic, P$_i$ will react with Al and Fe, while when more alkaline, Ca phosphates are formed (Jones and Oburger 2011,
Shen et al (2011). Although this P is considered non-labile, when soils are water-saturated creating reduced conditions, Al and Fe complexes are more likely to dissolve, releasing P (Spivakov et al 1999). Microorganisms can also produce secondary organic metabolites to prevent P forming mineral complexes or release protons, hydroxyl groups, and carbon dioxide (from respiration), which either acidify or basify their immediate environment, enhancing P dissolution (Jones and Oburger 2011).

Soil organic phosphorus (P₀) can make up to 80% of the total P in mineral soils and even more so in organic soils (Harrison 1987). The composition of P₀ may affect the rate at which it is mineralized (Tate and Newman 1982). In agricultural soils, P₀ is mainly present as phosphomonoesters, phosphodiesters, phosphonates, and large P-containing molecules (Condron et al 1990, Cade-Menun 2005, 2015). Though a majority of P₀ is not available to plants, some low molecular weight forms can be hydrolyzed by extracellular phosphatase enzymes, producing P₁ (Gessel et al 1996, Richardson et al 2011, Annaheim et al 2013).

4.1. Abiotic soil P pools

Extensive research has been conducted to characterize P in different abiotic and biotic soil pools. Abiotic pools are often assessed with the Hedley fractionation method (Hedley et al 1982). This procedure follows a sequential extraction with chemical solutions of varying ionic strength to separate operationally defined P pools. Distribution of P among these pools differs based on soil order, soil age and land-use and has been cataloged in Cross and Schlesinger (1995) for natural soils, and Negassa and Leinweber (2009) for natural and agricultural soils. While these reviews thoroughly assessed the available literature on P pools in abiotic soils, both studies overlooked organic soils, most likely due to the sparse available research published in the literature.

In the past decade, more studies have been conducted on the abiotic P pools in arable organic soils (table 2). Like arable mineral soils, arable organic soils have larger P pools compared to their natural counterparts due to the accumulation of fertilizer P throughout their cultivation history. Despite their differences in soil physical-chemical properties, the total P (TP stocks of arable organic soils (340–2000 kg ha⁻¹) are comparable to arable mineral soils (390–2100 kg ha⁻¹). Both soil types possess similar quantities of P₁ in the available pool (mineral soil P: 18–280 kg ha⁻¹; organic soil P: 0.12–400 kg ha⁻¹). However, Ca-bound non-labile P₁ in arable organic soils (86–975 kg ha⁻¹) can be nearly twice the amount found in arable mineral soils (62–458 kg ha⁻¹; Negassa and Leinweber 2009).

The plant-available P₀ pool in organic soils expresses great variability ranging from as low as 0.12 to 0.80 kg P ha⁻¹ (Litaor et al 2004, Castillo and Wright 2008) to three orders of magnitude greater with 240–400 kg P ha⁻¹ (Schlichting et al 2002, Parent et al 2014). This may stem from variables such as cultivation history (e.g. fertilization practices, intensive and long-term vs. extensive and short-term horticultural production); time of year when samples were collected, such as immediately after fertilization or post-harvest; or inherent mineral content of the parent peat material, where ombrogenous peatlands have lower concentrations of minerals compared to minerogenous peatlands (Kolka et al 2016). A ³²P leaching study demonstrated that organic soils with greater Al and Fe stocks (23 500 kg ha⁻¹) retained 100% of applied fertilizer P (Larsen et al 1958). Similarly, studies in Finland found that the risk of leaching is highest in organic soils with little inorganic mineral compounds (Kaila 1959, Saarela et al 2004). Certain organic soil studies may also have greater dissolved organic matter (DOM) concentrations which could compete with P for mineral sorption sites, resulting in greater available P. By modeling P sorption to goethite, Weng et al (2012) determined that P adsorption diminished by 37%–97% with DOM present. In addition, DOM may increase the negative charge on soil surfaces, which repels P (Guppy et al 2005). However, the role of DOM in P interactions is not clear, as DOM may provide low energy binding sites that keep P weakly sorbed (Johnston et al 2009), and should be studied further, especially in organic soils.

Fractionation studies demonstrate the capacity of arable organic soils to retain P in mineral fractions, subsequently reducing their risk of P export. Castillo and Wright (2008) exhibited the P retention of arable organic soils, determining that the Ca-bound non-labile pool grew by 8%, 21% and 40% after a 21 d incubation of cultivated organic soils with 10, 50 and 150 kg P ha⁻¹, respectively. The availability of minerals in these soils can result from the subsidence of organic soils, which releases metals bound in humic complexes and oxidizes minerals to more reactive forms like Fe (II) (Litaor et al 2004, Zak et al 2008). Tillage also influences the P retention capacity of arable organic soils by exposing mineral surfaces for P to bind, further exacerbating soil subsidence, which brings the surface layer closer to the bedrock (Graham et al 2005, Castillo and Wright 2008). This mineral substrate heavily influences the mineralogy of the soil and is therefore a controlling factor in the fate of soil P. Most of the arable organic soil studies found in table 2 mention the presence of a Ca-rich bedrock which could explain the importance of the Ca-bound non-labile P₁ pool in these soils (Litaor et al 2004, Castillo and Wright 2008, De Sena 2017, Audette et al 2018). However, if arable organic soils were cultivated on ombrogenous peatlands, mineral inputs from the bedrock are minimal due to their deep organic layer isolating the topsoil. In addition, most organic soils are naturally acidic with a pH than can be lower than 4. Therefore, most arable organic soils therefore
receive amendments of lime and gypsum to raise the pH which can be a significant source of Ca (Litaor et al 2004, Negassa and Leinweber 2009). Furthermore, the application of certain mineral fertilizers (e.g. calcium monophosphate) can introduce Ca to these fields (Vu et al 2010). While the studies presented in table 2 either did not use calcium contained fertilizers or do not mention their fertilizer source, previous applications during cultivation history may have contained such fertilizers. Though these arable organic soils demonstrate the ability to retain P in mineral fractions, those with greater available P, may constitute a eutrophication risk. P present in the soil solution can be susceptible to leaching during a precipitation or irrigation event (Castillo and Wright 2008). Consequently, the geochemistry of abiotic P pools in organic soils is crucial for understanding the risk for organic soils in exporting P to water bodies.

4.2. Biotic soil P pools
Microorganisms are an important pool of P in soils. Microbial reactions are the processes that predominately regulate the availability of P in soils (Cross and Schlesinger 1995), contributing to the accessibility of plant-available P to crops. Studies have found that the $\text{PO}_4^{3-}$ fluxes in organic soils are controlled by the soil microbial community present, as they can immobilize P in their biomass or lower the redox potential due to their oxygen consumption, therefore releasing P bound to Fe (Noe et al 2001). Microbial P has been found to relate directly to the microbial biomass (Annaheim et al 2015). The microbial biomass is largely made up decomposed plant residues found in the soil (Richardson and Simpson 2011). The uptake, cycling and release of P by microorganisms in soils strongly influence its availability for plants in ecosystems. Microbial turnover of P, which can be defined as the sum of all microbial mediated transformations and related fluxes of P, is regulated by two factors: temporal fluctuations of microbial P and microbial activity (Wardle 1998, Oberson and Joner 2005). Studies, which employed radioisotope techniques, indicate that microbial uptake of P does not necessarily correspond to a net change in the microbial P pool, suggesting equilibrium between P uptake and P release (Oberson et al 2001, Oehl et al 2001, Kouno et al 2002). Thus, there can be a large P flux through the microbial biomass without any net changes in microbial P. Chen et al (2003) calculated the turnover time of microbial P in forest and grassland soils using measurements of the temporal net changes in microbial P, whereas, Oehl et al (2001) estimated the turnover time in a soil where no net change in microbial P occurred by applying a radioisotope technique. The turnover times of the two studies showed a large variation, ranging from 70 d (Oehl et al 2001) to 1.25 years (Chen et al 2003). Hagerty et al (2014) found that microbial C had a faster turnover rate in organic soils compared to mineral, however, to our knowledge, there is no information on microbial turnover times of P in organic soils.

The microbial biomass P was found to increase in the Everglades wherever there was high P enrichment (Qualls and Richardson 2000). A study by Ivanoff et al (1998) found that the microbial biomass P in cultivated organic soil was 21% of TP. Noe et al (2001) suggested that the microbial biomass P relationship to TP is more important when there is a lack of nutrients within the soils. Other studies have found that P can limit microbial activities and growth in peat soils (Amador and Jones 1993). Furthermore, these authors found that $\text{PO}_4^{3-}$ can stimulate the respiration rates in peat soils with intermediate TP content (385 mg P kg$^{-1}$). Further research has found that adding nutrients to the soil changes the microbial biomass more readily in P-poor soils, but that even in P-poor soils, mineralization of organic P is driven more by microbial C than P (Heuck et al 2015).

4.3. Influence of soil hydrology on cultivation and P export
Understanding the hydraulic properties of organic soils is essential for optimizing irrigation and water quality management in cultivated farmlands on the one hand, and on the other hand to make predictions about the amount of P that is exported from organic soils. Cultivation of organic soils accelerates soil-forming processes such as decomposition and humification, which leads to changes in soil physical, chemical and hydraulic properties (Kecharvarzi et al 2010, Kroetsch et al 2011). For example, undecomposed peat has a greater water retention capacity, compared to decomposed peat, due to higher total porosity and a larger proportion of macropores (Boelter and Blake 1964). Undecomposed peat also has a greater drainage affinity due to low air-entry pressure, in comparison to decomposed peat (Kecharvarzi et al 2010), which can foster the export of P. Kecharvarzi et al (2010) reported that decomposition and humification result in degradation of the soil structure and shrinkage, which can lead to a decrease in water storage, water transmission and water retention. Further difficulties arise in predicting the drainage properties of cultivated organic soils, as different degrees of decomposition can be found in the same soil profile, leading to stratification where a coarse textured layer (mesic or fibric) is overlaid by a finer more humic layer (Lafond et al 2014). In these soil profiles (fine-over-coarse-textured profiles), preferential soil water movement develops, as hydraulic conductivity increases with depth (Hill and Parlange 1972, Dekker and Ritsema 2000). Furthermore, the hydrophobicity of organic soils can lead to unstable flow patterns along with irreversible drying
processes in OM introducing difficulty in the rewetting of soil (Dekker and Ritsema 2000). All these factors in the water movement within organic soils may create pathways for substantial P losses.

4.4. P forms in leached water

P can be found in both organic and inorganic forms within water. The form of P most often studied is TP, which includes all forms of P found in water without differentiation between the states of P. The P present in runoff regularly transitions between dissolved and particulate states and can be found in multiple forms, including dissolved orthophosphate (Spivakov et al 1999). A major portion of P enters rivers and lakes in the form of particulate P, which can then dissolve through weathering and mineralization, either becoming total dissolved P (TDP) or binding with minerals. The particulate state of P includes both the reactive and organic suspended P particles (Spivakov et al 1999). DRP, or PO₄-P, is readily available to aquatic biota, thereby causing degradation of flora and fauna in water bodies (Sharpley 1993, McDowell et al 2001, Maguire and Sims 2002, Hoefting 2009, Zheng et al 2014).

4.5. Methodological advancements in P assessment

More sophisticated methods are required in conjunction with sequential fractionation to gain greater insight into the P dynamics of organic soils. Such strategies have been applied to soil P studies on mineral soils, analyzing extracts with techniques such as radioisotope tracing using ³²P or ³³P (e.g. Buehler et al, 2002, Bünemann et al 2004, Vu et al 2010), x-ray absorption near-edge spectroscopy (XANES) (Liu et al 2015, Koch et al 2018), ³¹P nuclear magnetic resonance (NMR) (Liu et al 2015, Koch et al 2018), and O isotope tracing (Joshi et al 2016, Bauke et al 2018, Helfenstein et al 2018). There have been limited studies on organic soils that utilized sequential fractionation with more precise spectroscopic methods (Kruse and Leinweber 2008, Audette et al 2018, Schmieder et al 2020). Kruse and Leinweber (2008) used XANES on sequential extracts from degraded peat soils and determined that although the sequential fractionation procedure led to different peak intensities, there was an absence of unique spectral features with each extract. As such, the researchers suggested further research to delineate the contents of each extract. In a study by Audette et al (2018), a sequential fractionation procedure was used in conjunction with ³¹P NMR to characterize P in an arable organic soil. However, the fractionation method employed differed from the conventional Hedley et al (1982) method, where soil was sequentially extracted with NH₄Cl, borate dithionite, NaOH, and HCl to define loosely bound P, redox sensitive P, Al or Fe-bound P, and Ca-bound P. Further, liquid ³¹P NMR only characterizes P species (mostly organic) of the bulk soil with NaOH–EDTA extracts, and not of individual extracts. Therefore, there is an absence of insight into the geochemical nature of these P species. Furthermore, innovative techniques for water quality P analysis are also limited from organic agricultural sites. Li et al (2011) used ¹⁸O isotopes to study the DRP found in the Florida Everglades. The authors identified the ¹⁸O isotope analysis as a tool for tracing the impact of P fertilizer inputs from agricultural areas on freshwater ecosystems. As such research efforts on P in organic soils should be directed towards more deterministic methods in assessing P geochemistry.

4.6. Mineral soils and P dynamics

Mineral and organic soils are different from the soil structure, to preferential flow in soil and nutrient content. In relation to mineral soils, organic soils have higher C and fiber content in the soil, lower bulk density, lower plasticity, and high-water retention and aeration of the soil (Caron et al 2015). Extensive reviews have been conducted on P pollution on mineral soils for many decades (Sims et al 1998, Reid et al 2012, Kleinman et al 2015, Christianson et al 2016). Mineral soils are comprised of varying percentages of sand, silt and clay with limited amounts of OM. While organic soils are more uniform in texture in the parent material, mineral soils vary depending on their parent material and soil texture. Furthermore, soil texture has a large impact on agricultural production, as heavy clay soils have increased surface runoff and high compaction while sandy soils have good water infiltration but can cause water quality problems due to leaching, for example (Gramlich et al 2018). The differences in soil composition leads to variance in soil porosity between soil types. The Darcy–Buckingham equation, utilizing the unsaturated hydraulic conductivity, has been applied extensively on mineral soils to estimate fluxes in steady-state conditions and within short time intervals (Lafond et al 2014). Organic soils have very different water flow characteristics and exhibit non-Darcian flow, which influences P transport and dynamics.

In many areas, there are large stores of ‘legacy P’ found in the soils due to historical application, sorption and occlusion over time (Vue et al, 2010, Withers et al 2017). Mineral soils sorb greater amounts of P compared to organic soils (Kang et al 2009, Zheng et al 2014). Oberson et al (2001) found that the inorganic P fractions in mineral soils were more affected by P inputs than organic P. Soil type and properties are important for P transport in drainage (Sims et al 1998). Furthermore, organic soils have a diminished capacity to build up labile P caused by the high OM content, compared to mineral soils that can increase the labile pool more than 2500% (Jiménez et al 2019). Preferential and macropore flow
Table 3. The P concentration and load from different studies in Canada, the United States of America and New Zealand.

| Location and description                                                                 | TP/PO₄ concentration                                                                 | TP/PO₄ load                                                                 | Study                                      |
|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------|
| Ontario: Two separate areas in the Holland Marsh (one cultivated, one not), For spring thaw load in 1971 (March to end April). New York: Elba Oak swamp, Grinnel farm. Three locations were used from 1975 to 1977. Ontario: Organic soils south of Chatham in Kent County measured from 1971 to 1975 at three field sites New York: organic soils in Western New York State using two sites to determine factors effecting P loss New York: Elba Oak Creek with 1 year (1984–1985) of sampling five stream locations that account for the major drainage of the organic soil farmland Florida: Four field sites were used in the Everglades Agricultural Area looking at P release under different crop type from 1988 to 1989 Florida: Two fields in the Everglades Nutrient Removal Project were used in a column study that looked at the P with four different water table levels for 30 d each trial Ontario: Holland Marsh sub-watershed, values from the discharge water at the Pump Station Florida: Ten farms in Everglades Agricultural Area from 1992 to 2002, average monthly load New Zealand: Marginal lands on the South Island use of artificial drainage on dairy farms over an 18 month period | PO₄ concentration varies from 0.001 to 0.62 mg l⁻¹ on uncultivated and from 0.003 to 0.59 mg l⁻¹ for cultivated PO₄ concentration varies between 0.5 and 7.6 mg l⁻¹ TP concentration varies between 1.14 and 18.23 mg l⁻¹ TP concentration was found to vary between 0.20 and 1.0 mg l⁻¹, with the mean being 0.72 mg l⁻¹ TP concentration averaged between 0.14 and 0.35 mg l⁻¹ between the field sites TP concentration was between 0.25 and 0.83 mg l⁻¹ (1990–2004) | TP cultivated spring thaw load was between 0.0036 and 1.51 kg ha⁻¹ while the uncultivated was from 0.0026 to 0.17 kg ha⁻¹ PO₄ load varies annually between 0.6 and 30.7 kg ha⁻¹ PO₄ load varies annually between 1.6 and 26.8 kg ha⁻¹ Annual TP loads varies from 0.6 to 36 kg ha⁻¹ Annual TP load for three sites varied between 0.63 and 1.76 kg ha⁻¹, while the PO₄ loads varied between 0.34 and 1.37 kg ha⁻¹ Annual TP load for sugarcane was 0.72 kg ha⁻¹ and for radish was 0.88 kg ha⁻¹ TP concentration averaged between 0.14 and 0.35 mg l⁻¹ between the field sites | Nichols and MacCrimmon 1974 Duxbury and Peverly 1978 Miller 1979 Cogger and Duxbury 1984 Longabucco and Rafferty 1989 Izuno et al 1991 Martin et al 1997 Winter et al 2007 Daroub et al 2011 McDowell and Monaghan 2015 |
conditions in soils have a large impact on P loss (Eastman et al 2010). High clay content soils will lose more P when compared to coarse-textured soils. In mineral soils, P fixation occurs with Fe and Al as well as to clay (Gramlich et al 2018). However, in comparison, Ca-bound P is higher in organic soils (Litao et al 2004). In addition, Jiménez et al (2019) found through path analysis that unlike mineral soils which has continual interaction between the non-labile and labile P pools, the only source of labile P in organic soils was P application.

Subsurface tile drainage is essential for agriculture in humid areas where excess water can negatively affect crop production and in arid areas where it is used as a part of irrigation management (Kleinman et al 2015). P from drainage water has been a concern from mineral agricultural soils for decades (Sharpley and Seyers 1979). Bergström et al (2015) found a positive relationship between the soil P and dissolved P concentration in the drainage water. Furthermore, Miller (1979) found that the dissolved P water concentration was lower in mineral soils compared to organic. Eastman et al (2010) found that subsurface drainage in clay loam soils increased TP loss while also increasing surface runoff. It was further found that 80% of TP loss in mineral soils was in the form of particulate P, while in organic soils it was only 20%.

Models such as ICECREAM and RZWQM2 (Qi and Qi, 2016) can be used in P studies on mineral soils. However, transport models for P are not able to provide accurate P runoff estimations under diverse management scenarios, and have not been designed for organic soils, limiting the use of the models (Sharpley et al 2017). Mineral and organic soils have different soil properties and P dynamics, and one cannot draw inferences from mineral soils to study P dynamics in organic soils.

5. P concentrations and loading under tile drainage

Studies have found that P is of greater concern in fresh-water bodies, compared to N when looking at causes of eutrophication (Schindler and Fee 1974, Thomas et al 1995). Factors affecting P concentrations and drainage include fertilizer application, crop management practices, irrigation practices, climate, soil properties and site conditions (Skaggs et al 1994). Other studies found that weather and soil properties have a larger impact on P loss due to drainage than BMPs (Bergström et al, 2015, Kleinman et al 2015). Studies, documented in table 3, show the evidence of excess P loss from agricultural areas. Arable organic soils in New York were found to contribute approximately 55%-86% of the P load that enters Lake Ontario from Oak Orchard Creek (Longabucco and Rafferty 1989). Further studies of the Lake Simcoe watershed in Ontario found that organic soils contribute 1%-5% of the TP load into the lake while only covering 1% of land within the watershed (Winter et al 2007). The mandatory BMP program, Everglades Forever Act (Daroub et al 2009), implemented since 1995, for the Everglades Agricultural Area have reduced the P load outflow by 50% from the agricultural area to the Lake Okeechobee (Daroub et al 2011). Despite this successful reduction of P loads, studies within the Everglades have found that even small increase in P concentration in lakes and rivers can cause the immediate growth of algal blooms (McCormick and O’Dell 1996, McCormick and Stevenson 1998, Noe et al 2001). However, the P load entering Lake Okeechobee of the Everglades has been excessive to the point that the water body can no longer assimilate P (Havens and James 2005).

Saarela et al (2004) found that nearly 1 kg P ha⁻¹ was leached annually from arable fields in Finland with a weakly humified organic soil, while other studies have found up to 2.3% of total soil P can be leached (Martin et al 1997). Excessive P leaching and P loads have been consistently linked to organic soils despite their large proportion of non-labile P (table 2); this suggests over-fertilization and that soil-water fluxes may play a larger role than soil characteristics. Martin et al (1997) found that in drained organic soils there was a decrease in P concentrations as the water table rose closer to the soil surface. Furthermore, Thomas et al (1995) found that P loss can be reduced in organic soils when drainage water is retained within channels and field drainage infrastructure.

5.1. Climatic effects

Large areas of organic soils have been known to create a microclimate, which results in higher temperature amplitudes and air humidity (Ilincik 2003), and may affect P concentrations in subsurface drainage effluent and TP loads entering water bodies. A study by Lang et al (2010) shows a positive correlation between precipitation and the drainage volume at ten different farms on organic soils. Further, studies have found a positive relationship between rainfall and rise in water levels and drainage outflows, and between drainage and increased P in runoff (Nicholls and Maccrinnmon 1974, Williams et al 2015). This corroborates Longabucco and Rafferty (1989), whose study concludes that approximately half of the P loads from peat soils around Lake Ontario are from runoff during the initial spring thaw and rainfall events during the months of March, April and May. The discharge of water is a major source of P and therefore, nutrient release into the environment is linked to precipitation and freeze-thaw events in spring. A model using changes in temperature and precipitation within the Everglades predicts that a decrease in precipitation and an increase in temperature results in greater mineralization of P, forms (Orem et al 2015), and thus would increase P release into water bodies.
6. Water management for organic soil P

Reduction in P is critical to eutrophication management. Several studies have looked at various agronomic and water management practices aimed at reducing P losses from cultivated organic soils. This section focuses primarily on water management as a mitigation strategy and it is imperative that further research be conducted to assess potential BMPs for P reduction from intensively farmed organic soils (Carpenter 2008, Schindler et al 2008). Several studies (Minasny and McIntyre 2006a, 2006b, Miles et al 2013, McDowell and Monaghan 2015) have identified significant gaps in our understanding of how P losses via surface runoff and tile drainage are influenced by hydroclimatic drivers and agronomic practices, and the need for improved BMPs. In recent decades, mitigation measures have been implemented in agricultural watersheds, such as the Everglades (Daroub et al 2011). Some organic soil regions have adopted these BMPs (table 4). However, although BMPs exist, the enforcement of their use and their effectiveness in the long-term are not always apparent.

6.1. DWM as a BMP for P reduction

DWM permits the regulation of the water table in fields through the installation of a control structure at the tile drainage outlet. DWM on mineral soils has been studied extensively (Elmi et al 2002, Jamieson et al 2003, Skaggs et al 2010, 2012, Williams et al 2015, Schott et al 2017, Youssif et al 2018). Multiple studies have shown that using DWM can reduce drainage outflow and nutrient losses from farmlands (Lalonde et al 1996, Wesstrom et al, 2001, Williams et al 2015, Schott et al 2017). Consequently, farmers can drain their fields by removing gates such to improve field-machine trafficability, or to raise the gates during dry periods to maintain adequate soil-water in the root zone for crop growth (Mejia et al 2000, Stämpfli and Madramootoo 2006, Valero et al 2007, Skaggs et al 2012, Williams et al 2015). Williams et al (2015) reported that although nutrient loads are correlated to discharge, the P concentrations are not affected by water management. The computer simulation model, DRAINMOD, applied to arable organic soils in North Carolina, predicted that under DWM there would be slightly less TP load exported from the system, in comparison to free drainage (Deal et al 1986). Furthermore, the model predicted that the TP associated with subsurface drainage would vary between 0.1 and 3 kg ha⁻¹ and would be lower than under free drainage (Deal et al 1986). Studies in the Florida Everglades have used DWM to maintain and control water levels in fields and control soil subsidence (, Stephens 1955, Skaggs et al 2012). Since 1995, the Florida Everglades Agricultural Authority has a mandatory BMP program where DWM is an option through improved infrastructure (Daroub et al 2011).

A research study by Grenon et al (2016) on the effects of DWM through a control structure, identified the driver within the growing season for tile drain discharge to be precipitation, and that the DWM structure prevented discharge between August and January, reducing the impact of P loads on the environment. Furthermore, the study found that the TP concentrations (0.03–2.29 mg l⁻¹) were continuously above the recommended limit (0.03 mg l⁻¹; Chambers et al 2012) with the TP load largely occurring during the spring thaw (0.18 kg ha⁻¹) and during months of intense rainfall (0.27 kg ha⁻¹). The authors concluded that DWM had the potential to reduce P loads from an organic agricultural area (Grenon et al 2016). Similarly, multiple studies on mineral soils showed precipitation and spring-thaw as drivers for discharge events in subsurface drainage systems (Jamieson et al 2003, King et al 2015, Gramlich et al 2018). Grenon et al (2016) did not find a reduction of TP concentration with DWM, with concentrations fluctuating between 0.02 and 2.29 mg l⁻¹ over the 2 years. However, the largest concentrations were found within the growing season, between May and September, with 0.52 and 0.57 mg l⁻¹ respectively for the 2 years. The annual TP load for 2015 and 2016 was 0.45 and 0.50 kg P ha⁻¹, with approximately 72% of the TP loads in the form of PO₄−P making it bioavailable to aquatic life (Grenon et al 2016). The application of a DWM on these soils reduced the annual TP load released into the environment by reducing the periods of discharge.

6.2. DWM through open channels

Open channels or ditches are used extensively in organic soil farmlands to provide drainage. A review conducted by Needelman et al (2007) on improved management of agricultural ditches indicated several instances where ditches provided a sink for nutrients (N and P). Ditches play an important role in moderating downstream P losses. In the Lower Mississippi Alluvial Valley, DWM was implemented in the agricultural fields by means of a low crest weir, to increase hydraulic retention time in the field. Installation of the weirs created upstream zones of inundation, aiding increased sedimentation, sediment-bound P removal, and anaerobic conditions for increased N removal through denitrification (Faust et al 2018).

The most comprehensive information in this regard, on organic soils, is the work conducted in the Everglades, Florida, which used DWM in open channels (Izuno et al 1995). Contrary to what was expected, slowing drainage rates resulted in an increase in TP and total dissolved P loads rather than the expected reduction in TP from particulate matter removal in the drainage channel. The high nutrient loads occurred following heavy rainfall, which caused the release of excess P from the system as the water flushed out the nutrients (Izuno et al
Table 4. Mitigation measures for P used for organic soil agriculture.

| Practice                                      | Author          | Location                                  | Key finding                                                                                                                                                                                                 |
|-----------------------------------------------|-----------------|-------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Selected cover crops for P reduction.         | Jones et al 1994| Everglades                                | Rice as a cover crop has the added advantage of reducing soil subsidence, destroying soil pests and pathogens and uptake of residual fertilizers.                                                                    |
| Controlled drainage in open channel farmlands | Izuno et al 1995 | Everglades                                | Slow drained sugarcane plots exhibited significantly higher TP concentrations than the fast-drained plots. However, TP loads were significantly higher (0.97 kg ha\(^{-1}\)) for fast drained plots than for the slow drained plots (0.67 kg ha\(^{-1}\)). |
| Review of several mitigation measures         | Thomas et al 1995| North Carolina, South Carolina, Georgia, and Florida. | Thomas et al, presented several BMPs for mitigating P loss, including water table management, control drainage, retaining drainage water from vegetable and sugarcane fields (on sugarcane or fallow areas). The review provided an amalgamation of both organic and mineral soils. |
| Buffer zones and constructed wetlands         | Newbold et al 2010| Southeastern Pennsylvania                  | Controls runoff by reducing the surface flows. This increases deposition and interaction between incoming nutrients and soil matrices, and plant and microbial nutrient processes. Implementation of buffer zones and constructed wetlands led to particulate P concentration being lowered by 22%, but this removal was balanced by a 26% increase in soluble reactive P. |
| Water management: Detention of water in farmlands. | Daroub et al 2011 | Everglades                                | P load reduction can be obtained by lowering drainage volume and improving internal drainage. Installation of culverts with riser boards and land levelling reduced outflows.                                           |
| Buffer zones                                  | O’Driscoll et al 2014| Glennamong, Ireland                        | Grassed peatland buffer zone reduced total reactive phosphorus and suspended sediment loads by 18% and 33%, respectively, released from an upstream clear-felled blanket peat site.                                      |
Capone et al. (1995), also stated that retaining water within the soil profile through DWM, instead of allowing complete drainage, would greatly aid in reducing nutrient loading in the canals and Lake Okeechobee.

7. Summary and recommendations

In comparison to mineral soil, few studies have been conducted on agricultural water and P transport from organic soils. Organic soils differ in a variety of characteristics from mineral soils. The soil porosity is different for organic soils with ‘mobile’ and ‘immobile’ regions in the soil matrix, leading to increased preferential flow, hydrophobicity and varying expansion and contraction parameters compared to mineral soils. Furthermore, mineral soils have a higher sorption P capacity and fixate P more strongly with Al, Fe, and clay, while organic soils can have higher Ca-bound P. There is also less particulate P found in drainage water from organic soils, but they can have higher TP concentrations in comparison to mineral soils. These differences between organic and mineral soils alter their impacts on the environment and necessitates an understanding of the differences in soil water hydraulics and nutrient transport. Consequently, the objective of this paper was to review subsurface P loss and to assess the effectiveness of DWM strategies to control these losses on organic soils. Based on the literature reviewed and our field measurements, the following conclusions can be drawn: (a) water movement, which is a key driver for P transport, is affected by several physical soil parameters that change during wetting and drying, and biochemical degradation and humification of the soil OM; (b) water repellency and the geo-mechanical instability of these soils leads to the development of changing P flow pathways; (c) Ca-bound P is the dominant P pool within organic soils, demonstrating their potential for P retention; (d) organic soils have been linked to the excessive leaching of P, leading to large TP loads into the surrounding water bodies; and (e) DWM is a potential mitigation measure for reducing P in surface waters and the environment.

The following gaps in knowledge were identified, requiring further research: (a) assessment of P geochemistry in agricultural Histosols through the use of isotope tracing techniques (32P/31P and oxygen isotope ratios in phosphates), XANES, and 31P NMR, in conjunction with sequential fractionation; (b) the assessment of microbial turnover times, (c) long-term studies on the effectiveness of DWM strategies as methods to reduce TP loads from cultivated organic soils; (d) a new mathematical model to account for the geo-mechanical instability and variability in organic soil properties, to estimate water and nutrient fluxes; and (e) creation of P transport indices to predict P loss from these soils.

Data availability statement

All data that support the findings of this study are included within the article.

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