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RESEARCH ARTICLE

Soil phosphorus drawdown by perennial bioenergy cropping systems in the Midwestern US

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Abstract

Without fertilization, harvest of perennial bioenergy cropping systems diminishes soil nutrient stocks, yet the time course of nutrient drawdown has not often been investigated. We analyzed phosphorus (P) inputs (fertilization and atmospheric deposition) and outputs (harvest and leaching losses) over 7 years in three representative biomass crops—switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus × giganteus*) and hybrid poplar trees (*Populus nigra* × *P. maximowiczii*)—as well as in no-till corn (maize; *Zea mays* L.) for comparison, all planted on former cropland in SW Michigan, USA. Only corn received P fertilizer. Corn (grain and stover), switchgrass, and miscanthus were harvested annually, while poplar was harvested after 6 years. Soil test P (STP; Bray-1 method) was measured in the upper 25 cm of soil annually. Harvest P removal was calculated from tissue P concentration and harvest yield (or annual woody biomass accrual in poplar). Leaching was estimated as total dissolved P concentration in soil solutions sampled beneath the rooting depth (1.25 m), combined with hydrological modeling. Fertilization and harvest were by far the dominant P budget terms for corn, and harvest P removal dominated the P budgets in switchgrass, miscanthus, and poplar, while atmospheric deposition and leaching losses were comparatively insignificant. Because of significant P removal by harvest, the P balances of switchgrass, miscanthus, and poplar were negative and corresponded with decreasing STP, whereas P fertilization compensated for the harvest P removal in corn, resulting in a positive P balance. Results indicate that perennial crop harvest without P fertilization removed legacy P from soils, and continued harvest will soon draw P down to limiting levels, even in soils once heavily P-fertilized. Widespread cultivation of bioenergy crops may, therefore, alter P balances in agricultural landscapes, eventually requiring P fertilization, which could be supplied by P recovery from harvested biomass.

KEYWORDS

corn, legacy phosphorus, miscanthus, phosphorus, poplar, switchgrass

1 | INTRODUCTION

Phosphorus (P) is a potentially limiting nutrient for crop production that is commonly added to row crops as fertilizer or manure. Perennial bioenergy crops would ideally require little or no fertilization, not only because it is costly but also because it may lead to nutrient export to surface waters, where excessive loading of P together with nitrogen can result in eutrophication and harmful algal blooms (Dodds et al., 2009; Smith, 2003; Wurtsbaugh et al., 2019). Soils often accumulate P, and "legacy P" that builds up over long periods in agricultural soils can sustain P-driven eutrophication for years to decades after fertilizer or manure inputs diminish (Sharpley et al., 2013; Withers et al., 2014). Bioenergy crops, in which nearly all aboveground biomass is harvested, may gradually draw down soil nutrient stocks, which is beneficial if the soils start with excessive P stocks. However, years of net P removal by biomass harvest may eventually draw down soil P to the point where crop production becomes limited and P fertilization may be needed.

The rate of P removal by crop harvest depends on initial soil P stocks, crop productivity, and the P content of harvested biomass, the latter affected by the degree of P retranslocation to belowground root systems prior to harvest (Massey et al., 2020). Phosphorus budgets (comparisons of inputs to outputs) for specific cropping systems or entire agricultural watersheds are useful to identify whether the systems show a net P surplus or deficit over time. At field scales, previous studies have mainly examined P budgets in annual rather than perennial crops (Blake et al., 2000; Maltais-Landry et al., 2016; Nunes et al., 2020; Riskin et al., 2013; Zhang et al., 2020; Zicker et al., 2018). At watershed scales, comparisons of agricultural P inputs to harvest and stream exports have shown net P export from croplands to streams in the Midwestern US (Hanrahan et al., 2019; Lun et al., 2018; Morel et al., 2014; Stackpoole et al., 2019). In contrast, the P budgets for prospective perennial bioenergy crops are not well studied. For grassland crops, perhaps the closest analog that has been studied are pastures managed for hay production (Messiga et al., 2015; Obour et al., 2011; Sattari et al., 2016), although hay often is harvested prior to senescence and P retranslocation, and hay crops may be fertilized.

In this study, P budgets were quantified for three contrasting perennial biofuel cropping systems—switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus* × *giganteus*), and hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry 'NM6')—as well as conventionally managed continuous corn (*Zea mays* L.), all established on a former row crop field in Michigan, USA. We accounted for inputs from inorganic fertilizer (in the case of corn) and atmospheric deposition, and outputs via crop harvest and leaching losses. The objectives of this study were to: (i) quantify the P budgets of the unfertilized perennial cropping systems in comparison with conventional corn across 7 years (2009–2015) spanning establishment and stabilization of the perennial cropping systems and (ii) evaluate the time course for a drawdown of soil P to reach levels that would limit crop production. Owing to the high biomass production and removal by harvest, we hypothesized that perennial bioenergy crop production over 7 years would remove a substantial fraction of the legacy P from the soil in our system, which had previously received P inputs from fertilizer and manure.

2 | MATERIALS AND METHODS

2.1 | Experimental details

The Biofuel Cropping System Experiment (BCSE) is part of the Great Lakes Bioenergy Research Center (www.glbrc.org) at the Long-term Ecological Research site (www.lter.kbs.msu.edu) of Michigan State University's W.K. Kellogg Biological Station (KBS) (42.3956°N, 85.3749°W; elevation 288 m a.s.l.) in southwestern Michigan. Soils at this site are mesic Typic Hapludalfs developed on glacial outwash (Crum & Collins, 1995) with high sand content (76% in the upper 150 cm) intermixed with silt-rich loess in the upper 50 cm (Luehmann et al., 2016). Soils are well-drained with a deep unsaturated zone (12–14 m). The climate is humid temperate with a mean annual air temperature of 9.1°C and annual precipitation of 1005 mm, 511 mm of which falls between May and September (1981–2010) (NCDC, 2013).

The BCSE site was established in 2008 on pre-existing cropland. Prior to BCSE establishment, the field was used for grain crop and alfalfa (*Medicago sativa* L.) production for several decades. The experimental design consists of five randomized blocks, each containing one replicate plot (28 × 40 m) of 10 cropping systems (Figure S1). Details on experimental design and site history are provided in Gelfand et al. (2020), Robertson and Hamilton (2015), and Sanford et al. (2016). Prior to the establishment of the experiment, between 2003 and 2007, the field received a total of ~300 kg P ha^{-1} as manure from a nearby dairy operation, and the southern half, which contains one of the experiment blocks analyzed in this study, received an additional 206 kg P ha^{-1} as inorganic fertilizer. The phosphorus budget was quantified in three replicate plots of each cropping system for which all of the necessary measurements were available.

The corn (*Zea mays* L.; cultivar Dekalb (DKC52-59)) was planted in early May each year, while switchgrass (*Panicum virgatum* L.; variety Cave-in-rock), miscanthus

(*Miscanthus* × *giganteus*) and hybrid poplar (*Populus nigra* L. × *P. maximowiczii*; A. Henry 'NM6') were planted in May 2008. The switchgrass was re-seeded in 2009 due to intense storms in mid-summer 2008 that redistributed ungerminated seeds. Switchgrass and miscanthus emergence and poplar leaf-out in the subsequent years occurred in April and May. Annual harvesting, depending on weather, was carried out at the end of each growing season, usually between October and November for corn, and between November and December for switchgrass. Corn stover was harvested shortly after corn grain, leaving approximately 10 cm height of stubble above the ground. The poplar was harvested only once, as the culmination of a 6-year rotation, over the winter of 2013–2014. Application of nitrogen and phosphorus fertilizers to corn followed practices typical for the region with 175 kg N and 14 kg P ha^{-1} applied annually, while switchgrass and miscanthus were fertilized only with N at 56 kg ha^{-1} annually and poplar was fertilized just once with N at 157 kg ha^{-1} in 2010, after the canopy had closed. There was no P fertilization of the switchgrass, miscanthus, and poplar systems.

2.2 | P inputs, outputs, and soil test P concentrations

Phosphorus inputs and outputs were calculated for each cropping system over the seven growing seasons (2009–2015) except for poplar, which was harvested in February 2014, after its sixth (2013) growing season. Inputs included P fertilizer for corn, and atmospheric deposition (Table 1). During planting of the corn, P fertilizer was applied as a starter material at the rate of 14 kg P ha^{-1} with an additional 22 kg P ha^{-1} in spring 2015 (totaling 36 kg P ha^{-1} in 2015). According to Michigan State University Extension (Warncke et al., 2004), P fertilizer recommendations take into consideration the soil test level and crop yield, and for corn, P fertilization is recommended when Bray-1 soil test phosphorus (STP) is below the "agronomic P minimum" of 15 mg P kg^{-1} (for the STP sampling depth in this study, this is equivalent to 68 kg P ha^{-1}). There is no comparable P fertilizer recommendation for perennial cropping systems in the Midwest United States.

Atmospheric wet deposition of total dissolved P in rain and snow was measured nearby on an event basis over an annual cycle (Oct 2013–Oct 2014). Samples were collected with a funnel and bottle and filtered (0.45 μm) to remove any particulate matter, which was sometimes visible after windy events and appeared to be organic material of local origin. Total P was analyzed by persulfate digestion to convert all filtrable P forms to soluble reactive P, followed by colorimetric analysis by long-pathlength spectrophotometry (UV-1800 Shimadzu, Japan) using the molybdate blue method (Murphy & Riley, 1962), for which the method detection limit was ~0.005 mg P L^{-1}.

Phosphorus outputs from the plots included removal by harvest and leaching losses. Overland flow can carry P into or out of a plot, but it is not significant in the experimental plots because of the coarse soils and level terrain that facilitate rapid infiltration. Plant P uptake into aboveground biomass (kg P ha^{-1}) was determined by multiplying the dry weight of harvested biomass (kg ha^{-1}) by its tissue P concentration. In the case of corn, harvested biomass refers to harvested stover and grain (grain yield data were corrected for standard moisture of 15.5%). Because poplar accrued biomass from planting until it was harvested after the 2013 growing season, we estimated its annual P accumulation in aboveground biomass as an output from the soil, based on woody tissue P content and the annual increase in biomass, the latter estimated from measured diameter at breast height (dbh) and dbh/biomass relationships. P concentrations were analyzed in the harvested corn (grain and stover), switchgrass and miscanthus (whole aboveground biomass), and poplar (woody biomass). Although P in litterfall was measured in the poplar stands, poplar leaves were not included as an output because they returned to the soil surface each autumn, and the trees were harvested in the winter after leaf fall and the nutrient retranslocation that precedes leaf fall.

TABLE 1 Summary of the total phosphorus inputs (positive) and outputs (negative) over 7 years (5 for poplar) in the different cropping systems. Standard errors are based on the means of replicated plots ($n = 3$) across years of measurements ($n = 5$ for poplar or 7 for corn, switchgrass, and miscanthus).

Cropping system	Total inputs or outputs (kg P ha^{-1})				
	Fertilizer	Deposition	Harvest	Leaching	Net balance
Corn (2009–2015)	106	1.4	−78.1 ± 0.43	−0.2 ± 0.01	29.7
Switchgrass (2009–2015)	0.0	1.4	−41.0 ± 0.40	−0.4 ± 0.04	−39.6
Miscanthus (2009–2015)	0.0	1.4	−68.9 ± 0.89	−0.3 ± 0.02	−67.5
Poplar (2009–2013)	0.0	1.4	−39.3 ± 1.49	−0.3 ± 0.02	−38.3

To analyze the plant tissue P concentration, 0.5 g dry weight of the sample was combusted for 6 h at 500°C and then digested in 25 ml of 3 N nitric acid. The digest solution was filtered after allowing particulate matter to settle for an hour after acid addition. Approximately 1 ml of the filtered digestate was mixed with 9 ml of 0.3 N NaOH and the P concentration was subsequently determined by the ascorbic acid method (Blanchar & Caldwell, 1964) using a Brinkmann PC950 Probe Colorimeter.

Soil leachates were collected beneath the root zone (1.2 m) of each cropping system using suction samplers installed approximately 20 cm into the unconsolidated sand of 2Bt2 and 2 E/Bt horizons (sampler details given in Hussain et al., 2021). The soil leachates were sampled weekly to biweekly during non-frozen periods (April–November), and collected samples were filtered using different filter types (all 0.45 μm pore size) depending on the volume of leachate collected (Hussain et al., 2021). The concentration of TDP ($mg\,P\,L^{-1}$) in soil leachates was determined by the same method described above for precipitation samples.

P leaching losses ($kg\,P\,ha^{-1}$), which were previously reported by Hussain et al. (2021), were calculated by multiplying the total dissolved P concentration ($mg\,L^{-1}$) in the soil leachates by daily drainage (percolation) rates ($m^3\,ha^{-1}$) estimated with the Systems Approach for Land Use Sustainability (SALUS) crop growth model (Basso & Ritchie, 2015). The SALUS water balance sub-model simulates daily surface runoff, saturated and unsaturated water flow, drainage, root water uptake, and evapotranspiration during growing and non-growing seasons and has been well calibrated for KBS soil and climatic conditions. The SALUS model was originally developed at KBS and has been used in studies of evapotranspiration (Hamilton, 2015; Hamilton et al., 2018; Hussain et al., 2019) and nutrient leaching (Hussain et al., 2019, 2020, 2021) from KBS soils. SALUS predictions of growing-season evapotranspiration—and hence percolation as the balance between precipitation and evapotranspiration—are consistent with independent measurement based on eddy covariance (Abraha et al., 2015). Phosphorus leaching during cold periods when soil solutions could not be sampled due to frozen soils was estimated from modeled percolation and solution P concentrations interpolated between the last sampling in the autumn and the first sampling in the spring.

Soil samples (0–25 cm depth) were collected each autumn for the determination of soil test P (STP; $mg\,P\,kg^{-1}$) by the Bray-1 method (Bray & Kurtz, 1945), using as an extractant a dilute HCl and NH_4F solution, as is recommended for neutral to slightly acidic soils. The measured STP concentration in $mg\,P\,kg^{-1}$ was converted to $kg\,P\,ha^{-1}$ based on the soil sampling depth and measured soil bulk density (mean, 1.5 $g\,cm^{-3}$).

2.3 | Data analysis

One-way analysis of variance (ANOVA) was conducted to compare leaching rates and STP concentrations, as well as crop P removal (harvest) among the crop treatments, including all years in each crop group. When a significant ($\alpha = 0.05$) difference was detected among the groups, we used the Tukey's honest significant difference (HSD) post-hoc test to make pairwise comparisons among the groups. We lacked data on crop P removal in poplar in the years after harvest, resulting in unequal sample sizes, and therefore we used the Tukey–Kramer method to make pairwise comparisons among the groups with pooled variances.

3 | RESULTS

3.1 | Climate, hydrology, growing season length, and crop productivity

Air temperature recorded from a nearby weather station averaged 9.3°C (mean for 2009–2015), which was slightly warmer than the long-term average (1988–2015: 9.1°C). Annual precipitation was lowest in 2009 (725 mm), which was well below the long-term average (1988–2015: 915 mm), while the precipitation in later years was above the long-term average (mean for 2010–2015: 1000 mm) (data not shown). In 2012, the combination of warmer spring temperatures and a summer precipitation deficit resulted in a severe agricultural drought that reduced crop yields in the region. Annual drainage rates simulated by SALUS were indistinguishable among cropping systems ($p > 0.05$) and averaged 331 mm (data not shown).

The length of the growing season averaged 160–180 days for corn, whereas the growing periods for perennials including poplar were about a week longer than corn, lasting approximately from May through Sep for switchgrass and May through Oct for miscanthus. The annual dry matter yields (or woody biomass increases in the case of poplar) averaged across years were highest in miscanthus (17.0 ± 0.8 $Mg\,ha^{-1}$) followed by corn (12.6 ± 0.3 $Mg\,ha^{-1}$) and poplar (11.6 ± 1.9 $Mg\,ha^{-1}$), and lowest in switchgrass (6.2 ± 0.2 $Mg\,ha^{-1}$) (Figure S2). Data for poplar ended after the stands were harvested during the 2013–14 winter.

3.2 | Soil P stocks

Initial Bray-1 STP (0–25 cm depth) concentrations at the outset of the study period in Fall 2008 averaged 130 ± 57.1 97.5 ± 15.0, 147.5 ± 22.2 and 183 ± 29.1 $kg\,P\,ha^{-1}$ in corn, switchgrass, miscanthus, and poplar, respectively (means ± standard errors, $n = 3$), with high variation presumably reflecting spatial variability in spite of the similar crop management history across the site. Thereafter, a progressive decline in STP concentrations over the study period is evident for switchgrass, miscanthus, and poplar (Figure 1a). STP concentrations by the end of the study had decreased to 90 kg P ha^{-1} in corn, but the rate of decline (as indicated by regression slope) was less steep than observed for perennial crops. STP concentrations in switchgrass had decreased by 2015 to 45 kg P ha^{-1} (a 54% decrease; regression slope of −8.1 kg P ha^{-1} year^{-1}; $p<0.05$), and STP concentrations in miscanthus had decreased to 75 kg P ha^{-1} (a 49% decrease; regression slope of −10.2 kg P ha^{-1} year^{-1}; $p<0.05$), while STP concentrations in poplar had decreased by autumn 2013 to 145 kg P ha^{-1} (a 21% reduction; regression slope of −10.7 kg P ha^{-1} year^{-1}; $p<0.05$) (Figure S3).

3.3 | Phosphorus budgets

The contribution of P inputs by atmospheric deposition, which was the only input in the switchgrass, miscanthus, and poplar systems, was very small (~1.4 kg P ha^{-1} year^{-1}) compared with P removal by harvest (Table 1). Phosphorus fertilizer was a far larger input in the corn P budget (Table 1).

Outputs of P by leaching were even smaller than atmospheric inputs and did not differ ($p>0.05$) among the cropping systems, averaging 0.033, 0.059, 0.041, and 0.055 kg P ha^{-1} year^{-1} for corn, switchgrass, miscanthus, and poplar, respectively (Table 1). Approximately 65% of P leaching occurred outside the growing season (Dec–March), and P leaching rates were significantly ($p<0.05$) correlated with non-growing season precipitation

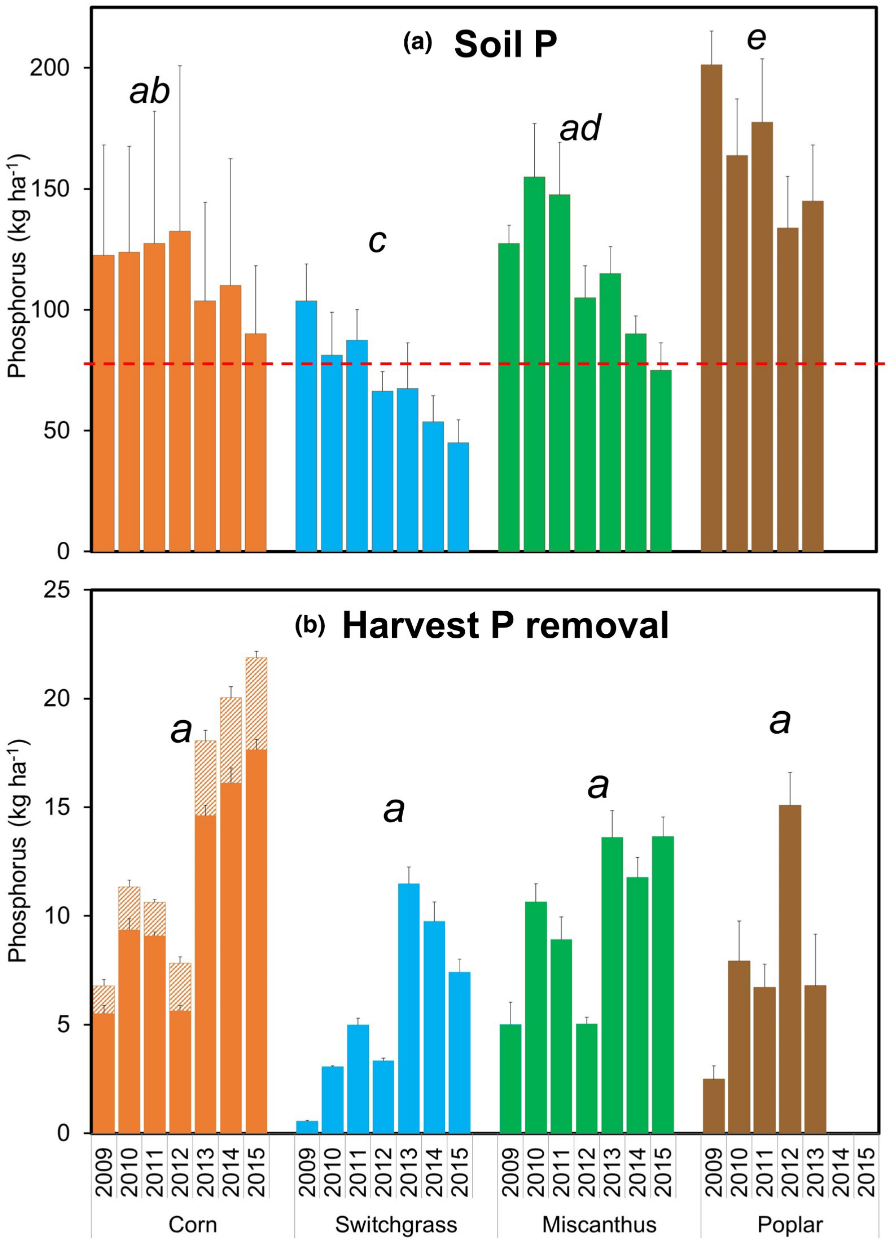

FIGURE 1 Soil test phosphorus stocks in the upper 25 cm (a) and phosphorus removal by crop harvest (b) in the fertilized corn and unfertilized switchgrass, miscanthus, and poplar systems. P removal by crop harvest is divided into grain (bold columns) and Stover (hatched columns). Dashed line indicates a critical lower threshold (agronomic P minimum) of soil test phosphorus recommended for crop production (68 kg P ha^{-1} for corn). Bars indicate standard errors of the mean for three replicate plots. When cropping systems share a similar letter, the means grouped across years are not significantly different as determined by the Tukey's honest significant difference post-hoc test ($\alpha = 0.05$).

(Pearson's $R = 0.55$) and drainage (Pearson's $R = 0.32$) (data not shown).

The removal of P in harvested biomass was by far the largest output in the P budgets for all three cropping systems (Figure 1b, Table 1). In the case of poplar, the annual incremental increase of P in the aboveground woody biomass represented a cumulative output from the soil that was harvested after the 2013 growing season. Mean annual plant P uptake into harvestable biomass was higher in corn (13.8 $kg\,P\,ha^{-1}$) than in switchgrass (5.8 $kg\,P\,ha^{-1}$), miscanthus (9.8 $kg\,P\,ha^{-1}$), and poplar (7.8 $kg\,P\,ha^{-1}$) (Figure 1b). In corn, the P uptake into the grain was higher than in stover biomass. These differences are mainly a function of yield because the tissue P concentrations were not very different; the mean tissue P concentrations for corn, switchgrass, miscanthus, and poplar were 0.08%, 0.09%, 0.06%, and 0.09% of dry weight, respectively.

The cumulative P inputs and outputs for each cropping system show that the corn system ended the 7-year period with harvest removal more than compensated by P fertilization (Figure 2a), whereas the switchgrass, miscanthus, and poplar systems gradually lost P, largely to harvest (Figure 2b–d). The net P balance in corn was positive (29.7 $kg\,ha^{-1}$) compared with the negative P balances in switchgrass (−39.6 $kg\,ha^{-1}$), miscanthus (−67.5 $kg\,ha^{-1}$), and poplar (−38.3 $kg\,ha^{-1}$) (Table 1).

4 | DISCUSSION

Results supported our hypothesis that the harvest of perennial crops without P fertilization would draw down the legacy reservoir of soil P. With continued harvest in the absence of fertilization, eventually P availability would become limiting in these cropping systems. Had the corn not been fertilized, P limitation would have been reached during the study period.

Some studies have reported P surpluses in continuous corn and corn-wheat systems receiving regular P fertilization (Zhang et al., 2020), but P deficits can exist in conventional corn systems in spite of fertilization (Maltais-Landry et al., 2016). An important role of legacy soil P in supporting crop P requirements has been reported in a Spodosol in Florida (Obour et al., 2011; Silveira et al., 2013), and in Cambisols and Luvisols in Germany (Ohm et al., 2017). Similar to P removal by crop harvest, net drawdown of soil P reserves in grazing lands occurs by harvest of livestock products, and the eventual impoverishment of grazing

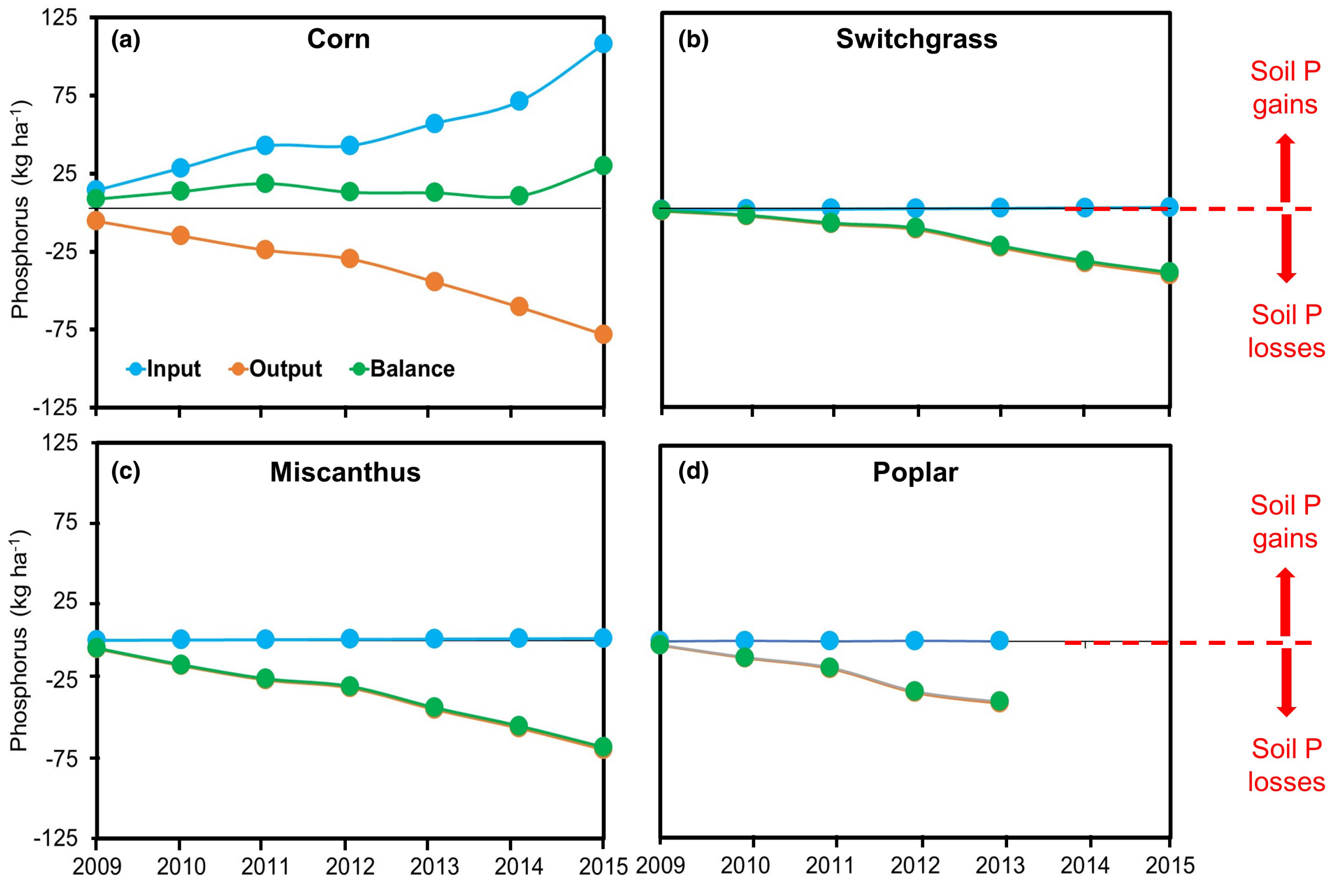

FIGURE 2 Cumulative phosphorus inputs, outputs and balances of fertilized corn (a) and unfertilized switchgrass, miscanthus, and poplar cropping systems (b–d). The output and balance curves overlay one another for the perennial systems.

lands by P removal may be a growing problem worldwide (Messiga et al., 2015; Sattari et al., 2016).

The dominant components of the P budgets—fertilization for corn and harvest removal for all of the cropping systems—are more accurately known than the lesser components. The mean annual rate of corn P uptake reported in our study (13.8 kg ha^{-1} year^{-1}; Figure 1b) was higher than reported by Niswati et al. (2021) (5–6 kg ha^{-1} year^{-1}) but generally lower than the range reported in other studies (24–30 kg ha^{-1} year^{-1}: Messiga et al., 2010; Pavinato et al., 2017; Pereira et al., 2020). Compared with what we observed for switchgrass (5.8 kg ha^{-1} year^{-1}), miscanthus (9.8 kg ha^{-1} year^{-1}) and poplar (7.8 kg ha^{-1} year^{-1}), similar or higher rates of annual P uptake have been reported in switchgrass (15.7 kg ha^{-1} year^{-1}: Ashworth et al., 2017; 39–44 kg ha^{-1} year^{-1}: Kimura et al., 2015; 5–9 kg ha^{-1} year^{-1}: Propheter et al., 2010), miscanthus (2–23 kg ha^{-1} year^{-1}: Gaston et al., 2019; 0.95–3.6 kg ha^{-1} year^{-1}: Haines et al., 2015; 3–4 kg ha^{-1} year^{-1}: Kering et al., 2012) as well as in grazed grass pastures (>60 kg ha^{-1} year^{-1}: Newman et al., 2009; >12 kg ha^{-1} year^{-1}: Obour et al., 2011; Silveira et al., 2013). Comparable rates were reported for poplar in one study in Quebec, Canada (6–16 kg ha^{-1} year^{-1}: Fortier et al., 2015). The lower rates of P uptake observed in our study compared with some others are likely explained by lower dry matter yields for switchgrass and poplar, which could reflect the delayed establishment of the crops during the initial years as well as the absence of P fertilization in the perennial systems.

The P balances we report here are consistent with previous studies. For perennial grasses, Obour et al. (2011) reported a negative P balance (−10.8 kg P ha^{-1} year^{-1}) in unfertilized bahiagrass managed for hay production in Florida; and Messiga et al. (2015) reported negative (ranging from −4.5 to −2.0 kg P ha^{-1} year^{-1}) and positive P balances (ranging from 2.0 to 26.0 kg P ha^{-1} year^{-1}) in grassland sites receiving lower and higher P fertilization, respectively, across Switzerland and Canada. For corn, P surpluses have been reported in continuous corn and corn-wheat systems fertilized with P (Zhang et al., 2020), while other studies reported P deficits in conventional corn in spite of P fertilization (Maltais-Landry et al., 2016). At least occasional additions of P fertilizer are usually necessary to avoid P limitation of corn and soybean yields in the Midwest United States (Boring et al., 2018).

The most uncertain terms in the P budgets we report here are atmospheric deposition of P and losses of P to leaching. Atmospheric deposition is relatively uncertain because it is based on just 1 year of sampling, and that sampling excluded dry deposition, but our estimate of 0.2 kg ha^{-1} year^{-1} would have to be vastly too low to be of consequence for the budget, and it is not far from other estimates in the literature. A review of 49 estimates of total P deposition (wet + dry) across the United States and Canada showed a mean of 0.42 kg ha^{-1} year^{-1} (Tipping et al., 2014). Our leaching losses are uncertain inasmuch as they are dependent on interpolation between fall and spring samples of concentration combined with modeling to estimate drainage rates. The observed leaching rates in the study have been analyzed previously (Hussain et al., 2021), who noted that they overlap with or are lower, but not greatly so, than those reported by other studies in agricultural systems of widely varying P management and soil characteristics (Sims et al., 1998). Despite their uncertainty, the estimated leaching losses were insignificant in the P budgets presented here, even though the P concentrations in drainage water may be high enough to be a concern for eutrophication of surface waters (Hussain et al., 2021).

Initial STP concentrations were high and variable (Figure 1a), and well above the agronomic P minimum recommended for corn. The high concentrations probably reflect legacy P that accumulated in the soil over decades of manuring and fertilization of grain crops prior to the establishment of the experimental treatments. As noted in the methods, farm records dating back to 2003 indicate that this site had received high P application rates for at least 5 years before the start of the experiment.

Over the 7 years of crop production studied here, total P removal by harvest in the unfertilized perennial crops (Table 1) was quite similar to the observed decrease in STP in these cropping systems (Figure 1a). In switchgrass, cumulative removal of 39.6 kg P ha^{-1} from 2009–2015 by harvest (Table 1, Figure 1b) corresponded with a decrease in STP of 52.5 kg P ha^{-1} (initial minus final STP; Figure S3) between autumn 2008 and autumn 2015. Similar comparisons for miscanthus and poplar show harvest P removals of 68.6 and 39.0 kg P ha^{-1} compared with STP decreases of 72.5 and 37.5 kg P ha^{-1}, respectively.

5 | CONCLUSIONS

When managed for bioenergy production without P fertilization, switchgrass, miscanthus and poplar systems showed significant removal of legacy soil P by biomass harvest, resulting in net negative P balances. Conventionally managed corn receiving P fertilizer at rates recommended for the region showed a slight net positive P balance despite higher P removal by annual harvest. Leaching losses of P were not clearly affected by the progressive decrease in STP (Hussain et al., 2021), and the contribution of leached P in the P budgets was relatively insignificant, as was atmospheric deposition. Successive years of the harvest of perennial cropping systems without P fertilization can remove legacy P from soils, but will eventually reach the point of P limitation of crop production.

Our observation that harvest of the unfertilized perennial cropping systems will eventually draw down soil P to the point where fertilization may be required underscores the potential value of recovering P (as well as other elements, particularly potassium and nitrogen and possibly silicon for grasses) from bioenergy processing facilities and returning it to the fields to ameliorate nutrient limitation (Carey et al., 2016). Whether used to produce electrical energy or liquid biofuels or other speciality bioproducts, these elements would be a byproduct that could serve as a source of fertilizer in more or less the same elemental proportions needed for biomass production.

AUTHOR CONTRIBUTIONS

Mir Zaman Hussain: Performed research, data analysis and writing original draft. Stephen K. Hamilton: Conceptualization, methodology, supervision, and reviewing the draft. G. Philip Robertson: Conceptualization, project administration, and reviewing the draft.

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CONFLICT OF INTEREST

The authors declare no conflicting interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study is available in Dryad https://doi.org/10.5061/dryad.dfn2z355r.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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