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Environ. Sci. Technol., **2009**, 43 (6), 1858-1863• DOI: 10.1021/es8030193 • Publication Date (Web): 18 February 2009

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Vegetated Buffer Strips Can Lead to Increased Release of Phosphorus to Waters: A Biogeochemical Assessment of the Mechanisms

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Received October 28, 2008. Revised manuscript received January 19, 2009. Accepted January 26, 2009.

Establishing vegetated buffer strips (VBS) between cropland and watercourses is currently promoted as a principal control of diffuse pollution transport. However, we lack the mechanistic understanding to evaluate P retention in VBS and predict risks of P transport to aquatic ecosystems. We observed that VBS establishment led to enhanced rates of soil P cycling, increasing soil P solubility and the potential amount leached to watercourses. Soil in VBS, relative to adjacent fields, had increased inorganic P solubility indices, dissolved organic P, phosphatase enzyme activity, microbial diversity, and biomass P. Small relative increases in the pool of soil P rendered labile had disproportionate effects on the P available for leaching. We propose a mechanism whereby the establishment of VBS on previous agricultural land causes a diversifying plant-microbial system which can access previous immobilized soil P from past fertilization or trapped sediment P. Laboratory experiments suggested that sediment-P inputs to VBS were insufficient alone to increase P solubility without biological cycling. Results show that VBS management may require strategies, for example, harvesting vegetation, to offset biochemical processes that can increase the susceptibility of VBS soil P to move to adjoining streams.

Introduction

Intensive agriculture and fertilizer usage often result in increased diffuse pollutant loads of sediments and phosphorus to streams that threaten aquatic ecosystems (1, 2). Reducing losses of phosphorus and sediments from agricultural land to waters is crucial to restoring and maintaining good ecological status in streams worldwide (3). Mitigating measures tackling pollution sources and transport need to be evaluated in terms of efficacy and risks. Vegetated buffer strips (VBS), interposed between streams and crop or pasture land, are increasingly used to minimize the transport of diffuse pollutants. VBS provide multiple benefits: physical separation of agrochemical applications from the stream, attenuation of sediment and nutrient transport to streams through particle trapping and sorption, stabilization of banks, and increases in biodiversity. Narrow VBS (5-15 m widths) fit cost-effectively into agricultural landscapes and are positively legislated for in the U. K. (4), Europe, and U. S. A. (5). Despite these benefits, existing literature studies mostly

concern larger buffers (10 to >30 m widths) less favorable to land managers (6, 7). However, narrower VBS may be less efficient at P retention. In one study in the U. S. A., 89% and 31% of total P was retained in VBS of 15 and 2 m widths, respectively (ϑ). Furthermore, retention efficiency was poorer for dissolved than for particulate P.

Buffers act to reduce the output concentrations and fluxes of sediment and nutrients relative to inputs from field slope runoff (9). Infiltration is enhanced by increasing root density to encourage particle trapping and sorption of percolating soluble P (8, 10). However, the consequences of direct attenuation of sediment and P transport to streams may be an increasing P buildup, leading to future P sources near streams. Unlike the situation for N, where pathways for a loss of gaseous N forms exist, there are fewer options to remove P stored in buffers except by active vegetation management such as phytoremediation (11), cropping, and removal (12). VBS share functions as landscape P sinks with stream wetlands (13). Recent concerns regarding the management of wetland vegetation to promote internal cycling that sequesters P and provides removal pathways (14, 15) may also be pertinent to VBS.

Accumulated riparian P may enter streams via bank erosion (accounting for 50% of the total P load to surface waters in Denmark) (*3*). This has implications for channel restoration promoting naturally eroding meanders since the erosion of P-enriched VBS soils would increase particulate P loads to the streams. P leaching following biogeochemical cycling in the VBS provides another pathway. P may be leached following geochemically or biologically mediated transformation of the P bound to soil into labile inorganic and organic P forms, both of which are implicated in stream eutrophication (*16*). Retained P, especially organic forms previously considered as refractory, may be rendered labile by biological processing (*16*). A small increase in the size of the labile P pool relative to total soil P may be sufficient to induce substantial increases in P leaching.

In this study, we are concerned with losses of bioavailable soluble P from narrow VBS used increasingly frequently across agricultural landscapes in Europe, U.S.A., Canada, Australia, and New Zealand. We expect that VBS establishment on previously cultivated land will induce a change in biological communities affecting P utilization and losses from the soil-plant-microbial system to adjacent watercourses. Following an initial field survey of VBS and adjacent field soils, we employed novel laboratory simulations and characterization to assess two mechanisms to explain increases in P solubility: (i) that P accumulation in the VBS during particle trapping or sorption of runoff P leads to a theoretical maximum retention of P that once exceeded results in P leaching or (ii) that an increased diversity of the VBS microbial and vegetation communities compared to the previously cultivated soil state enhances access and turnover of soil P.

These mechanisms have important messages for VBS management. Mechanism (i) implies a "predictable lifespan" of VBS before they become P-saturated and lose P-buffering efficiency. It is known that P retention capacities in VBS decline over time (7). However, mechanistic studies focus on nutrient and sediment budgets (6, 8, 17) and rarely on the processes of soil P accumulation. Mechanism (ii) suggests that, although enhanced P turnover may cause P leaching to streams, an improved understanding of the interactions of VBS conditions and P cycling could provide opportunities for better management of P retention or removal.

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Experimental Section

VBS were established between 2000 and 2005 in line with current best practice guidelines (*18*) within the Tarland catchment (NE Scotland 57°10′ N, 2°50′ W), an agricultural tributary of the River Dee. Fenced buffers (3–6 m widths) between agricultural land (both rotational barley and pasture) and streams were left for natural vegetation to establish without cutting or biomass removal. VBS established in 2000/2001 were dominated by herbaceous vegetation (*Holcus lanatus, Phleum pratense, Filipendula ulnana, Vricia cracca,* and *Festuca rubra*), those from 2005 had *Dactylis glomerata* and *Agrostis canina*.

Field Soil Characterization. In spring 2008, VBS and field soils were sampled across nine transects that extended from one field, across the VBS and stream, to the opposite field (Figure S1, Supporting Information). Sampling points along the transect were: (i) within-field (10 m upslope of the VBS fence), (ii) VBS outer edge (20 cm upslope of VBS fence), (iii) VBS inner edge (20 cm downslope of VBS fence), and (iv) stream-side (1 m from the stream channel). Single samples were collected at each position, giving a total of 17 samples for each transect position. Transects were made at stream sites 10-2000 m apart on two streams, encompassing samples from VBS established during 2000, 2001, and 2005 bordered by either winter barley (n = 7), spring barley rotation (not currently ploughed; n = 7), and permanent pasture (n = 3; detailed in the Supporting Information). Soils were sampled in 6-cm-diameter metal cores at 0-6 cm depths due to the importance of the surface soil for runoff water quality and biological cycling.

Separate surface soil cores for microbiological characterization were sampled at two sites with VBS established in 2000 and 2005 (Figure S1, Supporting Information). Triplicate samples (10 m spacing) were taken from two transect positions only: within-field (winter barley crop) and VBS midwidth.

Transect soils were air-dried (30 $^{\circ}$ C), sieved to <2 mm, and analyzed for the following soil P indices:

(1) Olsen-P

(2) P desorbed to an Fe hydroxide impregnated paper strip (a moderate-strength P sink) often termed "bioavailable P" (19)

(3) organic P (as the difference between ignited and nonignited soils extracted with $0.1 \text{ M} \text{ H}_2\text{SO}_4$) (20)

(4) P saturation of poorly crystalline Al and Fe mineral phases as molar ratio $Z = P_{ox}/0.5(Fe_{ox} + Al_{ox})$, where element_{ox} denotes the concentration determined by extraction of 0.06 g of soil with 30 mL of 0.2 M ammonium oxalate at pH 3

(5) batch isotherm equilibrium P concentrations (EPC₀) representing the strength of soil P desorption to waters (21), and the isotherm solid/solution partitioning coefficient K_d Soils for microbial characterization were kept field-moist, sieved to <2 mm, and stored at 4 °C in the dark prior to triplicate analyses for

(6) SRP (soluble molybdate-reactive P), total dissolved P (TDP), dissolved organic C (DOC), and dissolved organic P (DOP = TDP – SRP) in filtrates (<0.7 μ m) following extraction with 1 mM NaCl (1:3 equivalent dry mass/volume; 18 h at 5 °C)

(7) acid phosphomonoesterase activity (using *p*-nitrophenyl phosphate degradation at 37 °C and pH 6.5) (22)

(8) microbial biomass P (23)

(9) community-level physiological profiles (CLPP) employing 15 C sources using MicroResp (24)

Methods are further detailed in the Supporting Information.

Laboratory Experimentation. We sought to evaluate whether (a) P contents and sorption properties differed between sediments and their "parent soils", (b) sorption properties (as compared to total P contents) were conservative as soils and sediments mixed, or (c) biological, relative to geochemical, processes were important in P release from sediments to waters. Sediment was separated from an arable surface soil (0–6 cm depth) using a "minimal dispersion" technique. A total of 1 kg of field-moist soil was gently shaken (a single end-over-end revolution) in a 30 L container with 5 L of simulated rainwater (1 mM NaCl) to disaggregate the soil. Sediment was recovered by wet-sieving soil particles to <150 μ m size, and material was then air-dried (30 °C).

We determined geochemical characteristics of P release for mixtures of the arable field soil with increasing additions of sediment (0, 5, 10, 20, 30, 40, 50, and 100% sediment by dry mass). This aimed to investigate the effects on P release from the matrix that would result from the addition of trapped and incorporated sediments with VBS surface soils. The eight soil/sediment mixtures were analyzed in triplicate using batch extractions for Olsen P, Fe paper strip P, P saturation index, *Z*, and P sorption isotherms in batch extraction (methods as for transect soils).

To investigate the potential for biological processing in P mobilization, we combined soils and sediments but incubated one batch at elevated temperatures to induce biological activity. We placed 30 g dry mass of sediment, without mixing, onto the surface of two sets of triplicate intact soil cores (field-moist surface soils from a nonplanted arable field; cores 6-cm-diameter by 6-cm-depth). Another two sets of triplicate cores without sediment acted as controls. The 12 cores were moistened with artificial rain (1 mM NaCl) then incubated (for 5 weeks in the dark) at two temperatures in order to provide a contrasting degree of biological activity, giving the following four treatments (in triplicate): (i) control at 5 °C, (ii) sediment added at 5 °C, (iii) control at 20 °C, and (iv) sediment added at 20 °C. Cores were leached weekly with 35 mm of artificial rain. The leachate was filtered (<0.7 μ m) and analyzed for SRP, TDP, and DOC.

Results and Discussion

Indices of P solubility differed greatly along the transects. Compared to positions within the VBS, the soils in adjacent fields of all transects had consistently smaller values of Fe paper strip test P, EPC₀, and CaCl₂-extractable P (Figure 1, Table 1). Differences in these properties were more significant between field and VBS transect points for VBS bordering winter barley cultivation (tilled during winter) than for VBS bordering spring barley (not ploughed until spring) and were not significant for permanent pasture (Table S1, Supporting Information). Hence, VBS, especially adjacent to cropland sources of eroded particles and nutrients, showed a greater risk of solution P release than the neighboring field soils. This greater P mobility would cause an enhanced risk of P leaching given similar or greater soil-water fluxes for VBS, compared to cultivated soils. VBS depend, for erosion control, on their functioning as hydrological buffers, partly by encouraging infiltration to deposit sediments as flow energy decreases. Enhanced infiltration and P leaching have been observed at the field-buffer upslope margin (25) where, in the present study, the greatest EPC₀ values occurred. Soils exhibiting greater P mobility and enhanced infiltration may not provide the envisaged buffering and filtering capacity of VBS in terms of controlling dissolved bioavailable P losses to aquatic ecosystems.

The recent Water Framework Directive sets a 50 μ g L⁻¹ SRP threshold for good quality status of U. K. low-alkalinity rivers (*26*). An EPC₀ of 50 μ g L⁻¹ was exceeded in 8%, 27%, and 18% of our samples in VBS outer, VBS inner edge, and stream-side positions, respectively (Figure 1). Any soil or sediment EPC₀ value > SRP concentration in waters indicates the potential for P desorption with a tendency to increase



FIGURE 1. P release parameters at the different transect points across fields into buffer strips (n = 17). Sample distributions are represented by means, 25–75 percentiles (boxes), 10–90 percentiles (whiskers), and outliers (points).

water SRP concentrations. U.K. water quality targets are contentious and high according to ongoing research in the U. S. A. (27). EPC₀ values (Figure 1) may be more usefully compared to seasonal average SRP concentrations of 4-16 μ g L⁻¹ in a stream in the current study catchment (28). VBS soils trap sediment and nutrients from upslope as well as themselves being protected from erosion. However, VBS functioning may be best considered in terms of reductions in intensity, frequency, and variability of bioavailable nutrient outputs relative to inputs (9). Hence, we need improved knowledge of coupled P biogeochemistry and hydrology across riparian gradients to understand if internal cycling processes compromise buffer function in terms of P mobilization during critical periods of stream ecological sensitivity. The inferences of this study should be substantiated using P mass balances across VBS, incorporating processes of conversion between P forms and interactions with subsoils during transport to the stream.

Our subsequent investigations focused on evaluating two potential mechanisms, namely, (i) an increase in geochemical P solubility following exceedance of a "threshold" P saturation and (ii) the enhanced microbial access to stores of existing and incoming P. Studies have reported either increases (29) or no significant differences (30) in Olsen-P for VBS relative to control plots. We found no significant differences in soil Olsen-P or organic P between transect points (Table 1) and hence no suggestion of overall soil P accumulation in the VBS that would substantiate mechanism (i). Instead, the increases that we observed in EPC₀, CaCl₂-P, and Fe paper-P, indicated that changes to a relatively small pool of soil P are critical in determining drainage water quality. If the Olsen-P test is insensitive to changes in certain minor fractions of soil P which strongly influence P solubility, then this has implications for the common use of Olsen-P as an indicator of runoff water quality.

Increased P leaching is often predicted as soil P contents exceed certain thresholds (*31*). Dorioz et al. (*7*) in their comprehensive review of P cycling in VBS acknowledged that "the accumulation of particulate-P could, in theory, lead to the saturation of the P fixation capacity of the thin surface layer of the soil where the runoff occurs and increase the risk of release of dissolved-P". This mechanism implies a predictable effective lifetime of P loading to VBS soils before buffer function is impaired. We sought to address this geochemical mechanism in a laboratory system simulating additions of P-enriched fine sediments (47 mg kg⁻¹ Olsen-P, pH 5.7, 92 g kg⁻¹ organic matter content) to a soil (36 mg kg⁻¹ Olsen-P, pH 5.3, 71 g kg⁻¹ organic matter content). Although Olsen-P increased as the sediments were mixed in increasing quantities with the soil, there was a decrease in the overall affinity of the sediment/soil mixture to release P (as indicated by the EPC₀; Figure 2). This confirmed a previous observation that P release properties are not conservative when eroded fractions and soils mix (32). An explanation for this may be that sediments are at least as enriched in reactive surfaces compared to soils as they are in P. Hence, any addition of sediment to a soil would tend to maintain, or increase, the net P sorption capacity of the resulting mixture. This was evidenced by increases in the solid-solution partition coefficient (K_d) as the sediment component increased (Figure 2), even though differences in P saturation (Z ratio) were small between the bulk soil and sediment (0.27 and 0.33, respectively). This experimental system suggested that P entering the VBS with sediments was strongly sorbed and unlikely to be leached without further biogeochemical processing.

A second experiment tested the interaction between geochemical and biological controls on P solubility in sediment-amended soils manipulating temperature to control soil microbial activity. Unvegetated, intact soil cores with sediments added to the surface (or no additions as controls) were incubated at either 5 or 20 °C and leached weekly. Sediment addition at 20 °C led to significantly greater concentrations of SRP than sediment addition at 5 °C, or controls at either temperature (Figure 3). Temperature, addition of sediment, and temperature \times sediment were significant factors controlling SRP concentrations at p < 0.001, p < 0.05, and p < 0.05, respectively (repeated measures ANOVA). Time was not significant (p = 0.2), although the elevated leaching of SRP was sustained and generally increased over sequential leaching cycles (35 mm of rainfall weekly). The total SRP mass leached that was attributed to the addition of fines (SRP load from cores with sediment minus controls) equaled 0% (at 5 °C) and 3% (at 20 °C) of the Olsen-P added to the core by addition of the sediment. Therefore, a small increase in proportion of soil P rendered labile can have large implications for drainage water quality. Outputs of DOP and DOC both followed the treatment order: 5 °C control < 20 °C control < 5° + sediment < 20 °C + sediment. Hence, for organic nutrient leaching, the addition of sediment was more significant (p < 0.001) than the temperature effect (p < 0.01), or the sediment addition \times elevated temperature interaction (p < 0.05 for DOP and p =0.3 for DOC). These microcosms suggested that elevated temperature alone (ie. enhanced microbial activity) stimulated the release of "native" organic P and C from the soil, while increased SRP leaching required sediment-bound P and elevated temperatures. This temperature effect is likely to be dominated by biological, rather than chemical, kinetic processes.

We propose, for particulate P, that biological cycling is necessary to overcome the strong affinity of P for sediment surfaces. Biologically mediated P release may contribute to reported net losses of dissolved P in in situ studies of narrow VBS, even though sediment and total P fluxes were reduced across the buffers (*33*). However, our experimental system excluded any effects due to vegetation P cycling, known to

TABLE 1. Means and Standard Errors of Soil Properties at Transect Points with Overall Significance of Differences between Transect Points and Different Transects^a

	transect points ($n = 17$ each group)				ANOVA		
	within field	VBS outer edge	VBS inner edge	stream side	transect point	transect location	
Olsen P mg kg ⁻¹	$\textbf{27.9} \pm \textbf{4.1}$	$\textbf{28.8} \pm \textbf{2.7}$	$\textbf{27.5} \pm \textbf{4.1}$	$\textbf{25.5} \pm \textbf{3.2}$	ns	ns	
Fe paper strip P mg kg ⁻¹	$17.0\pm2.4^{\text{a}}$	$23.4\pm2.7^{ m ab}$	$34.3\pm5.1^{ ext{b}}$	$31.9\pm5.3^{ m b}$	p < 0.001	ns	
soil organic P mg kg ⁻¹	577 ± 55	701 ± 41	656 ± 51	619 ± 62	ns	ns	
SRP0.01 M CaCl2 μ g L ⁻¹	$7.1\pm0.7^{\text{a}}$	$21.4\pm4.9^{ m ab}$	$22.5\pm4.4^{ ext{b}}$	$25.2\pm4.9^{ ext{b}}$	p < 0.01	p < 0.05	
$EPC_0 \mu g L^{-1}$	$14.6\pm2.2^{\text{a}}$	$\textbf{22.1} \pm \textbf{4.1}^{\text{ab}}$	$34.6\pm6.8^{ ext{b}}$	$28.7\pm4.4^{ ext{b}}$	<i>p</i> < 0.01	p < 0.05	
$K_d \mathrm{L}\mathrm{kg}^{-1}$	478 ± 22^{a}	$473\pm42^{\text{a}}$	$355\pm29^{ m b}$	$363\pm26^{ m b}$	p < 0.05	ns	
Ζ	$\textbf{0.20} \pm \textbf{0.08}$	$\textbf{0.22}\pm\textbf{0.02}$	$\textbf{0.20}\pm\textbf{0.01}$	0.21 ± 0.02			
organic matter g kg ⁻¹	$70 \pm 2.0^{\text{a}}$	$107\pm5.1^{ m b}$	$105\pm4.8^{ m b}$	$109\pm7.2^{ m b}$	p < 0.001	ns	
рН	5.11	5.20	5.18	5.14	ns	<i>p</i> < 0.01	

^{*a*} Statistics are the results of a two-way ANOVA of transect points and the different transect locations. ns denotes not significant (p > 0.05). Different letters between transect points denote groups are significantly different at the p < 0.05 level.



FIGURE 2. Relationships between P isotherm properties (EPC₀ (\blacksquare) and K_d (\Box) including standard errors and soil Olsen P for the sediment—field soil mixtures (values next to points denote the % sediment in the mixtures).



FIGURE 3. Leachate SRP concentrations and standard errors for soil cores under the four treatment combinations (5 or 20 $^{\circ}$ C, with/without sediments) over six weeks incubation.

cause both net P uptake and retention and subsequent release after senescence (15, 29).

To further investigate differences in biogeochemical cycling of P, we characterized plant and microbial community function in VBS surface soils of different ages in relation to adjacent cropland (Table 2). Mean soil solution P and C concentrations, acid phosphatase enzyme activity, glucose SIR, and microbial biomass P were generally greater in VBS of both ages than in the adjacent croplands. Phosphatase activity, microbial biomass, and DOP and DOC concentrations were significantly greater in the 8-year VBS soil than either the adjacent cropland or the 3-year VBS soil. Solution

P was dominated by DOP in the 8-year VBS, and the microbial biomass contained a much greater biomass P in proportion to the glucose SIR (a surrogate of total microbial pool size). Relatively immature buffers may lead to enhanced leaching of SRP from VBS (even though they have similar SRP/TDP ratios to crop soils). However, the extent of DOP losses from established VBS soils suggested considerable soil organic P turnover by the microbial and plant communities. There were no significant differences in P saturation (Z values) between VBS and adjacent crop soils to indicate geochemical controls on differences in SRP release. The physicochemical implications for P solubility of the lower pH and greater organic matter contents in established buffers are unclear. A decrease in solution pH from 6 to 4 previously gave 25% and minimal reduction in adsorption onto goethite of organic (inositol hexaphosphate) and inorganic P, respectively (34). However, there may be some competitive sorption between DOC and P on soil surfaces (35).

Carbon source utilization patterns (Community Level Physiological Profiling; CLPP) discriminated between microbial communities in buffer strips of different ages and between VBS and the adjacent fields (Figure 4). Correlations between data variates and discriminant functions showed that CV1 (explaining 89% variation) was dominated by the SIR response to ketoglutaric acid (correlation 0.36), a compound linked with nitrogen transport in plants. CV2 (10% variation) was dominated by the SIR response to trehalose (-0.59), N-acetyl glucosamine, D-glucose, and D-galactose (-0.45, -0.43, and -0.41, respectively). Trehalose is a storage carbohydrate protecting fungi from stress conditions (moisture, temperature, and redox) and could indicate differences in the dominance of fungal/bacterial nutrient cycling between treatments (36). The CLPP carbon sources (see the Supporting Information) represent ecologically important compounds associated with plant root exudates (24). We interpret the differences in CLPP responses as indicating diversifying vegetation and microbial communities in VBS relative to those in adjacent croplands, which affects utilization and cycling of both C and P compounds as buffers become established. It was recently observed in the U.S.A. (37) that VBS soils had greater microbial numbers, diversity, and endogenous enzymes applicable to pesticide degradation than adjacent cropland under corn. These authors attributed this to the increasing presence of perennial vegetation, rhizodeposition of labile organic substrates, and accumulating litter layer as the VBS established.

C sources ketoglutaric acid and glucosaminic acid had high explanatory power in the present study. These compounds provided previous indications of altered fungal functional diversity across disturbance gradients in forested TABLE 2. Means (n = 3) and Standard Errors for Surface Soil Properties Sampled for Microbiological Characterization of VBS Soils and Their Adjacent Cropland Fields at Two Sites (Vegetated Buffer Zones of Either Eight or Three Years since Establishment)^a

soil solution nutrient concentratio	soil	oil solution	nutrient	concentrations	
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	soil pH _{CaCi2}	P saturation index, Z	OM, ^b g kg ⁻¹	SRP, μ g L ⁻¹	DOP, µg L ⁻¹	DOC, mg L ⁻¹	SRP/TDP	phosphatase activity, µg NP g ⁻¹ dm h ⁻¹	glucose SIR, ^c µgC g ⁻¹ hour ⁻¹	microbial biomass P, µg g ⁻¹	biomass P/ glucose SIR
ouffer (8 vears)	4.1	$0.19\pm0.01^{\text{\#}}$	164	202 ± 68	$1810\pm370^{*\#}$	$86\pm17^{*\text{\#}}$	0.10	$1095\pm33^{*\text{\#}}$	$\textbf{6.8} \pm \textbf{0.3}$	$108\pm10^{*\text{\#}}$	16
field	5.6	$\textbf{0.20} \pm \textbf{0.00}$	89	82 ± 30	215 ± 104	15 ± 6	0.28	673 ± 22	$\textbf{4.9} \pm \textbf{0.9}$	33 ± 10	7
ouffer (3 vears)	5.0	$\textbf{0.29} \pm \textbf{0.01}$	79	$\textbf{309} \pm \textbf{41}$	496 ± 62	12 ± 2	0.38	546 ± 19	$\textbf{8.0}\pm\textbf{0.7}$	43 ± 10	5
field	5.3	$\textbf{0.28} \pm \textbf{0.01}$	71	$\textbf{223} \pm \textbf{24}$	402 ± 71	11 ± 1	0.36	499 ± 31	$\textbf{4.9} \pm \textbf{0.9}$	32 ± 4	7
a t-toete	wore	used to dete	rmino	differences	botwoon the	buffer an	d adiaca	nt field soil	* indicatos r	< 0.05 a	nd hetween

^{*a*} t-tests were used to determine differences between the buffer and adjacent field soil (* indicates $p \le 0.05$) and between buffer soils of different ages (# indicates $p \le 0.05$). ^{*b*} Organic matter content. ^{*c*} Glucose substrate-induced respiration.



FIGURE 4. Plot of ordination of first and second CVs for MicroResp CLPP with 15 C sources generated by sole-carbon-source tests for surface soils taken from buffer strips of either eight-years (\blacksquare) or 3-years (\blacktriangle) establishment and from their adjacent arable fields (respectively, \Box and \triangle).

ecosystems (38), which were linked with fungal utilization of M-inositol (a form of the most abundant group of soil organic P complexes, but not a C source included in the present study). Inositol phosphates are abundant organic P compounds that until recently were considered refractory (39), although fungi may be key to their initial turnover. There is evidence that immobilized fertilizer P ultimately accumulates as inositol P that resists degradation under cropland due to strong adsorption to soil surfaces (39). The suggestion that increased microbial diversity in VBS unlocks potentially large stores of residual soil organic P offers fundamental support to our mechanism that biological turnover of soil P promotes a P pool liable to leaching to streams. Our observations using CLPP support the use of further genomics approaches to determine changes in community structure to inform better management aiming to minimize losses or promote P recovery and recycling from VBS.

Our results indicate how biological, in addition to geochemical processes, "unlock" sediment-bound P entering VBS, or existing P from a past legacy of fertilization and promote soil P forms which are readily leached. This questions the efficacy of promoting unmanaged VBS on previous cropland of high soil P status, or adjacent to cropland supplying excessive amounts of P-enriched sediments. It is important that VBS are managed as part of a whole "treatment train" system in unison with other "in-field" or nutrient-budgeting strategies (17), which act to limit the supply of P into the buffer. An improved knowledge of the relationships between soil conditions and the ability of the plant-microbial systems to access P pools in developing VBS would allow us to better manage buffer vegetation, both to minimize P leaching stimulated by senescing vegetation and litter (15, 29) and to actively encourage P uptake by phytoremediation (11, 14). Vegetation management may present an opportunity to "recycle" P from VBS back to fields, which would be beneficial to organic agriculture and counter rising concerns about available mineral P fertilizer reserves (40). The ability of changing biological communities to render a small, but critical, pool of soil P labile brings a likelihood of periods of leaching to the adjacent watercourses. Accordingly, VBS apparently have limited long-term potential to sequester P without active management to remove it. Current literature provides evidence that buffer presence is a major tool in interrupting sediment transport to streams. However, buffer function would be compromised if internal cycling resulted in P outputs of relatively greater bioavailability than direct particulate P transported in the absence of the VBS. Our message is therefore that manipulating soil and vegetation conditions may enhance VBS function with respect to P.

Acknowledgments

We thank L. Clark, P. Cooper, C. Cameron, and Y. Cook for technical assistance in analyses. We also acknowledge the financial assistance of the Scottish Executive Rural Environment Research and Analysis Directorate and the MacRobert Trust for access to land and for coordinating buffer strip development in this catchment.

Supporting Information Available

A map of the layout of sampling sites and transects along the stream network (Figure S1), and further details on the sites, methods and analysis of soil transect data according to the land use adjacent to the buffers (Table S1). This material is available free of charge via the Internet at http:// pubs.acs.org.

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ES8030193