RIPARIAN BUFFER STRIPS AS A MULTIFUNCTIONAL TOOL IN AGRICULTURAL LANDSCAPES

Phosphorus Retention and Remobilization in Vegetated Buffer Strips: A Review

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Diffuse pollution remains a major threat to surface waters due to eutrophication caused by phosphorus (P) transfer from agricultural land. Vegetated buffer strips (VBSs) are increasingly used to mitigate diffuse P losses from agricultural land, having been shown to reduce particulate P transfer. However, retention of dissolved P (DP) has been lower, and in some cases VBSs have increased delivery to surface waters. The aims of this review were (i) to develop a conceptual model to enhance the understanding of VBS functioning in terms of DP, (ii) to identify key processes within the model that affect DP retention and delivery, and (iii) to explore evidence for the controls on these processes. A greater understanding in these areas will allow the development of management strategies that enhance DP retention. We found evidence of a surface layer in buffer strip soils that is enriched in soluble P compared with adjacent agricultural land and may be responsible for the reported increased DP delivery. Through increased biological activity in VBSs, plants and microorganisms may assimilate P from particulates retained in the VBSs or native soil P and remobilize this P in a more soluble form. These conclusions are based on a limited amount of research, and a better understanding of biogeochemical cycling of P in buffer strip soils is required.

WORLDWIDE, COUNTRIES MUST IMPROVE water quality to meet increasingly stringent chemical objectives set by governing authorities. For example, the Water Framework Directive strives to achieve "good chemical status" in the surface waters of European Union member states by 2015. In the United Kingdom, it is estimated that 30% of surface waters will fail to achieve "good chemical status" due to diffuse pollution (NAO, 2010). Phosphorus (P) remains an important element of diffuse pollution because algal growth in freshwater aquatic systems is generally limited by P (Vollenweider, 1968). Excess P and subsequent algal growth in surface waters can reduce dissolved oxygen concentrations, increase turbidity, and produce harmful toxins, with secondary effects resulting in water treatment problems and reductions in biodiversity and leisure value of surface waters.

Natural background concentrations of P in soil are insufficient to maintain agricultural production at the current level. To increase agricultural yields, soils are supplemented with P fertilizer often in excess of plant requirements (Holford, 1997). Hence, P loss from agriculture can contribute a significant proportion of total P (TP) loadings to surface waters. It was estimated that agriculture contributed 50% to the TP load to American, Danish, and Finnish coastal waters during 2000 (OECD, 2001). Phosphorus transfer from agricultural land to surface waters can be considered in terms of the "transfer continuum" (Haygarth et al., 2005). This is a four-tier model that incorporates the source, mobilization, delivery, and impact of P transfer to surface waters. To meet regulatory requirements, substantial research efforts are being made worldwide to reduce P transfer. Vegetated buffer strips (VBSs) comprise noncultivated borders between agricultural lands and surface waters and provide multiple benefits in terms of water quality protection and biodiversity. Vegetated buffer strips are increasingly designed to modify the delivery tier of the P transfer continuum. This proceeds initially by physical processes such as deposition and infiltration of P from overland flow. Numerous studies have reviewed the literature on the retention of P from overland flow by VBSs (e.g., Muscutt et al., 1993; Dorioz et al., 2006; Hoffmann et al., 2009; Collins et al., 2009; Stevens and Quinton, 2009). All of these reviews identified studies where

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Abbreviations: DP, dissolved phosphorus; DRP, dissolved reactive phosphorus; DUP, dissolved unreactive phosphorus; EPC_0, equilibrium phosphate concentration; MBP, microbial biomass phosphorus; PP, particulate phosphorus; TP, total phosphorus; VBS, vegetated buffer strip; WEP, water-extractable phosphorus.

VBSs increased the delivery of dissolved reactive P (DRP). For example, Hoffmann et al. (2009) recently reviewed monitoring studies of VBS retention of P from overland flow. Of the studies where DRP was measured ($n = 6$), retention of TP ranged from 41 to 95%, whereas retention of DRP ranged from −71 to 95%. The fact that VBSs in two of the reviewed studies increased the delivery of DRP suggests that PP retained in VBSs or native soil P was mobilized within the VBSs and delivered as DRP. This is cause for concern because, on delivery to surface waters, DRP is immediately available for algal uptake. In addition, water quality objectives for P are set in terms of DRP concentration. For example, the Water Framework Directive sets a standard of 50 µg L^{-1} DRP during baseline flow conditions in low-alkalinity rivers in the United Kingdom (UK TAG, 2008). If VBSs are to be considered for large-scale implementation to meet regulatory targets, there is a need to improve our understanding of the specific in-soil processes that can lead to VBSs passing on a more bioavailable form of P.

Although numerous studies have reviewed the effectiveness of VBSs in retaining P from overland flow, few have reviewed the studies addressing in-soil processes occurring within the VBSs that are likely to affect dissolved P (DP) retention and delivery. Understanding these processes and how they interact through biogeochemical cycling will allow the design and management of VBSs to enhance DP retention and water quality protection. This review therefore aims to (i) develop a conceptual model to enhance the understanding of vegetated buffer strip functioning in terms of DP, (ii) identify key processes within the model that affect DP retention and delivery, and (iii) explore evidence for the controls on these processes.

Conceptual Model of Vegetated Buffer Strip Functioning

Under normal agricultural management practices, P transfer to surface water occurs along a continuum from source, via mobilization and delivery, to impact (Haygarth et al., 2005) (Fig. 1). "Source" describes any input of P to soil that creates the potential for an increase in transfer to the wider environment. Before sources of P can be delivered, they must be mobilized. "Mobilization" describes the initial separation of P molecules from their source via solubilization or detachment. It operates at the soil profile scale and involves physical, geochemical, and biological processes. "Delivery" of P from the point of mobilization to surface waters is complex and dependent on hydrology and may include surface and subsurface pathways. "Impacts" relate to an actual change or perturbation in a receiving water body resulting from the P transfers (Haygarth et al., 2005).

Buffer strips function by initially modifying P delivery via retention brought about by physical processes such as infiltration of DP and deposition of PP (Fig. 1). "Retention" can be viewed as the opposite of mobilization and also involves physical, geochemical, and biological processes. After physical retention, PP may be retained in biological pools and DP may be retained in geochemical or biological pools by sorption and assimilation, respectively. Mobilization of retained P in these pools can then reoccur within the VBS. This is referred to in the model as "remobilization," separating it from mobilization upslope of the buffer strip. This remobilization brings about the potential for altered "outputs" and delivery from the buffer strip to surface waters. Thus, rather than being the final sink for P mobilized from field slopes, VBSs become a modifying loop in the P transfer continuum, altering the extent, timing, and chemical form of P eventually delivered to surface waters. Unless we manage this retention–remobilization loop, we will be unable to maximize the efficiency of VBSs with respect to providing a true "buffer" for P transfers. Therefore, our review explores this set of processes via the following structure (following the layout of Fig. 1): (i) delivery inputs of P to vegetated buffer strips from upslope managed land, (ii) physical retention of P in vegetated buffer strips, (iii) geochemical retention and remobilization of P in vegetated buffer strips, (iv) biological retention and remobilization of P in vegetated buffer strips, and (v) delivery outputs of P from vegetated buffer strips.
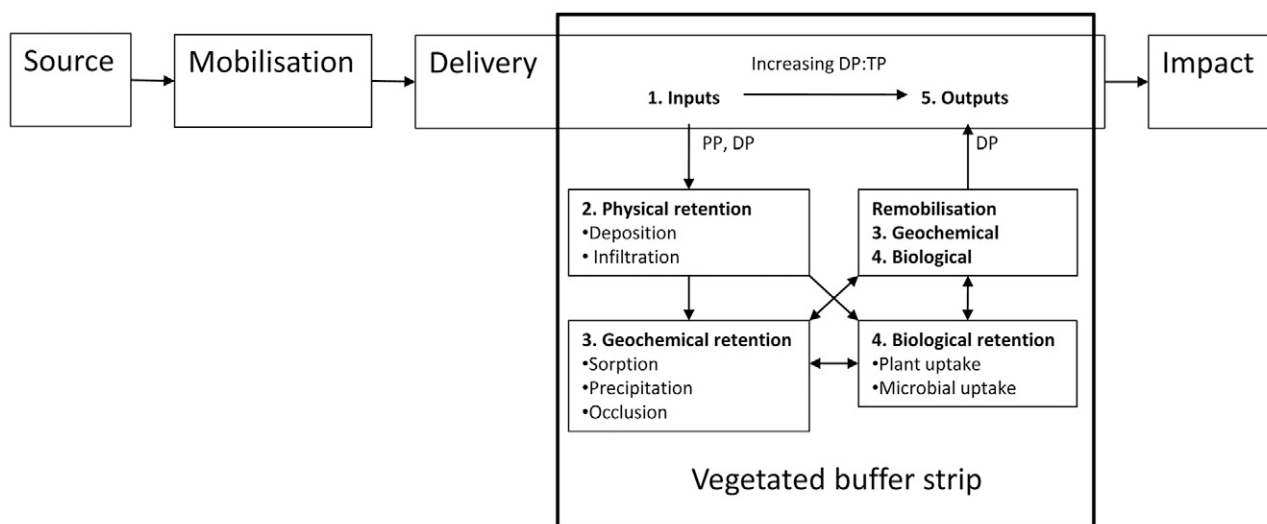

Fig. 1. Conceptual model of vegetated buffer strip functioning being embedded in the transfer continuum model of Haygarth et al. (2005). Arrows indicate movement of P through the transfer continuum and vegetated buffer strip retention and remobilization pools and processes. DRP, dissolved reactive phosphorus; PP, particulate phosphorus; TP, total phosphorus.

Delivery Inputs of Phosphorus to Vegetated Buffer Strips from Upslope Managed Land

There are many factors affecting P delivery (Beven et al., 2005) and inputs to VBS. We emphasize these here only briefly, concentrating mainly on the forms of P as a key factor in the fate of P entering the VBSs. Phosphorus inputs can be delivered to buffer strips via overland flow or subsurface flows such as interflow, return flow, or shallow ground water (Viaud et al., 2004; Hoffmann et al., 2009; Dorioz et al., 2006). However, it is thought that the majority of annual P loss from small catchments occurs during high-magnitude rainfall events with overland flow (Haygarth and Jarvis, 1999). We therefore pay particular attention to P inputs via overland flow. Phosphorus in overland flow is held in a combination of dissolved and particulate and inorganic and organic compounds (Haygarth et al., 1998). The operational definition used to distinguish between DP and PP is the total amount of P that can pass through a filter, in most studies with a cut-off of 0.45 µm. Some colloidal P passes through this filter size and is not truly dissolved in solution (Haygarth et al., 1997; Haygarth and Sharpley, 2000; Heathwaite et al., 2005). The operationally defined distinction between inorganic and organic P is the reactivity with ammonium molybdate as determined by colorimetry. However, some inorganic forms of P, such as polyphosphates, do not react with molybdate (Turner et al., 2003b). Dissolved reactive P is a measure of the minimum amount of P in a sample that is bioavailable. The unreactive fraction of P in overland flow contains P in a range of organic combinations, including inositol phosphates, nucleic acids, nucleotides, phospholipids, and sugar phosphates (Turner and Haygarth, 2000; Toor et al., 2003).

The factors affecting the proportions of these fractions in overland flow may include rainfall intensity, slope, hydrological conditions, fertilizer additions, land use, soil physical characteristics, mobilization mechanisms, and soil P geochemical characteristics (Haygarth and Jarvis, 1999; Kleinman et al., 2002; Nash et al., 2000; Quinton et al., 2001; Uusitalo et al., 2000). This gives rise to a wide variation in the relative proportions of dissolved and particulate and inorganic and organic compounds delivered to VBSs and therefore varies spatially and temporally. For example, Hodgkinson and Withers (2007) found that, over a 2-yr period, losses of PP in overland flow were lower from grassland (0.16 kg ha^{-1}) compared with arable land (0.22 kg ha^{-1}) within the same catchment. Nash and Murdoch (1997) discovered that dissolved unreactive P (DUP) in overland flow from grazed pasture with mineral fertilizer application represented only 2 to 9% of DP, whereas, Preedy et al. (2001) found on unfertilized grazed pasture that DUP constituted 29% of DP in overland flow.

A proportion of PP in overland flow will be inorganic and extractable by methods assumed to extract a bioavailable fraction of P. For example, Uusitalo et al. (2000) measured reactive P extracted by an anion exchange resin from the particulate fraction in 154 overland flow samples. The average amount of reactive extractable P in particulates ranged from 39 to 165 mg kg^{-1} at different sites, depending on soil P status.

Physical Retention of Phosphorus in Vegetated Buffer Strips

The physical processes of retention are some of the most thoroughly researched in VBS studies. Again, we provide a very brief overview. Physical retention is the initial step in the "retention–remobilization loop" (Fig. 1) and is generally confined to P in overland flow because the surface soil is where these processes occur. Two characteristic features aid physical retention in buffer strips: dense above-ground vegetation and a dense root system with an increased number of fine roots. Dense, above-ground vegetation in the VBSs increases hydraulic roughness, decreasing overland flow velocity and energy available to transport particulates (Dillaha and Inamdar, 1997; Uusi-Kämppä, 1997). Even so, P associated with clay and colloidal-sized fractions may not be deposited (Owens et al., 2007; Syversen and Borch, 2005). Denser root systems in VBSs encourage infiltration during infiltration excess overland flow by increasing the permeability and porosity of the soil (Cooper et al., 1995; Räty et al., 2010a; Zaimes et al., 2008). Infiltration, encouraged by the reduction in flow velocity mentioned above, increases contact time of DP with soil surfaces and the rhizosphere. The combination of these processes results in, as Dorioz et al. (2006) reported, "a partial decoupling and separate storage of DP and PP." However, during saturation-excess overland flow, no infiltration of DP may occur within the VBS.

Karr and Schlosser (1978) identified factors affecting the physical retention of P in VBSs as width and slope before water reaches the vegetated area and of the vegetated area and vegetation characteristics. In a recent review paper, Zhang et al. (2010) gave a very detailed account of the effect of these factors on P retention and found that VBS width had the greatest impact on retention of P from overland flow. Many studies investigating the factors affecting the physical retention of P in buffers strips have been short-term, event-based studies that focus on P retention from natural or simulated overland flow at the plot scale. Results tend to be expressed as a percentage of P retained from overland flow. Physical retention of P generally increases as the width of the VBS increases (see examples in Table 1), and Collins et al. (2009) provides a more comprehensive review of this. Physical retention of P decreases with increased slopes and resulting flow velocity. Dillaha et al. (1988) used a simulated feedlot plot experiment with simulated rainfall events to test the effect of slope (11 and 16%). For all of the experiments, the VBSs on the 11 and 16% slopes retained 63 and 52% TP, respectively, and −20 and −108% for DRP, respectively. Physical retention of P also varies depending on vegetation type in the VBSs (Table 2). From the studies reviewed, it is not clear which plant species enhances physical retention or whether single-species or multispecies VBSs retain more P. Lee et al. (1998) concluded that the single-species VBSs retained more P due to its uniform distribution. This was contrary to the results of Young et al. (1980), who found that multispecies VBSs retained more P (Table 2). There is still a need to identify the exact plant traits that allow physical retention processes to be maximized.

In summary, the evidence shows that physical retention mechanisms in VBSs effectively reduce TP delivery during individual studied events. This is mainly due to retention of

PP, which has been strongly correlated with retention of TP in many of the studies. However, the situation for DRP and DUP is uncertain, being considerably less well documented compared with TP. Although altering the physical properties of the buffer strip will likely effect DP retention, VBSs probably remain less effective for DP than PP retention. In some cases, DP delivery has been increased during VBS passing. Processes other than physical ones are likely to be of greater influence on DP.

Geochemical Retention and Remobilization of Phosphorus in Vegetated Buffer Strips

The geochemical retention of P in VBS soils is probably confined to DP because PP is already sorbed to sediments or held in high-molecular-weight organic combinations that are deposited on the soil surface. After infiltration during infiltration excess overland flow, DP percolates down through the soil profile where it may be sorbed to soil constituents (Fig. 1). Hoffmann et al. (2009) describe in detail the sorption/desorption and precipitation/dissolution processes that are relevant to geochemical retention of P in VBS soils. Here we are mainly concerned with the different pools of P in VBS soils, the equilibrium dynamics that govern sorption and desorption reactions, and the mobilization of P from these pools.

Concentrations of TP in the surface of VBS soils are generally lower than those in adjacent agricultural land (Zaimes et al., 2008; Owens et al., 2007; Aye et al., 2006). Owens et al. (2007) suggested that this is because VBSs trap coarse particulates that have a lower TP concentration than the bulk agricultural soil from which they were derived. Studies of labile P in VBS soils tend to be performed by extraction with $NaHCO_3$ (Olsen P), although other extractants are also used (Table 3). The results of these extractions seem to indicate variation in labile P between VBSs and adjacent agricultural land surface soils (Table 3), and it is difficult to draw conclusions from this.

Water-extractable P (WEP) in soil is determined with deionized water or mimicked by a weak (0.01 mol L^{-1}) $CaCl_2$ solution. Reactive WEP was, fairly consistently, found to be higher in VBS surface soils relative to adjacent agricultural land (Table 4). Stutter et al. (2009) also showed that unreactive WEP concentration to be significantly ($p < 0.05$) higher in VBS soils relative to adjacent arable land. Increased WEP in surface soils suggests that VBSs present a higher risk of DP leaching than adjacent arable land because this fraction has been shown to be strongly correlated to P concentration in overland and subsurface flow (Pote et al., 1996; McDowell and Sharpley, 2001). Hence, small changes in WEP pools that may indicate an increased risk of DP leaching are not reflected by the stronger extractions of soil. Reactive WEP concentrations

Table 1. Short-term studies investigating phosphorus retention from overland flow by vegetated buffer strips (VBSs) of varying widths.

Author	Location	Duration	VBS width	Retention†	
				TP	DRP
			m	——— % ———	
Dillaha et al., 1988	USA	2 d	4.6	57.5	−64
Dillaha et al., 1988	USA	2 d	9.1	68.5	−10.5
Lee et al., 1998	USA	2 h	3	37.4	34
Lee et al., 1998	USA	2 h	6	52.3	42.7
Abu-Zreig et al., 2003	Canada	54–101 min	2	32	–
Abu-Zreig et al., 2003	Canada	54–101 min	5	54	–
Abu-Zreig et al., 2003	Canada	54–101 min	10	67	–
Abu-Zreig et al., 2003	Canada	54–101 min	15	79	–
Syversen, 2005	Norway	2 d	5	78	–
Syversen, 2005	Norway	2 d	10	85.4	–

† DRP, dissolved reactive phosphorus; TP, total phosphorus.

Table 2. Short-term studies investigating phosphorus retention from overland flow by vegetated buffer strips with varying species composition.

Author	Location	Duration	Vegetation		Retention†	
			Common name	Latin name	TP	DRP
					——— % ———	
Young et al., 1980	USA	1 d	orchardgrass	*Dactylis glomerata*	66	–
Young et al., 1980	USA	1 d	sorghum and sudan grass	*Sorghum* sp. and *Sorghum bicolor*	88	–
Lee et al., 1998	USA	2 h	awitchgrass	*Panicum virgatum*	47	42
Lee et al., 1998	USA	2 h	bromegrass, timothy and fescue	*Bromus* sp., *Phleum pratense*, and *Fescuta* sp.	42	35
Syversen, 2005	Norway	2 d	unknown	unknown	84	–
Syversen, 2005	Norway	2 d	aspen	*Populus tremuloides*	77	–
Syversen, 2005	Norway	2 d	aspen, mountain ash, and birch	*Populus tremuloides*, *Fraxinus texensis*, and *Betula* sp.	98	–
Abu-Zreig et al., 2003	Canada	54–101 min	perennial ryegrass	*Lolium perenne*	65	–
Abu-Zreig et al., 2003	Canada	54–101 min	red fescue and birdsfoot trefoil	*Festuca rubra* and *Lotus corniculatus*	54	–
Abu-Zreig et al., 2003	Canada	54–101 min	native riparian vegetation	unknown	68	–

† DRP, dissolved reactive phosphorus; TP, total phosphorus.

have been shown to decline with depth in the soils of VBSs. Aye et al. (2006) found that reactive WEP declined rapidly from 0.17 mg L^{-1} at 0 to depths of 2.5 cm to 0.04 and 0.03 mg L^{-1} at depths of 2.5 to 7.5 cm and 7.5 to 15 cm, respectively. This suggests the increased risk of DP leaching is confined to surface soil horizons.

Sorption/desorption processes are governed by the concentration of P in solution, which controls the amounts of sorbed P. The point where sorption equals desorption is known as the equilibrium phosphate concentration (EPC$_0$). The EPC$_0$ in VBS surface soils has been found to be increased relative to adjacent arable land (Cooper et al., 1995; Aye et al., 2006; Schroeder and Kovar, 2008; Stutter et al., 2009). The EPC$_0$ has also been shown to decline rapidly with depth in VBS soils. Schroeder and Kovar (2008) found that EPC$_0$ declined rapidly from 0.5 mg kg^{-1} at 0 to 5 cm to 0.13 to 0.1 mg kg^{-1} at depths of 5 to 10 cm and 10 to 15 cm, respectively. This suggests that a change in soil conditions or other constituents within the surface soil that compete with P for sorption sites has led to altered sorption of P. Stutter et al. (2009) found that 1 mM NaCl–extractable organic C was higher in VBS soils than in arable surface soils, and it was found that fulvic acids may compete with P for similar sorption sites (Guppy et al., 2005a, 2005b). This increase in EPC$_0$ is likely to be a key indicator of sorption processes affecting solution P concentration at the soil surface. Vidon et al. (2010) suggested that direct desorption of P from sediments deposited in the VBSs could be a significant source, or "hot spot," for DP leaching. Stutter et al. (2009) mixed sediments with their parent field soils in different proportions and found that the EPC$_0$ of the resulting mixtures decreased with an increasing percentage of sediment. It was concluded that PP entering VBSs was strongly sorbed and unlikely to be leached without further biological processing.

After infiltration, sorption, and retention in geochemical pools, there is the potential for remobilization of DP. Because Fe is important for P sorption and geochemical retention in VBS, reductive dissolution of Fe(III) after a shift to an anaerobic metabolism could be an important remobilization mechanism given the right environmental conditions and hydrological setting of the buffer strip. Young and Briggs (2008) found a weak negative correlation between water table depth and DRP concentration in VBS soil solution at 50 cm depth ($r = -0.47$; $p = 0.06$), suggesting remobilization of P in the lower soil horizons by reductive dissolution of Fe(III).

It is also possible that, after repeated overland flow events, VBS soil sorption sites could become saturated with DRP, resulting in conditions favorable for the release of DRP. In such a case, saturation of the soil with DRP retained from overland and subsequent remobilization would reduce the apparent effectiveness of VBSs at retaining DRP rather than resulting in an increase in delivery. Young and Briggs (2008) studied some chemical properties of field and buffer strip soils at 16 locations spread between two different sites. They found that the percentage saturation of poorly crystalline Fe and Al oxides by P was lower in the buffer strip soil at most locations ($n = 13$). This is further confirmed by the work of Stutter et al. (2009), who found little difference in the saturation of poorly crystalline Fe and Al oxides by P between VBS soils and adjacent agricultural land. This suggests that, in these cases, the functioning of buffer strips as a sink for P from overland flow has not led to saturation of the soil with P.

In summary, VBS soils do not seem to become saturated with P but show elevated P solubility and EPC$_0$ values in surface soils. The observed increased WEP represents an increased risk of DP leaching from the surface layer, delivered via overland flow passing through VBSs during saturated conditions. Any DP percolating vertically down the soil profile during

Table 3. Labile phosphorus concentrations extracted from vegetated buffer strip (VBS) and adjacent agricultural soils.

Author	Location	VBS age	Sample depth	Method	Units	VBS soil P	Agricultural soil P
Aye et al., 2006	New Zealand	4–5 yr	0–15 cm	Olsen P	mg kg^{-1}	36	48
Aye et al., 2006	New Zealand	4–5 yr	0–15 cm	Olsen P	mg kg^{-1}	58	48
Aye et al., 2006	New Zealand	4–5 yr	0–15 cm	Olsen P	mg kg^{-1}	51	76
Cooper et al., 1995	New Zealand	15 yr	0–5 cm	Olsen P	mg kg^{-1}	49.2	16
Schroeder and Kovar, 2008	USA	13 yr	0–5 cm	Bray P-1	mg kg^{-1}	45.9	81.2
Stutter et al., 2009	UK	3 and 8 yr	0–6 cm	Olsen P	mg kg^{-1}	27.5	27.9
Stutter et al., 2009	UK	3 and 8 yr	0–6 cm	Fe hydroxide impregnated paper strip P	mg kg^{-1}	34.3	17
Uusi-Kämppä, 2005	Finland	8 yr	0–2 cm	Olsen P	mg L^{-1}	51	40
Uusi-Kämppä, 2005	Finland	8 yr	0–2 cm	acetate and acetic acid extractable P	mg kg^{-1}	14	7.5
Young-Matthews et al., 2010	USA	unknown	0–15 cm	Olsen P	mg kg^{-1}	22.3	14.6

Table 4. Water or CaCl$_2$–extractable reactive phosphorus concentrations extracted from vegetated buffer strip (VBS) and adjacent agricultural soils.

Author	Location	VBS age	Sample depth	Method	Soil:solution	Units	VBS soil P	Agricultural soil P
Aye et al., 2006	New Zealand	4–5 yr	0–15 cm	0.01 mol L^{-1} CaCl$_2$	1:5	mg L^{-1}	0.19	0.14
Aye et al., 2006	New Zealand	4–5 yr	0–15 cm	0.01 mol L^{-1} CaCl$_2$	1:5	mg L^{-1}	0.19	0.12
Aye et al., 2006	New Zealand	4–5 yr	0–15 cm	0.01 mol L^{-1} CaCl$_2$	1:5	mg L^{-1}	0.14	0.16
Cooper et al., 1995	New Zealand	15 yr	0–5 cm	deionized water	1:10	mg kg^{-1}	2.09	1.27
Stutter et al., 2009	UK	3 and 8 yr	0–6 cm	0.01 mol L^{-1} CaCl$_2$	1:3	mg L^{-1}	0.21	0.07

infiltration of excess overland flow is more likely to be sorbed to soil surfaces in subsoil with increased sorption (manifested in lower EPC_0). Here, there is the potential for remobilization by Fe(III) reduction, which would reduce the effectiveness of the VBS at retaining P in geochemical pools. However, this mechanism is unlikely to contribute to increases in DP delivery and the reported WEP concentrations that are elevated solely in the surface layer.

Biological Retention and Remobilization of Phosphorus in Vegetated Buffer Strips

Phosphorus is an essential macronutrient for plants and microorganisms and is necessary for an array of functions (e.g., as a structural element in nucleic acids and phospholipids) (Schachtman et al., 1998; Cole et al., 1977; Turner et al., 2001). Plants and microorganisms therefore represent important pools for the retention of P in VBSs (Fig. 1). Despite the abundance of P forms in most soils, plants and microorganisms almost exclusively derive their P requirement from P anions contained within the soil solution (Richardson, 2001). Because soil solution P concentrations are often low due to sorption, plants and microorganisms may release exudates to solubilize P from soil surfaces (Richardson et al., 2005; Rodríguez and Fraga, 1999) and enzymes to liberate P anions from the soil organic P stock. In addition to native soil P and DP retained in the VBS, sources of P to plants and microorganisms include a proportion of PP retained from overland flow by physical processes (Fig. 1). Deep rooting plant species may access P delivered to VBSs via shallow groundwater or interflows (Gascuel et al., 2008).

Retention and Remobilization of Phosphorus in Plant Pools

Dosskey et al. (2010) reviewed the role of plants in VBSs and noted that plant stand age, plant species, season, and P inputs influence P retention and mobilization. In general, nutrient incorporation into biomass increases rapidly in early succession, reaches a maximum, and then slowly declines to zero as a steady state is approached (Vitousek and Reiners, 1975). Kelly et al. (2007) found that P incorporation into switchgrass (*Panicum virgatum*) and alfalfa (*Medicago sativa*) stands reached this steady state after 4 yr of growth, whereas cotton-tree (*Hibiscus tiliaceus*) continued to accumulate P. Different plant species accumulate different amounts of P. For some common herbaceous species in VBS, TP concentrations in tissue increase in the order: timothy (*Phleum pratense*), common bent (*Agrostis castellana*), meadow fescue (*Festuca pratensis*), white clover (*Trifolium*), milfoil (*Achillea millefolium*), and dandelion (*Taraxacum officinale*) (Räty et al., 2010b). Sovik and Syversen (2008) investigated differences in biological retention between tree and grass species. Phosphate-enriched water was added to vegetated soil columns, and the quantity of DRP in leachate was measured. Although P retention could not be attributed solely to biological retention, columns with tree species retained 40% (±13%) more P than grass species.

On a seasonal basis, uptake and plant TP concentration are highest during the growing season and lowest when plants are dormant during winter. Kelly et al. (2007) showed how plant TP in a VBS sown with smooth bromegrass (*Bromus inermis*) increased from 1.7 g m^{-2} in May to 4.1 g m^{-2} in August and then declined to 2.6 g m^{-2} in September, with 1.5 g m^{-2} being lost during autumn. Leaf senescence occurs when light conditions no longer favor photosynthesis. A proportion of P within the senescing tissue is redistributed to other organs within the plant so that only a proportion of the initial P is released from decaying leaf and root tissues (Dosskey et al., 2010). Uusi-Kämppä (2005) monitored DRP retention in an unmanaged grass buffer strip over a 10-yr period. Over the course of the experiment, the mean concentration was higher in spring in the unmanaged buffer strip plots (0.12–0.28 mg L^{-1}) compared with the plots without a buffer strip (0.06–0.14 mg L^{-1}). This was attributed to the freezing of senesced vegetation over winter and the release of DRP during spring snow melt. Such a situation shows how VBSs can alter the timing, extent, and forms of P released through retention and remobilization. The proportion of P in senescing plant material that is likely to be released as DP is increased by freezing and thawing and by drying and rewetting cycles (Roberson et al., 2007). A further proportion of P in senescing plant material is held in organic combinations that require decomposition before remobilization or further retention.

Soil P status in the VBSs also affects the magnitude of P uptake and remobilization by plants. Fortier et al. (2010) found that plant TP in poplar (*Populus* sp.) aboveground biomass was positively correlated with the P supply rate to the roots ($R^2 = 0.21$; $p < 0.001$). Of the aboveground plant parts, this relationship was strongest for TP concentration in leaves ($R^2 = 0.22$; $p < 0.001$). Having higher tissue P concentrations, especially in leaves, they also have the potential to remobilize more P during leaf senescence. Kröger et al. (2007) found that rice cutgrass (*Leersia oryzoides*) subjected to high P supply had significantly higher plant TP concentration and mobilized more DRP during senescence than plants subject to low P supply ($p < 0.001$).

Plant communities play an important role in the retention of P in VBSs. Even in mature communities where net uptake is near zero, plants can provide a sink for P by storage in plant tissues with woody species representing a larger pool than grass species. Plants can also provide additional P storage when P inputs to the buffer strip are high, but this is also likely to result in increased mobilization during leaf senescence. Because of a combination of P-solubilizing exudates and remobilization during senescence, plants may play a role in converting PP to more soluble forms, which may be released during autumn and contribute to increased WEP in VBS soils.

Retention and Remobilization of Phosphorus in Microbial Pools

The soil microbial biomass can represent significant pools of P in grassland ecosystems (Cole et al., 1977; Halm et al., 1972) and regulate the turnover of organic P in soils (Oberson and Joner, 2005). Despite this, very little attention has been paid to the microbial biomass in research into VBSs in terms of P retention, mobilization, and cycling. In a similar way to plants, retention and mobilization in the microbial biomass exhibits changes caused by succession and seasonal variation in environmental conditions.

Organic matter and organic carbon (C) provide energy for growth and C for the formation of cell structures and are therefore essential soil constituents for the microbial biomass

(Coyne, 1999). The soil microbial biomass is often limited by C in arable systems due to tillage and plant biomass removal. As arable land is converted to VBSs or unmanaged grassland, tillage and biomass removal stops and organic matter and organic C accumulates in the surface soil (Potthoff et al., 2005; Marquez et al., 1998). This is further stimulated by an increase in plant root turnover and activity in VBSs (Tufekcioglu et al., 1998). As a result, total fungi, total bacteria, microbial biomass C, microbial biomass P (MBP), soil respiration, and phosphomonoesterase activity have been shown to be greater in VBS soils compared with adjacent agricultural land (Cooper et al., 1995; Marquez et al., 1998; Staddon et al., 2001; Tufekcioglu et al., 2001; Tufekcioglu et al., 1998; Krutz et al., 2006; Stutter et al., 2009). Cooper et al. (1995) measured microbial biomass C and found it to be greater in VBS soils (1900 mg kg^{-1}) compared with adjacent agricultural soils (1081 mg kg^{-1}). Because C/P ratios in the microbial biomass are relatively constrained (Turner et al., 2001; Cleveland and Liptzin, 2007), it is also likely that MBP was greater. Stutter et al. (2009) measured MBP directly and found it was greater in the surface soil of an 8-yr-old VBS (108 μg g^{-1}) than of a 3-yr-old VBS (43 μg g^{-1}) and adjacent arable land (33 μg g^{-1}). These were greater concentrations than those of Olsen P (extracted on dry soil) measured in the same study. This suggests that the microbial biomass is an important pool for P retention and may increase with organic matter and C because VBSs are established on agricultural soils.

Microbial activity determines microbial turnover and the associated pools of organic and inorganic P in solution (Seeling and Zasoski, 1993; Lee et al., 1990). Microbial activities in buffer strips have been inferred from measurements of below-ground soil respiration. Tufekcioglu et al. (1998; 2001) found that soils under VBSs had significantly greater ($P < 0.05$) respiration rates than under adjacent arable land. Greater microbial activity suggests that the soil solution pools of P associated with microbial turnover are greater. Stutter et al. (2009) executed a laboratory experiment where unvegetated soil cores with and without sediments were incubated at 5 and 20°C to enhance microbial activity and leached weekly. Soil cores with sediments added and incubated at 20°C produced the highest concentrations of DRP, suggesting increased solubilization of P from the sediments or increased turnover of MBP. However, rather than enhancing microbial activity, Syversen and Haarstad (2005) inhibited microbial activity in one set of soil columns while leaving the other set unaltered. These columns were leached daily for 2 wk with a P-enriched solution. The columns with inhibited microbial activity increased the amount of DP leached. This is contrary to the results of other studies exploring the role of microbial activity on soil solution P concentrations (Seeling and Zasoski, 1993; Lee et al., 1990).

Plant litter containing organic P that is not immediately soluble requires decomposition and mineralization before being remobilized or assimilated by plants and microorganisms. When inorganic labile and solution P falls below a certain point, microorganisms release extracellular enzymes that mineralize P from organic compounds (Sharpley, 1985), driven by the organisms' need for P (McGill and Cole, 1981). Cooper et

al. (1995) found that phosphomonoesterase enzyme activity was lower ($P < 0.05$) in VBSs (0.89 mg P h^{-1} mg^{-1} biomass C) than in adjacent agricultural land (2 mg P h^{-1} mg^{-1} biomass C) and attributed this to the increase in labile P pools. However, Stutter et al. (2009) discovered increased phosphomonoesterase enzyme activities in VBS soil (1095 μg NP g^{-1} DM h^{-1}) relative to adjacent agricultural land (673 μg NP g^{-1} DM h^{-1}) ($P < 0.05$), which suggested that, even though reactive labile and WEP concentrations were high, phosphate monoesters were being mineralized. Immediately after enzymatic mineralization, P may be immobilized (retained) in the microbial biomass or, because enzymes operate independently from the organisms' need for P, may be remobilized into the soil solution. If the atomic C/P ratio of this organic matter is below 100, P can be mineralized and remobilized into solution (White and Ayoub, 1983; Tezuka, 1990). Plants growing in VBSs that exhibit luxury uptake of P have higher P concentrations in tissues and therefore lower C/P ratios in decomposing tissues. Phosphorus in decomposing organic matter of VBS soils is therefore more likely to be remobilized into solution.

Because MBP can be greater in VBS soils relative to adjacent agricultural land, a greater amount of P could be mobilized during periods of environmental stress. On a temporal basis, the size of the microbial biomass in grassland soils is positively related to soil moisture (Chen et al., 2003). An increase in the size of the microbial biomass suggests retention of P, and a reduction in size suggests remobilization of P. Remobilization from microbial pools in VBSs increases during drier months, and retention increases during wetter months, giving seasonal variation in P retention. Shorter-term fluctuations in MBP due to drying and wetting cycles also remobilize P. Soil drying leads to microbial death, whereas rapid rewetting leads to cell lysis and the release of intracellular P (Bottner, 1985; Turner et al., 2003a). The greater the initial MBP, the greater the amount of P that is released during drying and rewetting cycles (R^2 = 0.58) (Turner and Haygarth, 2001). Because microbial biomass and MBP is greater in VBS soils relative to adjacent arable soils, more P is expected to be remobilized in VBSs as a result of drying and rewetting. Other factors, such as the rate of rewetting, influence the amount of P remobilized (Blackwell et al., 2009), as does soil freezing and thawing (Blackwell et al., 2010).

In summary, the microbial biomass has the potential to retain P in VBS. The extent of this retention varies seasonally and may increase as C increases in VBS soils through plant root turnover and leaf senescence. Phosphorus also has the potential to be remobilized from this pool. Remobilization processes identified include seasonal decline in MBP, mineralization, drying and rewetting effects, and microbial turnover of P. The magnitude of P remobilization by these mechanisms is likely to be greater than for P in adjacent agricultural soils because MBP and microbial activity have been found to be greater in VBS soils. Although microbial activity may benefit pesticide degradation and denitrification processes in VBS, the effect on P retention may be negative through increased turnover and subsequent remobilization of P. Because of disagreements between the limited numbers of studies on the role of microbial activity in VBS, more research is needed into whether microbial

activity is responsible for elevated WEP concentrations. Soil microorganisms have the potential to use native soil P and PP retained in VBS and therefore may play a role in remobilizing this P in a more soluble form and contributing to increased WEP in VBS soils.

Delivery Outputs of Phosphorus from Vegetated Buffer Strips

Due to retention and remobilization, vegetated buffer strips have the potential to alter the forms of P that are delivered to surface waters and therefore act as a delivery modifier. In all monitoring studies reviewed, VBS significantly reduced TP delivery to surface waters. This reduction is attributed to the retention of PP by physical retention processes. In the majority of cases, VBSs also reduced DP delivery, but to a lesser extent (Hoffmann et al., 2009). Therefore, the DP/TP ratio in delivery inputs to buffer strips is lower than the DP/TP ratio in delivery outputs from buffer strips. We identified several additional cases in the literature where VBSs increased DP delivery by overland flow over the medium term (Hodgkinson and Withers, 2007; Daniels and Gilliam, 1996; Nieminen et al., 2005; Newbold et al., 2010). In these cases, this ratio is likely to be even more marked. Most of the monitoring studies reviewed have been conducted at the plot scale. McKergow et al. (2003) studied stream water P concentrations in a small catchment 6 yr before and 4 yr after VBS implementation. After implementation, the ratio of DRP to TP in stream water changed from 0.5 to 0.75. In addition, the median DRP as a mean concentration during events increased by 60%, and the raw median concentration increased from 0.18 to 0.35 mg L^{-1}. In this example, P delivery has clearly been modified due to VBS implementation and completion of the retention–remobilization loop with a subsequent impact on the forms of P in surface water. Because of a lack of information of organic P retention in VBSs, it is not clear how VBSs modify the delivery of organic DUP forms.

Discussion

Retention of DP from overland flow by VBSs is generally lower than retention of PP. There are also numerous examples in the literature where the implementation of VBSs has led to increased DRP delivery. Even when the physical properties of the VBSs are altered to increase physical retention, VBSs can increase DRP delivery, and therefore other factors must influence its retention. Geochemical remobilization of DP retained in VBSs by soil saturation and Fe(III) reduction has the potential to reduce apparent VBS effectiveness. However, to increase P delivery, P other than retained DP must be remobilized within the VBSs. Remobilization of P from particulates retained in the VBSs or native soil P (accumulated in the soil through fertilizer addition before VBS establishment) could be responsible for the reported increases in DP delivery. The latter may also be highly relevant because some studies have found an increase in DP leaching after conversion of arable land to grassland (Meissner et al., 1998; Ylaranta et al., 1996).

In the studies by Stutter et al. (2009) and Zaimes et al. (2008), MBP and soil TP concentrations were around 0.1 and 0.5 mg kg^{-1}, respectively, in VBS soils. If we assume a soil bulk density of 1 g cm^{-3}, then for a 5-cm soil layer these pools are 5 and 25 g m^{-2} for MBP and TP, respectively. Kelly et al. (2007) found that plant TP in smooth bromegrass was around 4 g m^{-2}. Because microbial P is also extracted and measured as part of total P, MBP and plant TP together could constitute up to an equivalent of 45% of the soil TP. This highlights the importance of biological pools in retention and remobilization, especially when a considerable amount of total soil P may be refractory or immobile. Biological processes have the potential to assimilate P from particulates that have been retained by physical processes and native soil P that was otherwise refractory or immobile. Remobilization of this P by microbial turnover, decline in microbial biomass, drying and rewetting cycles, and leaf senescence have the potential to increase soil P solubility, resulting in increases in surface soil WEP concentrations in VBSs. These observations are made on a limited amount of evidence, and more research is required into the role of different mobilization mechanisms in enhancing solution P concentrations.

Vegetated buffer strips that possess a surface soil layer enriched in soil solution P pose an increased risk of DP leaching and are likely to be responsible for reported increases in DP delivery to surface waters via overland flow. How this remobilized P is delivered to surface waters depends on the hydrological conditions of the VBSs. During saturation excess overland flow or return flows within the VBSs, when little infiltration exists, considerable amounts of remobilized P could be delivered by overland flow. During infiltration excess overland flow upslope of the VBS, infiltration within the VBS may be great, with remobilized P percolating vertically down the soil profile. Infiltrated DP is more likely to be sorbed to soil surfaces in subsoil with increased sorption (manifested in lower EPC$_0$). Here, there is potential for remobilization by Fe(III) reduction, with subsequent delivery via interflows or shallow groundwater. It is possible that studies measuring only P retention from overland flow could have overlooked this delivery pathway.

The majority of studies on the retention of P in VBSs from overland flow only measured TP. As a result, there is a lack of information on the retention of DRP and, even more so, on the retention of DUP. This is important because phosphatase enzymes can be transported with dissolved organic P in overland and subsurface flow with the potential to liberate the associated phosphate anions (Toor et al., 2003). Recent studies have shown that aquatic algae also possess these enzymes (Cotner and Wetzel, 1992). Most VBS studies have been short- to medium term and have been compiled into reviews that may not give a true picture of the long-term P retention in VBSs. A combination of a lack of long-term studies and information on the retention of different P forms confound attempts to identify seasonal patterns caused by retention and subsequent remobilization.

Vegetated buffer strips represent a unique situation where P is transferred from an agricultural system of relatively low biological activity to a VBS system of high biological activity. Mobilization processes differ between these systems with mobilization in agricultural land dominated by physical processes such as particle entrainment in overland flow and remobilization in VBSs dominated by biological and geochemical solubility processes. The difference in mobilization mechanisms between the systems and the physical retention of PP

and subsequent remobilization in VBS can, in certain situations, result in a reduction in PP and an increased DP delivery outputs from buffer strips. Therefore, rather than being the final sink for P mobilized from field slopes, VBSs become a modifying loop in the P transfer continuum, altering the extent, timing, and chemical form of the P that is eventually delivered. Given the multiple benefits that VBSs provide, this review is not intended as a case against VBS implementation but as a case for VBS management.

To improve our understanding of VBS functioning in terms of DP retention, research should be performed in the following areas: (i) identification of plant traits that enhance physical and biological retention of DP, (ii) long-term retention of P forms in buffer strips from surface and subsurface delivery pathways, (iii) identification of key P remobilization mechanisms within VBSs, and (iv) catchment scale affects of VBSs on P forms in surface waters. A greater understanding in these areas will allow the development of management techniques that enhance DP retention and water quality protection by tightening the "retention-remobilization loop."

A number of management techniques have been suggested, including soil liming, Al sulfate and Fe chloride addition, tillage, and vegetation removal (Aye et al., 2006). Removal of above-ground vegetation shows particular promise, having been used to reduce soil P solubility in former agricultural land with high P status (Chardon, 2008). Also, in the study by Uusi-Kämppä (2005), the unmanaged VBSs increased DP delivery, whereas the managed VBSs (vegetation removal) reduced DP delivery relative to control plots with no VBS. Removal of above-ground vegetation has the potential to reduce soil solution concentrations in VBS soils by increasing plant uptake, reducing remobilization through senescence, removing P from the VBSs, and reducing a C priming effect on the microbial biomass and its activity. Reducing soil solution P concentrations will also be beneficial in terms of biodiversity by allowing a greater diversity of plant species.

Acknowledgments

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