Runoff phosphorus retention in vegetated field margins on flat landscapes

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Received 14 October 2005, accepted 10 July 2006.

Sheppard, S. C., Sheppard, M. I., Long, J., Sanipelli, B. and Tait, J. 2006. **Runoff phosphorus retention in vegetated field margins on flat landscapes**. Can. J. Soil Sci. **86**: 871–884. Vegetated buffer strips (VBS) are often recommended as a management practice that farmers can use to help mitigate the environmental effects of runoff from agricultural fields. Previous research has shown that VBS can be effective at trapping phosphorus (P) and other farm-sourced environmental contaminants. This project measured the effectiveness of established vegetated strips at decreasing P in runoff from agricultural fields in Manitoba. Paired samples of runoff, taken at the field edge and in the vegetated strip, indicated that in 11 of the 22 cases sampled (50%), P concentrations in the runoff decreased (on average 30%) as the flow passed through the vegetated strip. In 7 of the 22 case (32%) there was no difference; however, in four of the 22 cases (18%), runoff P concentrations increased, indicating the vegetated strip had become a source of runoff P. Soil samples from the VBS showed high available P concentrations at positions within the vegetated strip along the runoff flow path, and in 7 of 10 cases these concentrations were higher (33% on average) than in the field soil. Although the observations and numerical results suggest that VBS can be effective at removing P in runoff, perhaps the major limitation in this flat-land region is that runoff tends to flow through rather small portions of the VBS, and these may not have sufficient capacity to retain the runoff P in the longer term.

Key words: Vegetated filter strips, VBS, VFS, manure, soluble, particulate, ortho, riparian

Sheppard, S. C., Sheppard, M. I., Long, J., Sanipelli, B. et Tait, J. 2006. **Rétention du phosphore présent dans les eaux de ruissellement par la végétation en bordure des champs sur les terrains plats**. Can. J. Soil Sci. **86**: 871–884. On recommande souvent aux agriculteurs d'aménager des bandes enherbées afin d'atténuer les effets du ruissellement des eaux venant des cultures sur l'environnement. Des recherches antérieures ont en effet montré que de telles bandes piègent efficacement le phosphore (P) et d'autres polluants d'origine agricole. Le projet devait établir l'utilité de telles bandes de végétation pour réduire la concentration de P dans les eaux de ruissellement issues des cultures, au Manitoba. Les couples d'échantillons d'eau de ruissellement prélevés en bordure des champs et dans la bande enherbée indiquent que la concentration de P dans les eaux de ruissellement diminue (d'en moyenne 30 %) dans 11 cas sur 22 (50 % des échantillons) lorsque l'eau traverse la bande de végétation. Aucune variation n'a été notée dans sept cas (32 %) alors que dans quatre autres (18 %), les auteurs ont relevé une hausse de la concentration de P, signe que la bande enherbée devenait elle-même une source de P lors du ruissellement. Les échantillons de sol tirés des bandes enherbées révèlent une concentration élevée de P disponible aux endroits situés le long du trajet suivi par les eaux et, dans sept cas sur dix, la concentration était plus élevée (d'en moyenne 33 %) que dans le sol cultivé. Bien que ces observations et les données quantitatives laissent croire à l'efficacité des bandes enherbées pour retenir le P présent dans les eaux de ruissellement, le principal problème de cette région au relief plat est peut-être que les eaux ont tendance à ruisseler à travers de petites sections des bandes de végétation, dont la capacité de rétention pourrait s'avérer insuffisante à plus long terme.

Mots clés: Bandes enherbées, fumier, soluble, particules, ortho, riverain

Although the environmental importance of phosphorus (P) in runoff from agricultural fields is well known, there remain questions of how to mitigate this problem. Given the inevitable flow of materials from terrestrial watersheds to the sea, there is probably no permanent mitigation other than removal of P such as in harvested crops. However, short-term mitigation measures that may work for a few years or decades, such as conservation tillage and vegetated buffer strips (VBS), have been developed and are used.

Vegetated buffer strips are variously defined. The USDA-NRCS (2005) described seven types of VBS, but even these formal standards are ambiguous and not mutually exclusive. Hickey and Doran (2004) provided a definition in the Canadian context, which specified VBS as "any strip of vegetation between a river, stream or creek and an adjacent upland land use activity", and that they "may be composed of native vegetation that is intentionally left intact … as well as vegetative buffers that are re-established". They state their intent to use the terms "buffer strips", "riparian buffers" and "vegetated buffer strips" interchangeably. In some contexts, such as the USDA-NRCS standards, the land is assumed to be set aside from crop production, therefore representing a cost to the farmer because of decreased field size. In this paper, we adopt the definition of Hickey and Doran (2004), which includes downslope vegetated field margins as a form of VBS.

Abbreviations: **VBS**, vegetated buffer strip; **FIA**, flow injection analysis; **CV**, coefficient of variation

The vegetation in VBS is managed to varying degrees (Dabney et al. 2006). Control of noxious weeds is generally mandatory, and control of woody shrub vegetation by mowing is common. Removal of vegetation biomass is probably beneficial for removal of P, so that hay cropping might be encouraged, although presently uncommon in VBS. Coppice harvesting for fuel in the VBS is also an option (Florineth et al. 2003; Jørgensen et al. 2005).

The buffering mechanisms related to P (Dabney et al. 2006; Syversen 2005) include:

(1) sorption of dissolved P onto dead or living vegetative material or the fine soil particles that have accumulated in the VBS;
(2) uptake of P by growing vegetation;
(3) slowing the runoff flow rate to enhance infiltration of water and dissolved P and sedimentation of particulate P;
(4) filtration entrapment of particulate P from the runoff flow;
(5) improved soil permeability, because of root channels and earthworm activity, to enhance infiltration; and
(6) retention of snow, which may itself slow runoff and augment the filtration effects, and may indirectly enhance infiltration if the underlying soil is unfrozen or protected from rainfall impact.

In contrast, the negative aspects of VBS (Hickey and Doran 2004) include:

(1) the vegetation in the VBS becomes a source of dissolved P, which is a more problematic form than particulate P, because of leaching of P from living or senesced vegetation; and
(2) the P-retention capacity of the VBS is exceeded such that it no longer delivers an environmental benefit to offset the cost to the farmer.

In effect, the VBS delays the delivery of P from the runoff to the surface drainage, but because the runoff flow is always toward the surface drainage, transfer of P is probably inevitable. Soil and vegetation cannot retain anything (including the soil matrix) indefinitely against a uni-directional flow. Perhaps the only long-term solution is to create a counter-flow, such as removing the vegetation or soil that contains the P from the VBS (Hickey and Doran 2004).

The use of VBS is widely advocated, perhaps without sufficient evidence of value (Hickey and Doran 2004; Daniels and Gilliam 1996; Lee et al. 2000). As an example, the Province of Manitoba has recently proposed legislation that would prescribe VBS as part of a plan to mitigate problems with P runoff (or transport). Researchers often report high VBS efficacies, where their observations suggest the VBS has retained a large fraction of the P, or other contaminants, from the runoff stream. Table 1 lists a number of papers where VBS were remarkably effective. However, as noted by Dillaha et al. (1989) and Schmitt et al. (1999), these results often reflect experimental situations and much lower efficacy is expected in production situations.

Characterizing runoff P is complicated by the presence of both dissolved and particulate forms. Particulate P may be retained by the filtration capability of the VBS, where the particles themselves are entrapped in the vegetation, litter or root mat. Infiltration is considered the most effective mechanism for retention of dissolved P (Barfield et al. 1998; Lee et al. 2000). Infiltration of runoff water carrying dissolved P is enhanced by the better soil structure and more frequent vertical channels typical of perennial vegetation. From a practical perspective, a key issue is the width of VBS required, and quite often researchers have concluded that to retain dissolved P, the VBS must be relatively wide, from 10 to 90 m (Castelle et al. 1994; Lee et al. 2003).

The objective of this study was to obtain direct evidence of the efficacy of VBS on cropped land in south-east Manitoba. To achieve this we examined long-established vegetated field margins, as a common form of VBS used on farms from predominantly flat, prairie landscapes in this region.

METHODS AND MATERIALS

Research Design

Two experimental approaches were used. The first addressed the hypothesis that if a VBS is effective, this should be evident in decreased P concentrations in runoff passing through the VBS. The minimum requirement for this was a series of paired runoff samples, one from the field edge and another from a set distance (5 m) into the VBS along the flow path. At some sites depending on the width of the VBS, a third sampling position, located a further 5 m into the VBS, was possible. The samples were collected from a series of sites and runoff events (Table 2). The sampling dates were dictated by the occurrence of runoff events and the requirement that samples had to be unambiguously paired. If for a given event one of the paired samples at a site was not available (e.g., empty or physically disturbed sample bottle), then all samples from that event/site were discarded. Similarly, samples were only retained where there was evidence that in fact both samples came from the same runoff event along the same flow path.

The second approach addressed the hypothesis that if a VBS is effective, then in the long term the soil in the VBS (that intercepts runoff) should have elevated P concentrations compared with soil in the adjoining field margin soil away from the runoff flow path. Further evidence of VBS effectiveness would be provided where soil P concentrations decreased with increasing distance from the field edge into the buffer strip. Because infiltration is assumed to be a key process in determining the efficacy of VBS, additional evidence of P retention would be provided where soil P concentrations were higher at depth (in the order of 10 cm) in the runoff flow path of VBS compared with corresponding samples taken away from the flow path. The minimum requirements for these comparisons are measures of background soil P concentrations (measured where runoff did not occur in the VBS) in each of several VBS and corresponding measures of soil P along runoff flow paths in the VBS starting from the field edge and progressing as far as possible into the VBS. Important ancillary data included measures of soil P in the cropped fields adjacent to the VBS, soil texture and the ratio of plant-available to total soil P.

Table 1. A summary of published research describing the effectiveness of VBS in reducing P in runoff flow

Water source and plot details	Vegetation type	Reported slope (%)	VBS width (m)	% Reduction in P as a result of flow through the VBS[z]	Reference
Simulated overland flow	Grass and legume	2.3 and 5	2, 5, 10 and 15	32% TP[y] load for 2-m depth linearly to 79% for 15-m depth	Abu-Zreig et al. (2003)
Natural rainfall, runoff plots	Grass and mixed grass/shrub	–	12	40 to 60% TP concentration	Barden et al. (2003)
Natural rainfall	Grass or multiple species in adjacent strips	5	7 (grass) or 16 (multi-species)	78% TP load with grass and 91% TP with multi-species, 58% TDP[b] with grass and 80% TDP with multi-species	Lee et al. (2003)
Natural rainfall, manure grass as upstream source	Grass	1	16.4	0% to 95% (mean 47%) total ortho P load	Sanderson et al. (2001)
Simulated rainfall, runoff plots	Grass or multiple species in adjacent strips	5	7 (grass) or 16 (multi-species)	68% and 46% TP load in grass VBS for low and high intensity rain, 93% and 81% TP load in multi-species VBS for low and high intensity rain, 44% and 28% TDP load in grass VBS for low and high intensity rain, 85% and 35% TDP load in multi-species VBS for low and high intensity rain,	Lee et al. (2000)
Simulated rain, replanted VBS runoff plots	Grass and multi-species	6.5	7.5 and 15	55% to 79% of TP concentrations, 24% for TDP concentrations with 7.5-m width, 39% for TDP concentrations with 15-m widths	Schmitt et al. (1999)
Simulated rainfall and simulated overland flow	Grass	3	3 and 6	37% TP load with 3-m width and 52% TP with 6-width, 34% TDP load with 3-m width and 43% TDP with 6-width	Lee et al. (1999)
Natural rainfall giving runoff from a feedlot into runoff plot	Grass	1	59 and 79	24% to 82% TP load, 14% to 72 TDP load	Komor and Hansen (1998)
Simulated rainfall, 2 events, natural grass in runoff plots	Grass	9	4.6, 9.1 and 14	90% to 100% of soluble P load	Barfield et al. (1998)
Natural and simulated rainfall	Grass	–	6, 12 and 18 m	22% to 89% TDP load	Patty et al. (1997)
Simulated rainfall, runoff plots	Grass	3	3 to 18, sampled along flow path	20% TP load with 3-m width linearly to 48% TP with 12-m width, 22% TDP load with 3-m width linearly to 80% TDP with 18-m width	Srivastava et al. (1996)
Natural rainfall, natural vegetation, not plots	several, mostly grass	2.1 to 10	6 to 20	60% of TP load, 20% to –200% of TDP load	Daniels and Gilliam (1996)
Simulated rainfall, runoff plots	grass	3	3 to 24, sampled along flow path	40% TP load with 3-m width linearly to 91% TP with 21-m width, 39% TDP load with 3-m width linearly to 90% TDP with 21-m width	Chaubey et al. (1995)
Rainfall and snowmelt	grass	–	5,10 and 15	65% to 95% ortho P	Vought et al. (1995) citing various sources
–	grass	–	4.3 to 5.3	26% TP load	Parsons et al. (1991) cited by Barfield et al. (1998)
Simulated rainfall, established grass, runoff plots	grass	5 to 16	4.6 m or 9.1 m	35% to 95 % of TP load, –258 to +79% of TDP load	Dillaha et al. (1989)
simulated rainfall	grass	3 (estimated from Fig. 1)	4.6 and 9.2	27% TP load for 4.6 m, 46% TP load for 9.2 m	Magette et al. (1989)
Natural rainfall and milkhouse wastewater overland flow	grass	2	26	86% TP concentration, 89% TP load, much less retention during snowmelt	Schwer and Clausen (1989)
–	grass	10	1.5 and 4	8% TDP load at 1.5% slope and 62% TDP at 4% slope	Doyle et al. (1977) cited by Barfield et al. (1998)

[z]Note that many authors report effectiveness based on decreased total P load (product of concentration and flow), whereas others and this paper report effectiveness based on decreased P concentration. The difference between these reporting methods arises because of loss (infiltration) or gain (rainfall) of water in the VBS.

[y]TP, total phosphorus; TDP, total dissolved phosphorus.

Table 2. Descriptions of sites where runoff samples were collected

Site labels	Field characteristics	VBS characteristics
B series, 7 runoff sites, 3 of which were also VBS soil sampling sites	Clay to clay loam, 4.2 to 6.9% organic carbon; pH 5.9 to 7.3; undulating level; 31 to 35 mg kg^{-1} available P; no recent manure but solid hog manure more than 3 yr ago; cereal, field pea and flax as previous crops; tine cultivated in the fall except for peas in fall 2004 that were left unharvested.	Natural vegetation not cultivated in recent memory, sedge and grass species with some willow clumps, variable width of 20 to 50 m between field edge and fast-flowing creek, prone to flooding in spring, parts were burned in late fall. No runoff sample was possible at site B3.
S series, 2 runoff sites, both also VBS soil sampling sites	Clay loam to silty clay, 2.5 to 4.1% organic carbon, pH 7.7, undulating level upland with sloping near creek, 26 to 32 mg kg^{-1} available P, solid dairy manure in 2004, canola as previous crop, tine cultivated in the fall.	Natural vegetation not cleared or cultivated in recent memory, 5- to 15-cm width no history of burning, S1 was willow samplings with sedge understory and was prone to flooding, S2 was mature trees with leaf litter floor.
H series, 1 runoff site and also a VBS soil sampling site	Silty clay, 1.9% organic carbon, pH 7.7, 56 mg kg^{-1} available P, no history of manure, wheat as previous crop.	Mowed grass, ~8-m width, not cultivated in recent memory, no history of burning.
T series, 3 runoff sites, all also VBS soil sampling sites	Sandy loam, 2.0 to 2.5% organic carbon, pH 7.2 to 7.8, very level to undulating level, 52 to 65 mg kg^{-1} available P, history of injected hog manure but not in the study years, white and soy beans as previous crop, tine cultivated in the fall with little residue left on the surface.	Grass and sedge, not burned in the study years, variable width from 5 to 35 m. No runoff sample was possible at site T1.
W series, not used for runoff sample, was a VBS soil sampling site	Clay loam, 2.7% organic carbon, pH 7.4, 5 to 10% slope mid field and very level near runoff outlet, 71 mg kg^{-1} available P, canola	Grass with some shrubs, variable width, no apparent management, flow path exceeded 60 m

The experimental design did not necessitate that the sites for runoff sampling and VBS soil sampling be the same, but most of the sites were common to both (Table 2).

Site Selection

The site selection criteria were slightly different for the two approaches, although a number of the sites were common to both. A total of 14 sites in five general areas (Fig. 1 and Table 2) were included in the study. Key characteristics of the soils and management history information for the fields and field margins are given in Table 2. To sample runoff, the ideal site had cultivated soil high in P with a vegetated area at least 5-m wide in a downslope position. Slope lengths greater than 100 m were preferred, and there was an emphasis on relatively flat land (<2% slope) in order to represent prairie soils. A history of manure application, but no surface application in the sampling year, was desirable. In practice, because of the intent to use only farm production settings, the only perennial vegetated strips found were field margins where roadways, high water tables or risk of outright flooding defined the edge of the cultivated field. Thus, the VBS chosen for study could not be considered as set aside from the production field. None-the-less, they had other key attributes of VBS: a strip of perennial, long-established vegetation that was managed to some extent and that intercepted runoff.

At each site, it was necessary to identify the flow path. In these relatively flat landscapes, runoff was slow enough that discrete flow paths formed; rill or sheet erosion was uncommon or very isolated. The sampling positions and on-site design modifications were driven by where the flow paths crossed the VBS.

Vegetation in the selected VBS was generally grass or sedge. At the B series sites, the farmer burned the residue in parts of the VBS in the fall to minimize the woody vegetation. This affected six of the seven sites to varying degrees. One VBS (site S2) was a mature treed fencerow, and in this case the soil properties changed dramatically from the field to the VBS because of an emerging LF horizon in the VBS.

Runoff Sampling Weirs and Sample Bottles

Because the sampling sites were over 50 km apart, a sampling method was needed that could collect an appropriate sample during a rainfall event without an operator. The method described by Daniels and Gilliam (1996) and Sanderson et al. (2001) was adopted. The key attribute was a 200-mL sampling bottle made of plastic pipe with a passive shut-off value, a floating ping-pong ball, so that once the bottle was full, the ball sealed out any further runoff and sediment. In this way, the runoff to sediment ratio of the sample was preserved. It also meant that each sample represented the initial runoff during an event, which was considered desirable in terms of consistency. It was recognized that the P content of the runoff will change during an event, and the intent was to characterize that change with samples collected by hand when possible. The bottles and associated materials were acid-washed and rinsed with deionized water after construction and before each use in the field. Glass bottles used to transport water samples from the field were similarly washed and rinsed.

Galvanized steel weirs, or rectangular funnels, were constructed that were 0.5 m wide at the mouth, and 25 cm deep. The sod underneath the weir was removed so the bottom of the weir was about 15 cm below grade. The bottom of the weir extended beyond the sides and was inserted under the sod so the water flowed uninterrupted off the sod into the weir. The interior surfaces of the weir were coated with a clear polyurethane finish. The outlet from the weir was about 2 cm wide.

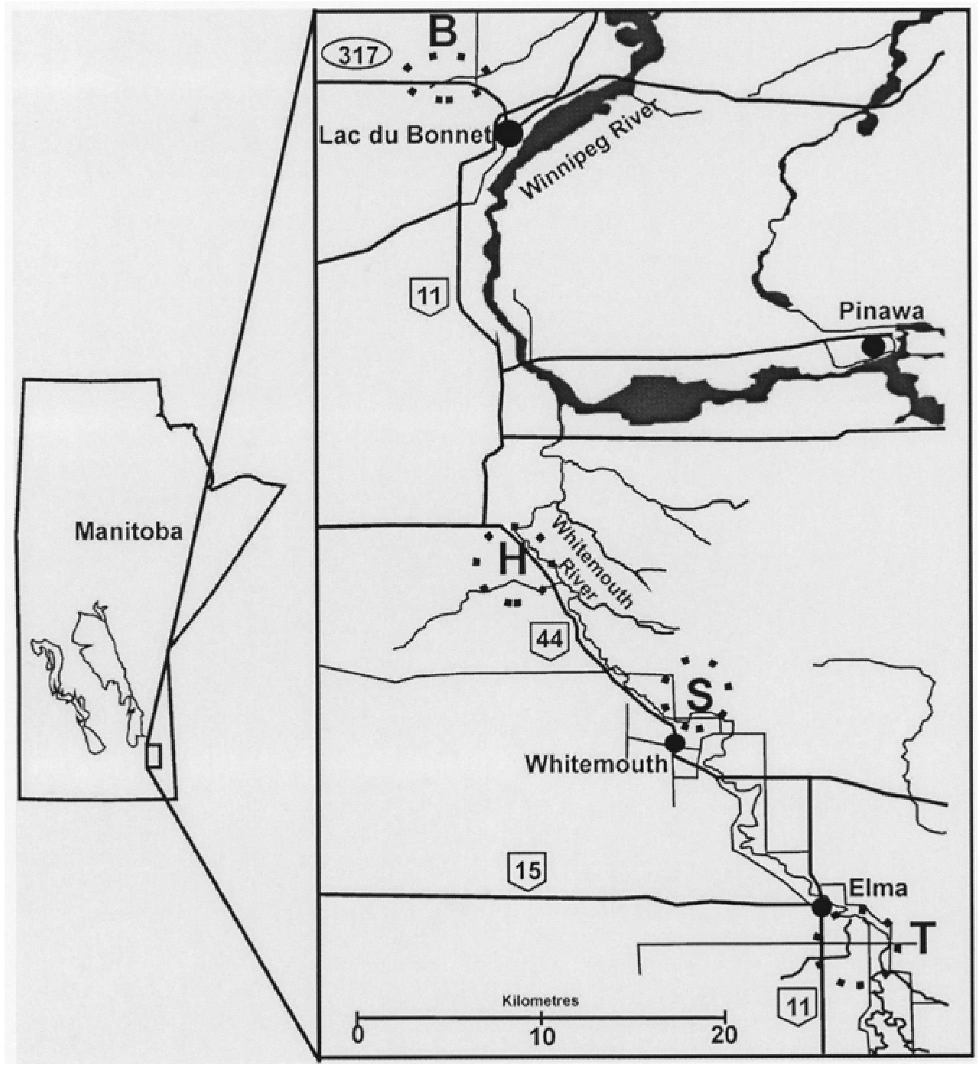


Fig. 1. Location of the B-, H-, S- and T-series runoff sampling areas in Manitoba, Canada. There were several sampling sites in each series (see Table 2).

Behind the weir, a 12-cm-diameter hole was dug to hold the sampling bottle. The hole was lined with plastic pipe. In order to gain access to the holes in the spring prior to snow melt, the holes were filled with rigid Styrofoam. In this way, although some holes filled with water which froze, the Styrofoam could be easily chipped out to allow placement of sample bottles. Styrofoam was also used to position the sample bottles under the weir outlets.

Runoff Sampling

The original experimental design was to place three weirs at the field edge, another three offset and about 5 m into the VBS, and if possible a third set another 5 m into the VBS. However, this proved impractical because in most cases the flow path was quite narrow, often less than 1 m wide. Most sample sites included two or three weirs, one at the field edge and the others downstream along the apparent runoff flow path within the VBS. Samples were only retained when the field edge and at least one other weir both held samples. Data from these were treated as paired samples (i.e., field-edge sample vs. in-VBS sample), and VBS efficacy was defined as the concentration in the field-edge sample less that in the in-VBS sample, divided by the concentration in the field-edge sample and expressed as a percent. Runoff was collected from April to June of 2004 and 2005. No runoff occurred at other times of year, as is typical of this semi-arid prairie region where most of the runoff results from snow melt. Both snow melt and spring rainfall events were sampled. Sampling snowmelt was problematic because snow, ice, mud and road closures limited access, and the apparatus sometimes froze overnight. The numbers of events successfully sampled are given with the results in Table 4.

As noted by Daniels and Gilliam (1996), it requires a substantial event for there to be sufficient runoff to sample 5 m into the VBS. As a result, many small rainfall events did not allow the opportunity to collect paired runoff samples. In fact, this observation is in itself evidence of VBS effectiveness; the runoff from small events was fully retained by the VBS.

Soil Sampling in the VBS

This sampling design was based on the observation that the runoff always followed a narrow flow path at the point where it entered the VBS. The hypothesis was that the soil or vegetation in the VBS would be elevated in P concentration at the point where the runoff flow path entered the VBS as compared with other sample (background P) positions either side of the runoff path. Similarly, if the VBS is effective, the concentration of P in the VBS soil should decrease away from the field edge, especially as these soil concentrations integrate the P removal from both low- and high-energy runoff events. Anticipated complications included that there may be unintentional overspread of P fertilizers or manure into the VBS. A preliminary sampling at one well-established VBS included vegetation (grass), litter (senesced grass blades and root crowns) and soil (0- to 5-cm deep and 5- to 10-cm deep). The concentrations of P were elevated where the runoff flow path entered the VBS compared with other comparable positions away from the runoff flow path, and this was most evident in the litter and upper soil layer. The results for the vegetation were somewhat ambiguous. Soil rather than vegetation P concentrations were considered a better indicator of P retention in the VBS because vegetation P levels are likely to be affected by many other factors, such as soil moisture availability, which can modify plant growth and hence tissue P concentrations. Preliminary measurements indicated there was P enrichment in the soil at the 5- to 10-cm depth in the runoff flow path, suggesting that infiltration in the VBS was enhanced and that it was important to sample soil both at and below the surface.

The final sampling design was as follows (and is illustrated in Fig. 2). The primary sample was at the runoff outlet (i.e., the point at which the runoff flow path enters the VBS) within 0.5 m of the field edge. On either side, 10 and 20 m along the field edge (four sampling positions), further samples were collected, also within 0.5 m of the field edge, to determine if the P concentration at the runoff outlet was indeed higher than the average (background) P concentration along the field edge. Four sampling positions were required to ensure that random overspreading of fertilizer or manure was not confounding the results. Another five samples were collected, 5 m into the VBS from each of the field-edge positions. Care was taken to ensure the sample 5 m into the VBS from the outlet position was in the runoff flow path. Where the VBS was sufficiently wide, further samples were collected along the flow path, in one case up to 60 m from the outlet. Thus, the design specified at least 10 sampling positions at each site, with some modification to accommodate less uniform sites. Although the exact layout of sampling positions was subject to site-specific modification, the generic layout is shown in Fig. 2.

At each sampling position, three core tubes 10 cm in diameter and 10 cm long were driven into the soil so the upper edge was level with grade. The three cores were positioned within 1 m of each other, and were intended to provide a composite to control local spatial variation. The cores were dug out intact, the soil cut to be level with the bottom end of the tubes, and then they were wrapped in foil and labeled.

In addition to the samples from the VBS, composite samples were collected from the cultivated field. An Oakfield core tube (2-cm diameter) or a shovel was used to sample about 10 positions in the field, in a concentric pattern approximately log-scaled with distance out from the runoff outlet. Thus, the sample was drawn from a radius of 200 m from the outlet, with most of the composite drawn within ~50 m of the outlet. The 0- to 5-cm and 5- to 10-cm depths were collected, and one composite for each depth prepared. If present, any soil crust on the cultivated field near the outlet was sampled separately by hand, making a composite from the area where there was crust. Crust was defined as surface soil that when dry in the field became physically separated from the bulk soil, often cracking and curling upward as plates.

In the laboratory, each core tube was weighed. The exact volume of soil in each core tube was measured by putting the core in a flexible plastic bag, measuring the amount of water displaced when the core was immersed, and then subtracting the volume displaced by the empty plastic core tube. The top 2 cm and the bottom 2 cm of each core were removed with a rotary tool (squared-ended router bit) or in some cases with a hand-held metal scoop. In most cases, the samples from the three replicate cores were composited, but 25 sets were kept separate to quantify the local spatial variability.

Each core sample was weighed wet, air-dried at room temperature and weighed again to determine the moisture content of the soil in the original core tube. The bulk density was computed for each soil core. The samples were retained for P analysis.

The data for the soil samples at the outlet were central to the interpretation, and data for other sampling positions at each site were considered relative to those for the outlet. There were 10 sites, and each was sufficiently different that interpretation was done for each separately, rather than averaging across sites.

Analysis of Phosphorus in Runoff and Soils

Runoff water samples were frozen within 2 h of sampling, except when it was possible to filter them immediately. Although it is not possible to quantify precisely how long the samples collected in the self-closing bottles were in the bottles, the bottles were checked about daily when runoff was anticipated. Aliquots of the water samples were filtered to pass 0.45 µm and results from these were defined as dissolved P. Thawed or freshly collected prepared samples were delivered for analysis within 24 h to preserve sample integrity. No acid was added to the samples for preservation, since this could interfere with the analysis. The filtered sample was analyzed directly to obtain the concentration of dissolved ortho P, and after a rigorous sulfuric acid persulfate digestion (Method 4500-P, APHA-AWWA-WEF 1998) to

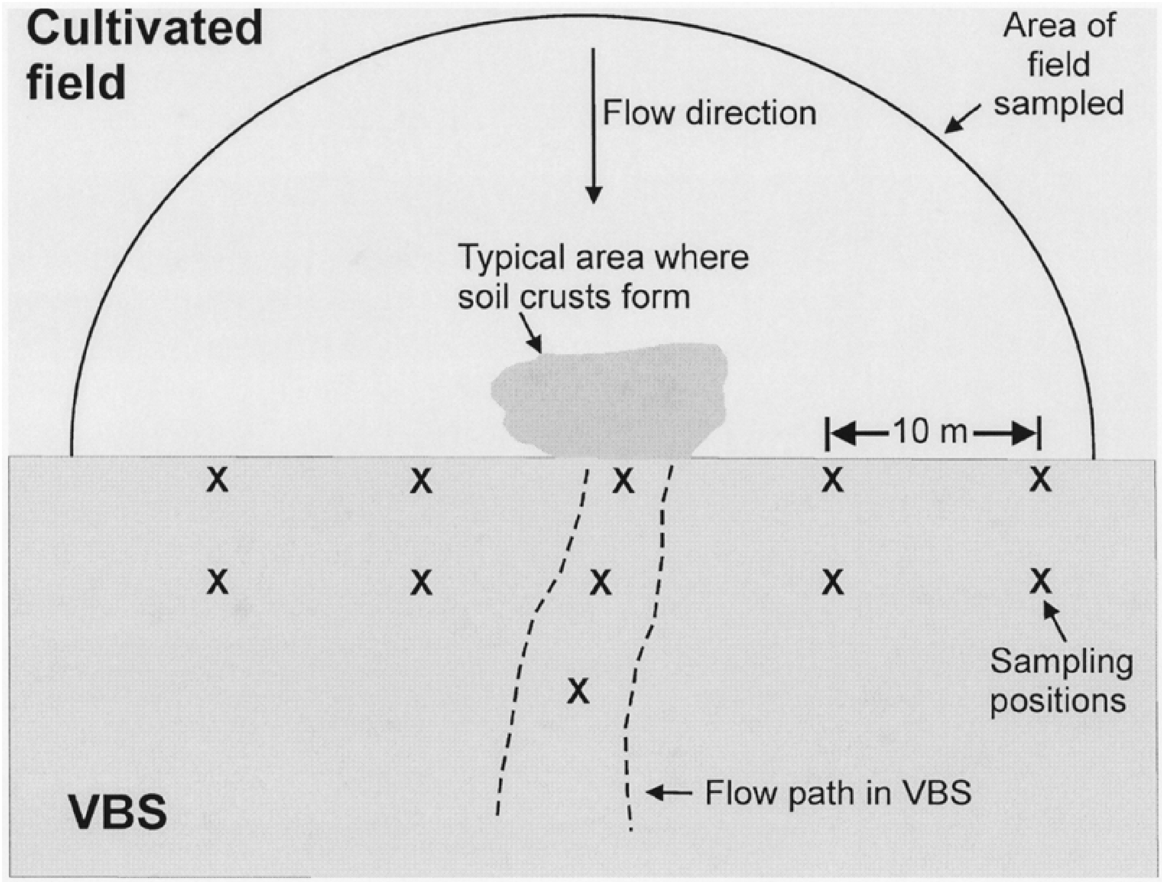


Fig. 2. Diagrammatic of soil sampling positions in the VBS. Triplicate 10-cm-diameter core samples were collected at each position, and composite samples were collected of the cropped field soil and any soil crusts that may have formed in the field (see text for details).

obtain total dissolved P. The unfiltered sample was digested and analyzed to obtain total P. The difference between total P and total dissolved P was assumed to be particulate P and the difference between total dissolved P and dissolved ortho P was considered to represent dissolved organic P. These fractions correspond with routine analyses done for surface waters.

The liquid samples were then analyzed by Flow Injection Analysis (FIA) using a Lachat QuikChem 8000 automated ion analyzer. FIA utilizes an analytical stream, unsegmented by air bubbles, into which reproducible volumes of sample are injected. Ortho P reacts with ammonium molybdate and antimony potassium tartrate under acidic conditions (Method 4500-P-H, APHA-AWWA-WEF 1998). The resulting complex is reduced with ascorbic acid to form a blue complex that absorbs light at 880 nm. The detection limit was 1 µg L^{-1}.

All soil samples were extracted with the prevailing Manitoba soil fertility test extractant (0.025 M HOAc, 0.25 M NH_4OAc, 0.015 M NH_4F at pH 4.9 as described by Qian et al. 1994) and results expressed on a per dry weight basis. The P analysis method was the same as for water samples. Selected soil samples, including those in the runoff flow path and from the cultivated field, were also analyzed for total P using a strong acid (HNO_3 and $HClO_4$) extraction (Kuo 1996), pH in a 1:2 soil:water extract (Hendershot et al. 1993), texture by hydrometer reported in three mineral particle size classes (Kalra and Maynard 1991) and total organic carbon by wet oxidation (Tiessen and Moir 1993).

RESULTS AND DISCUSSION

Field Observations

A primary observation for these flat landscapes is that rill and sheet erosion are rare or non-existent events. In a typical rainfall event, some portion of the field, perhaps in the order of 20%, is ponded before there is lateral water movement. Flow occurs across topographic micro-contours, and tends to focus toward relatively narrow outlets along the field margin. This is where the runoff samplers were located and where the detailed soil sampling was done.

The only runoff events successfully sampled were in the early spring prior to renewed plant growth. Later in the seasons, the soil was dry enough that it absorbed some or all the rainfall and there was no appreciable runoff from these flat landscapes. As a result, for the VBS to be effective, the initial P retention mechanisms could only be physical/chemical, such as filtration and infiltration, rather than as a result of plant uptake.

Snowmelt runoff was sampled by both the self-closing sample bottles and by hand. A notable feature was that because the weirs were situated in topographic lows (in order to capture flow) and had vegetation residues, the snow accumulation over the weirs was substantially more than in the cropped field, up to 1.5 m deep in April 2005. Snow accumulation must be expected in VBS, especially in the parts of the VBS where flow will concentrate. The result is that a VBS may well retain snow some time after most of the cropped field has become bare. The runoff occurs under the snow in VBS, and in fact the snow itself appears to serve as a filter and to slow flow rate, just as is expected of the vegetation in the VBS. The soil in the VBS under the snow may remain frozen or may thaw even before all the snow is gone, probably changing its role related to P runoff.

Because the outlet points for runoff were at topographic lows (even if only by centimeters in elevation) they were often prone to ponding or flooding. In fact, flooding of one or both pairs of weirs was a major cause of lost samples in this study. Flooding rendered almost all the sites useless for some portion of each snowmelt event. It is important to consider the effect of flooding on VBS efficiency; the flooding will leach P from residual vegetation, may remove some soil P and may contribute sediment to the VBS from fluvial sources.

Every site and every runoff event had unique features, so that overall averages have little value. In order to present results in a more coherent manner, the results for two sites are presented and discussed in detail, followed by a more general summary of the results for the other sites.

Effect on Runoff P Concentrations

Sites S1 and S2 are on different fields of the same farm. They had moderate P concentrations in the field, but were unique compared with the other sites for low P concentrations in the VBS, from 4 to 21 mg kg^{-1} available P. These low concentrations in the VBS probably helped to make these VBS quite effective on average (Table 3).

Site S1 on 2005 Apr. 01 and site S2 on 2005 Apr. 11 showed notable reductions in P concentrations from the edge of the fields to the second weir, 5 m into the VBS along the flow paths (Table 3). In both cases, there were marked reductions in both dissolved and particulate P. Site S1 is in riparian grass and sedge, and the snowmelt runoff on Apr. 01 passed through a mat of vegetation and snow. Site S2 has mature trees with little groundcover vegetation, but very different soil properties compared with the field because of the litter horizon. At this site in particular, infiltration into the VBS soil would be important, and may be the process underlying the results of Apr. 11.

Interestingly, there was little or no difference in P concentrations in snowmelt runoff measured at the field edge and 5-m positions in S2 on Apr. 04 or Apr. 05, suggesting that the VBS was not effective at P retention in these cases. Note that the dissolved P (and total P) in the runoff decreased two- to threefold with time at this site from Apr. 04 to Apr. 11, perhaps because this dissolved P came from crop residues on the field and these residues were becoming depleted in soluble P over this time period. Although this trend with time appears related to the lack of an effective role of the VBS in the earlier events, a negative relationship between runoff P concentration and VBS effectiveness was not consistently evident in this study. The results from these two sites (Table 3) provide an example of the variation in VBS effectiveness that may occur among runoff events even at the same site.

Over all sites and events, there were 22 cases where valid paired samples were obtained (Table 4). Of these, in 11 cases the VBS was effective in reducing P concentrations. In these 11 cases, there were lower total and dissolved P concentrations 5–10 m into the VBS compared with the field edge (with one exception), and this was more consistent than was the decrease in particulate P concentrations. Thus, the VBS did seem able to mitigate dissolved P in runoff, and this happened in 50% of the 22 cases sampled.

In contrast, there were seven cases where the VBS had no apparent effect on P concentrations (Table 4). These were not different from the 11 effective cases in any obvious way. They included both snowmelt and rainfall runoff. One site, H1, was always in this group, both for snowmelt runoff when most of all the P was dissolved and for rainfall runoff when half of the P was particulate. The H1 site was at the outlet of a long shallow, unvegetated swale, and it may be that the flow rate was relatively high for such a narrow outlet, thus allowing less time for P interactions in the VBS.

Of more concern is that in four cases, the VBS was an apparent source of P (Table 3). In these, the P concentration increased as the runoff flowed through the VBS. Bechmann et al. (2005) reported that freezing of vegetation accelerated the release of soluble P, and this may have been a factor affecting P loss in these four cases. This is always a concern with VBS; if they do retain P and no action is taken to remove the P-loaded soil and vegetation from the VBS, at some time (maybe far in the future) they have the potential to become a source of P for downstream runoff. Site B4 on 2005 Apr. 01 provided an excellent example: a grab sample of runoff in the field had 1.34 mg L^{-1} total dissolved P, at the field edge it was 1.53 mg L^{-1} and 5 m into the VBS it was 1.92 mg L^{-1}. This site was a source of P on 2004 Mar. 25 as well.

Note that for all sites, generally about 75% of the total runoff P was dissolved, mostly as ortho P, and about 25% was particulate. This breakdown was the same for the sites where the VBS was effective and for the other sites, and so the form of P in the runoff did not explain the differences in VBS effectiveness among the sites.

Overall, the results suggest that VBS were not consistently effective at lowering the concentration of P in runoff as it moved from the field edge. In particular, VBS appeared to attenuate runoff P in some events and not in others. The results showed that VBS were effective at lowering P concentrations in runoff in 50% of the cases, but appeared to be

Table 3. Runoff samples from sites S1 and S2, as an illustration of results. Site S1 on Apr. 01 and site S2 on Apr. 11 showed good VBS effectiveness with decreased P concentrations 5 m into the VBS compared to the edge of the field

Site	Date in 2005	Water source	Data source	Total P	Total dissolved P	Particulate P	Ortho P	Dissolved organic P
S1	Apr. 01	Snow	Edge (mg L^{-1})	3.01	2.92	0.09	2.76	0.16
S1	Apr. 01	Snow	5 m (mg L^{-1})	1.81	1.84	ND[z]	1.76	0.08
			Difference	1.20	1.08	0.09	1.00	0.08
			% reduction	40	37	100	36	50
S2	Apr. 04	Snow	Edge (mg L^{-1})	0.515	0.438	0.077	0.428	0.010
S2	Apr. 04	Snow	5 m (mg L^{-1})	0.517	0.466	0.051	0.449	0.017
			Difference	–0.002	–0.028	–0.026	–0.021	–0.007
			% reduction	0	–6	34	–5	–70
S2	Apr. 05	Snow	Edge (mg L^{-1})	0.302	0.238	0.064	0.237	0.001
S2	Apr. 05	Snow	5 m (mg L^{-1})	0.275	0.218	0.057	0.216	0.002
			Difference	0.027	0.020	0.007	0.021	–0.001
			% reduction	9	8	11	9	–
S2	Apr. 11	Rain	Edge (mg L^{-1})	0.256	0.14	0.116	0.095	0.045
S2	Apr 11	Rain	5 m (mg L^{-1})	0.102	0.082	0.020	0.041	0.041
			Difference	0.154	0.058	0.096	0.054	0.004
			% reduction	60	41	83	57	9

[z]ND, non-detectable, assumed to be zero for calculations of difference and % reduction.

a source of P in about 18% of the cases. Dillaha et al. (1989) also reported a number of cases where experimental VBS were a source of P to runoff. In those cases where VBS were effective at reducing total P concentrations in runoff, they were able to reduce dissolved P concentrations as well as filter particulate P from the runoff.

Concentrations of Phosphorus in VBS Soil

The cropped soils in the 10 sites sampled had a reasonably broad range of properties (Table 5). It is important to note that in many cases the soil from 5- to 10-cm depth in the cropped soil had markedly lower available P concentration than the soil from 0- to 5-cm depth. This was especially true on the soils with higher clay contents, and reflects that on these soils, tillage that thoroughly mixes the soil, such as moldboard ploughing, is not practiced. For the sites where a soil crust resulting from rainfall impact had formed, the crust had markedly elevated available P concentrations. The exception was site W1 where there was substantial gully erosion in the middle of the field, and the subsoil from that area had been transported overland to the area of the outlet sampled here. Thus, the crust at this site represented subsoil and had a lower concentration than the surface layer.

There was considerable spatial variation in available P in the VBS soils. The average coefficient of variation (CV) among the triplicate cores that were analyzed separately was 16%. These triplicate cores were taken within 1 m of each other at each of 25 sampling locations. As expected, there was greater variation (CV = 26%) among the surface soil background samples at each site. These were the samples taken 10 to 40 m apart parallel to the edge of the VBS (excluding the runoff outlet), and there were 18 sets of these.

The results from site S2 are presented in detail (Fig. 3, with statistical interpretation in Table 6). There were notably higher available P concentrations at the runoff outlet and along the flow path into the VBS, when compared with the concentrations in samples 10 and 20 m either side. This illustrates the effect of runoff flow through a relatively narrow portion of the VBS. The flow came from several hectares of adjacent cropped land, but most of the VBS along the field edge did not receive runoff. This indicates that relatively small areas of the VBS actually play a role in mitigating P runoff, an observation that was common on all sites sampled and in most fields observed during runoff events.

Two other observations from Fig. 3 are important. The available P was elevated at both 5 and 10 m from the field edge, and this VBS was only about 15 m wide. Clearly there was “breakthrough”; a much longer flow path in the VBS would be required for the downstream VBS soil P concentrations to be not elevated. Additionally, the soil at 8- to 10-cm depth was elevated in P, indicating that P did penetrate the soil, probably because infiltration of runoff water did occur.

The results of the 10 sites are summarized in Table 6 where the data were used to answer specific research questions. The first row of Table 6 is the increase in soil available P at the outlet compared with soil either side of the outlet along the field edge. For site S2, this was 132%, as also shown in Fig. 3. The increase was largest at this site because, as noted previously, the soil P concentrations in the VBS were exceptionally low. Only 2 of the 10 sites were not increased to some extent, and the overall average was a 40% increase (significantly different from 0% by t-test, $P < 0.05$). The second row of Table 6 does the same comparison for 5 m into the VBS, and the increase in soil P along the flow path is still evident, although not as distinctly and not statistically significant overall.

Rows 3 and 4 in Table 6 address the issue of enrichment. Where it was present and sampled, the soil crust in the field had higher available P concentrations than the bulk soil

Table 4. Results for paired runoff samples for all 22 cases, sorted to show the 11 cases where the VBS apparently decreased P concentrations, the seven cases where the VBS had no apparent effect, and the four cases where the VBS apparently increased the runoff P concentrations. Also shown, averaged for these three groups of cases, are the average concentrations at the field edge, the average differences in P concentration as a result of the VBS, and the corresponding average percent reductions in P concentrations. All values are mg L^{-1} except for percents (as indicated)

Site	Date	Water source	Data source	Total P	Total dissolved P	Particulate P	Ortho P	Dissolved organic P
Cases where VBS was apparently effective (n = 11)								
B2	2004 Mar. 25	Snow	Edge	1.20	1.15	0.05	1.13	0.02
			5 m	0.754	0.617	0.14	0.563	0.05
B5	2004 Mar. 25	Snow	Edge	0.854	0.684	0.17	0.646	0.04
			5 m	0.193	0.148	0.05	0.157	–0.01
B1	2005 Apr. 01	Snow	Edge	0.695	0.331	0.364	0.285	0.046
			5 m	0.407	0.167	0.240	0.109	0.058
			20 m	0.535	0.198	0.337	0.133	0.065
B5	2005 Apr. 01	Snow	Edge	0.470	0.320	0.150	0.306	0.014
			5 m	0.372	0.333	0.04	0.284	0.049
S1	2005 Apr. 01	Snow	Edge	3.01	2.92	0.09	2.76	0.160
			5 m	1.81	1.84	–0.03	1.76	0.080
T2	2005 Apr. 01	Snow	Edge	1.79	1.55	0.24	1.44	0.110
			5 m	1.52	0.996	0.52	0.855	0.141
T2	2005 Apr. 02	Snow	Edge	1.36	1.22	0.14	1.15	0.070
			5 m	0.979	0.876	0.10	0.782	0.094
S2	2005 Apr. 11	Rain	Edge	0.256	0.140	0.116	0.095	0.045
			5 m	0.102	0.082	0.020	0.041	0.041
B2	2005 Jun. 03	Rain	Edge	1.12	0.868	0.25	0.796	0.072
			10 m	0.947	0.692	0.26	0.602	0.090
			15 m	1.33	0.682	0.65	0.608	0.074
B6	2005 Jun. 03	Rain	Edge	1.73	1.43	0.30	1.41	0.020
			10 m	1.33	0.9	0.43	0.853	0.047
B7	2005 Jun. 03	Rain	Edge	2.14	1.74	0.40	1.68	0.060
			5 m	1.75	1.49	0.26	1.44	0.050
Average concentration at edge				1.3	1.1	0.21	1.1	0.06
Average difference[z]				0.34	0.35	–0.01	0.35	0.00
Average % reduction[y]				29%	34%	–2%	40%	–39%
Cases where VBS had no apparently effect (n = 7)								
B2	April 1/05	snow	Edge	1.48	1.16	0.32	1.05	0.11
			5 m	1.49	1.17	0.32	1.07	0.10
S1	April 1/05	Snow	Edge	2.26	2.21	0.05	2.17	0.04
			5 m	2.16	2.09	0.07	2.03	0.06
S2	April 4/05	Snow	Edge	0.515	0.438	0.077	0.428	0.010
			5 m	0.517	0.466	0.051	0.449	0.017
S2	April 5/05	Snow	Edge	0.302	0.238	0.064	0.237	0.001
			5 m	0.275	0.218	0.057	0.216	0.002
H1	April 5/05	Snow	Edge	0.276	0.222	0.054	0.211	0.011
			5 m	0.308	0.256	0.052	0.239	0.017
H1	June 3/05	Rain	Edge	2.19	1.21	0.98	1.04	0.17
			5 m	1.98	1.20	0.78	1.06	0.14
T3	April 1/05	Snow	Edge	1.96	1.40	0.56	1.31	0.09
			5 m	1.71	1.38	0.33	1.36	0.02
Average concentration at edge				1.3	0.98	0.30	0.92	0.06
Average difference				0.08	0.01	0.06	0.00	0.01
Average % reduction				3%	–1%	10%	–2%	–24%
Cases where VBS apparently increased runoff P concentrations (n = 4)								
B1	Mar. 25/04	Snow	Edge	1.490	0.230	1.260	0.205	0.025
			5 m	0.587	0.512	0.075	0.458	0.054
B4	Mar. 25/04	Snow	Edge	0.415	0.346	0.069	0.316	0.030
			5 m	1.790	0.851	0.939	0.823	0.028
B4	April 1/05	Snow	Edge	1.77	1.53	0.24	1.14	0.39
			5 m	2.00	1.92	0.08	1.78	0.14
T2	Mar 30/05	Snow	Edge	1.25	1.24	0.01	1.18	0.06
			5 m	1.47	1.37	0.10	1.36	0.01
Average concentration at edge			1.2	0.84	0.39	0.71	0.13	
Average difference			–0.2	–0.33	0.10	–0.40	0.07	
Average % reduction			–75%	–76%	–500%	–89%	10%	
Overall (n = 22)								
Average concentration at edge				1.30	1.03	0.27	0.95	0.07
Average difference				0.2	0.14	0.03	0.13	0.01
Average % reduction				4%	6%	–82%	6%	–27%

[z]Differences are computed as concentration at the field edge minus that at the indicated distance into the VBS.
[y]Percent reductions are computed as the difference (footnote [z]) divided by the concentration at the field edge.

Table 5. Available P, Clay content and pH in field soils at the VBS soil sampling sites

Site[x]	Depth (cm)	Available P[z] mg kg^{-1}	Available P as fraction of total P % (total P mg kg^{-1})	Clay %	pH
S2	0 to 5	26	3.9 (660)	28	7.7
	5 to 10	13	2.1 (610)	24	7.7
S1	Crust[y]	45	2.2 (720)	39	7.9
	0 to 5	32	3.2 (710)	39	7.8
	5 to 10	15	2.4 (620)	39	7.9
T1	0 to 5	52	8.0 (650)	17	7.8
	5 to 10	49	7.7 (640)	18	7.8
H1	0 to 5	51	6.6 (770)	42	7.9
	5 to 10	15	2.3 (660)	41	7.7
T3	Crust	92	13.0 (710)	33	7.5
	0 to 5	65	8.8 (740)	27	7.7
	5 to 10	34	5.0 (680)	34	7.6
B4	Crust	46	7.0 (660)	43	6.4
	0 to 5	31	4.8 (650)	46	6.3
	5 to 10	10	1.7 (590)	45	6.6
B3	Crust	52	7.3 (710)	46	5.7
	0 to 5	35	4.9 (720)	50	5.9
	5 to 10	5	1.4 (350)	48	6.3
B5	Crust	37	6.0 (620)	43	7.1
	0 to 5	34	5.6 (610)	43	7.3
	5 to 10	9	1.6 (560)	39	7.8
T2	Crust	92	10.0 (920)	38	7.4
	0 to 5	65	9.8 (660)	20	7.2
	5 to 10	missing			
W1	Crust	21	2.9 (720)	42	8.0
	0 to 5	71	8.0 (890)	38	7.4
	5 to 10	36	4.7 (770)	38	7.6
Range		5 to 92	1.4 to 10 (350 to 920)	17 to 50	5.7 to 8.0

[z]Available P based on the modified Kelowna extraction procedure (Qian et al. 1994).
[y]Surface crusts were found and could be sampled only on some sites.
[x]Sites S2, S1, H1, T3, B4, B3 and B5 were among the 11 sites where paired runoff samples were obtained.

(overall 38% higher, significant at $P < 0.05$), and very often the soil in the VBS at the field-to-VBS outlet also had higher P concentrations than the bulk soil in the field (overall 33% higher but not statistically significant). Similar enrichment results were obtained for soils in a VBS by Lee et al. (2000). This illustrates the potential for the VBS to become a source of runoff P because it retains runoff sediment that is enriched in P.

Rows 5 and 6 in Table 6 show those cases where soil P concentrations decreased along the flow path into the VBS (Y indicates a numerical difference, statistical interpretation was not possible). Thus, the VBS show some ability to retain P; if the P-retention capacity of the VBS had reached its maximum or saturation value, the concentrations would not decrease with distance. Site S2 may have reached a level of P saturation (Fig. 3). Note that, in this context, saturation is not meant to infer chemical sorption saturation, but rather an overall systems saturation that may be related to physical attributes of the soil such as decreased infiltration because of clay deposition in the runoff.

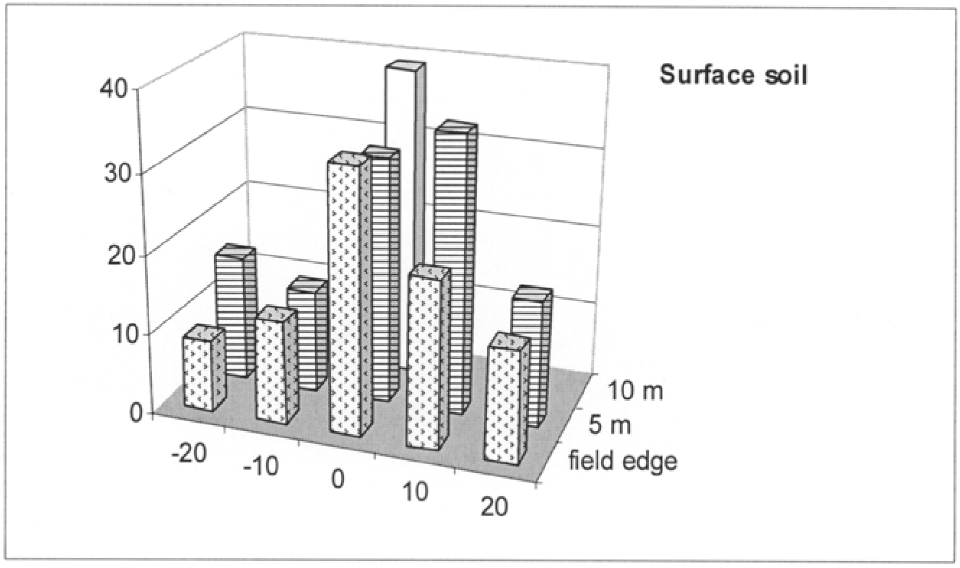
The remaining rows 7 to 9 in Table 6 show that P accumulated at the 8- to 10-cm depth at most sites where runoff entered the VBS, and that soil P concentrations at this depth tended to decrease along the flow path from the field edge into the VBS in many cases. This result is consistent with the infiltration and retention of dissolved P from runoff (Barfield et al. 1998; Lee et al. 2000).

Overall, the field observations indicated that only small areas within VBS actually intercepted runoff flow. Never-the-less, at these sites the P concentration in runoff declined as it moved along the flow path in 50% of the cases. However, in nearly one-fifth of the cases the results indicated that VBS may be a source of the P measured in runoff, although the data are not sufficient to conclude that P was actually transported beyond the VBS in these cases. The soil analysis also indicated that VBS accumulate P along the flow path at runoff positions, and often had higher concentrations of available P than the field soil because of the enrichment processes of erosion and runoff. If the soil crusts on the field edge (Table 5) are indicative of particles in the runoff, then the sediment entering the VBS along the runoff flow path is enriched in clay that contains high concentrations of P. The soils along the runoff flow paths within VBS also had elevated P concentrations (compared with adjacent background soil), and these P concentrations tended to decrease with increasing distance away from the field edge into the VBS. Finally, soil at 8- to10-cm depth in the VBS had elevated P concentrations, indicating the P had penetrated into the soil in the VBS, perhaps by infiltration of runoff water or by plant- or earthworm-mediated processes.

CONCLUSIONS

Vegetated field margins composed of grasses, sedges, willows and occasional shrubs represent a common form of vegetated buffer strips (VBS) in the flat land prairies of Manitoba. The results of this study showed that these VBS have potential to retain P from runoff. However, their effectiveness may be limited by at least two important factors. Most importantly, runoff flow on flat landscapes tends to occur along narrow flow paths, so that only very small portions of a VBS actually intercept runoff from the field edge. Vegetated swales [shallow flow channels, Code 412 VBS as defined by USDA-NRCS (2005)] that extend into the field along shallow gullies may prove more effective at retaining runoff P than a uniform-width VBS because of the increased contact between the vegetated soils in the swale and runoff.

Effective VBS will necessarily be positioned in the topographic lows around a field, because this is where runoff will occur. In many landscapes, and particularly in Manitoba, these areas are also prone to ponding of runoff water or flooding from connected surface water systems. Both positive and negative aspects with regard to P retention



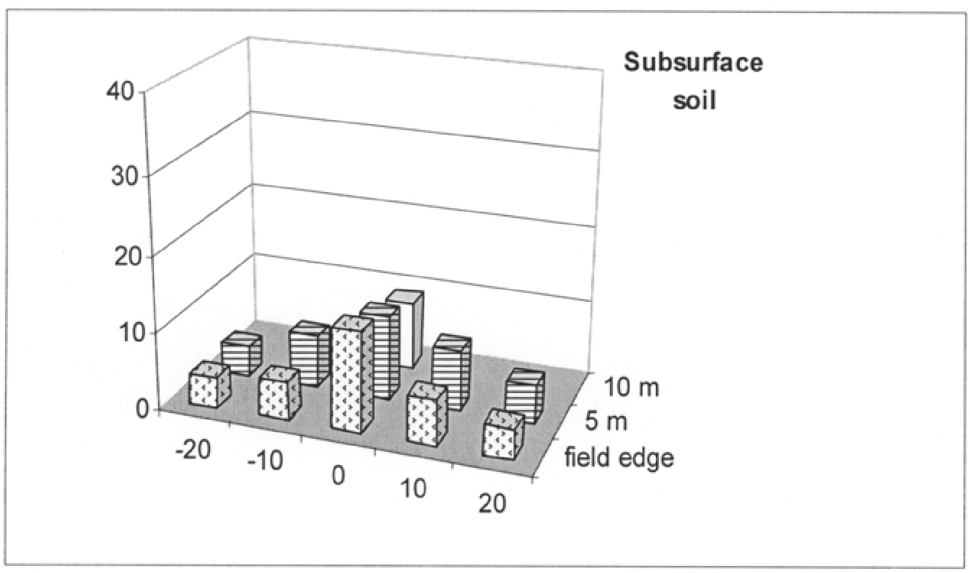


Fig. 3. Available P concentrations (vertical axis, mg kg^{-1}) in soils of the VBS at site S2. The x axis is distance from the runoff outlet (m) both directions along the field edge. The remaining axis is distance into the VBS (field edge, 5 m and 10 m). At 10 m into the VBS, only one sample was taken, in the flow path (as shown diagrammatically in Fig. 2). The surface soil is 0 to 2 cm and the subsurface is 8 to 10 cm

could be envisioned, but flooding certainly increases the prospect of loss of dissolved P from the VBS to the surface water systems.

The effectiveness of the VBS inevitably varies with time, on two scales. Within a year, the VBS probably functions to retain P both while under snow in the melt runoff, and later when there is active growth. However, the mechanisms involved and the relative effectiveness will vary with season. The mechanisms for retaining P during snowmelt may include that the VBS accumulates snow over winter and this snow slows runoff rates. On another time scale of perhaps decades, as the VBS accumulates P the VBS may eventually become a source of P for runoff unless specifically managed to avoid this problem. Removal of vegetation seems the only effective management practice to remove P from the VBS. The (limited) practice in Manitoba of burning field-edge vegetation in spring may exacerbate the problem of P in runoff, because

Table 6. Summary of relative differences in extractable P concentrations from soil samples around runoff outlets at 10 VBS sites. Results are expressed as percent increase

	Site number										
Question and specific comparison	S2	S1	T1	H1	T3	B4	B3	B5	T2	W1	Avg
Surface soils (0–2 cm)											
(1) Does P accumulate at the VBS edge? (% increase in surface soil P at the runoff outlet compared with the average of other field edge samples)	132 *[w]	44 *	37 *	52 *	42 NS	14 NS	14 NS	–4 NS	–7 NS	78[z] NS	40*
(2) Does P penetrate past the edge of the VBS? (% increase in surface soil P 5 m into the VBS in the flow path compared with outside the flow path)	120	– *	32	12 NS	– NS	2	15 NS	–7 *	24 NS	– NS	28 NS
(3) Is P enrichment evident in soil crusts? (% increase in soil crust P when compared with bulk field soil).	–	41	–	–	42	46	49	9	42	del[y]	38*
(4) Is P enrichment evident in VBS relative to field? (% increase in surface soil P at the runoff outlet [field edge] compared with bulk field soil)	29	25	42	19	–19	103	97	–21	20	del[y]	33 NS
(5) Within the runoff flow path, are surface soil P concentrations at the field edge higher than 5-m into the VBS?	N	Y	Y	Y	Y	Y	Y	N	Y	Y	
(6) Within the runoff flow path, are surface soil P concentrations 5 m into the VBS higher than at 10 m into the VBS?	N	–	N	–	–	Y	–	–	Y	N	
Subsurface soil (8–10 cm)											
(7) Does P infiltrate into the soil of the VBS? (% increase in subsurface soil P at the outlet within the flow path compared with outside the flow path)	174[x] *	87 *	2[z] NS	61 NS	38 NS	72*	–4 NS	– 11 NS	– 14 NS	110[z] NS	52*
(8) Within the runoff flow path, are subsurface soil P concentrations at the field edge higher than 5-m into the VBS?	Y	Y	Y	Y	N	Y	N	N	Y	Y	
(9) Within the runoff flow path, are subsurface soil P concentrations at 5-m into the VBS higher than at 10 m into the VBS?	Y	–	Y	–	–	N	–	–	N	N	

[z]At these three sites, 1 of the 4 of the field-edge sampling positions other than the runoff outlet had high P, if those samples were disregarded as artifacts, these three tabulated values would be substantially higher (146, 39 and 345 instead of 78, 2 and 110).
[y] Values were deleted, this site had deep gully formation and the eroded material in the field was actually low-P subsoil.
[x] The subsurface soil 5 m into the VBS also had significantly higher P in the flow path than others in the VBS.
[w]Tests of significance (* and NS) at the 5% probability level by one-tailed t test. Tests within each site compare results for samples at the runoff outlet versus those either side of the outlet. Tests of the averages across sites are based on the data shown in this table.
– indicates no sample was possible.

the plant residue ash is typically enriched in P; however, further research is needed to quantify the magnitude of this problem.

ACKNOWLEDGEMENTS

The gracious permission of the farmers to allow sampling on their land is sincerely acknowledged. Funding was provided jointly by the Manitoba Livestock Manure Management Initiative Inc. (MLMMI) and the Manitoba Rural Adaptation Council Inc. (MRAC).

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