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Management options to reduce phosphorus leaching from vegetated buffer strips

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Abbreviations:

VBS – vegetated buffer strips

P – phosphorus

Pox – ammonium oxalate-extractable soil phosphorus

TP – total soil phosphorus

TPw – total water-soluble soil phosphorus

PET – potential evapotranspiration

Keywords: vegetated buffer strips, phosphorus leaching, management, harvesting, topsoil removal, P mining

Abstract

Vegetated buffer strips (VBS) between agricultural areas and surface waters are important retention areas for eroded particulate phosphorus (P) through which they may obtain critically high degrees of P saturation imposing high risk of soluble P leaching. We tested topsoil removal and three harvesting frequencies (once, twice or four times per year) of natural buffer vegetation to reduce P leaching with the aim to offset erosional P accumulation and high degrees of P saturation. We used a simple numerical time-step model to estimate changes in VBS soil P levels with and without harvest. Harvesting offset erosional deposition as it resulted in an annual ammonium oxalate-extractable P (Pox) reduction of 0.3 – 2.8% (25 cm topsoil content) in soils of the VBS, thus, with time reduced potential P leaching below the of 50 µg L^{-1} baseline. Topsoil removal only marginally reduced potential leaching at two sites and not anywhere near this baseline. The harvest frequency only marginally affected the annual P removal, making single annual harvests the most economical. We estimate 50 to 300 years to reach the P leaching baseline, due to substantial amounts of P accumulated in the soils. Even in high erosion risk situations in our study, harvesting reduced soil P content and the P leaching risk. We suggest harvesting as a practical and efficient management to combat P leaching from agricultural VBS not just for short-term reductions of dissolved P, but also for reductions of the total soil P pool and for possible multiple benefits for VBS.

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Nutrient application in intensive agricultural and livestock production areas amplified nitrogen (N) and phosphorus (P) losses to the aquatic environment (Sharpley et al., 1994; Kronvang et al., 2005a, 2009), with negative impacts on aquatic ecosystems (e.g. Correll, 1998; Smith et al., 1999; Scheffer et al., 2001). Mitigation of not only N losses from agriculture but also P losses to waterbodies has become a regulatory focus in many countries (e.g. in the EU, following the requirements of the Water Framework Directive; European Parliament and Council, 2000).

Vegetated buffer strips – the narrow, uncultivated transition zone between surface water and agricultural fields – reduce P losses by trapping P-rich soil particles originating from the field above (Peterjohn and Correll, 1984; Correll, 1996; Syversen and Borch, 2005; Hoffmann et al., 2009; Stutter et al., 2012; Schoumans et al., 2014). Due to their previous use as agricultural land and to P eroded from the field, many soils of VBS are, or quickly become P saturated (Meals et al., 2008). Nutrient recycling during plant senescence and increased microbial activity can further increase concentrations of mobile soluble P in the surface soil layers of VBS (Uusi-Kämppä, 2005; Stutter et al., 2009; Roberts et al., 2012). Consequently, critically high levels of P saturation may build up in soils of VBS (Stutter and Richards, 2012), and if no action is taken to remove P from the VBS, these can become localized areas of P leaching (Stutter et al., 2009). Thus, it has been recommended that P saturation should be counteracted by implementing appropriate VBS management (Osborne and Kovacic, 1993; Stutter et al., 2012; Roberts et al., 2012).

Topsoil removal is a common management measure for contaminated land restoration and was recently used to effectively removing soluble P in rewetted peatlands (Zak et al., 2017).

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Its potential for rapidly reducing the soil P content in VBS and thus counteracting P leaching is thus worth assessing.

Conversely, removing P bound in the plant biomass through harvesting is a simpler and less destructive strategy to mitigate P accumulation (Osborne and Kovacic, 1993; Stutter et al., 2009), and may prevent the increased P leaching associated with vegetation decay (Uusi-Kämppä, 2005). Phosphorus accumulation rates are highest in successional vegetation and it has been reasoned before that harvesting is necessary to keep removal rates high (Mander et al., 1997a; Mander and Lõhmus, 2006), thus cumulatively more P may be removed from the soil by several harvests during each growing seasons. However, an intermediate harvesting regime may represent a trade-off between harvested biomass and harvesting effort.

The objective of our study was to evaluate the usefulness of topsoil removal and harvesting as management methods to reduce P leaching over time in six VBS in Denmark. We applied three harvesting frequencies (once, twice and four times a year) in replicated plot experiments to explore if P removal varied with harvesting frequency and used a simple model to estimate the time it would take to remove P in soils of VBS via plant harvesting to a threshold leaching concentration of 50 µg P L^{-1}.

We hypothesized that: i) the threshold leaching concentration could be reached by both topsoil removal and harvesting; ii) harvesting could balance annual erosional P inputs to the VBS from adjacent fields; iii) an intermediate harvesting frequency would be most efficient in reducing soil P contents and iv) depending on the initial P status of the soil, reaching leaching concentrations below the baseline through vegetation harvesting would take decades to centuries.

Methods

Study sites and experimental design

We studied six VBS in two catchments (Spjald and Sillerup) in Denmark (Appendix 1, Fig. 1). The Spjald sites were dominated by sandy soils and the Sillerup sites by loamy soils. The VBS were approximately 12 m wide, with an old 2 m part established in the 1990s and a newer 10 m wide part established 2 to 22 years prior to the start of the experiment (Appendix 1, Table 1). Vegetation in all VBS was mixed, with tall herbs and grasses dominant in all Sillerup sites and Spjald 3, while Spjald 1 was dominated by a rich fen/wet meadow community and Spjald 2 by ryegrass (Appendix 1, Table 1). The experiment was initiated in July 2014 and lasted until November 2016 (for a timeline see Appendix 1, Fig. 2).

In each VBS, we applied five treatments in randomized 1 m² plots near each other: 1) Topsoil removal where the top 20 to 25 cm soil was removed in eight plots in July 2014, 2) harvesting down to 5 cm once a year in June, 3) harvesting twice a year in June and August, 4) harvesting four times per year (May, June, July and August) and 5) reference, no topsoil removal or harvesting (Appendix 1, Fig. 3). Treatment 2, 3 and 4 were replicated four times and treatment 1 and 5 eight times in each VBS. In the VBS with a clear distinction between the older 2 m part (at the stream bank) and the adjacent, newer 10 m part (Appendix 1, Table 1), four additional replicates of only treatment 3 (harvest twice a year) and 5 (the reference) were established in the older 2 m part due to restricted space. In all harvested experimental plots depth-integrated soil samples were taken as composite samples of five soil cores down to 25 cm using an auger of 2 cm in diameter in November in 2014 and 2016.

We took 10 to 14 soil samples per VBS to perform a general characterization of soil texture and soil P status. These samples were taken as depth-integrated soil samples to 25 cm using an auger of 4.7 cm in diameter, in two transects placed perpendicular to the stream with

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three to four samples per transect within the VBS and two to three samples per transect on the adjacent field.

All soil samples from the experimental plots were dried at 40°C and sieved to <2 mm. Soil samples from the transects were dried at 105°C and bulk density was calculated by dividing the dry soil mass by the auger volume (433.5 cm^3).

Chemical analyses

Phosphorus concentration in the plant tissue was determined following standard methods as described by Anthon Paar and Perkin Elmer after microwave digestion (Anton Paar Multiwave 3000) of 100 mg dried plant sample under high pressure in a mixture of 4 mL nitric acid (65%) and 2 mL hydrogen peroxide (30%) on an ICP mass spectrometer (Perkin Elmer Optima 2000 DV OES).

Soil samples taken in 2014 and 2016 from the experimental plots were analyzed for total water-soluble soil P (TPw) by extraction of 1 g air dry soil (Appendix 1, Table 3: TPw data from the harvest treatments and control). Soil was rewetted with 1 mL deionized water for 24 hours, then subsequently at a final 1 g:50 mL, shaken end-over-end for 1 hour at 20°C followed by centrifugation for 10 min at 20°C with RCF at 1831 x g. The supernatant was analyzed for TPw content after peroxydisulfate oxidation according to the ISO standard for water analyses (ISO 6878, 2004). Plot samples from 2014 were also analyzed for total soil P (TP) after digestion of 0.100 to 0.120 g air-dried finely ground soil in a mixture of 2 mL concentrated (9.2 M) perchloric acid and 1 mL concentrated (18.4 M) sulphuric acid at 250°C until all perchloric acid had evaporated (Kafkafi, 1972). After cooling and dilution, P was determined colorimetrically using the molybdate reaction as for the TPw.

Soil samples for general VBS characteristics were analyzed for TP, TPw, soil texture (Gee and Bauder, 1986), pH in 0.01 $CaCl_2$, and ammonium oxalate-extractable P (Pox) according to Schwertmann (1964).

Calculations and statistics

Topsoil removal

We tested for the effects of topsoil removal on TPw concentrations by comparing reference plots and the treatments with topsoil removal from 2014 within each of the six VBS using an analysis of variance (ANOVA, *aov* function in R; R Core Team, 2017). Variance homogeneity and normal distribution of the residuals were given.

Mass balance calculations

Using R, we calculated a P mass balance for the harvesting treatments in all VBS based on measured soil P concentrations, plant tissue P concentrations and harvested plant biomass in 2016, net precipitation for the study catchments in 2016, the modelled P deposition for the studied VBS, and the calculated potential P leaching:

$$\Delta P\ mass\ soil = \ P\ offtake_{plants} - P\ leaching + P\ deposition\ [1]$$

All data are calculated per square meter, corresponding to the size of the experimental plots. Phosphorus deposition was modelled with the spatially distributed WaTEM tool (Van Oost et al., 2000) as annual rates of soil erosion from adjacent fields and sediment deposition to our studied VBS, assuming total retention and linear deposition locally. Net precipitation was calculated as the difference between precipitation and potential evapotranspiration (modelled the Soil and Water Assessment Tool (SWAT), after the Penman-Monteith method; Neitsch et al., 2011). Leaching was calculated based on TPw concentration of the plots and net precipitation. See Appendix 1, Table 4, for level and data origin of input variables and Appendix 2 for details on models and calculations.

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Numerical time-step model for predicting soil P in the VBS

The rationale for projecting the P mass balance modelling into the future was to elucidate if and at which timescales it is possible to reduce soil P levels below a P leaching concentration corresponding to a baseline of 50 μg P L^{-1}, solely by harvesting of plant biomass. The temporal analysis used a numerical model with a one-year time step to calculate the development of soil P mass for each plot within each VBS. For each year and plot, we based the removal of the soil P mass in the upper 25 cm on the soil P mass of the previous year. For the initial year (2016), we used the mass balance described above which uses 2014 P mass data as a starting point. For subsequent years, we used a net precipitation based on the annual mean from 1980 to 2016 to account for temporal variation, which depends, for instance, on temperature (see Appendix 2, section: net precipitation for details).

For P leaching, we assumed that, within each annual time-step of the model, 1 g of the considered soil could supply the same TPw concentration as reached per mL water in an equilibration of a 1 g soil:50 mL distilled water extraction. The mL water was based on the whole volume of net precipitation that passed through the topsoil.

Plant P offtake and potential P leaching were positively correlated with Pox in the soil (Appendix 2, Fig. 1). These correlations were used to predict the change of P leaching and plant P offtake in the time-step model after 2016. See Appendix 2 for further details on the model.

Error propagation for the mass balance and numerical time-step model

All errors reported are based on an error propagation using a Monte-Carlo simulation with 60,000 iterations in R. However, the error propagation of the numerical time-step model was done with 10,000 iterations only due to limited memory (32 GB) of the PC. We assumed normal probability distribution (expressed as standard deviation, *rnorm* function in R) based on means and measurement errors (either measured or estimated) for each variable. See Appendix 2, for details on the errors of all variables used.

Statistical evaluation of the data resulting from the error propagation

We accumulated the data on each harvesting regime and VBS by combining all probability distributions from all plots belonging to these groups. Based on the accumulated probability distributions, we calculated a median value (*median* function in R) and the 2.5% and 97.5% quantiles (*quantiles* function in R). Since these quantiles represent the lower and upper limit of the 95% confidence intervals of the probability distributions, we assumed that overlapping confidence intervals indicated that the distributions did not differ from each other with a probability of 95%. We used this solution since there is no formal test for Monte-Carlo based probability distributions due to the high number of random iterations used within the error propagation.

Results

General differences between the studied VBS

The VBS studied varied in initial plant composition, but the dominant species (mean abundance >10% per VBS) were overall similar in five of the six VBS. Spjald 1 differed the most in regard to plant composition as this buffer was wetter than the other VBS (Appendix 1, Table 1). Furthermore, Spjald 2 was dominated by perennial ryegrass (*Lolium perenne* L, Appendix 1, Table 1). Spjald 2 had the lowest and Spjald 3 the highest biomass production (263 versus 474 g dry matter per m^2, respectively), while the P concentration in the plant tissue was similar in all studied VBS (Appendix 1, Table 1). The soils of the studied VBS varied texture, parent material and topsoil Pox stocks, with Spjald 1 having the lowest and Spjald 3 the highest stocks (192 and 856 mg kg^{-1}, respectively, Appendix 1, Table 2).

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Topsoil removal

We found a significant effect (ANOVA, $p < 0.05$) of topsoil removal on TPw concentration (Fig. 1). This was due to reduced TPw concentrations after topsoil removal in two of the six sampling sites (Sillerup 1 and Sillerup 3); however, it did not suffice to reduce potential TPw leaching levels to the proposed baseline concentration of 50 µg L^{-1}. Phosphorus concentrations were below the baseline only in Spjald 2, in both the reference and topsoil removal plots.

Harvesting

Phosphorus concentrations in plant tissue ranged from 3.19 to 3.99 mg g^{-1} (Appendix 1, Table 1), and harvesting of the biomass in the buffers led to a median P removal varying between 0.5 to 2.4 g m^{-2} yr^{-1} (Fig. 2) in 2016. This P removal was larger than the modelled amount of P deposited in the VBS by water erosion-induced soil redistribution from upslope fields (up to 0.48 g m^{-2} yr^{-1}; Fig. 2) in all six VBS. We found no significant difference in the amounts of P removed according to the different harvesting regimes (Fig. 2, overlapping 95% confidence intervals from Monte-Carlo error propagation indicate $p > 0.05$).

P mass balance for the studied VBS

For 2014, we found substantial variation in topsoil Pox stocks between the six VBS (47 to 216 g m^{-2}, Table 1). Accordingly, harvesting reduced the topsoil Pox stock varyingly (by 0.3% in Spjald 3 and by 2.8% in Spjald 1; Table 1), while the VBS also received very different amounts of total P through erosion (ranging from 0 to 0.48 g m^{-2} yr^{-1}; Fig. 2).

We estimated potential TPw leaching amounts of 0.02 to 0.11 g m^{-2} yr^{-1} (Fig. 2), which translates into TPw leaching concentrations of 0.08 to 0.48 mg L^{-1} water (4.1 to 23.8 mg kg^{-1} soil). Although harvesting reduced P concentrations in 2016, the leaching concentration of a 50 µg L^{-1} baseline was not met in any of the VBS.

Prediction of harvesting effects on soil P by numerical time-step model

Since the harvesting treatments affected P removal similarly, we used the mean annual harvesting offtake for all harvesting treatments for each VBS to calculate model predictions (Fig. 3). The time-step model further incorporated the linear relationship identified between TPw (1 g:50 mL) and the topsoil content of the Pox pool (intercept: -11.21 (±0.80), slope: 0.82 (± 0.069), n = 79, adj. $R^2 = 0.64$, $p < 0.001$ in log-log space). Using the time-step model we found that it would take between 50 (Spjald 1) and 300 years (Spjald 3) of yearly harvesting of the plant biomass in the buffers to reduce topsoil Pox stocks to a concentration (21.16 g m^{-2}) whereby VBS leaching of P would be 50 µg L^{-1} or less (Fig. 3). Without harvesting of plant biomass, topsoil P was predicted to either decrease only negligibly or increase substantially, and none of the studied VBS would reach the 50 µg L^{-1} baseline within the next 300 years (Fig. 3). The error ranges for all input variables are shown in Appendix 2, Fig. 4.

Discussion

Topsoil removal

Although topsoil removal significantly affected the TPw concentration in two (Sillerup 1 and Sillerup 3) of the six VBS, the potential P leaching concentration of a 50 µg L^{-1} baseline was not accomplished. The baseline was only reached in Spjald 2, but since the effect of topsoil removal did not differ from the reference, topsoil removal has only insignificant effects. Accordingly, we rejected our first hypothesis that topsoil removal would reduce P concentrations to or below our chosen basline.

We removed between 20 and 25 cm topsoil, which is less than in other studies comparing the effects of removal/non-removal of top soil, all demonstrating that topsoil removal does affect soil P levels (Hölzel and Otte, 2003; Zak et al., 2017; 30 and 40 cm respectively). However, deeper removal would not have changed our results significantly since the soil P

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stock in the top 45-50 cm (20-25 cm topsoil removal + 25 cm soil sampling) was similar to that of the topsoil. These high P amounts throughout the soil column, also in deeper soil layers, are likely caused by residual effects of mixing following long-term erosional processes, a changing groundwater influence and stream overbank sedimentation burying historical plough layers.

We did not compare P reductions by topsoil removal with erosional P inputs as the former is a singular event and the latter a re-occurring process. Topsoil removal might offset erosional P inputs for a short period but depending on initial soil P levels and erosion rates the effect is only temporary. Topsoil removal is a high cost (>£2000ha −1; Manchester et al., 1999) and invasive technique, which probably disrupts some of the functionality that buffer vegetation provides, namely the stabilization of stream banks (Welsch, 1991; Dosskey et al., 2010), thereby increasing erosion risk of buffer zones in sloping terrain or during high flows. Establishment of a new vegetation cover after topsoil removal takes between four to eight years (Kiehl and Wagner, 2006; Klimkowska et al., 2010). Therefore, and based on our findings, we do not consider topsoil removal to be a suitable method for management of VBS other than for very special cases where P accumulation is restricted to the uppermost soil layers or when disturbance of soil and vegetation is inevitable e.g. due to construction of integrated buffer zones (Christen and Dalgaard, 2013; Zak et al., 2018).

Harvesting

In all the six studied VBS, P in the harvested plant biomass was found to offset the annual input of erosional P into the buffer, which supports our second hypothesis. The distinction in an old and a new part of the VBS did not influence the effect of harvest but was part of another aspect of a wider project and only mentioned to explain the differences in sampling size between the treatments. The amount of P retained in the plant tissue (5-24 kg ha^{-1} yr^{-1}, average 14 kg ha^{-1} yr^{-1}) was similar to that recorded for a riparian meadow in Denmark (Hoffmann et al., 2006; 15 kg ha^{-1}). The observed removal rates in the present study were slightly higher than those recorded in VBS in Finland (5-8 kg ha-1 yr-1; Uusi-Kämppä and Yläranta, 1996), wet meadows in Estonia (1.6-6.0 kg ha^{-1} yr^{-1}; Mander et al., 1997b) and fens in the US (1.7-9.3 kg ha^{-1} yr^{-1}, Carex ssp. only; Richardson and Marshall, 1986). These studies were conducted in more natural habitats with soil most likely exhibiting lower P levels and less productive plant communities. Studies conducted on P mining of soils with higher soil P levels via harvest found similar to slightly higher P removal (e.g. 28-40 kg ha^{-1} yr^{-1}: van der Salm et al., 2009; 11-27 kg ha^{-1} yr^{-1}: Noij et al., 2013). These studies mention a very high P removal efficiency in the long-term (> 60% after 3-5 years) however, in all these studies the P removal efficiency was only related to the dissolved P pool of the soil. The authors and also Koopmans et al. (2004) could thus show that harvesting efficiently reduces leaching already in the short-term, but only as long as harvesting is maintained. In our study we could show that plant harvesting is furthermore able to remove 0.3 to 2.8% of Pox stocks of the topsoil and thus to reduce also the total soil P pool in the long-term, as we consider Pox as the pool that replenishes the soluble P pool which is leached. Thus, harvesting is able to directly reduce P leaching risks and if applied long-term can permanently abolish the risk of P leaching from the VBS since soil P levels can be reduced to the point where a low leaching concentration can be maintained, even if harvesting is stopped.

P removal in our study is within the range measured in single hay harvesting experiments in natural fens and meadows in the Netherlands and Belgium (0.5-3.0%; Venterink et al., 2002). Our study results and those of Venterink et al. (2002) combined suggest that net P removal occurs and that a maximum annual P run-down of around 3% can be expected in

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consequence of biomass harvesting irrespective of vegetation type (natural fen-like vegetation or common plant species in agricultural VBS).

Contrary to our third hypothesis, we found that almost the same reduction of P levels was achieved by one harvesting and multiple annual harvests, which is due to the reduction in biomass yield per harvest when repeated during the growth period (Appendix 1, Fig. 4). We expected to find a reduction in P yield when going from two to four annual harvests due to exposure of the vegetation to elevated stress, but our results showed that the P yield decreased already when shifting from one to two annual harvests. From a management viewpoint, this is a positive result since it is more economical to harvest only once at the peak of the growth period than multiple times a year. We harvested between 263 and 474 g m^{-2} of dry plant material in the buffer zones (Appendix 1, Table 1), at a cost of 16 \$ t^{-1} for harvest and 5.90-7.55 \$ t^{-1} for transport (as established for riparian buffer strips sown with switchgrass; Turhollow, 2000); harvesting once a year would thus cost approximately 5.8 – 11 \$ ha^{-1} (not including labor and machinery costs). However, costs are dependent on yield (Turhollow, 2000) and yields in our study were only about one twentieth of the yields in Turhollows study that applied an energy crop instead of using semi-natural vegetation in the VBS.

Further implications of harvesting

Harvesting is easier and economically more feasible in wide VBS as it allows use of machinery both efficient and gentle to the soil and vegetation. Thus, P removal by harvesting encourages establishment of wider buffers for production of, for instance, a species-rich hay crop and use of the harvested material for biogas, green manure or, in the future, high-quality, refined bio-based products. Wider VBS would also add further value to the landscape in that they promote diversity (Castelle et al., 1992, 1994; McCracken et al., 2012) by permitting natural communities to develop under less influence from the cultivated land and that they strengthen the retention of other nutrients and pesticides (Rasmussen et al., 2011). Direct grazing in buffers could conflict with diffuse pollution mitigation aims, except for low-intensity grazing restricted to autumn/winter (McCracken et al., 2012), minimizing the impact of animal presence and benefitting diversity in the VBS.

Factors influencing P removal by harvesting

The relative annual reduction in Pox depends largely on the initial Pox mass of the soil but also on P amounts transported into the VBS by erosion; reductions being highest at initially low Pox conditions (Spjald 1). In our study, we had a wide range of soil Pox levels (192 to 855 mg kg^{-1} Pox) and found the lowest plant offtake (0.48 g m^{-2} yr^{-1}) in the VBS having one of the lowest soil Pox levels (Spjald 2) dominated by a single grass species (*L. perenne* L.). Higher offtakes were found in VBS with higher Pox levels dominated by taller grasses and herbs (tall oat-grass: *Arrhenatherum elatius* (L.) P.Beauv. ex J.Presl & C.Presl, ground-ivy: *Glechoma hederacea* L., Sillerup 1 and 3), indicating that more productive communities could incorporate more P. We found that plant P offtake depended on soil Pox levels (see description of the numerical time-step model in Appendix 2) and used this fact in the time-step model to progressively reduce the vegetation P offtake as soil P mining proceeded at each annual step. In soils, dissolved P is directly available for uptake by plant roots, which we found to correlate with soil Pox (Appendix 2, Fig. 2). Again, from a management viewpoint, this is a positive result since the effects of regular harvesting of the standing plant biomass will be highest in VBS with high P levels and high risk of leaching.

P leaching threshold

We focused on potential leaching from topsoil, thus assumed that all P leaves the VBS in dissolved form. The chosen TPw baseline of 50 µg P L^{-1} is comparable with the standards for UK streams, where soluble reactive phosphate (28-52 and 52-91 µg L^{-1} in, respectively, low

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and high alkalinity classes for lowlands) is a key parameter for the good ecological status of streams (UK TAG, 2013). Long-term (1989-2002) measurements in Danish forested streams with low anthropogenic pressure had an average TP level of 53 µg L^{-1} (Kronvang et al., 2005b) and water-dependent fen and meadow vegetation in Danish riparian areas favored in-stream TP concentrations of below 40 to 50 µg L^{-1} (Baattrup-Pedersen et al., 2011). Since, only around 50% of the TP concentration in streams is in dissolved form, our chosen leaching objective could still be twice as high as necessary to achieve near-natural, in-stream P concentrations. However, in an intensively agricultural environment such as Denmark (Kronvang et al., 2008), baselines much below 50 µg L^{-1} would not be realistic.

Numerical time-step model

With our simple time-step model, we found that harvesting not only offset erosional P inputs but eventually also reduced P leaching below the baseline of 50 µg L^{-1} in all VBS. Without removal of P by harvesting, our model suggested that half of the studied VBS would accumulate more P due to deposition, which would endanger the aquatic environment through high P concentrations in the leachate. Thus, harvesting promises to be an efficient method for reducing P amounts in VBS compared to the current management practice that does not involve removal of plant biomass.

Broad error ranges characterize the predictions by the numerical model and this should be borne in mind when predicting the success of harvesting in reducing P leaching from VBS. For example, the median prediction for the VBS Spjald 2 suggested that 50 years of harvesting were needed to reach the 50 µg L^{-1} threshold. However, based on the error propagation during the model runs, the confidence interval for Spjald 2 is 25-165 years. The model assumes a linear correlation between TPw and Pmass for the whole prediction period, since the studied soils span a wide range of TP/ Pmass and this range was maintained during the prediction period.

Our model is simple and does not consider factors such as climate and the resulting land-use change (although land-use change is believed to have only minor effects on P loads in Denmark; Molina-Navarro et al., 2018), even though these may affect input variables such as net precipitation and erosional P inputs. Furthermore, did the model only consider erosion from the field beyond the buffer, while stream bank erosion did not enter into the calculations. Consequently, our model cannot be used to predict time-scales of P removal from VBS precisely. Furthermore, all our calculations are based on topsoil measurements only, whereas P removal from subsoils is not considered. Depending on whether soil water flow paths are shallow or go deeper, P leaching from subsoils could offset some benefits of the topsoil P run-down. Under such a scenario, the time-scales of P removal might become even longer than predicted by the time-step model. Yet, considering the marked differences between the current management and the harvesting scenarios, the model clearly shows the high risk of diffuse nutrient pollution of the aquatic environment by unmanaged VBS; a risk that could be greatly diminished by harvesting.

Conclusions

Topsoil removal had limited success of reducing predicted P leaching and we conclude that due to its disruptive nature this method should only be implemented where P accumulation is restricted to top soil layers or where disturbance of the VBS is acceptable or taking place anyway.

Harvesting offsets erosional transport of P into VBS and reduces the soil P content, diminishing the risk of P leaching permanently in the long-term. It may take several centuries before lower P leaching from VBS results in semi-natural stream P levels, but from the

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moment that harvesting is implemented it can outbalance erosional P inputs and attenuate the P leaching risk in the critical near-stream corridor.

The number of annual harvests did not affect the P removal. Based on this, we recommend single annual harvesting as an efficient management method to mitigate P leaching from agricultural VBS. Reduction of P leaching to the aquatic environment by managing VBS using a suite of in-field and field-edge measures, among which harvesting would be highly useful, could produce multiple benefits compared with the current unmanaged situation. However, regular harvesting could also affect biodiversity as well as community composition and thus plant P uptake in the VBS and would need further research.

The model used in this study to illustrate the reduction of P leaching is very simple but clearly demonstrates the benefit of harvesting, but it is not suitable to predict accurate timeframes. More detailed models with broader input data would be needed to give better predictions on long-term P mining effects in VBS.

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Supplemental material

Details on calculations as well as nine figures and four tables are available in two appendices online.

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Figures captions:

Figure 1: Boxplots of total water-soluble soil phosphorus (TPw) concentration measured in 2014 in the six vegetated buffer strips (VBS) with and without (reference) topsoil removal (upper 20-25 cm) and without harvesting. There is a strong significant difference (ANOVA, $p<0.001$) in the amount of TPw between VBS and a weaker significant difference between the treatments (ANOVA, $p <0.05$). Horizontal lines indicate the median, boxes the interquartile range, whiskers the 95% confidence interval and circles outliers of the data. The dashed horizontal line corresponds to a TPw concentration of a 50 µg L^{-1} baseline in the leachate.

Figure 2: Boxplots of calculated change in soil phosphorus (P) mass in 2016. Panels are a) to c) Sillerup 1-3 and d) to f) Spjald 1-3. H1 = harvest once per year, H2 = harvest twice per year, H4 = harvest four times per year (measured as P concentration and weight of the plant tissue), E = erosion (P deposition into the vegetated buffer strip – VBS, modelled), L = leaching from the VBS (calculated). P in H1 to H4 = total P mass (TP) removed from VBS in plant tissue. P in E = TP mass deposited in the VBS through erosion from the fields. P in L = soluble P mass potentially leached from the VBS. Horizontal lines indicate the median, boxes the interquartile range and whiskers the 95% confidence interval of the data. Overlapping whiskers indicate $p > 0.05$. For a better visualization of the L and E data please refer to Appendix 1, Fig. 5.

Figure 3: Numerical time-step model for the annual median amount of ammonium oxalate-extractable P (Pox) mass in the vegetated buffer strips over the course of 300 years, with

harvesting of the biomass (solid line) and without harvesting of the biomass (dashed line). Panels are a) to c) Sillerup 1-3 and d) to f) Spjald 1-3. Dark grey and light grey areas indicate the 95% confidence interval of the data. The dotted horizontal line corresponds to a total water-soluble P (TPw) concentration of a 50 µg P L^{-1} baseline in the leachate.

630 *Table 1: Median (min - max of the 95% confidence interval) of ammonium oxalate-extractable phosphorus (Pox) mass in the experimental plots in*
631 *2014 and Pox mass balance and annual change in Pox mass in 2016 in each vegetated buffer strip and harvest treatment. Pox is calculated from*
632 *total soil phosphorus (TP) via a correlation, depending on soil type (see Appendix 2, Fig.3). Mass balance is the erosional P input minus plant P*
633 *offtake and P leaching in 2016 (Figure 2).*

Buffer strip	Treatment	Pox mass 14 [g m^{-2}]	Pox mass balance [g m^{-2} $year^{-1}$]	Annual change of Pox mass [%]
Sillerup_1	1 harvest $year^{-1}$	148 (63 - 181)	-1.0 (-1.3 - -0.8)	-0.79 (-1.27 - -0.51)
Sillerup_2	1 harvest $year^{-1}$	199 (154 - 234)	-1.4 (-1.7 - -0.9)	-0.71 (-0.97 - -0.39)
Sillerup_3	1 harvest $year^{-1}$	108 (80 - 136)	-0.8 (-1.1 - -0.7)	-0.74 (-1.11 - -0.54)
Spjald_1	1 harvest $year^{-1}$	59 (45 - 75)	-1.1 (-1.2 - -1.0)	-1.92 (-2.66 - -1.39)
Spjald_2	1 harvest $year^{-1}$	47 (19 - 133)	-0.3 (-0.6 - -0.2)	-0.66 (-1.36 - -0.42)
Spjald_3	1 harvest $year^{-1}$	217 (180 - 261)	-1.2 (-2.0 - -0.5)	-0.56 (-1.05 - -0.19)
Sillerup_1	2 harvests $year^{-1}$	129 (94 - 225)	-1.7 (-1.9 - -1.0)	-1.08 (-1.63 - -0.83)
Sillerup_2	2 harvests $year^{-1}$	154 (117 - 246)	-1.6 (-2.4 - -1.2)	-1.08 (-1.46 - -0.51)
Sillerup_3	2 harvests $year^{-1}$	102 (68 - 141)	-1.7 (-1.9 - -1.1)	-1.53 (-2.71 - -0.90)
Spjald_1	2 harvests $year^{-1}$	47 (38 - 58)	-1.3 (-1.4 - -1.3)	-2.82 (-3.46 - -2.38)
Spjald_2	2 harvests $year^{-1}$	51 (17 - 216)	-0.6 (-1.5 - 0.2)	-0.85 (-2.02 - 0.43)
Spjald_3	2 harvests $year^{-1}$	183 (94 - 253)	-0.7 (-2.8 - 0.3)	-0.30 (-1.40 - 0.25)
Sillerup_1	4 harvests $year^{-1}$	142 (96 - 232)	-2.4 (-2.8 - -1.5)	-1.31 (-2.91 - -1.09)
Sillerup_2	4 harvests $year^{-1}$	204 (145 - 255)	-1.4 (-2.1 - -0.8)	-0.72 (-1.04 - -0.39)
Sillerup_3	4 harvests $year^{-1}$	113 (77 - 148)	-1.9 (-4.3 - -1.4)	-1.83 (-3.96 - -1.09)
Spjald_1	4 harvests $year^{-1}$	64 (44 - 95)	-1.2 (-1.4 - -1.1)	-1.87 (-2.45 - -1.45)
Spjald_2	4 harvests $year^{-1}$	92 (32 - 226)	-1.1 (-1.5 - -0.6)	-1.13 (-2.10 - -0.64)
Spjald_3	4 harvests $year^{-1}$	204 (170 - 246)	-1.7 (-2.0 - -1.0)	-0.85 (-1.08 - -0.43)

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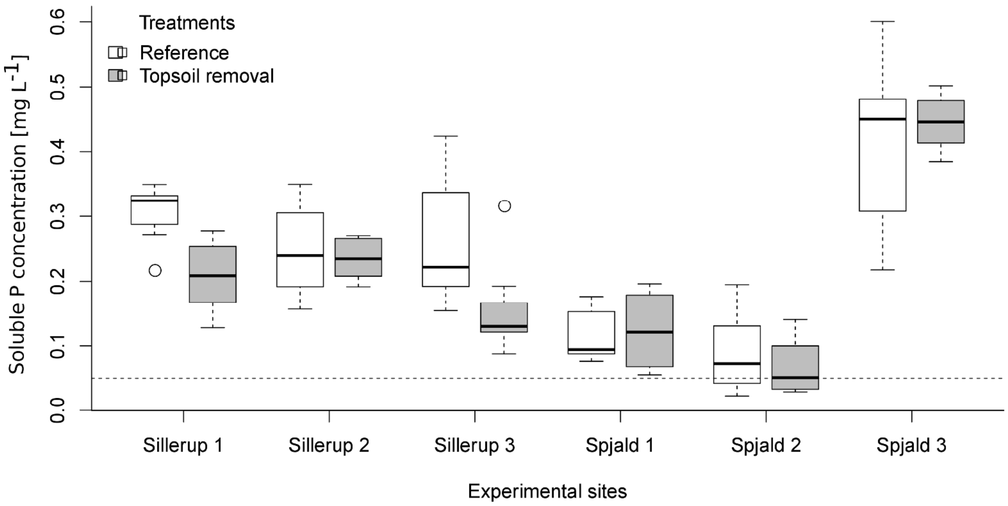

Boxplots of total water-soluble soil phosphorus (TPw) concentration measured in 2014 in the six vegetated buffer strips (VBS) with and without (reference) topsoil removal (upper 20-25 cm) and without harvesting. There is a strong significant difference (ANOVA, p<0.001) in the amount of TPw between VBS and a weaker significant difference between the treatments (ANOVA, p <0.05). Horizontal lines indicate the median, boxes the interquartile range, whiskers the 95% confidence interval and circles outliers of the data. The dashed horizontal line corresponds to a TPw concentration of a 50 µg L-1 baseline in the leachate.

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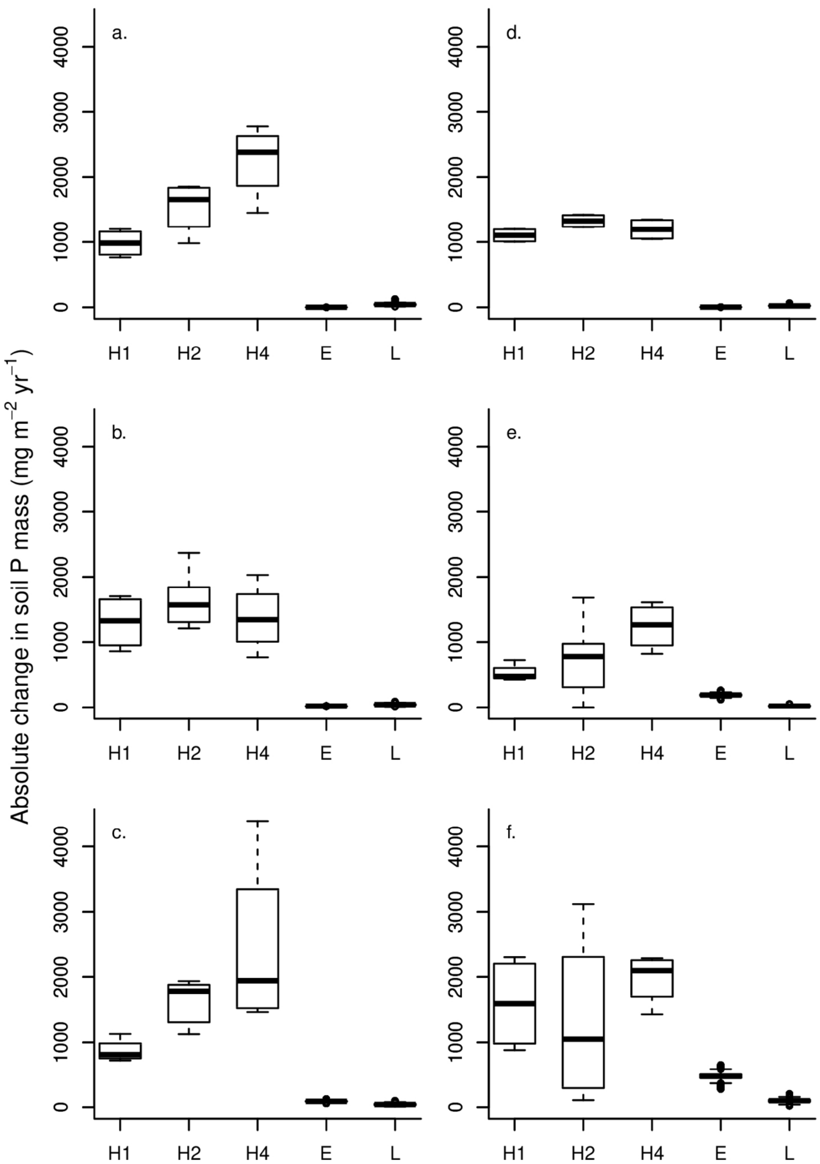

Boxplots of calculated change in soil phosphorus (P) mass in 2016. Panels are a) to c) Sillerup 1-3 and d) to f) Spjald 1-3. H1 = harvest once per year, H2 = harvest twice per year, H4 = harvest four times per year (measured as P concentration and weight of the plant tissue), E = erosion (P deposition into the vegetated buffer strip – VBS, modelled), L = leaching from the VBS (calculated). P in H1 to H4 = total P mass (TP) removed from VBS in plant tissue. P in E = TP mass deposited in the VBS through erosion from the fields. P in L = soluble P mass potentially leached from the VBS. Horizontal lines indicate the median, boxes the interquartile range and whiskers the 95% confidence interval of the data. Overlapping whiskers indicate $p > 0.05$. For a better visualization of the L and E data please refer to Appendix 1, Fig. 5.

127x177mm (300 x 300 DPI)

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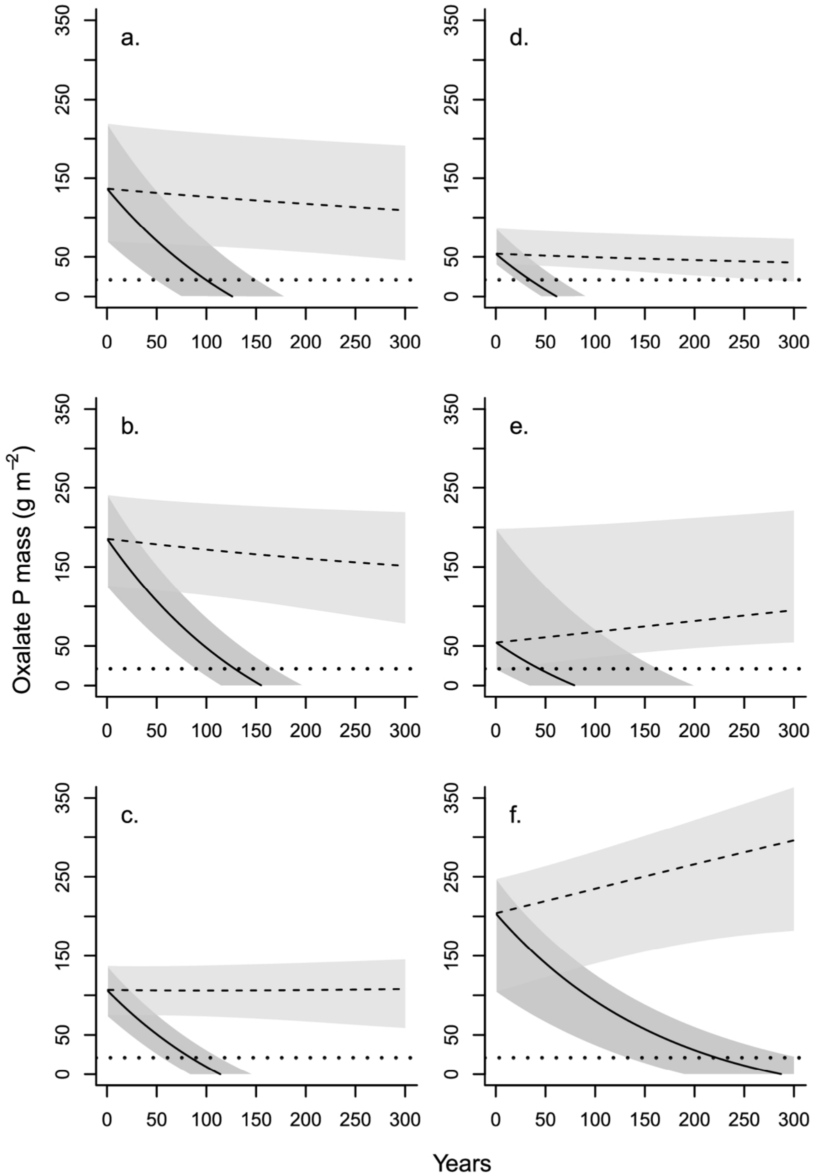

Numerical time-step model for the annual median amount of ammonium oxalate-extractable P (Pox) mass in the vegetated buffer strips over the course of 300 years, with harvesting of the biomass (solid line) and without harvesting of the biomass (dashed line). Panels are a) to c) Sillerup 1-3 and d) to f) Spjald 1-3. Dark grey and light grey areas indicate the 95% confidence interval of the data. The dotted horizontal line corresponds to a total water-soluble P (TPw) concentration of a 50 µg P L-1 baseline in the leachate.

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Appendix 1 to 'Management options to reduce phosphorus leaching from vegetated buffer strips'

Sandra Hille*, Daniel Graeber, Brian Kronvang, Gitte H. Rubæk, Nils Onnen, Eugenio Molina-Navarro, Annette Baattrup-Pedersen, Goswin J. Heckrath, Marc I. Stutter

Number of pages: 8

Number of figures: 5

Number of tables: 4

Abbreviations:

VBS – vegetated buffer strips

P – phosphorus

Pox – ammonium oxalate-extractable soil phosphorus

TP – total soil phosphorus

TPw – total water-soluble soil phosphorus

PET – potential evapotranspiration

BD – bulk density

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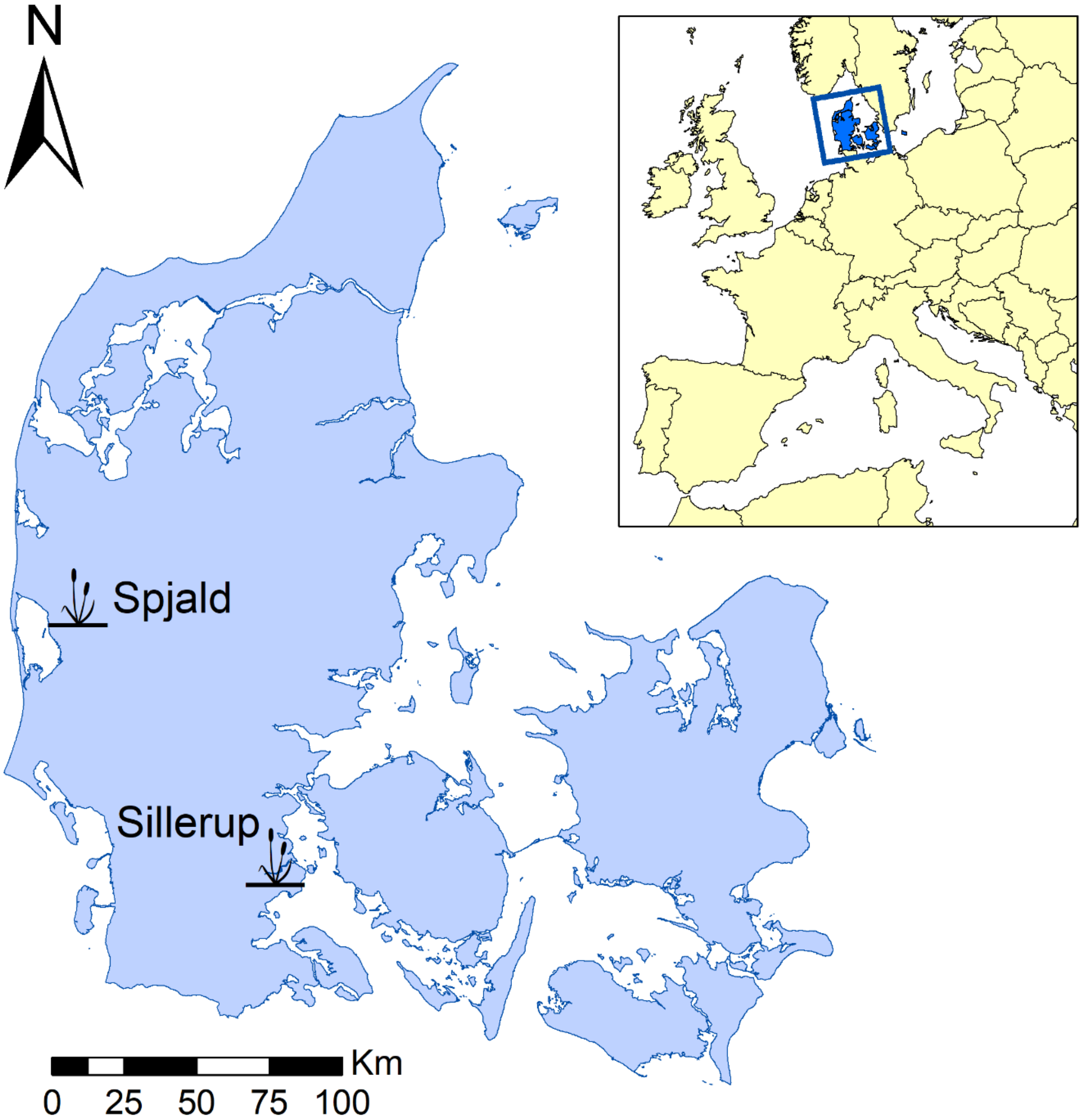
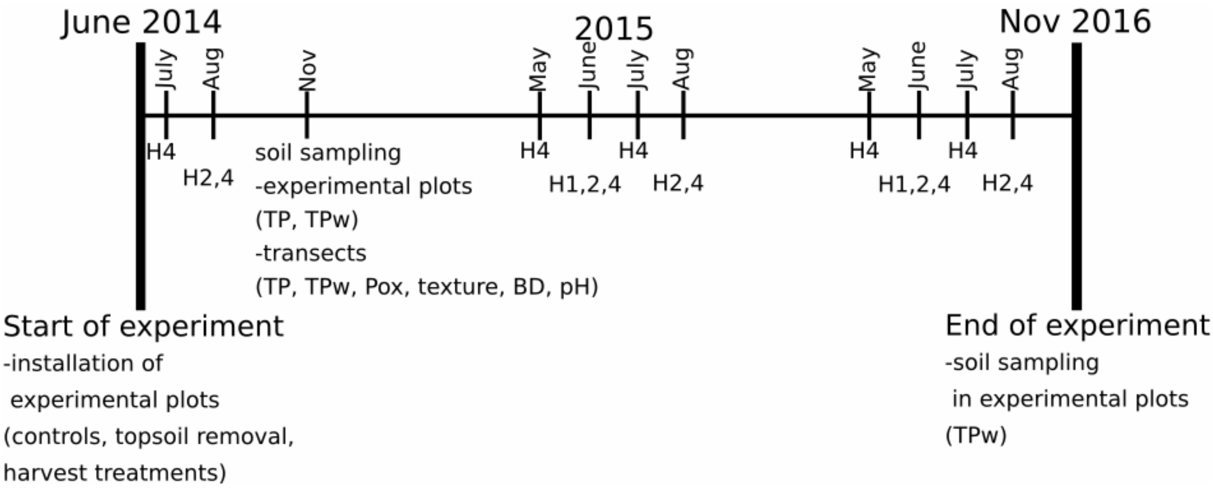
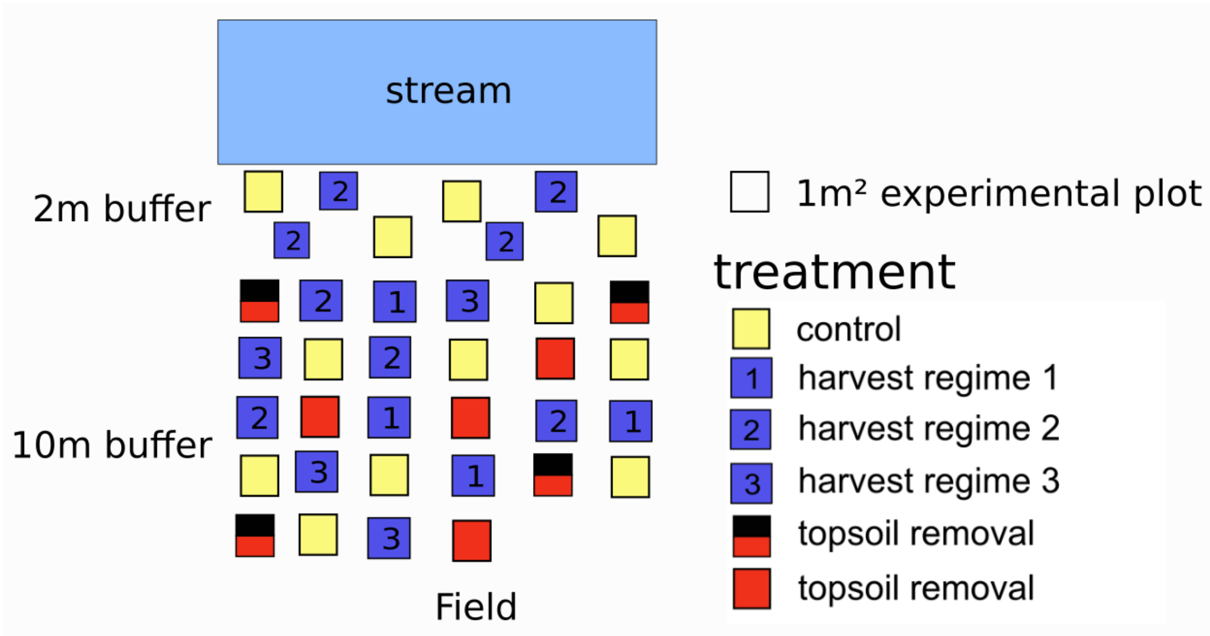


Appendix 1, Figure 1: Location of the sampling catchments within Denmark. Spjald vegetated buffer strips (VBS): 32N E 535315, N 6128263; Sillerup VBS: 32N E 467397, N 6217821.



Appendix 1, Figure 2: Timeline of the experiment. H1 = harvest once per year, H2 = harvest twice per year, H4 = harvest four times per year, TP = total phosphorus concentration, TPw = total water-soluble phosphorus concentration, Pox = ammonium oxalate-extractable phosphorus concentration, BD = bulk density.



Appendix 1, Figure 3: Experimental set-up treatments within vegetated buffer strips (VBS).

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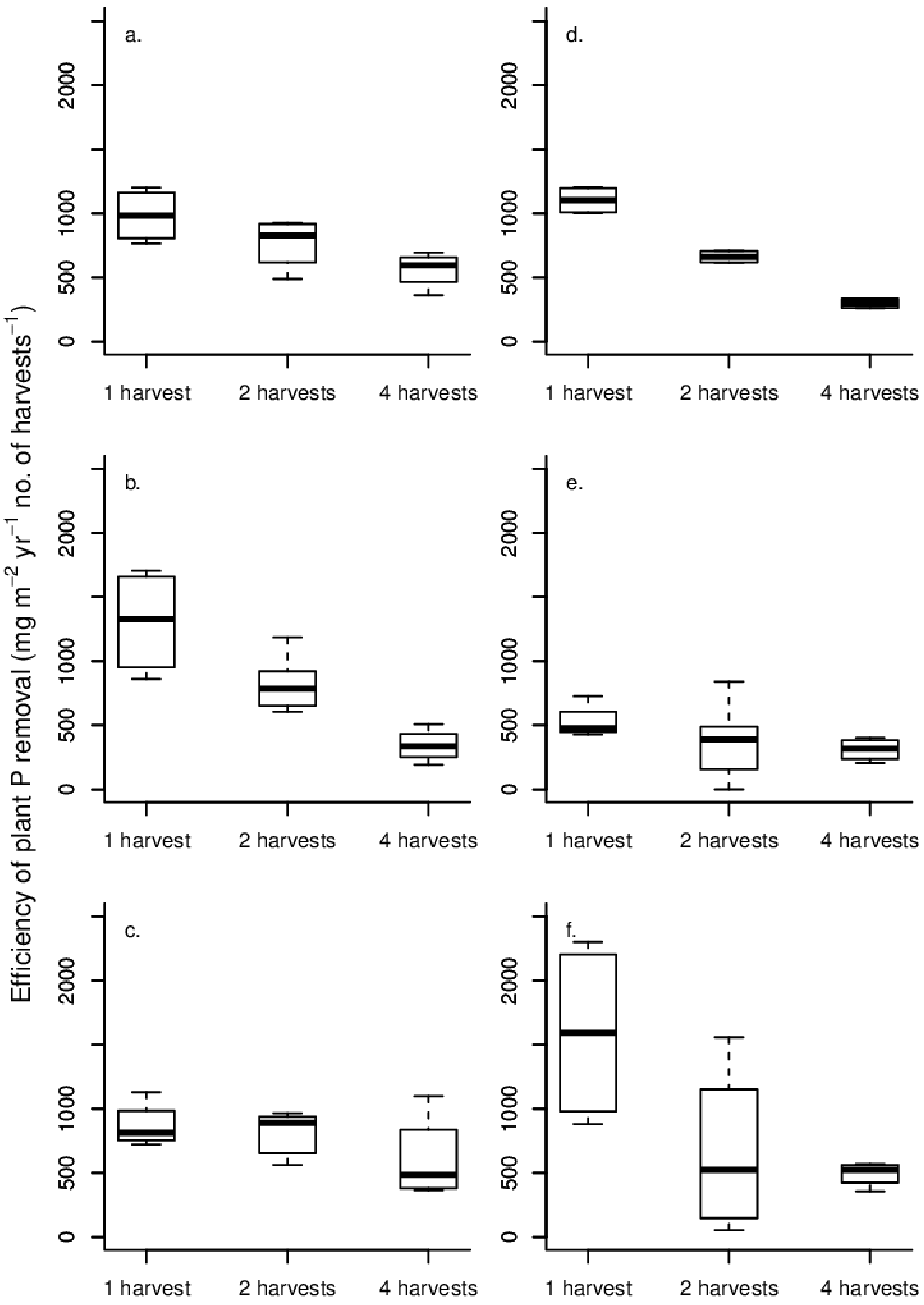
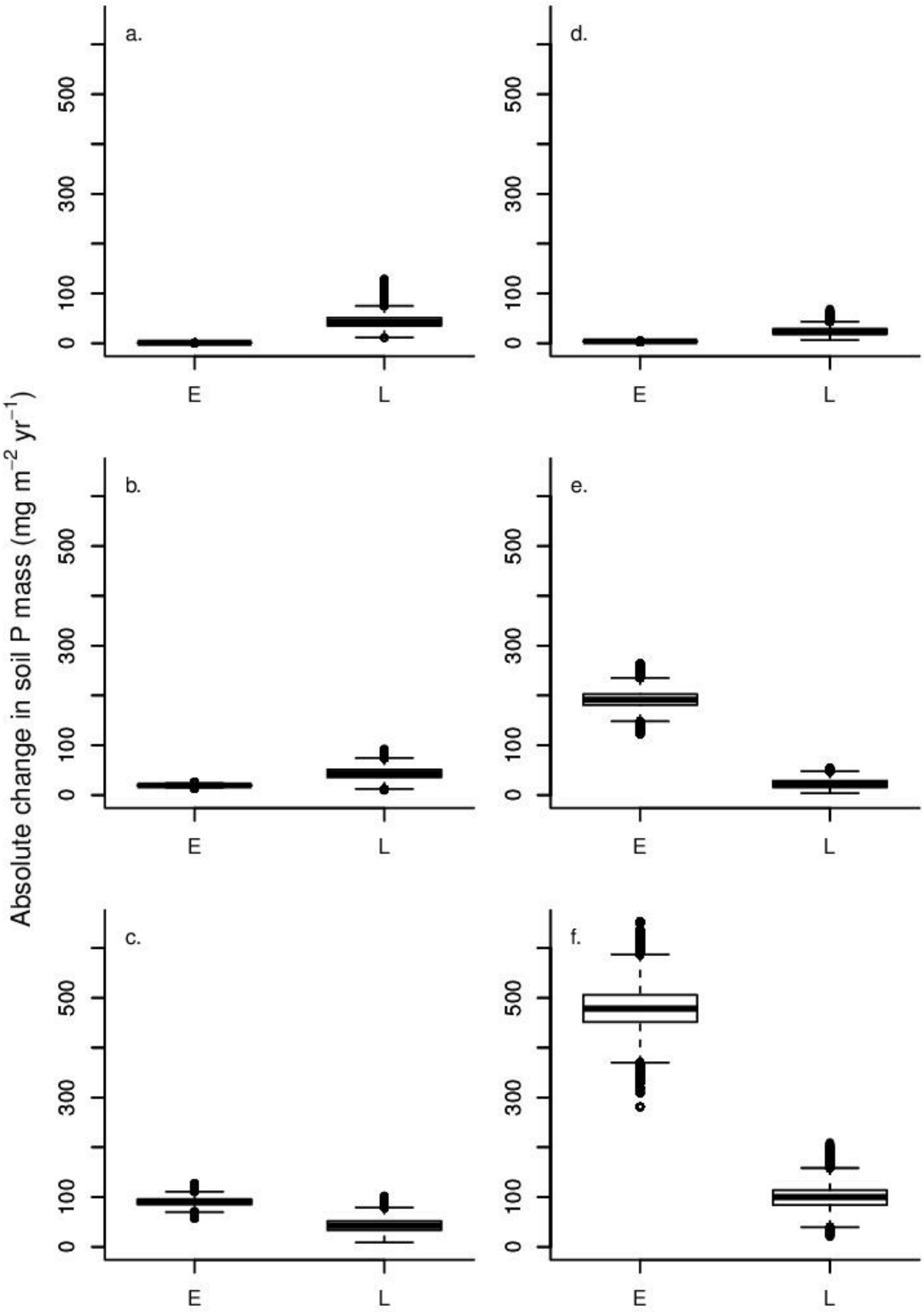


Appendix 1, Figure 4: Boxplots of phosphorus (P) plant offtake efficiency (plant offtake divided by number of harvests per year). Panels a) to c) are Sillerup 1-3 and d) to f) are Spjald 1-3. Horizontal lines indicate the median, boxes the interquartile range and whiskers the 95% interval of the data. Overlapping whiskers indicate p > 0.05.



Appendix 1, Figure 5: Boxplots of calculated change in soil phosphorus (P) mass in 2016 for the modelled erosion (E, refers to P deposition into the vegetated buffer strip – VBS) and calculated leaching from the VBS (L). Panels are a) to c) Sillerup 1-3 and d) to f) Spjald 1-3. P in E: total soil phosphorus (TP) mass deposited in the VBS through erosion from the fields. P in L: soluble P mass potentially leached from the VBS. Horizontal lines indicate the median, boxes the interquartile range, whiskers the 95% confidence interval and circles outliers of the data.

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Appendix 1, Table 1: General and vegetation characteristics of the six studied vegetated buffer strips (VBS). All VBS consisted of an old ca. 2m VBS (established in the 1990s), which was ca. 10 m wide in Sillerup 1 and Spjald 1, and a newer 10m VBS established from agricultural soil as indicated in the table for the other four VBS (and was missing in Sillerup 1 and Spjald 1). The average input of phosphorus (P) in agriculture in Denmark is 25 kg ha^{-1} (Blicher-Mathiesen et al., 2016), however, this is depending on animal density and can thus vary locally. The average annual temperature for both Sillerup and Spjald was 8.7°C (2001-2010; "Danmarks Meteorologiske Institut," 2017). Net precipitation = precipitation – potential evapotranspiration.

Buffer strip	**Buffer age**	**Crops on adjacent fields 2016**	**Mean (SD) length of field slope[a]**	**Mean (SD) field slope[a]**	**Sum (2016) or mean of sum (SD, 1980-2016) of annual net precipitation[b]**	**Number of experimental plots studied**	**Most dominant plant species[c]**	**Mean (SD) of plant biomass harvested 2016[d]**	**Mean (SD) of plant P concentration in 2016[d]**
			m	%	mm			g DW m^{-2}	mg g^{-1}
Sillerup 1	Old buffer (> 10 years)	Meadow	21.4 (2.0)	0.0 (0)	2016: 187 1980-2016: 313 (161)	12	*Arrhenatherum elatius* (L.) P.Beauv. ex J.Presl & C.Presl, *Dactylis glomerata ssp. glomerata* L., *Glechoma hederacea* L.	430 (125)	3.87 (1.08)
Sillerup 2	2/3 of buffer area converted in 2012	Grain	242.6 (4.0)	4.5 (3.6)	2016: 187 1980-2016: 313 (161)	15	*Arrhenatherum elatius* (L.) P.Beauv. ex J.Presl & C.Presl, *Lolium perenne* L., *Festuca rubra ssp. rubra* L.	422 (133)	3.96 (1.17)
Sillerup 3	2/3 of buffer area converted in 2009	Grain	144.5 (2.0)	4.6 (2.8)	2016: 187 1980-2016: 313 (161)	16	*Lolium perenne* L., *Arrhenatherum elatius* (L.) P.Beauv. ex J.Presl & C.Presl, *Taraxacum_sp.*	466 (138)	3.99 (1.44)
Spjald 1	Old buffer (min. 22 years)	Fallow	39.9 (2.7)	2.2 (0.5)	2016: 231 1980-2016: 433 (182)	12	moss sp, *Juncus effusus* L., *Festuca rubra ssp. rubra* L.	322 (126)	3.52 (0.98)
Spjald 2	2/3 of buffer area converted in 2011	Grain	297.1 (36.7)	3.5 (1.3)	2016: 231 1980-2016: 433 (182))	14	*Lolium perenne* L.	263 (130)	3.19 (0.77)
Spjald 3	2/3 of buffer area converted in 2011	Grain	77.6 (4.9)	2.6 (1.4)	2016: 231 1980-2016: 433 (182)	16	*Lolium perenne* L., *Dactylis glomerata ssp. glomerata* L., *Elytrigia_repens_ssp._repens* (L.) Gould	474 (300)	3.64 (1.14)

Notes: [a] These values were calculated based on 5 measurements of a digital elevation model in ArcMap 10.3.1 per VBS. [b] These values were calculated based on the catchment by SWAT. [c] As those species that have a mean abundance > 10% in each buffer zone. [d] These values are calculated from the number of experimental plots studied per VBS. For an overview over data sources and levels see #Appendix 1 Table 3.

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Appendix 1, Table 2: Soil characteristics of the six studied VBS. Soil type at location Sillerup: Luvisol and location Spjald: Podzol (Adhikari et al., 2014), but buffer zones consist of very disturbed materials without clear layering, so should probably all be characterized as Anthrosols (originating from differing parent material and eroded sediments from the adjacent fields). Values given are means of all experimental plots per buffer strip before the application of any treatments with SD in parenthesis. TC = total carbon concentration, TN = total nitrogen concentration, TP = total phosphorus concentration, TPw = total water-soluble phosphorus concentration, Pox = ammonium oxalate-extractable phosphorus concentration, BD = bulk density.

Buffer strip	**Soil character (parent material)**	**Soil pH 2014[a]**	**Initial soil nutrient levels in 2014**					**Soil texture in 2014**				**Soil BD[a]**
			Mean (SD) TC[b]	**Mean (SD) TN[b]**	**Mean (SD) TP[b] (H_2SO_4 extract)**	**Mean (SD) TPw[b] (organic and inorganic)**	**Pox[a] [mg kg^{-1}]**	**Humus[a]**	**Clay[a]**	**Silt[a]**	**Sand[a]**	
			---------g $100g^{-1}$---------		--------------------mg kg^{-1}-----------------			-------------------------%----------------------				
Sillerup 1	Clay and silt deposits (Clayey till)	5.4 (0.60)	3.42 (0.68)	0.32 (0.08)	958 (227)	13.46 (3.38)	573 (103)	5.4 (0.7)	23.7 (3.8)	15.6 (3.5)	55.4 (7.4)	0.85 (0.12)
Sillerup 2	Clay and silt deposits (Clayey till)	5.9 (0.36)	2.48 (0.25)	0.25 (0.02)	1069 (169)	12.51 (2.47)	732 (188)	4.3 (0.5)	22.2 (2.6)	14.0 (1.7)	59.5 (4.0)	1.00 (0.18)
Sillerup 3	Clay and silt deposits (Clayey till)	6.3 (0.54)	2.30 (0.48)	0.20 (0.04)	647 (77)	11.77 (4.51)	348 (96)	3.5 (0.8)	14.4 (2.9)	8.1 (2.0)	74.1 (5.1)	1.05 (0.32)
Spjald 1	Glacial sand and gravel deposits (Diluvial sand and till)	5.1 (0.25)	3.39 (1.72)	0.26 (0.12)	479 (128)	5.75 (2.16)	192 (35)	4.4 (1.7)	6.4 (1.5)	5.5 (1.5)	83.8 (3.3)	0.78 (0.16)
Spjald 2	Glacial sand and gravel deposits (Diluvial sand and till)	4.5 (0.41)	5.54 (2.89)	0.36 (0.22)	504 (337)	3.88 (2.56)	333 (274)	10.0 (5.9)	6.7 (2.3)	4.9 (2.3)	78.5 (10.2)	0.78 (0.36)
Spjald 3	Glacial sand and gravel deposits (Diluvial sand and till)	4.2 (0.55)	4.22 (2.23)	0.30 (0.14)	1027 (189)	21.04 (4.62)	856 (236)	6.1 (2.1)	5.9 (0.6)	5.9 (0.5)	82.2 (2.9)	0.96 (0.21)

Notes: [a] These values were calculated from 6-8 transect measurements per VBS. [b] These values are calculated from the number of plots studied per VBS (see Appendix 1 Table 1). For an overview of data-sources and levels, see #Appendix 1 Table 3.

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Appendix 1, Table 3: Median (5th and 95th percentile) of the total water-soluble soil P concentration (TPw) data from both 2014 and 2016 for all harvest treatments and control.

	TPw (mg kg^{-1})	
Treatment	**2014**	**2016**
1 harvest	9.3 (0.5 - 22.3)	12.6 (3.2 - 23.5)
2 harvest2	8.2 (0.6 - 19.7)	10.6 (3.8 - 23.6)
3 harvests	6.8 (0.6 - 18.7)	11.1 (1.8 - 24.1)
Control	8.7 (1 - 22.9)	11.6 (3.1 - 29.7)

Appendix 1, Table 4: Data source and level of input variables used for the mass balance. WaTEM: Water and Tillage Erosion Model (Van Oost et al., 2000) , DMI ("Danmarks Meteorologiske Institut," 2017), SWAT: Soil and Water Assessment Tool (SWAT2012 rev. 664), net precipitation: precipitation – potential evapotranspiration, VBS: vegetated buffer strip

Variable	Original data source	Original data level
Total soil P concentration (TP)	Measured	Experimental plot
Ammonium oxalate-extractable P concentration (Pox) of the plots	Calculated by correlation with total soil pool P	VBS
Total water-soluble soil P concentration (TPw)	Measured	Experimental plot
Plant P concentration in the tissue	Measured	Experimental plot
P mass through erosion	Potential sediment mass received by the VBS: Modelled (WaTEM), total P concentration in the field soil: Measured	VBS
Bulk density (BD)	Measured	VBS
Precipitation	Measured (DMI) and catchment aggregated (SWAT)	(10 x 10 km grid) Catchment
Potential evapotranspiration (PET)	Modelled (Penman-Monteith via SWAT)	Catchment
Potential P leaching	Calculated from TPw concentration and net precipitation	Experimental plot

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Appendix 2 to 'Management options to reduce phosphorus leaching from vegetated buffer strips'

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Number of pages: 14

Number of figures: 4

Number of equations: 10

Abbreviations:

VBS – vegetated buffer strips

P – phosphorus

Pox – ammonium oxalate-extractable soil phosphorus

TP – total soil phosphorus

TPw – total water-soluble soil phosphorus

PET – potential evapotranspiration

BD – bulk density

DOP – dissolved organic phosphorus

DIP – dissolved inorganic phosphorus

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Rationale for using TPw as leaching estimations

We focused this study on possibilities to manage the P stock in the topsoil of the VBS whereby in turn the losses of dissolved P from this soil layer to the aquatic environment can be reduced. We used TPw instead of only the dissolved inorganic phosphorus fraction since it has been shown that plants (Richardson et al., 2009) as well as phytoplankton (Cotner and Wetzel, 1992) can utilize the dissolved organic phosphorus fraction (DOP) as well as dissolved inorganic P (DIP). Furthermore has it been shown that more DOP (Andersen et al., 2016) and solid phase organically-complexed P forms (Stutter et al., 2012) are appreciable P forms in agricultural runoff and soils in Denmark.

The P leaching metric was governed by the linear relationship found between extracted topsoil TPw (1 g : 50 mL) and the calculated topsoil Pox pool ($n = 79$, adj. $R^2 = 0.64$, $p < 0.001$ in log-log space). Ammonium oxalate-extractable P has long been used as a soil test P index for assessing risks of runoff P (Pote et al., 1996); being a moderate strength extractant, it represents the potential exchangeable P that may partition into solution for leaching or plant uptake. The leaching we calculated within this study (0.08-0.48 mg L^{-1}) is potential TPw concentration transferred from riparian soils to watercourses, which is within the same range of dissolved total P concentrations in soil- and drainage water (0.007-0.6 mg L^{-1}) from 23 stations in five monitoring catchments in Denmark measured between 2008 and 2015 (Blicher-Mathiesen et al., 2016).

Calculations for mass balance

Uptake of P into plant tissue (*P offtake plants*) was calculated by multiplying the P concentration in the plant tissue with the harvested biomass

$$Pofftake_{plants} = Pconc_{plant\ tissue} * DW_{plant\ tissue} \quad [1]$$

Units: $$mgP = \frac{mgP}{gDW_{plant\ tissue}} * g$$

were $Pconc_{plant\ tissue}$: concentration of P in plant tissue,

$DW_{plant\ tissue}$: dry weight of plant tissue harvested per plot

We then summed up all the harvests per plot within 1 year according to treatment, to get the total amount of phosphorous taken off the buffer for each plot.

We calculated the **P mass of the soil** (P mass soil) in mg for each experimental plot as:

$$P\ mass\ soil\ = \frac{Pox\ conc_{plot}}{1000} * BD_{site} * V_{soil}\ \ [2]$$

Units: $$mgP = \frac{mgP}{kg\ soil} * \frac{g}{cm^3} * cm^3$$

where $Pox\ conc_{plot}$: is the calculated Pox concentration (based on a soil type dependent correlation with TP, Appendix 2, Figure 3) from the experimental plot (1 m^2) expressed per unit mass (kg) of soil dry matter. The Pox was considered the measure for the soil P pool since it is a widely used measure of the potentially accumulated anthropogenic P added to the soil acting as the exchangeable P pool in P saturation indices (van der Zee and van Riemsdijk, 1988).

BD_{site}: is the mean dry BD of the buffer topsoil (the upper 25 cm, on VBS level, as a mean of BD measurements in 2 transects in each of the 6 different VBS studied, with 3-6 measurements per VBS),

V_{soil}: is the volume of the topsoil in the 1 m^2 experimental plot to 25 cm depth and 1000 is a conversion factor.

All mass balance calculations are based on the upper 25 cm depth of the topsoil since this was deemed as an appropriate layer for which P is accumulated by erosion and may be easily taken up via roots into plant biomass (rooting depth of the plants could be anywhere between 10 cm - some grasses and in general small specimen - and 1 m - tall herbs) and since soil samples for P concentrations were taken with a small auger down to ca. 25cm depth.

Net precipitation

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Daily precipitation data was derived from the Danish meteorological institute ("Danmarks Meteorologiske Institut," 2017) for each study location (Sillerup ad Spjald). Potential evapotranspiration (*PET*) was modelled with the latest version of the Soil and Water Assessment Tool (SWAT2012 rev. 664; SWAT is open source software and available to download at http://swat.tamu.edu). The Penman-Monteith method was used (Neitsch et al., 2011), basing *PET* calculations on temperature, solar radiation, humidity and wind speed data. The difference between precipitation and *PET* was used as a proxy of the net precipitation (Henriksen et al., 2003) on the catchment scale of the study locations to calculate the effective volumes for leaching through the topsoil.

$$Net\ precipitation\ =\ Precipitation - PET\ \ [3]$$

Unit: $\frac{L}{m^2 * yr}$

P Leaching

In the calculation of the leaching component of the plots and for setting baseline thresholds for leaching, we used TPw (Hooda et al., 2000). Annual **P leaching** (*P leach year*) for each experimental plot was calculated as:

$$P\ leach_{year} =\ TPw\ conc_{plot}\ * Net\ precipitation\ \ [4]$$

Units: $\frac{mgP}{m^2 * year} = \frac{mgP}{l} * \frac{l}{m^2 * year}$

where $TPw\ conc_{plot}$: is the water soluble total P concentration in a 1:50 extraction. Leaching for the mass balance was calculated from 2016 data of TPw and net precipitation.

Erosion (sediment mass field)

Amounts of eroded sediment were derived from Danish national water erosion modelling (Onnen et al., unpublished data), for each of the six different VBS. The national erosion modelling is based on the spatially distributed WaTEM tool (Van Oost et al., 2000), to estimate soil redistribution by water in the catchments.

The water erosion component in WaTEM is based on RUSLE (Renard et al., 1997) and calculates long-term average annual soil erosion rates:

$$E = R\ K\ LS2D\ C\ [5]$$

where *E* is the mean annual soil loss (t ha^{-1} yr^{-1}), *R* is a rainfall erosivity factor (MJ mm h^{-1} m^{-2} yr^{-1}), *K* is a soil erodibility factor (t h MJ^{-1} mm^{-1}), *LS2D* is the unitless two-dimensional slope-length factor accounting for convergent and divergent flow (Desmet and Govers, 1996), and *C* is a dimensionless crop management factor. The *C* factor scales the erosion risk associated with a given crop compared to bare fallow. Input data include long-term rainfall data from weather stations across Denmark typically for the period 1988 to 2012 for estimating the *R* factor. A national soil texture map (Adhikari et al., 2013) was used to derive the *K* factor according to Renard et al. (1997). A 10-m resolution digital elevation model (DTM) derived from LiDAR data (Rosenkranz and Frederiksen, 2011) is the input for calculating the *LS2D* factor (Desmet and Govers, 1996). The *C* factor is estimated from 10-year crop rotation data from a LPIS database. Additionally, the model used Basemap 2012 (Levin et al., 2012), a 10-m land use raster map of Denmark, to account for land use classes. WaTEM has been calibrated based on 10-year riverine sediment export data from 31 small catchments in Denmark and has previously been employed for estimating soil redistribution by water in various studies (e.g. Van Rompaey et al., 2005; Alatorre et al., 2010; Lieskovský and Kenderessy, 2014). Our model operates at a 10 m resolution, resulting in the best available data on soil redistribution by water erosion at national level in Denmark. The model setup produced two outputs: i) rates of net soil loss (erosion) or gain (deposition) for each grid cell (deposition rates), ii) sediment exported from fields recorded as sediment mass for all grid cells along the field border with fields (sediment export output). At our sites, erosion was never predicted in or directly adjacent to the VBS, only deposition.

At 10-m, the resolution of our model was too coarse to always distinguish the small VBS from surface water. Therefore, we could not specifically extract deposition rates for all VBS. In those cases, deposition in VBS was calculated based on the map of sediment exported from fields where gridded sediment export

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overlapped with VBS polygons. When both output maps overlapped with the VBS polygons, deposition was estimated as average of sediment export and deposition rates.

The grid cells (10x10 m) of the sediment export output that overlapped with our studied VBS show deposition as

$$\frac{t\ soil}{cell * year} = \frac{t\ soil}{100m^2 * year} \quad [6]$$

(where $t\ soil$ is the mass of the soil in ton).

While the output with deposition rates was modelled in

$$\frac{t\ soil}{ha * year}$$

We averaged both model outputs and converted to

$$sediment\ mass_{field} = \frac{1}{n}\sum_{i=1}^{n} grid\ cells \quad [7]$$

Units: $$\frac{kg\ soil}{m^2 * year} = \frac{1}{n}\sum_{i=1}^{n}\frac{kg\ soil}{m^2 * year}$$

At the fine spatial scale (1 m²) used in this study, other factors like roughness of the soil, residual cover, soil moisture, etc., would be influencing erosion/deposition and these are not included in the model. Thus, we decided on averaging per VBS as the best approach to estimate erosion for this study.

P mass of the deposited sediment (*P deposition*) was calculated by multiplying the mean modelled amount of deposited sediment in each VBS by the mean total soil P concentration (TP) measured for the field soil adjacent to each VBS. In this case, TP was considered as the pool for input to the buffer via erosion since within decadal timescales (as in our P run-down scenarios) this can convert into more reactive P pools, e.g. Pox or TPw.

$$P\ deposition = sediment\ mass_{field} * TP\ conc_{field} \quad [8]$$

Units: $\frac{mgP}{m^2*year} = \frac{kg\ soil}{m^2*year} * \frac{mgP}{kg\ soil}$

$TP\ conc_{field}$: total soil P concentration measured on the fields adjacent to each VBS.

Deposition was thus calculated for each VBS, not on plot level.

Mass balance

The **annual P mass balance** according to the different VBS treatments was then calculated for 2016 as:

$$\Delta P\ mass\ soil = P\ offtake_{plants} - P\ leaching + P\ deposition \quad [9]$$

Numerical model

Based on the annual P mass balance [9], the P mass soil was calculated for each time step in the numerical model as:

$$P\ mass\ soil_{t+1} = P\ mass\ soil_t - P\ offtake_{plants} - P\ leaching + P\ deposition \quad [10]$$

Plant P offtake and P leaching in the numerical time-step model

In the model, calculations for 2016 were based on the mass balance. For the years subsequent to 2016, we calculated P leaching and plant P offtake based on strong relationships between P leaching or plant P offtake with soil P mass (Appendix 2, Figure 1a) and b)). For this, we used linear models (*lm* function in R), correlating P leaching ($n = 79$, adj. $R^2 = 0.54$, $p < 0.001$, $\ln(\text{mg } P_{leach}\ yr^{-1}) = -4.41\ (\pm 0.90\ SE) + 0.74\ (\pm 0.08\ SE) * \ln(\text{mg } P_{Ox\ mass\ soil}\ m^{-2})$) and plant P offtake ($n = 79$, adj. $R^2 = 0.18$, $p < 0.001$, $\text{mg } P_{offtake\ plants}\ yr^{-1} = 713.8\ (\pm 182.6\ SE) + 0.0051\ (\pm 0.0012\ SE) * \text{mg } P_{Ox\ mass\ soil}\ m^{-2}$) with soil P mass. Furthermore, we calculated the soil P mass at which TPw concentration should be below the threshold of 50 µg P L^{-1} based on a linear correlation between both TPw and Pmass (Appendix 2, Figure 2, $n = 79$, adj. $R^2 = 0.64$, $p < 0.001$, $\ln(TPw\ \mu g\ P\ L^{-1}) = -11.21\ (+-0.80) + 0.82\ (+-0.069) * \ln(Pmass\ \mu g\ P)$. For the linear model of P leaching and soil P mass, as well as TPw concentration and soil P mass, the dependent and independent variable were log-transformed to meet the assumptions of the linear model.

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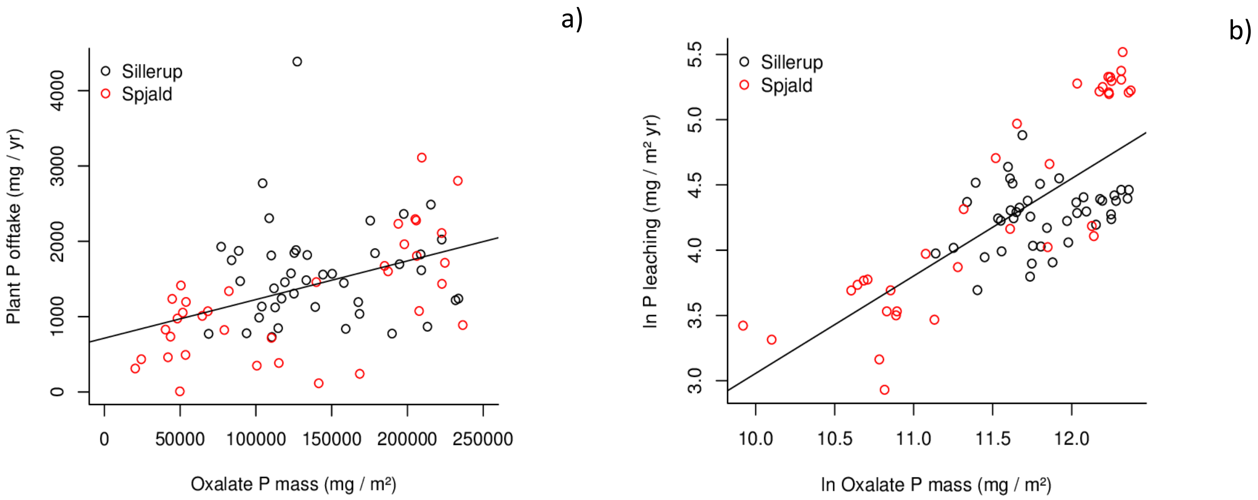
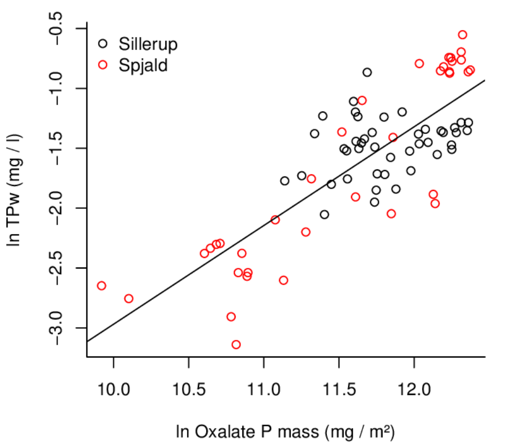


Appendix 2, Figure 1: a) Correlation between plant P uptake and ammonium oxalate-extractable P mass. b) Correlation between P leaching and ammonium oxalate-extractable P mass.



Appendix 2, Figure 2: Correlation between total water-soluble soil phosphorus concentration and ammonium oxalate-extractable P concentration.

Error propagation

Most calculations were done with an error propagation based on a Monte-Carlo simulation with 60000 iterations in R. However, the error propagation of the numerical time-step model was done with 10000 iterations only, due to limited memory (32 GB) of the PC used for the calculations. In all cases, we assumed normal distribution of the probabilities. This was generated by the *rnorm* function within R, based on means and measurement errors which were either measured or estimated to generate a probability distribution (expressed as standard deviation) for each variable. For precipitation we estimated a coefficient of variation of 1% (Allerup and Madsen, 1980) and for potential evaporation in 2016 a coefficient of variation of 5%. Here, we assumed a higher error for potential evaporation, since the model is based on five meteorological variables (Neitsch et al., 2011; see section 'Net precipitation' above). For precipitation and potential evaporation in 1980 - 2016, we used the standard error of the annual means as error, since these standard errors include both measured variability and measurement error.

We based the probability distribution of plant P concentrations on the median coefficient of variation of 124 measured recovery rates for phosphate standards (SCP science, Canada; median coefficient of variation = 1.69%). We assumed a very small error for the plant weights; hence, this was set to 0 for the error propagation.

To get an idea on the soil P available to leaching or plant offtake, we used Pox concentrations. However, Pox was not available from each of the experimental plots within the VBS, only from the general characterization of the buffer soils by transect sampling (see sections ‘Study sites and experimental design’ and ‘Chemical analyses’ in the main document). Therefore, we calculated Pox in our experimental plots based on the Pox measured in the transects in each VBS in a two-step process. In the first step, we calculated the probability distribution based on 18 samples, for which TP was measured twice. For each of the samples, we calculated a coefficient of variation. We used the median coefficient of variation to generate a probability distribution for all samples. In the second step, we calculated Pox based on a correlation between Pox and TP for transects from the field to the stream bank separately for the VBS in Sillerup and Spjald (Appendix 2, Figure 3a) and b)), because these variables were highly correlated, but slopes differed between the two locations (Sillerup: adj. $R^2 = 0.88$, slope = 0.83, $p < 0.001$, $n = 22$; and Spjald: adj. $R^2 = 0.81$, $p < 0.001$, slope = 0.86, $n = 22$). We also used the coefficient of variation calculated in

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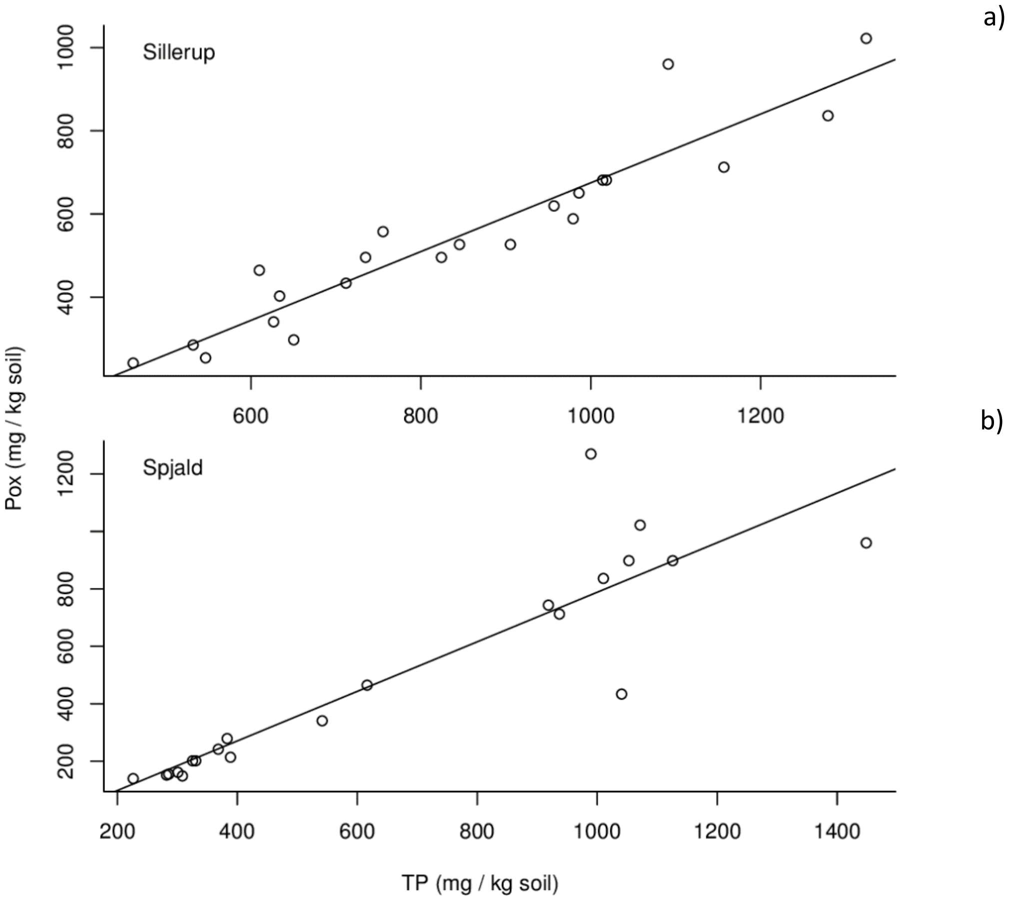
the first step to generate a probability distribution around the mean for values of TP and Pox used in the correlations, because we assumed measurement errors to be independent of location.



Appendix 2, Figure 3: Correlation between ammonium oxalate-extractable P concentration and total soil P concentration for both locations a) Sillerup and b) Spjald.

We calculated the probability distribution of TPw separately for each sample, as we had measurement repetitions available for each sample. Of the 142 samples measured replication was two, three and four replicates for 123, 14 and 2 samples, respectively.

We assumed an error for the erosion model of 8.4% as calculated from the transport capacity coefficient and its deviation for Denmark (Onnen et al., unpublished data) . That error does not necessarily represent an estimated error for the erosion model though, as it only takes one input factor of multiple factors into account. Nevertheless, based on the model we got an estimate of the amount of soil reaching the VBS.

We analysed duplicates for 23 soil samples from topsoil of the fields adjacent the VBS from the general soil characterization (see sections ‘Study sites and experimental design’ and ‘Chemical analyses’ in the main manuscript) to estimate the error associated with the soil TP concentration. The amount of P available to plant offtake and P leaching were estimated using the coefficients and their probability distributions from the linear correlations between TP and Pox as described above.

To calculate the soil Pox mass uncertainties we multiplied the Pox concentrations and their probability distributions by the BD of the soils and the probability distribution of the BD from three to four measurements per transect (see section ‘Study sites and experimental design’ in the main manuscript). We used the standard errors of the transect-wise mean BDs to calculate the probability distribution of the BDs for each of the sites within a VBS.

To include the errors of the linear correlations between plant P offtake and P leaching or plant P offtake and soil P mass in the numerical model we did models for all calculated solutions of the Monte-Carlo error propagation (60000 models each) and randomly picked one of these for each iteration within each time step of the numerical model (10000 models per time step) to calculate the range of model results for each time step. With this measure, we included the error of the linear model results into the numerical time-step model.

See Appendix 1, Table 4 for level and data origin of input variables.

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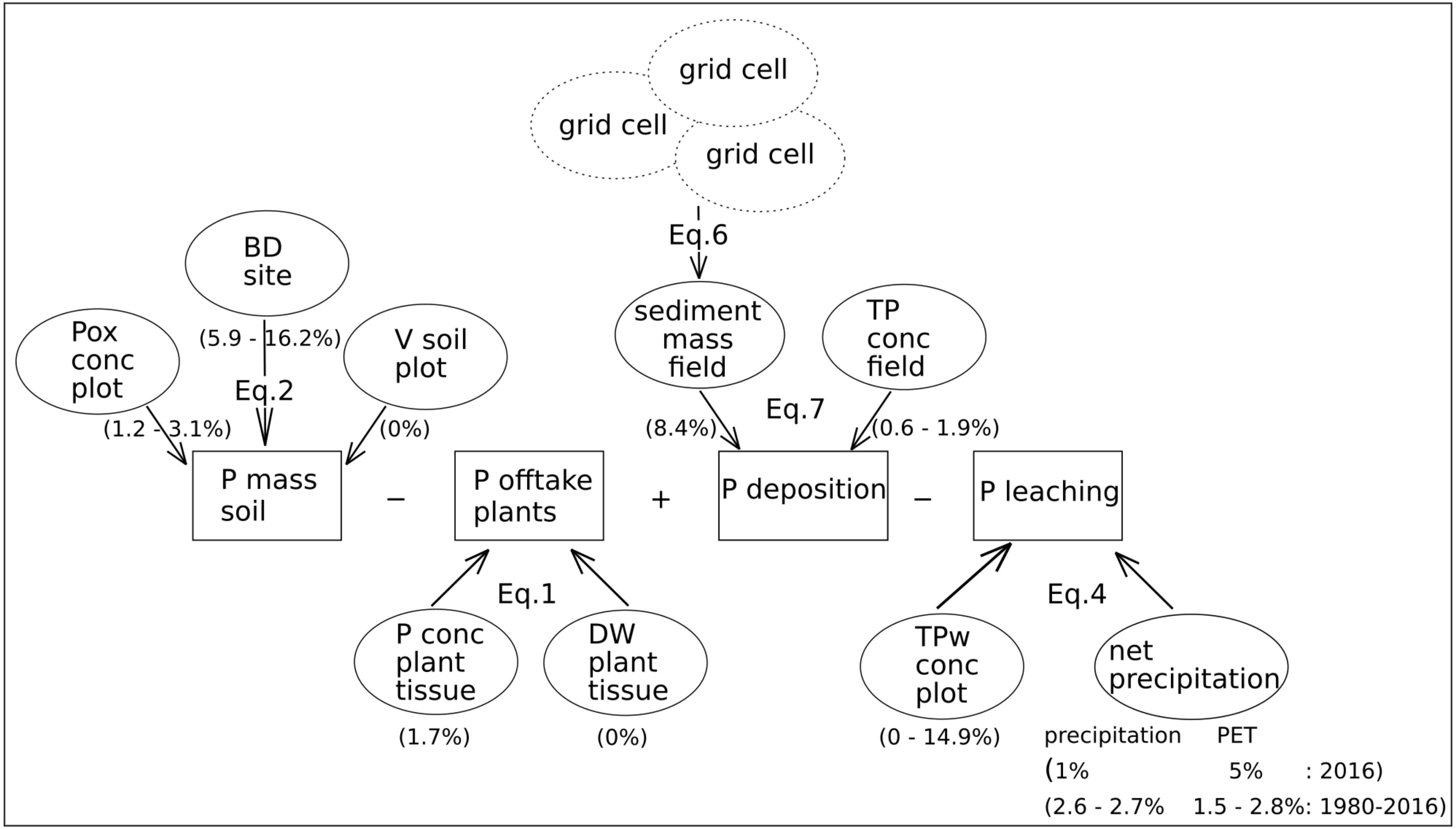

Appendix 2, Figure 4: Flowchart depicting the input variables for the phosphorus mass-balance used in the numerical time-step model in vegetated buffer zones (VBS). Errors are given in brackets as coefficients of variation (% of measurement) either as single number, if only one error figure was available, or as range if more than one coefficient of variation was available. Please refer to the description of the error propagation in this Appendix 2 for further details on the calculation of the errors. BD = bulk density, net precipitation = precipitation – PET, PET: potential evapotranspiration.

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