

# Effects of Riparian Grazing on Distinct Phosphorus Sources

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## Abstract

Riparian areas play an important role in maintaining water quality in agricultural watersheds by buffering sediment, nutrients, and other pollutants. Additionally, these areas are also an important sources of forage, particularly during drought. Recent studies have shown that riparian areas are less effective buffers and, in some cases, are a net source of phosphorus (P) in cold climates. The repeated freeze-thaw cycles increase the availability of P in both the vegetation and soil sources. Cattle grazing or harvesting of riparian areas prior to the onset of winter conditions may be a viable management practice to reduce the loss of P during the spring snowmelt. This study measured the water-extractable phosphorus (WEP) in four distinctive sources: biomass, litter, organic layer, and Ah horizon. Overall, the Ah (0-10cm) soil was the largest (~44%) source of WEP; however, the biomass (i.e., standing vegetation) was a considerable proportion (~25%) of the total. In addition to control plots, the riparian areas were subjected to grazing, high density grazing, and mowing treatments. Findings revealed significant reductions in biomass WEP with high density grazing and mowing treatments, particularly in lower riparian zones. There were no detectable changes in the other sources of WEP. This suggests that autumn short-term grazing may be a mechanism to use this important forage resource and reduce the potential P loss during the snowmelt period.

## Plain Language Summary

Riparian areas are important for keeping water clean in agricultural watersheds because they help filter out sediment, nutrients, and other pollutants. Some recent studies found that in cold climates, like the Canadian Prairies, riparian areas are not as effective at filtering out nutrients. During the spring snowmelt riparian areas can be a source of phosphorus to the water instead of removing it. This happens because the freezing and thawing of the ground and vegetation releases more phosphorus. To see if we can reduce the loss of phosphorus we looked at different sources of phosphorus in riparian areas including plants, dead vegetation, and soil. The top layer of soil was the biggest source of phosphorus, followed by the plants. Two intensities of cattle grazing, along with mowing, were tested as ways of managing the riparian areas. Both cattle grazing and mowing in the fall before winter helped reduce the amount of plant-based phosphorus without increasing the amount of phosphorus in other sources. This shows that letting cows graze in the fall might be a good way to use this forage and also prevent too much phosphorus from getting into the water when the snow melts in the spring.

## Core ideas

- Biomass and litter are substantial sources of WEP in riparian areas
- Autumn cattle grazing and mowing treatments reduced the amount of WEP in riparian biomass
- No Measurable change in the amount of WEP in the litter, organic layer, or Ah horizon post grazing
- Large spatial variability in WEP exists in riparian areas

## Abbreviations

FTC, freeze-thaw cycle; MBFI, Manitoba Beef and Forage Initiatives; P, phosphorus; WEP, water extractable phosphorus

## 1 Introduction

Riparian areas are transitional areas within watersheds that are important for the health and functionality of both terrestrial and aquatic environments (Gregory et al., 1991). Riparian areas buffer the delivery of water, sediment, nutrients, and pollutants from upland areas before they enter surface water and are commonly

conserved, restored, or managed in an effort to improve downstream water quality (Dillaha et al., 1989; Borin et al., 2005; Dorioz et al., 2006). Additionally, riparian areas also provide essential habitat and corridors for range of plants and animals, particularly in highly fragmented or modified landscapes (Montgomery, 1996; Luther et al., 2008; Forio et al., 2020). Within the aquatic environment riparian vegetation stabilizes banks, regulates water temperature, provides woody debris and other organic matter, and generally supports aquatic habitat and biodiversity (Studinski et al., 2012; Dauwalter et al., 2018; Verdonschot and Verdonschot, 2024). Beyond ecosystem services, riparian zones can offer recreational opportunities (e.g., hiking, fishing, canoeing, foraging) and are key components of the agricultural landscape. Beyond improving water quality, riparian areas benefit agricultural production through providing habitat for beneficial organisms (e.g., pollination, pest control), a source of forage during drought (livestock health and productivity), and other opportunities (e.g., agroforestry, carbon sequestration) (Cole et al., 2015, 2020).

Increasing frequency and extent of algal blooms are typically linked to increased nutrient loading into lake and rivers. Of particular concern is phosphorus (P) loading as this is generally the limiting nutrient in fresh water systems (Schindler et al., 2012). There have been many lab and field studies demonstrating the role and functionality of riparian areas to reduce P loading to surface water in agricultural settings (Yu et al., 2019). Infiltration, absorption, biological uptake, microbial activity, and sedimentation are the key processes that intercept and buffer the delivery of P (Lacas et al., 2005; Owens et al., 2007; McGuire and McDonnell, 2010). Convergence within the landscape coupled with climatic/weather conditions creates variability in hydrologic conditions and pathways reducing the buffering capacity of riparian areas and ultimately resulting in reduced, inconsistent and/or unsustainable reductions in P loading relative to many controlled experimental studies (Roberts et al., 2012; Habibiandehkordi et al., 2017).

In cold climates, the the reduced infiltration due frozen ground, limited vegetation uptake, and low microbial activity coupled with a flashy hydrograph during snowmelt creates conditions that further compromise buffering capacity of riparian areas (Kieta et al., 2018; Nsenga Kumwimba et al., 2023). Additionally, research increasingly shows that riparian areas can contribute P (i.e., net source) to the surrounding environment (Roberts et al., 2012). The sources of this riparian-derived P are soil and vegetation. As soil P content increases over time, so does the risk of P loss through leaching and runoff (Habibiandehkordi et al., 2019). This process can be intensified during periods of inundation, in addition to a longer period of soil-water contact, the solubility of iron-bound P increases as redox conditions lower (Carlyle and Hill, 2001; Young and Briggs, 2008). Furthermore, mineralization of P from dead vegetation near the soil surface will also contribute to the P available to be lost during runoff (Liu et al., 2019b). Both the soil and vegetation P sources can also be affected by freeze-thaw cycles (FTC). Repeated FTCs result in the cell disruption of microbial and plant biomass, releasing inter-cellular P to the surrounding environment (Kieta and Owens, 2019). Removing or harvesting the vegetation prior to freeze-up will help draw-down the soil P content and reduce the amount of vegetation contributing P during the spring snowmelt.

Environmental conditions, particularly hydrological and temperature fluctuations, create considerable spatial and temporal variability in both P sources, transformations, and transport processes. These hot spots and hot moments in riparian processes create challenges for effective management (McClain et al., 2003; Vidon et al., 2010). From a surface water quality perspective, understanding the near-surface P distribution, both vertically and longitudinal will help in the development and identification of best management practices for reducing P loading. There are often four identifiable sources of near-surface P: 1) biomass consisting of living standing vegetation; 2) litter consisting of fresh (~1-3 yrs) residues; 3) partially to well decomposed

organic material; and 4) mineral soil (Reid et al., 2018). A better understanding of the spatial variability and relative contributions of the different sources of P is needed assess the risks and benefits of different management strategies.

Management of riparian areas to maintain or enhance the buffering capacity of P is typically needed in the long term. Unlike nitrogen (N) where there can be significant loss of N to the atmosphere through the processes of nitrification and denitrification to offset the continued input (Lyu et al., 2021), P is only generally lost through runoff or leaching. Harvesting and removal of biomass from the riparian area can be a practice to remove P and use the biomass for forage. However, mechanized harvesting of biomass may be impractical or unsafe due to steep gradients, wet soil, and other obstacles such as trees. Livestock grazing of riparian areas (riparian pastures) is a common practice in the Canadian Prairies due to the abundance of forage, particularly during time of drought. Livestock exclusion from riparian areas have been suggested as a best management practices to reduce the direct inputs of P, limit bank erosion, and avoid soil compaction (Krall and Roni, 2023). However, alternative water sources, rotational, timed-controlled, or rest-rotation grazing, and corridor fencing are strategies that can all reduce those risks (Fitch et al., 2003).

Significant efforts have been put into managing P in agricultural systems, through in-field management practices, and also the use of riparian areas (includes vegetative filter or buffer strips) adjacent to ditches and streams. Unfortunately, many conservation practices are less effective under cold climates (Liu et al., 2019a). Thus, conservation practices adapted for the Canadian environment are needed. This is especially important in the Prairie region where a greater proportion of the total runoff occurs during the spring snow melt period, when vegetation in the landscape (including riparian vegetation, cover crops, crop residues) can be a significant P source (Elliott, 2013) due to repeated FTCs. These processes appear to have less of an impact on P release in the more temperate regions, where FTCs are less severe (Cober et al., 2019) and there is more interaction between P and the soil, which buffers P released by plants (Lozier and Macrae, 2017).

Given the timing and processes of P dynamics with riparian areas in cold climates, like the Canadian Prairies, reducing the near-surface concentration of soluble P prior to spring snowmelt would be a strategy to limit the contribution of P from the riparian area to surface water. Because of the difficulties in harvesting forage from riparian areas short term livestock grazing might be an effective strategy that both uses the forage and reduces potential P loss. The objectives of this study were to assess the: 1) vertical and longitudinal profile of WEP; and 2) change in the sources of WEP in response to grazing and harvesting of biomass. Understanding how riparian management practices affect the sources of P can be used to help tailor management strategies in cold climates and ultimately reduce P loss and improve downstream water quality.

## 2 Methods

### 2.1 Site description

Source: [Article Notebook](#)

The study was conducted at the Manitoba Beef and Forage Initiatives (MBFI) research farm (50.06°N, 99.92°W), approximately 25 km north of Brandon, Manitoba, Canada, in the Prairie Pothole region of North America (Figure 1). The normal (1981 – 2010) average daily air temperature was 2.2 °C and the cumulative annual precipitation at Brandon was 474.2 mm with 24.8 % falling as snow (Environment and Climate Change Canada, 2024). The Köppen-Geiger climate classification is cold, without dry season, and with warm summer (Dfb) (Beck et al., 2018). The land use in the region is predominately agriculture including annual crops (grains and oil seeds) and grazing/forage. MBFI is a 260 ha research and demonstration

farm with a mix of pasture, hay, and cropland. Prior to the establishment of MBFI the site was part of the Manitoba Zero Tillage Research Association farm (1993-2014) where annual crops, including oil seeds and grains, were grown. There are also numerous small permanent and ephemeral wetlands (potholes) and associated riparian areas which account for ~35% of the total farm land (Manitoba Beef & Forage Initiatives, 2024). The riparian areas surrounding the larger permanent wetlands are fenced off to exclude livestock and are not actively managed. The farm has an irregular undulating to hummocky relief with soils developed on fine loamy, moderately calcareous glacial till. The riparian soils are poorly drained and primarily consist of Humic and Luvic Gleysols and generally the soil profile can be described by a 1-10 cm organic layer overlying a 10-18 cm Ah horizon (Podolsky and Schindler, 1993). The vegetation in the riparian areas are dominated by grasses, sedges, and forbs.

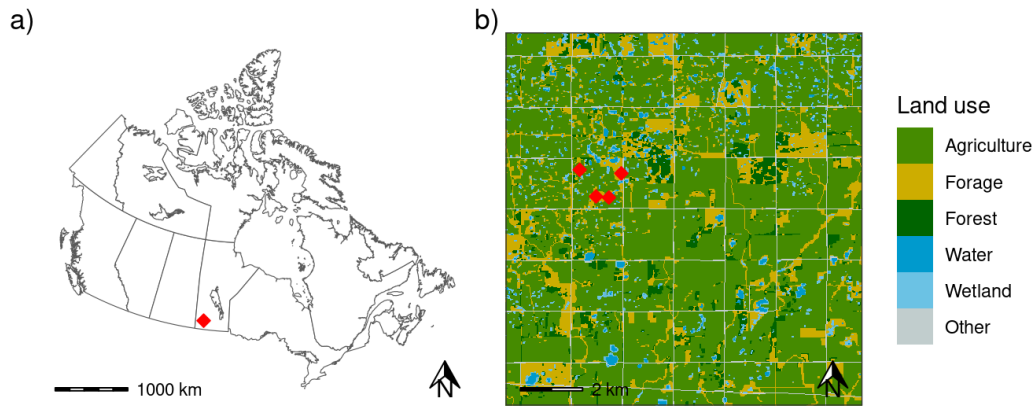


Figure 1: Showing a) the study site in southwestern Manitoba and b) the four riparian areas included in this study and the regional land use (data from <https://mli.gov.mb.ca/>).

Source: [Map of study area](#)

## 2.2 Experimental design

Four riparian areas surrounding permanent wetlands were selected (Figure 1) and were subdivided into four ~450 m<sup>2</sup> plots. Within each riparian area each plot was randomly assigned a treatment. The treatments consisted of a: 1) control, 2) graze, 3) high density graze, and 4) mow and harvest. The grazing treatments consisted of a five hour grazing period with the graze treatment having ~3.1-3.5 animal units (AU) per plot and the high density graze with ~11.75-12 AU. For the mowing treatment, the vegetation was cut to a height of ~10cm and the vegetation manually raked out of the plot. The cattle were rotated daily over four consecutive days among the four riparian areas and the grazed plots were fenced on all four sides,

including the waters edge, and provided with supplemental water. Treatments were applied early to mid September, before the first frost, in three consecutive years (2019-2021) (Figure S1). Within each plot three distinctive sampling zones, or landscape positions, were established, adjacent to the waters edge (Lower), adjacent to the field/pasture (Upper), and the mid-point (Mid). To assess the impact of grazing and mowing, samples were collected in each plot and zone 1-3 days prior and immediately adjacent 1-3 days following the treatments (including the control).

### 2.3 Sampling and analysis

Four types of samples were collected: 1) biomass, 2) litter, 3) organic layer, and 4) Ah horizon. Using a 0.25 m<sup>2</sup> quadrat, biomass was collected by cutting the standing live vegetation and litter by raking the surface and picking up previous years growth. Both the biomass and litter were dried at 40 °C, weighed, and homogenized using a blade grinder (<1cm). A composite of five soil samples were collected within the same quadrat as the biomass/litter using a 19 mm diameter soil probe and were divided into the organic layer and the top 10 cm of the Ah horizon. The organic layer and Ah soil were air-dried, disaggregated with a mortar and pestle, and passed through a 2-mm sieve. Additional bulk density samples of both the organic layer and Ah and the depth of the organic layer were collected in 2023. Daily air temperature and rainfall data were collected from an onsite station (Figure S1) (Manitoba Agriculture, 2023).

Water Extractable Phosphorus (WEP), an environmental soil and vegetation P test, was used to mimic soil P release to runoff water. Dried and homogenized samples were extracted by shaking (150 RPM) with deionized water for one hour at a mass to volume ratio of 1:30 for the biomass and litter samples (1 g) and 1:15 for the organic and Ah samples (2 g). Extractions were gravity filtered through a Whatman 42 filter followed by syringe filtration with a 0.45 µm nylon filter. WEP in the extract was measured spectrophotometrically by the colorimetric molybdate-ascorbic acid method (Murphy and Riley, 1962; Sharpley et al., 2006).

The concentration of WEP in the biomass and litter combined with the mass of material in collected from the quadrat was used to calculate the total WEP (mg kg<sup>-1</sup>). Only the change in concentration (mg kg<sup>-1</sup>) was measured for the organic layer and Ah horizon. The vertical profile of WEP within the riparian area was assessed using samples collected before treatments were implemented across the 3-year study. The total WEP in the organic layer and Ah were estimated using the bulk density and depth measurements collected in 2023 (Figure 2 b).

### 2.4 Statistical analysis

All statistical analysis was undertaken using the R Statistical Software (v4.3.3), through the RStudio Integrated Development Environment v2023.12.1.402. Generalized Linear Mixed Models (R package *glmmTMB* v1.1.8) were used to investigate the relation between the change in WEP (before - after treatment) and treatment and riparian zone for each of the four sources of WEP. Year and riparian area were included as crossed random factors to control for the variability between years and riparian areas. Additionally, when investigating the change in biomass WEP the WEP prior to the treatment was included as a co-variate because the magnitude of the difference (i.e., before - after) is directly related to the amount initially available.

If there were no significant (p < 0.5) interaction between main effects the interaction term was removed. When a main effect or interaction were significant a post-hoc pairwise comparisons with a Benjamini-Hochberg p value adjustment were used (*emmeans* v1.8.9). Model assumptions were assessed using DHARMA residual plots (DHARMA v0.4.6), main effects were tested for collinearity (*performance* v0.10.8.7), and results are presented as type III ANOVA (*car* v3.1.2). All plots were created using the R package *ggplot2* (v3.5.0).

### 3 Results

There is strong vertical stratification in both the concentration and total WEP (Figure 2). The median concentration in the vegetation sources (82.8 - 39.0  $\text{mg kg}^{-1}$ ; biomass and litter) are more than an order of magnitude greater than the soil components (0.9 - 3.4  $\text{mg kg}^{-1}$ ; Ah and organic). The median concentrations are similar between the upper, mid, and lower positions in the biomass, organic, and Ah sources. There is a gradient in the median WEP concentration for the litter where an increase of  $\sim 20 \text{ mg kg}^{-1}$  is observed from the upper to lower riparian zone. There is considerable variability in the WEP concentration in the biomass and litter sources with interquartile ranges (IQR) of 54.3 and 32.9  $\text{mg kg}^{-1}$  for the biomass and litter sources, respectively. In contrast, the IQR for the organic and Ah sources were  $< 2.5 \text{ mg kg}^{-1}$ . Overall, in terms of the total amount of WEP, the top 10 cm of the Ah horizon is the largest source of WEP (42.5  $\text{mg m}^{-2}$ ) followed by the biomass (26.3  $\text{mg m}^{-2}$ ), organic layer (14.3  $\text{mg m}^{-2}$ ), and lastly the litter (13.7  $\text{mg m}^{-2}$ ). In contrast to the concentration the total WEP does show an impact of the riparian zone. For the biomass and litter sources the lower riparian zones had greater amounts of WEP whereas the organic and Ah sources had greater amount of WEP in the upper riparian zones. The amount of variability is greatest in the Ah (IQR = 32.0  $\text{mg kg}^{-1}$ ) and biomass (IQR = 23.3  $\text{mg kg}^{-1}$ ) sources. The variability of the other two sources were similar with IQRs of 15.6 and 14.3  $\text{mg kg}^{-1}$  for the litter and organic layer, respectively.

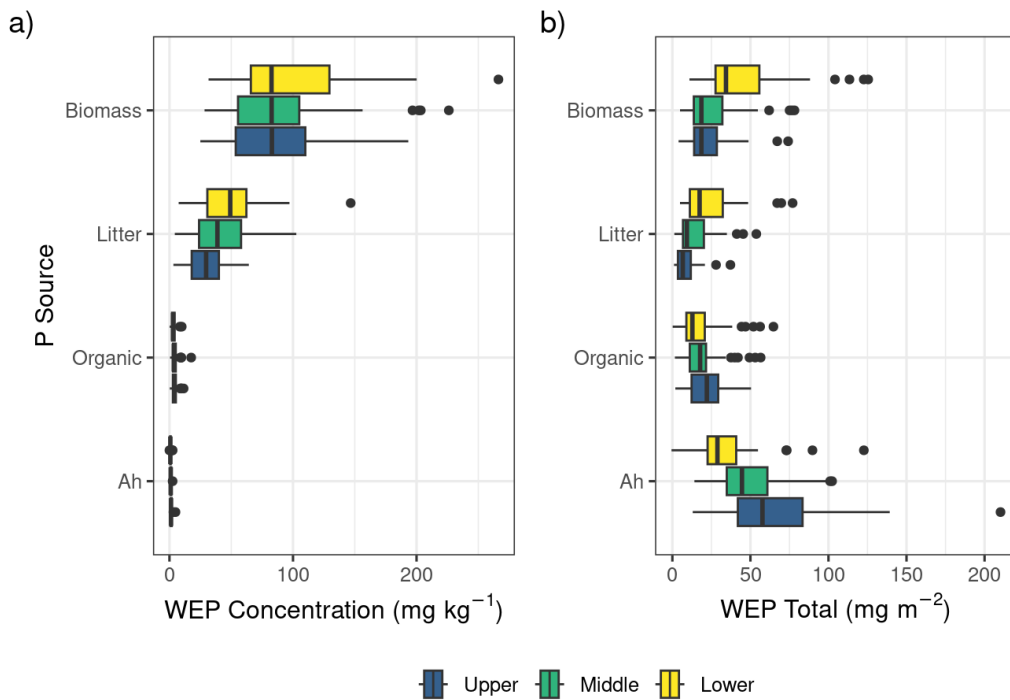


Figure 2: Vertical and longitudinal profiles of a) WEP concentration and b) WEP content in the riparian areas prior to grazing and mowing treatments.



Both the high density grazing and mowing treatments significantly ( $p < 0.05$ ) reduced the total amount of the biomass WEP compared to the control and graze treatments (Figure 3 a). The mowing and high density grazing reduced the average WEP amount by 7.4 and 4.2  $\text{mg m}^{-2}$  relative to the control, respectively. The reduction in biomass WEP was significantly ( $p < 0.05$ ) greater in the lower zones as compared to the upper and mid zones (Figure 3 b) with a difference in average WEP of 10.2  $\text{mg m}^{-2}$  between the lower and upper zones of the riparian area.

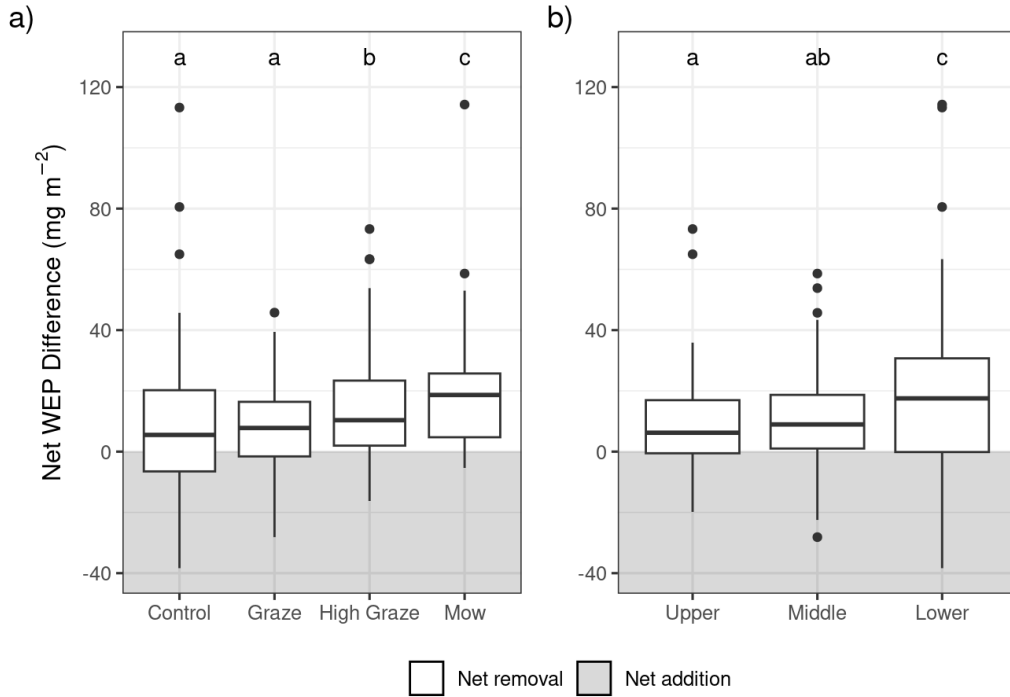


Figure 3: Change in riparian biomass WEP following grazing or mowing in each riparian zone. Within each plot significant differences ( $p < 0.05$ ) between treatments or riparian zones are denoted with different letters.

Source: [Riparian vegetation WEP in response to grazing](#)

There were no significant impacts of either treatment or riparian zone on the amount of litter WEP (Figure 4). The ANOVA detected a significant ( $p = 0.04$ ) effect of treatment on the WEP concentration in the organic layer; however, no significant differences were observed between any post-hoc pairwise comparisons (Figure 5). Lastly, there was no significant effect of treatment or riparian zone in the concentration of WEP in the top 10 cm of the Ah horizon (Figure 6). There was considerable variation across all treatments and riparian zones in all four sources of P. This high variability in WEP amount/concentration is best reflected in the control treatment where the expected difference is 0 but there were measured WEP losses and gains despite no treatment being applied.



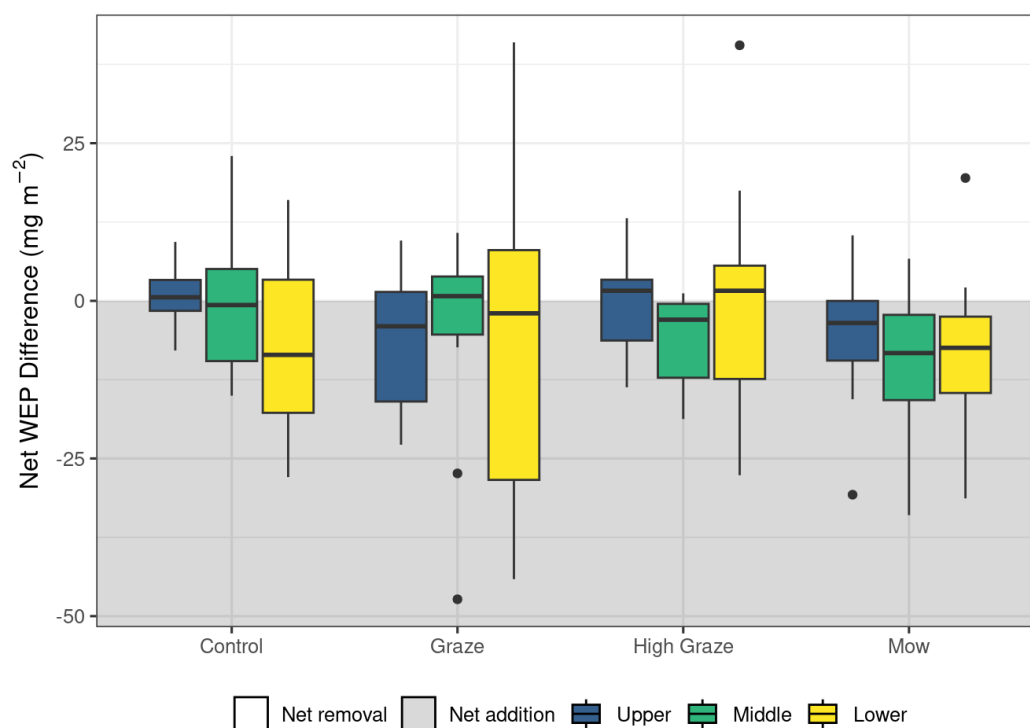


Figure 4: Change in riparian litter WEP following grazing or mowing in each of the riparian zones. No significant effect of treatment or riparian zone on the litter WEP content was detected

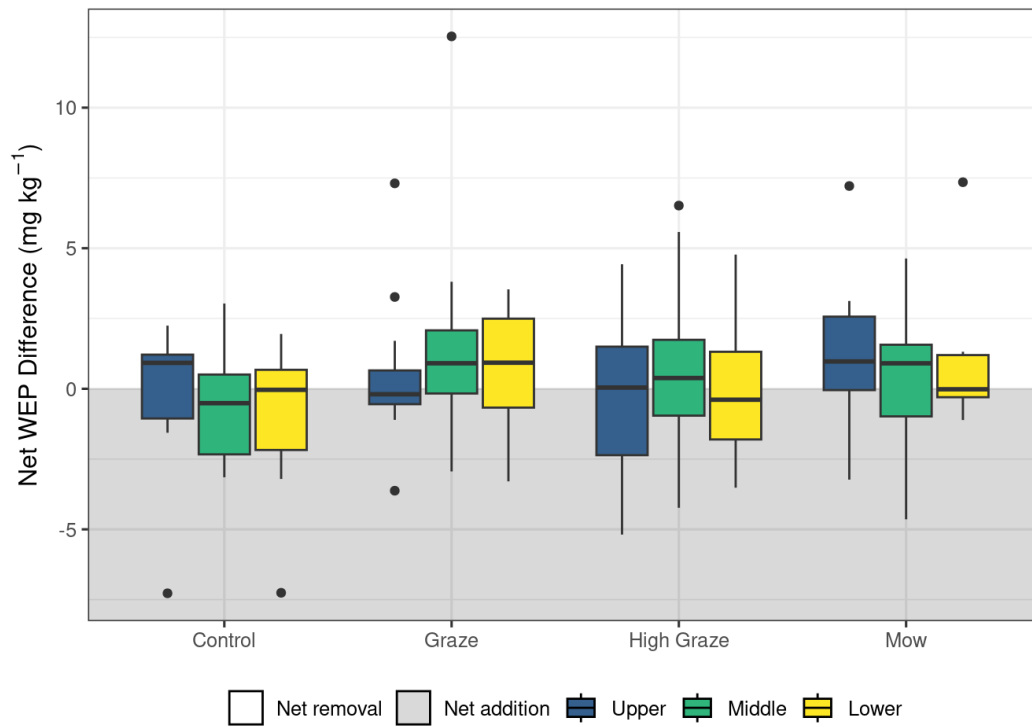


Figure 5: Change in riparian organic layer WEP concentration following grazing or mowing in each of the riparian zones. A significant effect of treatment was detected; however, the post-hoc analysis was not able to detect any significant ( $p < 0.05$ ) pairwise contrasts.

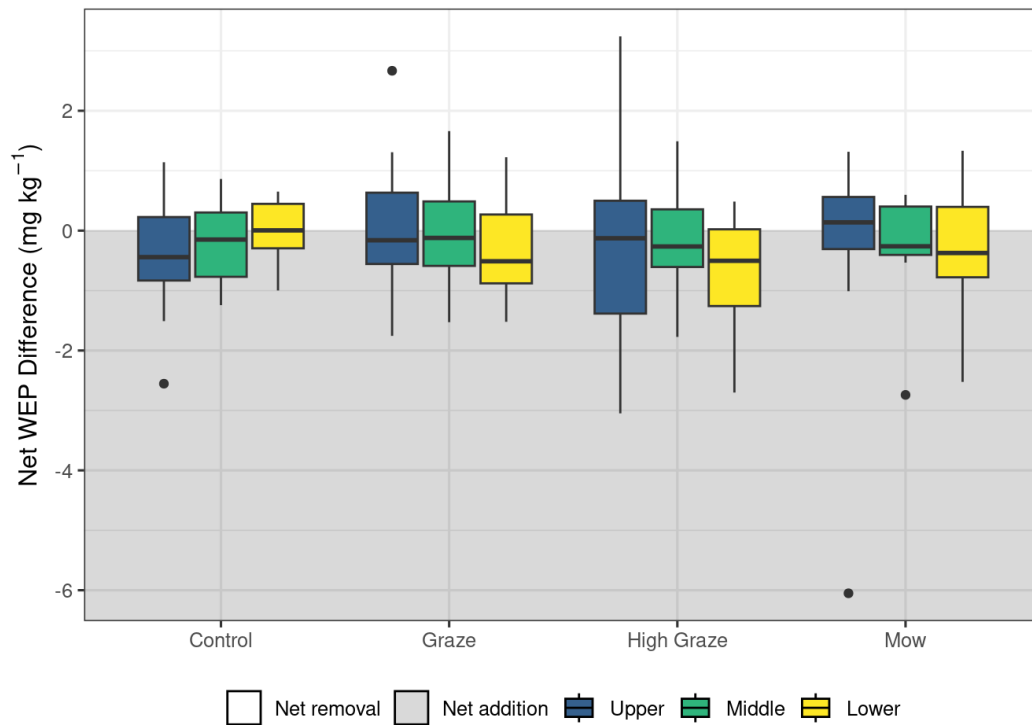


Figure 6: Change in riparian Ah layer (0-10cm) WEP concentration following grazing or mowing in each of the riparian zones. No significant effect of treatment or zone was detected.

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Source: [Riparian organic and mineral soil WEP in response to grazing](#)

## 281 4 Discussion

282 The vertical profile of WEP in riparian areas (Figure 2) observed in this study sup-  
 283 ports the concept that a soil test P alone is likely missing a large proportion of the  
 284 near-surface P that can be potentially lost during the spring snowmelt (Liu et al.,  
 285 2019a; b; Cober et al., 2019). The substantial proportion of WEP above the soil  
 286 surface provides evidence that that managing the biomass in riparian areas in the  
 287 autumn may reduce the contribution of P lost directly from this area during the  
 288 spring. The measured WEP in this study may underestimate the total WEP dur-  
 289 ing the spring snowmelt as the as repeated and severity of FTC on WEP was not  
 290 characterized (Roberson et al., 2007; Lozier and Macrae, 2017). Additionally, har-  
 291 vesting of this biomass results in an export of P which can maintain or enhance the  
 292 buffering or storage capacity of P derived from upslope sources further improving  
 293 downstream water quality (Kelly et al., 2007; Hille et al., 2019). The longitudinal  
 294 gradient of WEP shows an inverted symmetry where the biomass WEP is largest  
 295 near the waters edge and the Ah soil WEP is larger in the upper zone adjacent to  
 296 the fields (Figure 2 b). The high soil water content in the lower zone creates con-  
 297 ditions that favour high biomass production (Figure S2) coupled with high biomass  
 298 WEP concentrations (Figure 2 a) results in a considerable source of P. The higher  
 299 amount of WEP in the Ah soil in the upper zone of the riparian area is due to the  
 300 higher bulk density (Figure S2) and higher WEP concentration (Figure 2 a). The  
 301 higher bulk density is most likely due to the lower soil organic matter content and  
 302 the higher WEP concentration may be related to the interception of P-rich runoff  
 303 from upslope areas (Tomer et al., 2007). Understanding and quantifying the sources

and patterns of P within riparian areas is a key part of assessing the risk of P loss and designing effective management plans (Reid et al., 2018).

The results of this study suggest that short-term autumn high density grazing may be a potential management tool that can reduce the amount of P lost directly from the riparian area (Figure 3 a). In addition to managing P loss, grazing riparian areas can also provide an important source of forage, particularly during drought. Mechanized harvesting of biomass will also achieve this reduction in P loss (Figure 3 a) if the landscape and soil conditions are favourable. Despite the cycling of nutrients by the removal of P through grazing of biomass (Figure 3) and the deposition through excretion no differences were detected in the litter and Ah sources of P (Figure 4, and 6). The ANOVA did detect a significant effect of treatment on the organic layer WEP; however, the pairwise comparisons was not able to detect any significant differences and the exact nature of the impact of the treatments remains unclear. The ability to detect changes in the WEP sources in riparian areas is difficult due to both the inherent and post-grazing treatment spatial variability. Even within the control plots, both net addition and removal of WEP were measured and in many cases the amount of variability was similar across treatments. This inherent variability (i.e., pre-grazing) is a result of a combination of hydrological factors like ground water fluctuations, soil attributes such as texture, ecological dynamics involving plant community composition, and anthropogenic influences like historic land management practices (McClain et al., 2003; Vidon et al., 2010). Post-grazing treatment, the added urine and manure creates additional hotspots of P that may carry forward to subsequent years (Subedi et al., 2020; Donohoe et al., 2021). The single 0.25 m<sup>2</sup> sampling quadrat within each riparian zone may have been insufficient to capture the spatial variability. Therefore, larger, composite, and/or several sampling locations within each zone is recommended. Appropriate sampling design becomes more important as the scale of observation of similar research increases to the farm scale so will the amount and source of variability. As the scope of research is expanded to the farm level, the importance of using an appropriate sampling design becomes increasingly critical (Hale et al., 2014).

Autumn was selected for the mowing and grazing treatments for three reasons. First was to reduce the amount of biomass P available that can contribute to the P loss during the spring snowmelt. Secondly, the drier soil conditions reduced the amount of pugging and soil compaction which limits the disruption of soil structure and damage to plants (Batey, 2009). Lastly, the prairie potholes and associated riparian areas are important breeding habitat for migratory birds and late season grazing may reduce the ecological impact (Stanley and Knopf, 2002). However, the type of grazing system (timing, stocking rate and density etc.) may impact habitat quality and breeding success (Carnochan et al., 2018; Hansen et al., 2019; Kraft et al., 2021). Corridor fencing at the waters edge and alternative water sources were used in this study to limit livestock access to prevent bank erosion and protect water quality (e.g., direct deposition) (Dauwalter et al., 2018). Scaling this up to the farm level will be expensive (fencing infrastructure) (Aarons et al.,) and time consuming (short-term grazing), especially in prairie pothole region where there are numerous and small riparian areas (Manitoba Agriculture, 2024). The long-term impacts of repeated grazing of riparian areas also needs to be considered. From a nutrient loss reduction perspective, a shift in the magnitude of the sources of P could be expected as less biomass is available to be added to the litter source, which in turn effects the organic layer and Ah sources of P. The regular inclusion of cattle will also introduce new manure source of P which can spatially redistribute P, and initially be more water soluble and readily transported (Franzluebbers et al., 2019). Grazing can also reduce the litter layer through trampling increasing the soil-vegetation contact speeding up the decomposition process. These changes in biomass and litter quantities may result in changes to habitat structure. Understanding how of forage

management directly impacts both the plant and soil P dynamics is important for understanding both the agronomic and environmental P considerations (Subedi et al., 2020).

## 5 Conclusion

Biomass and litter are significant sources of near surface WEP in riparian areas that historically have been disregarded as important. Management of the biomass prior to the onset of winter conditions in cold climates has the potential to reduce the amount of P directly lost during the spring snowmelt and maintain or enhance the nutrient buffering capacity. The results from this experiment demonstrated that short-term high density cattle grazing and mowing both resulted in a reduction in the amount of biomass WEP, particularly in the lower riparian zones. The grazing and mowing treatments had no detectable effect on the other three near-surface sources of WEP. However, detecting changes in the near-surface sources of WEP is challenging due to high spatial variability.

Comparatively less riparian research has occurred in landscapes that experience a cold climate with strong temperature seasonality (e.g., Canadian prairies). In these regions the runoff and nutrient losses occur predominately during the spring snowmelt period. The repeated FTC of the vegetation and soils increase the potential P losses during this key time. Continued research to identify, quantify, and manage these sources of P to improve water quality remains a priority. In addition to water quality improvement, the development of riparian management strategies should also prioritize the protection other ecological goods and services and recognize these areas as an integral part of the farm.

## Acknowledgements

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## Data availability

Data and source code for analysis and manuscript available on GitHub: <https://github.com/alex-koiter/riparian-grazing-manuscript>

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## 578 Supplemental materials

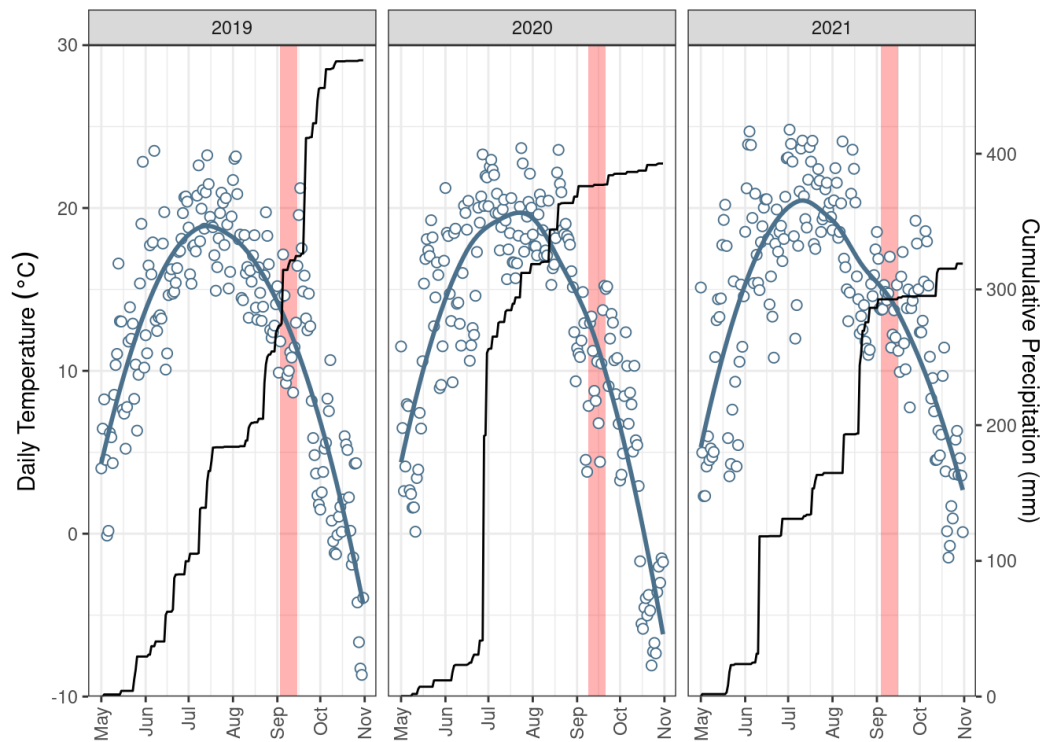


Figure S1: Average daily air temperature and cumulative rainfall over the growing season over the three year study. Red bars indicate sampling dates

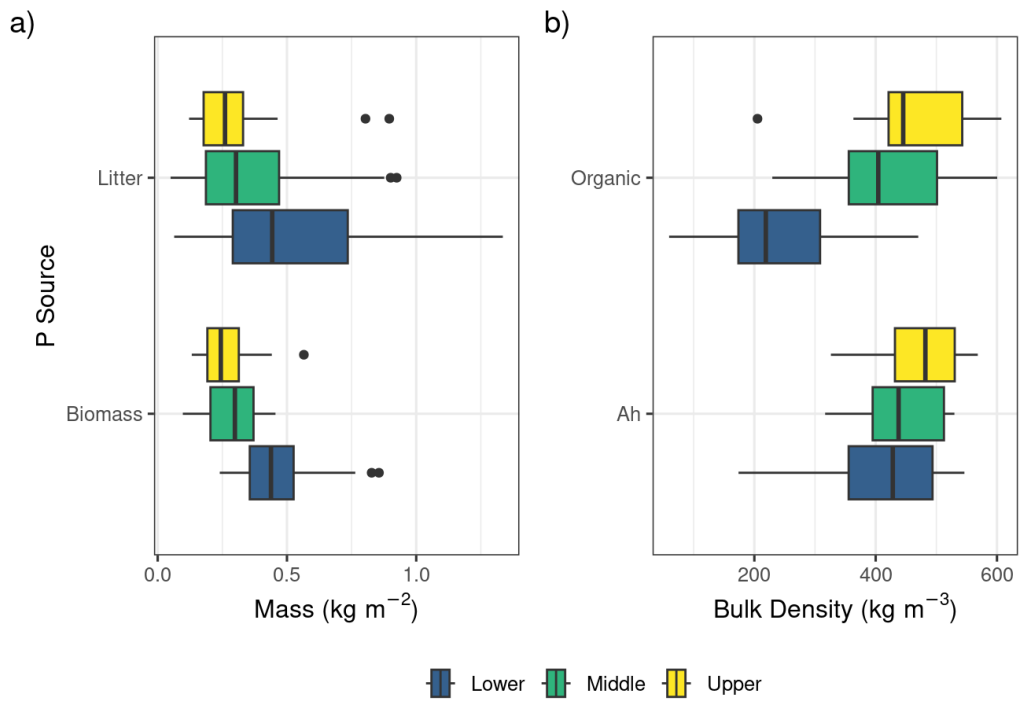


Figure S2: a) Mass of biomass and litter before grazing and mowing (2019-2021) and b) the bulk density of the organic layer and 10 cm Ah horizon (2023)