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Evaluating scenarios to reduce phosphorus transport in surface waters from slurry applications in temperate grasslands

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ABSTRACT
This study evaluates a range of scenarios to reduce soluble reactive phosphorus (SRP) losses using the surface runoff phosphorus transport model (Surphos) to simulate the application of liquid manure (slurry) to grassland catchments. Surphos was applied using data from two contrasting sites in the Republic of Ireland and Northern Ireland. It explored scenarios that investigated changes to the timing of slurry applications, based both on policy (i.e. a “closed” period where regulations prohibit any slurry spreading) and on climate-based restrictions, where soil moisture and antecedent rainfall were important factors. The observed data showed a considerable spatial variability in runoff at both sites, which resulted in a corresponding variable range of SRP losses predicted by the model. However, at both sites the model results showed that maintaining a closed period led to a greater reduction in SRP losses than opening this period up to slurry applications under climate-based restrictions.

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1 Introduction

Eutrophication of freshwater remains a significant environmental issue, with agriculture identified as a primary source of nutrients in many countries (Withers *et al*. 2014). Agricultural phosphorus (P) sources include topsoil and subsoil P stores (Schulte *et al.* 2010), farmyards, and inorganic and organic fertilizer applications, with Withers *et al*. (2003) reporting that surface applications of organic and inorganic fertilizers can potentially contribute 50–98% of the P load in runoff from many agricultural fields, primarily as dissolved forms. The investment in mitigation measures in many countries has reduced diffuse P losses from agriculture (Barry and Foy 2016); however, slurry application remains a high-risk practice, particularly in temperate maritime climates where there are episodic high rainfall events and low soil moisture deficit for much of the year, generating large volumes of overland flow (Doody *et al*. 2010). Over a four year period Doody *et al*. (2012) demonstrated that in Northern Ireland (NI) overland flow occurred on an average of 18% of days per month outside of the closed period for slurry spreading (15 October–31 January). On an annual basis, soils were saturated 24–36% of the year, while rainfall occurred on 110–145 d year^{-1}. O’Rourke *et al*. (2010) demonstrated that there was still a risk of nutrient loss 48 h after slurry application, with elevated nutrient concentrations recorded for more than nine days post application. Shore *et al*. (2016) reported high flow-weighted mean concentrations of P at the catchment scale, indicative of slurry applications during wet summers and in autumn. A study in the Republic of Ireland looked at climatic controls on slurry spreading and found that elevated losses would be associated with winter spreading in the northeast of the Island of Ireland (Holden *et al*. 2004).

A study by Bishop *et al*. (2005) found that the implementation of best management practices (BMPs) in a small (1.6 km^2) catchment in New York State resulted in reduced soluble reactive phosphorus (SRP) export. The BMPs included constructing additional manure storage so that manure would not have to be spread daily. At the regional scale, the study of Barry and Foy (2016) demonstrated the positive impact of a combination of incentivized and regulatory approaches on water quality in NI. The improvements observed by Barry and Foy (2016) arose after the European Union Nitrates Directive I (91/676/EEC) imposed limits on manure applications and/or closed periods from the 1990s onwards (Kleinman *et al.* 2015). In Norway, Bechmann and Stålnacke (2005) found that there was a significant decrease in total phosphorus (TP) export over a 16 year period in a small (114 ha) grassland catchment with dairy farming where manure spreading was restricted in winter. In the Netherlands manure spreading has been restricted by law since 1986 and since then agriculture has lowered P surpluses, with a downward trend identified in 76% of the 87 headwater catchments and no increases observed in any of them (Rozemeijer *et al.* 2014). In other Scandinavian countries there has also been an observed decline in P concentrations in streams and rivers; in southeastern Sweden (Ulén and Fölster 2007) this was observed over a 20-year period.

The aim of this paper is to evaluate the effectiveness of the current regulations controlling the application of slurry to temperate grassland, by modelling the edge of field P losses in surface runoff resulting from this practice using the Surphos model Vadas *et al.* (2007). In addition, the paper will consider additional measures to reduce these losses further post slurry application

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during high-risk periods. The paper uses the Nutrient Action Programme Regulations (DAERA 2019) and their application in NI as a starting point for this analysis.

2 Material and methods

2.1 Case study – Northern Ireland

In NI, agriculture has experienced over 30 years of government policy designed to improve water quality by implementing numerous nutrient-reduction measures and schemes (Barry and Foy 2016). Agriculture in NI is dominated by livestock farming, with 95% of agricultural land under grassland including rough grazing, with arable land accounting for <5%. Typical of regions with high animal densities, the region has a low P use efficiency (38%) (Withers *et al.* 2020). Phosphorus from animal manures exceeds total crop P demand by nearly 20% and the resulting P surplus (e.g. 12.4 kg P ha^{-1} in 2019) has led to a high P accumulation in the soil (7300 t $year^{-1}$) (Rothwell *et al.* 2020). A recent national soil sampling scheme demonstrated that 38% of NI soils are above the agronomic optimum soil P level of 20–25 mg L^{-1} Olsen P (Higgins *et al.* 2020).

A major step in legislating for nutrient load reductions in 2004 was the implementation of the EU Nitrates Directive, which designated NI as a "Total Territory" so that restrictions apply to the entire area (DOE-DARD 2004). This includes a restriction on the spreading of liquid manure (slurry) between 15 October and 31 January (termed the "Closed Period" (CP)), where the remainder of the year is termed the "Open Period" (OP). This directive also imposes spatial and temporal limits on the applications of slurry to minimize nutrient losses to water outside of the CP. The limits include restriction on slurry application when the soil is saturated or frozen, when rainfall >4 mm h^{-1} is predicted within 48 h and on steep-sloping land, which is defined in the directive. In 2006 the Phosphorus (Use in Agriculture) Regulations (NI) came into effect (implemented from 2007 onward) to limit application of chemical fertilizers. However, these restrictions did not apply to the application of manures. The Nitrates Action programme and P Use in Agriculture regulation have periodically undergone review since 2004, with the last review occurring in 2019 (DAERA 2019), when they were incorporated into a single programme renamed the Nutrients Action Programme (NAP). Due to on-going concerns about slurry application in the weeks following the CP, the new NAP programme imposed greater restrictions on application in February, including limiting application rates to 30 m^3 ha^{-1} (down from 50 m^3 ha^{-1}).

To explore the impact of the current NI NAP regulations on P losses post slurry application, this study employed modelling using field data collected from two studies on the island of Ireland which are described below (Fig. 1).

2.2 Study sites

The two selected study sites provide a range of different conditions to model P loss post slurry application and have good data availability in terms of physical parameters (e.g. soil properties) and hydrometeorology. Although these sites are quite similar in some aspects (e.g. soil types and climatic zone), their local-scale hydrological responses are quite different and are discussed below.

2.2.1 CENIT

The first study site Central Nitrogen (CENIT) is located at the Agri-Food and Biosciences Institute (AFBI) Hillsborough Research Centre in Co. Down in NI (54°27ʺN, 6°05ʺW) and will be referred to as "Site 1." Overland flow, drainflow discharge and contaminant export studies were carried out on five hydrologically isolated 0.2 ha drumlin grassland hillslope plots. The plots were hydrologically isolated in spring 1987, as described in Watson *et al.* (2000), and tile drainage systems were installed at the site at that time. The site was ploughed and reseeded with perennial ryegrass in August 1987 and has been used for investigating nitrogen and phosphorus export from grazed grassland systems. Since the plots were established, they have been used for a variety of phosphorus, nitrogen, and hydrological studies (Watson *et al.* 2000, 2007, Watson and Matthews 2008, Doody *et al.* 2010, Thompson *et al.* 2012, Cassidy *et al.* 2017).

The soil at Hillsborough is a slightly gleyed sandy clay-loam (48% sand, 31% silt and 21% clay) overlying Silurian shale (greywacke) till (Food and Agriculture Organization (FAO) classification: Dystric Gleysol). The soil has a hydraulic conductivity of 0.2 m d^{-1} (Watson *et al.* 2000), giving it a Hydrology of Soil Types (HOST) classification of 24, which accounts for approximately 54% of the land cover of NI (Cruickshank 1997) and is of high risk for P losses due to surface runoff, in which measured concentrations of SRP between 2000–2005 were higher than in drainflow (Watson *et al.* 2007). The region has a cool temperate maritime climate, with an average annual rainfall and average annual evapotranspiration for the period 1971–2000 of 890 mm and 524 mm, respectively.

The dataset collected from the five plots (2008–2012) comprised a time series of daily rainfall and runoff data from each plot with associated meteorological data (air temperature and precipitation) from the nearby automatic weather station; these data were used for the model simulations described in section 2.4.1.

2.2.2 Solohead

The second study site (Site 2) is situated at the Solohead research farm (52 ha) managed by Teagasc in the Irish Republic (52°30ʺN, 8°12ʺW) (Tuohy *et al.* 2016). The study area comprised 12 isolated plots, each 15 m wide and 100 m long. One of four different treatments was deployed at each plot in a randomized pattern. The four treatments deployed were (A) un-drained control; mole drainage installed in (B) January 2011 or (C) July 2011; and (D) gravel mole drainage installed in July 2011. Runoff was collected at an outlet point from each plot where it was piped into a measurement tank, giving 12 plots in all with recorded runoff data, as the data from the control plots (A) were not analysed. These data were used in the model simulations described in section 2.4.1.

The Solohead site suffered from waterlogging and poor trafficability during adverse weather conditions (Tuohy *et al.* 2016). High soil moisture and associated ponding of surface water were observed during periods of persistent rainfall,

Figure 1. Map of the Island of Ireland showing the two study sites (CENIT = Central Nitrogen).

hence surface runoff would be the main pathway for P losses. The soil types are grouped into the Elton soil association and classified as poorly drained gleys (90%) and grey brown podzolics (10%). Saturated hydraulic conductivity was found to decrease strongly with depth from 0.047 m d^{-1} for the top 25 cm of soil down to 0.007 m d^{-1} for the 130–200 cm horizon. The subsoil consists of Quaternary till with a shallow water table (0–2.2 m below ground surface) and an underlying Devonian sandstone bedrock. The long-term (1981–2010) mean recorded at the closest Met Éireann climate station (Shannon Airport) was 977.6 mm. The average annual Potential Evapotranspiration (PET) is 510 mm, the meteorological conditions indicating that this site, like Site 1, has a cool temperate maritime climate.

2.3 Surphos model

The Surphos (Surface runoff model for Phosphorus) is a daily time-step model developed to simulate surface application of manure and fertilizer and associated dissolved P loss in surface runoff, as well as soil P cycling (Vadas *et al.* 2007, 2011, 2017). Surphos was designed to be integrated into more complex field- or catchment-scale models to improve how these models simulate agricultural P cycling (Vadas *et al.* 2013, Collick *et al.* 2016), therefore it does not simulate all the processes that affect P availability in a soil–manure system. Other, simpler models are available to assess losses at the field scale from applications of P in slurry (e.g. Annual Phosphorus Loss Estimator Tool (APLE); Benskin *et al.* 2014), but these models tend to work on an annual time step meaning that they are not capable of simulating either (i) repeated slurry applications during a year or (ii) episodic-rainfall-driven events that transport high concentrations of SRP in overland flow, so these models were discounted for use in this study. Vadas *et al.* (2013) found that, compared to observed data of P losses from an 11.9 ha field with surface-applied poultry manure, the Soil Water Assessment Tool (SWAT) model underpredicted these losses in the first few years of the simulation and allowed excess P to accumulate in the upper soil layer in the model as the model incorporates surface manure into the top 1 cm soil layer. The Surphos model predicted P losses in surface runoff that did not increase over time and tended to be more realistic, given the improved simulation of surface manure pools in the model.

2.3.1 Surphos model structure and data requirements

A detailed description of the model's structure can be found in Vadas *et al.* (2007), (2011). For modelling purposes, Surphos requires input data for initial soil labile P content, porosity, percentage of organic matter, total P content and the water-extractable phosphorus (WEP) fraction of manure. Users also specify the day and rate of manure application and the application method (e.g. trailing shoe). The model time step is daily so average air temperature, total precipitation and runoff are required for each simulation day; these data were obtained from Sites 1 and 2 as described above in section 2.2. The model simulates the release of WEP from manure stored in a "pool" on the soil surface when there is a rainfall event. Dissolved P in runoff is estimated by multiplying this released P by a unitless P distribution factor which is the ratio of runoff to rainfall raised to a power. The model also simulates the following physical and chemical processes that will govern the amount of available P from manure for runoff loss for a given event (Vadas *et al.* 2011):

1. The decomposition of manure mass on the soil surface over time.
2. The conversion of manure that is in non-WEP forms to WEP through mineralization.
3. Assimilation of solid manure and P into soil through bioturbation, which acts a sink in the model decreasing the amount of WEP available for runoff P loss.

The model will output daily SRP concentrations as well as SOP (soluble organic phosphorus) concentrations in surface runoff.

2.3.2 Validation of Surphos

The validation of the Surphos model in Irish hydrological and agricultural conditions was undertaken by O'Rourke *et al.* (2021) using data collected from both natural events and events generated by a rainfall simulator. The field site was a permanent grassland field also located at the Hillsborough Research Centre, less than 1 km from Site 1, with identical soil and climatic data. That study found that Surphos was able to predict SRP from both simulated rainfall and natural events reasonably well given the variability found in natural and simulated events, with Root Mean Square Error (RMSE) errors of 0.56 and 0.64 mg P L^{-1} for simulated and combined simulated plus natural events, respectively. To further assess the model's performance, earlier studies from the USA using the model to simulate SRP were also reviewed. Vadas *et al.* (2011) found that when comparing the modelled versus observed SRP concentrations from nine experimental studies that explored the effect of modifying the time between manure applications and the first runoff event, the model achieved a relatively high goodness of fit in terms of the Nash-Sutcliffe efficiency (0.89). The trend line fitted to the results had a slope of 0.92, indicating a slight underprediction overall. Following on from this study, model simulations of slurry applications to a 1.6 ha field in Wisconsin, USA, during five winters from 2008 to 2012, where slurry was applied in early November each year (Vadas *et al.* 2017), achieved an R-Squared (RSQ) of 0.82 and RMSE of 0.46 mg P L^{-1}, which are within the bounds of acceptable model performance, and indicated that Surphos can reproduce observed SRP concentration data accurately on a daily time step using field data recorded over several years and in winter conditions with melting snow, as opposed to reproducing the results from single experiments carried out under controlled conditions at the plot scale.

2.4 Identification of scenarios

In developing our different scenarios, the approach used by Vadas *et al.* (2017) to examine slurry spreading during winter months was applied, whereby plot-years of data (one year of runoff and rainfall data) were joined together to form a longer time series. Surphos was then used to simulate SRP concentrations and thus export concentration × runoff for the different scenarios of slurry application. If multiple calendar years are available, then this approach allows for different combinations of wet and dry periods to be investigated. The approach is shown schematically in Fig. 2.

Firstly, the model simulated the entire time series of N plot-years, but with slurry applications only on 1 May in each calendar year, repeated each year. The choice of start date of 1 May is not significant; it corresponded to the start date of the one year of runoff data from Site 2. The model was reset after each run with the manure application moved to the next calendar day, as manure was only applied in the model simulation on that specific day once per year, and this was repeated until manure was applied on 30 April. The total annual export of SRP was calculated by the model over the year and then summed over the N year period (termed E).

For the 365 simulations (one per day of the year), the mean annual E was calculated as (E/N). The results were then processed to calculate the annual maximum and minimum SRP export for each application date. In the results shown below, either the CP can be represented by setting the export from the days during the period to zero, or the results can be processed for this period only and the mean and other statistics can be

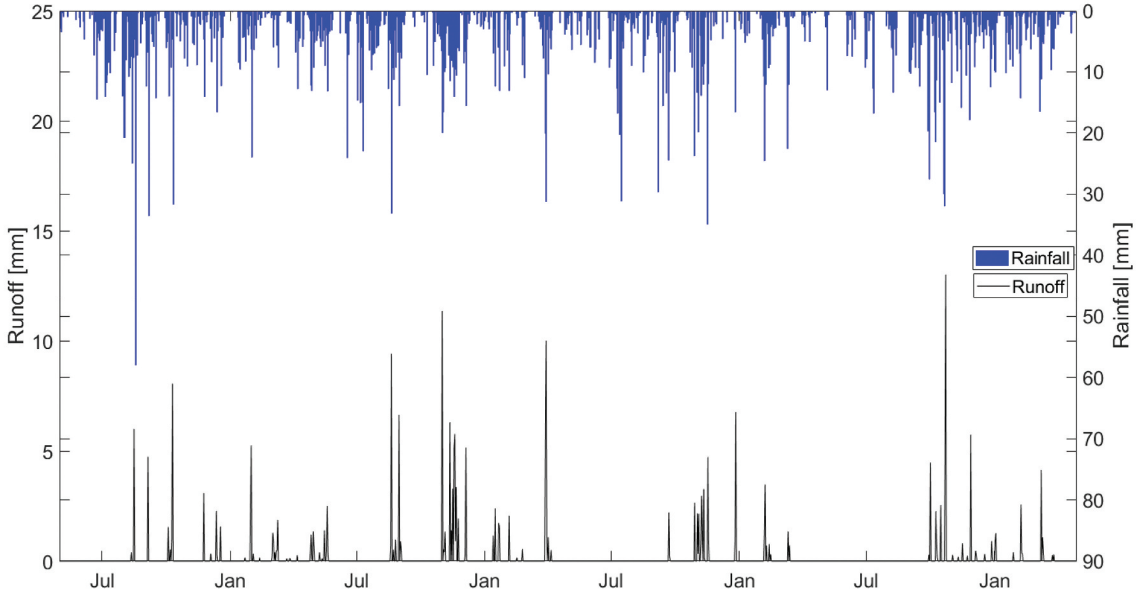

Figure 2. Rainfall and runoff for four plot-years : Site 1, Plot 1.

calculated for comparison. The second approach can be used to investigate what would happen if the CP was modified (e.g. lengthened) or even removed. For example, a "shoulder" period that extends the CP on either side of the current period can also be extracted and analysed. The same methods can be applied in processing the results from applications during the OP.

Firstly, we constructed a 'baseline scenario' to calculate SRP export with no restrictions (NR) on applications and with daily slurry applications, using data from both sites, which represents a worst-case scenario. Following on from the NR scenario, a second scenario investigated the impact of the application of the current NAP regulations (NAP scenario). Lastly, an additional set of mitigation scenarios were evaluated (Table 1) and the changes in SRP losses caused by the mitigation measures individually introduced in each scenario were assessed relative to the baseline NR scenario. Here, scenario codes "A*x*" denote that the application rate was set to *x* kg ha^{-1} year^{-1} in a scenario, and names "P*y*" denote that the total phosphorus content of the slurry was reduced by *y* percent in a given scenario.

Note that in terms of imposing climatic restrictions on specific spreading dates, the A50, A10 and P30 scenarios used the same criteria as the NAP scenario to limit spreading to certain dates. The restrictions, based on soil moisture deficit (SMD) values, were enforced using a value of SMD below which spreading was not allowed in that particular scenario, to restrict spreading to certain dates. The restrictions based on rainfall prevented spreading on dates when the rainfall total was above the indicated amount in the preceding time period (shown in parentheses).

These scenarios are shown in Table 1 and include (1) different application rates "A*x*"; and (2) a 30% reduction in P content in the slurry "P30." On certain days in the scenarios with restrictions when spreading was not allowed, the modelled annual SRP export (for applications on these particular days) was set to zero, as shown by the flowchart in Fig. 2; however, on most application days an application on at least one of the N plot-years was still possible. SMD values were calculated using Schulte *et al.* (2006)'s model for "poorly drained" soil types, which was calibrated against field monitoring data collected from soil moisture probes inserted into Irish soils. Under the current NAP regulations, slurry cannot be spread if land is "waterlogged," meaning "where water appears on the surface of the land when pressure is added" (i.e. SMD = – 10 mm) or when 4 mm h^{-1} of rain is forecast to fall within 48 h. For the model runs where restrictions were applied to simulate these regulations, it was assumed that the rainfall restriction would be based on 16 mm d^{-1} falling on any day of a three-day period comprising the day of application and the next two days, as sub-daily rainfall data were not available for modelling purposes. In

Table 1. List of the modelled scenarios showing the application rate and P content and detailing the restrictions on spreading that were imposed based on rainfall and soil moisture deficit (SMD). The scenarios are as follows: NR = no restrictions (baseline); NAP = Nutrients Action Programme; FC = field capacity; Ax = application rate modified to × m^3 ha^{-1}; P30 = 30% reduction in P content.

Scenario	Restriction on SMD (mm)	Restriction on rainfall (mm, timing)	Application rate (m^3 ha^{-1})	P content	Sites
Baseline (NR)	None	None	30	Default	1, 2
NAP	≤ −10	<16 (48 h)	30	Default	1
FC	≤0	<16 (48 h)	30	Default	1
A50	≤ −10	<16 (48 h)	50	Default	1
A10	≤ −10	<16 (48 h)	10	Default	1
P30	≤ −10	<16 (48 h)	30	Reduced by 30%	1

the field capacity restricted (FC) scenario, spreading during the CP was restricted when SMD was at field capacity (0 mm) or wetter; this was thus more restrictive than the "NAP" scenario.

For Site 2 the model was only used to investigate the annual average SRP export from the baseline simulation with no restrictions on spreading (i.e. Scenario NR), for reasons that are discussed in section 2.4.1.

2.4.1 Model input data for scenarios

The model's soil property parameter values were obtained from earlier studies at Site 1 (Watson and Matthews 2008, Doody *et al.* 2010, Thompson *et al.* 2012); we assumed that under baseline conditions the slurry application in the model was 30 m^3 ha^{-1} and an application was made only once per year. Since only one application is made per year, the model may be simulating fewer applications than take place in reality; however, the purpose of these simulations was to examine how sensitive the annual export of P was to the timing of the slurry application. The P content of the slurry was fixed at 0.87% (by mass) with a dry matter content of 6%; these figures are typical nutrient concentration values for cattle slurry in NI (DAERA 2019), giving a volumetric P content of 1.2 kg P_2O_5 per m^3 of liquid slurry. Results from the current CP (from 15 October to 31 January) and the OP outside this period were analysed using the model results to investigate whether P export is affected by seasonality. The site-specific details of the datasets follow, and hydrological data collected at the two sites during the runoff experiments are summarized in Table 2.

2.4.1.1 Site 1. Four years of rainfall and runoff data from five runoff plots at Site 1 (2008–2012, with each year starting on 1 May) were available, giving 20 plot-years (*N*) of simulation (see section 2.2.1). A time series of rainfall and runoff data is shown in Fig. 3 for Plot 1. Precipitation and runoff were highly variable in the five plots and are summarized in Table 2, along with runoff coefficients (runoff/rainfall) and the number of events over a certain size recorded on an annual basis. The annual percentage of hydrologically effective rainfall (i.e. Rainfall-Actual Evapotranspiration) measured as surface runoff ("overland flow") was available from earlier studies at the site (Watson *et al.* 2007, Doody *et al.* 2010) but not for the 2008–2012 period, and is shown in Table 2. The SMD data were calculated using parameters measured from the Site 1 weather station using the method described above (Schulte *et al.* 2006) and were used to restrict spreading dates in the model in scenarios where SMD was used as a limiting factor to indicate that conditions were too wet for spreading.

Table 2. Summary of hydrological data from Sites 1 and 2. Values in parentheses indicate the range of a particular measurement that was recorded. AET = actual evapotranspiration; KSat = saturated hydraulic conductivity; SD = standard deviation; RC = runoff coefficient; HER = hydrologically effective rainfall (P_{ann}-AET).

Measurement	Unit	Site 1	Site 2
Mean annual rainfall[1] P_{ann}	mm	890	1042
AET	mm	524	510
KSat (upper soil layer)	$m\ d^{-1}$	0.2	0.05
Runoff (range)	mm $year^{-1}$	36–131	54–210
Runoff (mean)	mm $year^{-1}$	71	142
Runoff (SD)	mm $year^{-1}$	27	45
RC (range)	(-)	0.05–0.13	0.04–0.17
RC (mean)	(-)	0.08	0.12
RC (SD)	(-)	0.02	0.04
Drainflow (as % total runoff)	%	N/A	0 (U), 39–54 (D)
Drainflow (as % HER)	%	11–35	0 (U), 19–34 (D)
Events (> 5 mm total runoff)	(-)	3–5	12

[1] Mean annual rainfall during the experimental period.

D = drained plots; U = control plots, which were undrained; N/A = not applicable to this site.

2.4.1.2 Site 2. For Site 2 there were flow data available from 12 different runoff plots but only one full year of runoff data (2012–2013) was available to provide input to the model, so the rainfall and runoff data were combined into a single 12 plot-year (*N*) time series (see section 2.2.2 for a description of the site and the data). On-site rainfall, collected using an automatic weather station, totalled 1131 and 953 mm in 2012 and 2013, respectively. The hydrology of the site is summarized in Table 2 using data from Tuohy *et al.* (2016) on runoff and drainage flow volumes, including the number of runoff events observed over the 12 month period.

3 Results

3.1 Scenarios

The results from the different scenarios are presented in Table 3 in terms of the change in SRP export predicted (annually) relative to either (i) the baseline "NR," or (ii) the NAP scenario (i.e. relative to "NAP") simulations for applications of slurry during the OP, the CP, and the entire year. The penultimate column shows the number of days in the OP that were unavailable for spreading (as a percentage of the total number of days in this period, which currently stands at 257 days under the NAP regulations) when spreading is allowed on some days under the limitations imposed by regulations in place in that scenario (i.e. the current soil moisture and rainfall limitations for the NAP, A10, A30 and P30 scenarios, and the more stringent restriction on spreading when SMD = 0 mm in the FC scenario).

The final column in Table 3 shows the number of days in the CP available for spreading (as a percentage of the total number of days in this period, which currently stands at 108 days) if the total ban on spreading during this period were to be lifted. In these cases spreading would be allowed on some days depending on the SMD and rainfall restrictions, whereas at present it is completely closed off.

3.2.1 Results for the NR scenario

Figure 4 shows the mean, minimum and maximum annual SRP export depending on the date when the application was made, for the NR scenario for Site 1 (Fig. 4a) and Site 2 (Fig. 4b). The annual SRP exports for Site 1 are calculated from the 20 plot-years of simulation (e.g. the mean, minimum or maximum export from the 20 annual totals). For Site 2, SRP exports are calculated from the 12 plot years of simulation (e.g. the mean, minimum or maximum export from the 12 annual totals). The entire year is shown, i.e. the exports resulting from 365 different application dates between 1 May and 30 April.

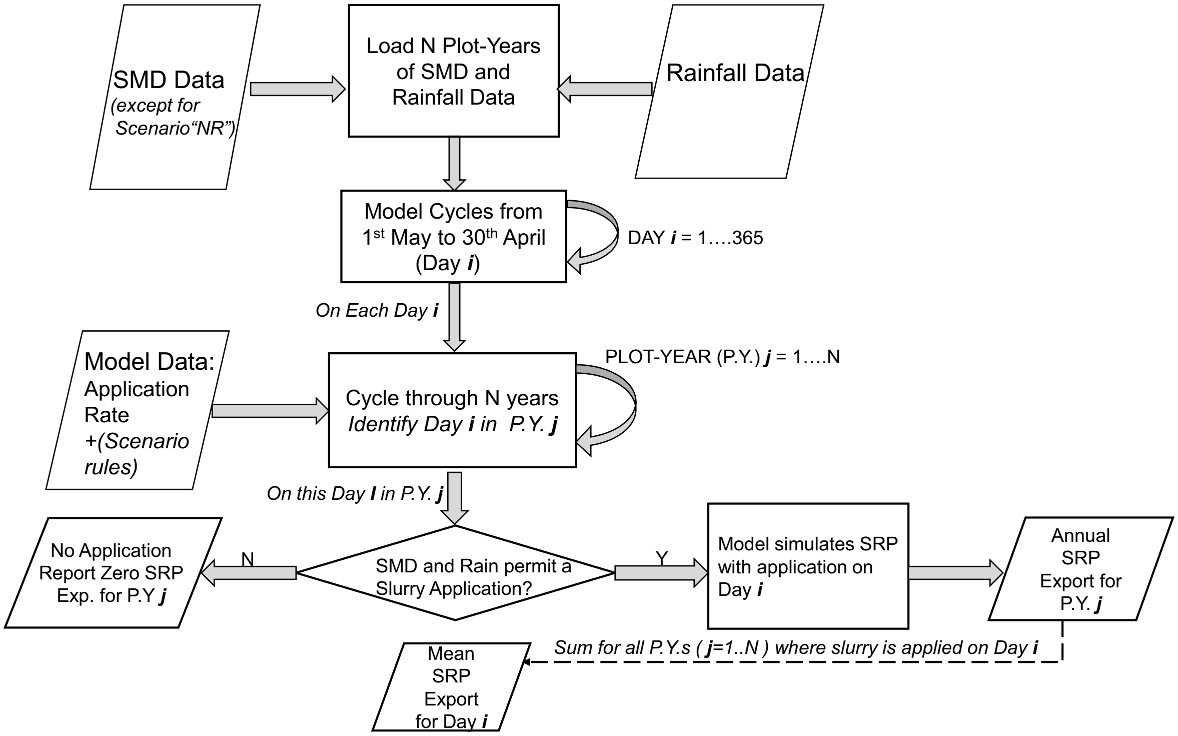

Figure 3. Schematic flowchart of the model simulation procedure (where "model" refers to Surphos).

Table 3. Results for applications made during the open and closed periods and the entire year for both sites. SRP = soluble reactive phosphorus; OP = open period; CP = closed period; The scenarios are as follows: NR = no restrictions (baseline); NAP = Nutrients Action Programme; FC = field capacity; Ax = application rate x; P30 = 30% reduction in P content.

Scenario	Mean SRP export (kg P ha^{-1}year^{-1})	Mean SRP export (OP only) (kg P ha^{-1}year^{-1})	Mean SRP export (CP only) (kg P ha^{-1}year^{-1})	Reduction (OP only) relative to NR (%)	Reduction (OP only) relative to NAP (%)	Days with with restrictions (OP only) (%)	Days available (CP only) (%)
Site 1							
Baseline (NR)	0.13	0.086	0.22	–	–	0	100
NAP	0.086	0.065	0.14	24.8	–	14.8	66
FC	0.032	0.036	0.023	58.3	44.6	38.7	7.6
A50	0.17	0.14	0.26	−60.9	−114	14.8	66
A10	0.02	0.013	0.035	85.0	80.0	14.8	66
P30	0.06	0.046	0.096	46.8	29.2	14.8	66
Site 2							
Baseline (NR)	0.21	0.14	0.38	–	–	0	100

3.2.2 Scenario results – additional scenarios

Figure 5 shows the variation in mean annual SRP export depending on the date when the application was made, for each of the scenarios described above. The results from the NR or NAP scenario are shown for comparison against the scenario(s) being considered. An SRP export of zero on a particular day indicates that spreading was not possible on that day in any of the N plot years according to the restrictions imposed by the scenario. These scenarios were explored for Site 1 only, and the data in both Figs 5 and 6 are presented in the same format as the results for the entire year shown in Fig. 4.

Figure 5c shows results from the scenarios with different application rates (A10 and A50). The model results indicated that there was a decrease in SRP export under A10 and an increase under A50, as expected. Figure 5d shows the results from the P30 scenario where the P content of slurry was reduced by 30%. The corresponding reduction in SRP export was as expected; an additional simulation (results not shown) with a 10% reduction in P content indicated that the reduction in SRP export was linearly related to the P content.

3.2.3 Open- and closed-period results

Figure 6, using results from the NAP (red lines) and FC scenarios (blue lines) (for Site 1 only) separately compares the results from the OP (Fig. 6 a and b) and CP (Fig. 6 c and d), each pane showing the SRP export from the two scenarios against the baseline NR scenario (black lines). The shorter time frame makes it easier for comparisons to be made between time periods.

In Fig. 6, the curves show that periods when spreading was allowed in at least one plot-year generated a non-zero SRP export, and periods when spreading was not allowed (on any of these OP and CP days in the 20 plot-years) were allocated zero

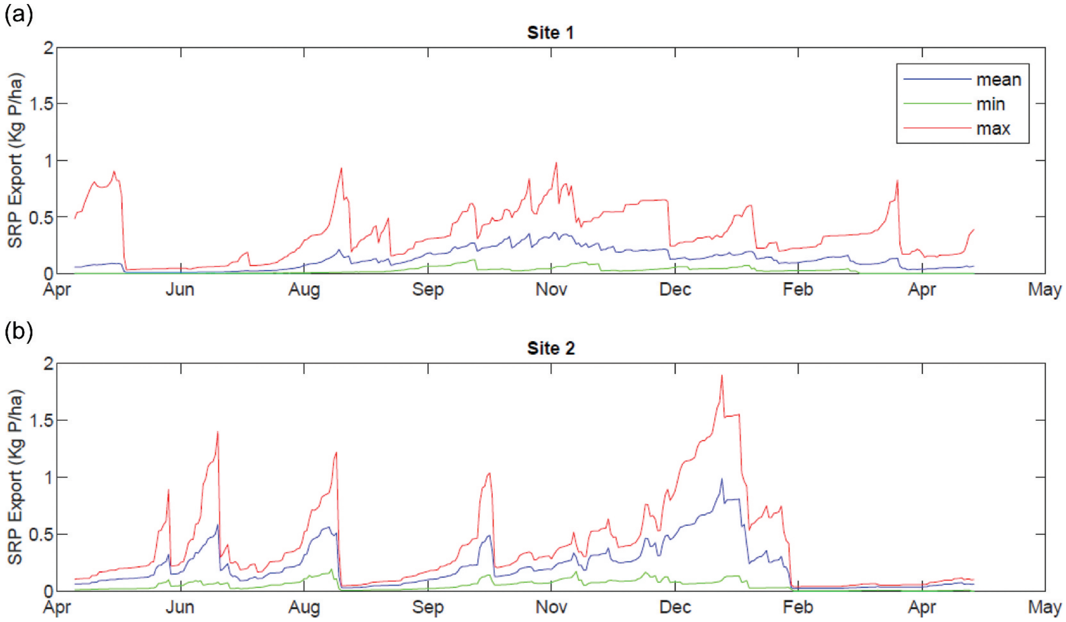

Figure 4. Results from the no restrictions (NR) scenario showing the entire year: mean, (min)imum and (max)imum annual SRP export for each application day for (a) Site 1; (b) Site 2.

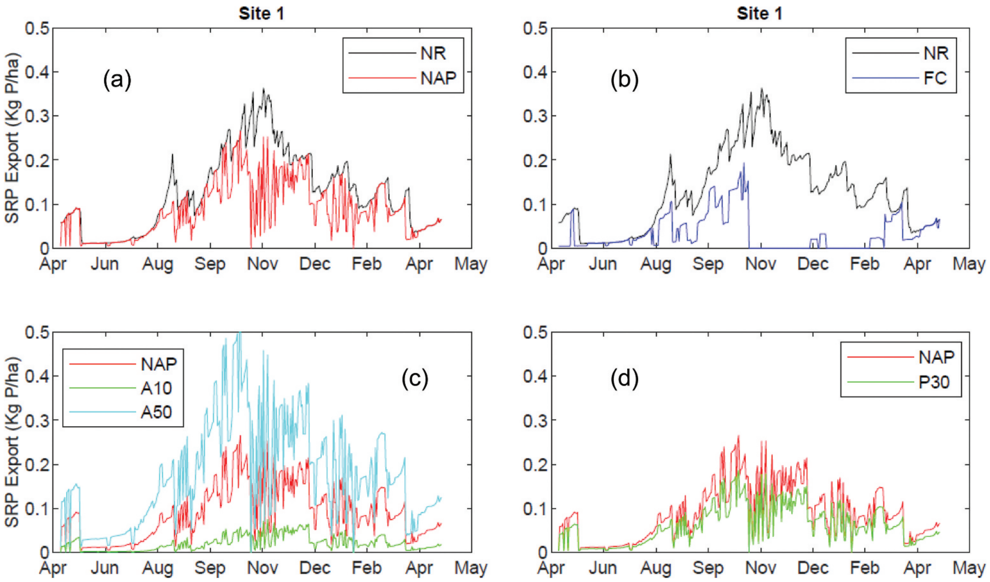

Figure 5. Results from various scenarios for the entire year, comparing (a) no restrictions (NR) vs. Nutrients Action Programme (NAP); (b) no restrictions (NR) vs. FC; (c) export under the NAP scenario vs. scenarios of application of slurry under the current NAP regulations, under different application rates of 10 and 50 m^3 ha^{-1} (A10 and A50); (d) export under the NAP scenario vs. a scenario where the P content of slurry was reduced by 30% (P30). Only the mean annual SRP export is shown.

SRP export. Spreading may have been allowed only on these specific days of the year in some of the 20 modelled plot-years as climatic conditions (rainfall and SMD) were different in each year. For the OP, on days when spreading was allowed in some of the 20 modelled years in both the NAP (red line) and FC (blue line) scenarios, there was a non-zero SRP export predicted by the model (e.g. June in the OP). During the shoulder period (February) in the FC scenario, spreading was not allowed in any plot-year due to the restrictions imposed due to low SMD even though it was technically part of the current OP. In Fig. 6 this is clearly shown by periods with zero values for the average annual SRP export.

For the CP, the model still calculated the SRP export as if spreading was allowed under the restrictions imposed by the scenarios, in order that comparisons could be made both with the OP and between the results from the different scenarios themselves. In Fig. 6 (lower right pane) zero SRP export (indicated by blue line) for most of the CP indicates that the FC scenario has restricted spreading to all but a few dates, which were mostly in the second half of October. Comparing against the OP from February to mid-October, the restrictions had less impact on the SRP export during this period than during the CP. The NAP scenario (lower left pane, export indicated by a red line) indicated that spreading was possible on nearly all days, but due to restrictions in some of the 20 years the average SRP export

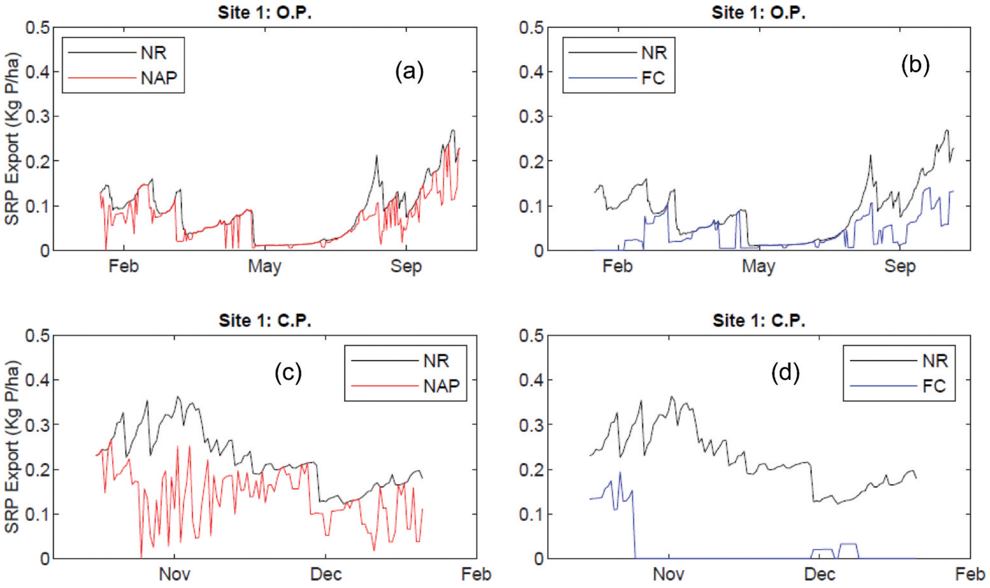

Figure 6. Results from the (a) Nutrients Action Programme (NAP) and (b) Field Capacity (FC) scenarios compared to having no restrictions for the open period (OP: 1 February–15 October); and (c, d) for the closed period (CP: 15 October–31 January). Only the mean annual SRP export is shown.

for spreading on a particular day was calculated to be less than the export under the NR scenario. This will be discussed further below.

4 Discussion

4.1 *Model sensitivity*

We investigated the model's sensitivity to changes in application rates and P contents and the results indicate that the sensitivity of SRP export was linearly related to both variables, as expected from the model's structure. Reducing application rates and/or P contents of slurry therefore provides a simple way of reducing SRP export, providing that sufficient P is available to promote good pasture health through enabling sufficient grass growth. The study of Ferris *et al.* (2010) highlights the scope to achieve such a reduction without compromising animal health. They reported that feeding dairy cows a low-P diet of ration P level 3.6 g P kg $^{-1}$ Dry Matter (DM) had no significant impact on any of the animal health indicators or on milk output or composition, when compared to a high-P total a diet with a total ration P level varying between 4.2 (summer) and 4.9 (winter) g P kg^{-1} DM. Following on from this, O'Rourke *et al.* (2010) demonstrated that this reduction in the P content of slurry resulted in a significant reduction in P loss to water post slurry application.

4.2 *Closed period*

The presence of a CP reduced SRP export from Site 1 by about 33% if no restrictions were applied during the rest of the year. Having no restrictions during this period resulted in the highest average SRP export, with the export during the CP averaging 0.224 kg P ha^{-1} year^{-1}. Following on from the work of Jordan *et al.* (2012), Shore *et al.* (2016) found disproportionately high phosphorus export during the CP in five catchments in Ireland, concluding that additional applications of P in the form of slurry during this period would increase these losses further. While there was evidence of incidental nutrient losses due to slurry application just prior to the CP, these signals declined over time during this period (Jordan *et al.* 2012, Shore *et al.* 2016). Under the best-case scenario in the current study (in terms of mitigation: FC) the SRP export was reduced to 0.023 kg P ha^{-1} year^{-1}, which was a significant reduction (90%), but the downside would be that only 7% of the days are available for spreading, which are in two subperiods of the CP: late October and early January (Fig. 4). Holden *et al.* (2004) developed a method to estimate the probability of safe spreading periods arising on an annual basis. They found that safe periods for slurry spreading in winter occurred every 3–6 years out of 10. However, based on the results presented here there is currently little evidence to suggest re-opening this period is viable unless accurate rainfall and soil moisture data is available to farmers to identify the limited number of safe slurry spreading periods referred to by Holden *et al.* (2004). If the NAP restrictions are enforced, then the percentage of available days rises to 66% (compared to the FC scenario); however, over the four years of climate data analysed there was usually at least one year out of four when spreading would not be possible on any date in the CP. The 66% thus represents the fact that spreading would be allowed in some years but not in others. Extending NAP regulations to the entire year with no CP is one option that could be explored as an alternative to introducing an extended CP. A more drastic scenario would be to apply the FC restrictions for the entire year, which reduces the annual SRP export further to 0.032 kg P ha^{-1} year^{-1}.

4.3 *Open period*

During a four year study in NI, Doody *et al.* (2010) highlighted the challenges posed in identifying periods suitable for slurry spreading during the OP, with soil moisture field capacity exceeded on 50% of days in February, and runoff recorded on average on 33% of days in May. The current study has demonstrated that full implementation of the current NAP regulations reduced SRP export (relative to having no regulations) by 25% or 0.021 kg P ha^{-1} year^{-1}. In general, the period between late May and early August is the most favourable part of the OP for spreading based on the Site 1 dataset (Fig. 4), with low SRP exports resulting from spreading dates during this period. The FC scenario was more than twice as effective as NAP at lowering SRP export (by 58%) during the OP. Despite the current regulation allowing slurry applications at < -10 mm SMD, ideally slurry spreading on many soils in Ireland should be undertaken closer to field capacity. Vero *et al.* (2014) investigated the impact of a tractor and slurry tanker on the soil density and rut profiles of three Irish soil types at four SMD values. They reported that an SMD of 10 mm was the threshold for safe slurry spreading in terms of preventing compaction. While 10 mm SMD was optimal in terms of avoiding compaction, the soils remained trafficable up to an SMD of 5 mm, and generally recovered from the effects of compaction and yield loss within the subsequent 60 days.

Having no restrictions on spreading during an OP followed by a CP would reduce SRP export by a third compared to the annual average export from allowing spreading on all 365 days with no restrictions (0.086 vs. 0.13 kg P ha^{-1} year^{-1}). Introducing the FC-based restriction on spreading on soils at or wetter than field capacity would rule out applications in most of February as the ground conditions were too wet (see Fig. 6).

4.4 Shoulder periods

The periods before (1–15 October) and after (1–29 February) the current CP are often high-risk periods for SRP export. During the establishment of the CP in 2006, some evidence supported the inclusion of these periods within the CP. However, 1–15 October was finally excluded from the CP based on the analysis of rainfall and climate data which indicated that the ground conditions in October were suitable for slurry application in 11 out of 31 years (35%) (DOE-DARD 2005). February was excluded from the CP based on strong evidence of the positive response of grass to earlier application of N in manure, thereby increasing the overall N farm efficiency. However, the difference between allowing a first application in February instead of March is not large in terms of difference in yield (DOE-DARD 2005). In the current study, the SRP export from the NR and NAP scenarios during the shoulder periods was 0.16 and 0.11 kg ha^{-1} year^{-1}, respectively. If the CP were extended to include the shoulder period, then under NAP regulations the annual SRP export would be reduced from 0.065 to 0.056 kg ha^{-1} year^{-1} (14%). Reducing the P content in slurry by 30% and retaining the current regulations reduced SRP export from the shoulder period to 0.080 kg P ha^{-1} year^{-1}. It appears that an extended shoulder period may not be the best solution if the current NAP regulations are retained, in terms of achieving the greatest possible decrease in SRP export; a similar reduction is achievable by reducing the P content in slurry by approximately 35% (Ferris *et al.* 2010, O'Rourke *et al.* 2010).

Based on the results from the FC scenario, most if not all of February would be unsuitable for application (if it were still open but with more stringent restrictions on spreading put in place). Under the current NAP regulations spreading during this month is allowed, with tighter restrictions on application rate (30 m^3 ha^{-1}), and this reduces the annual SRP export by about 20% (refer to Fig. 5). The evidence from the scenario results of reducing SRP export in an autumn shoulder period (from the OP graphs in Fig. 5 (upper panes)) would indicate that SRP export was still quite high from this period even under the FC scenario. Results from the NAP and FC scenarios showed the late summer–mid-autumn period is not the preferable time for applying slurry, even though it is permitted under the current regulations. Therefore, an extended CP including 1–15 October, or even from mid-September onwards, would achieve large reductions in annual SRP export by eliminating these spreading dates. However, the addition of shoulder periods would require sufficient slurry storage capacity and would result in increased application rates of slurry during the shortened OP.

4.5 Comparison of sites

The range of SRP exports for different application dates at Site 2 was considerably wider than for Site 1 (ca. 0.01–2 kg P ha^{-1} year^{-1} compared to 0.01–1 kg P ha^{-1} year^{-1}). The annual maximum SRP export was also much higher at Site 2, due to the higher runoff compared to Site 1's plots. For example, the maximum SRP export was nearly 2 kg P ha^{-1} year^{-1}, compared to 0.9 kg P ha^{-1} year^{-1}. The data from the 12 plots at Site 2 included three replicates of three treatment types (see above) (Tuohy *et al.* 2016), so the variability in runoff shown between the 12 plot-years was influenced by the differences in the drainage treatments of the groups rather than the climate. An interesting finding was that runoff was more variable between the 12 plots for one year of climate data (SD (RC) = 0.04) than for four years at five different plots at Site 1 (SD (RC) = 0.025). It is runoff that is the key factor, along with the application day, that controls the magnitude and timing of SRP export from the Surphos model. This is consistent with previous field- and catchment-scale studies highlighting the impact of soil hydrology in determining the magnitude and timing of P export (Doody *et al.* 2012, Jordan *et al.* 2012). There was a surprisingly large difference in P export among the 12 plots, as Fig. 3 (lower pane) shows, in terms of the range of maximum export of SRP predicted. This points to a high degree of spatial heterogeneity between plots, which was partially due to the different treatment types, although even within groups of three plots (with the same treatment) there was considerable variability.

Since there was only one year of climate data from Site 2 used by the modelling, with a fairly dry spring (an absence of significant runoff events from mid-February to April and 118.3 mm of precipitation recorded in March and April can be seen in the lower part of Fig. 3), care must be taken when interpreting these results in terms of drawing conclusions on the seasonality of P export from the runoff plots at Site 2.

4.6 Summary

In general, at a plot scale the relationship between P concentration and P export (*viz.* concentration × runoff per unit area) is a complex one due to the influence of various factors including runoff potential, soil moisture, seasonality and episodic-event-driven export (Doody *et al.* 2010, Thompson *et al.* 2012, Cassidy *et al.* 2017). Here, the use of a dynamic model (Surphos) enables some of these factors to be explored in more depth than data analysis alone can provide. Moving from the plot scale to the catchment scale, based on a long-term study using historical datasets collected over many decades, it appears that reducing SRP export from NI catchments from circa 0.6–.8 kg P ha^{-1} $year^{-1}$ to 0.28 ± 0.12 kg P ha^{-1} $year^{-1}$ is required (Jordan *et al.* 2000). While the figures of Jordan *et al.* (2000) related soil P (not slurry applications) to SRP export, they still indicated a very high export from these grassland catchments where slurry is frequently applied. More recently, using the same long-term data, Barry and Foy (2016) commented on the uncertainty as to whether changes in P fluxes over time were related to farming practices (e.g. the adoption of BMPs) or high levels of agronomic soil P (legacy P). However, their comparison between sub-catchments in the Upper Bann and Colebrooke catchments indicated that annual flow-weighted mean concentrations of TP and SRP showed strong positive correlations with sub-catchment manure P loadings. In general terms, reducing the slurry P load by 30–60% should contribute up to 16% of the total reduction required from all sources of P in a typical NI agricultural catchment in order to reduce SRP export down to levels that should enable compliance with the EU Water Framework Directive limits for achieving “Good” status. Reducing slurry P must be considered alongside the nutritional requirements of livestock ingesting the grass; if the grass is not sufficiently nutritious then insufficient nutrition may be ingested by cattle (S. Higgins pers. comm. September 2020).

From the Surphos model results the export of P was predicted to be as high as 0.13 kg P ha^{-1} $year^{-1}$ (in surface runoff) from unrestricted slurry applications. If we assume that the current NAP restrictions are maintained, then the SRP export is 0.086 kg P ha^{-1} $year^{-1}$, so a reduction of 30–60% of this load should contribute up to 16% of the total reduction required from all sources of P in a typical NI agricultural catchment.

The adoption of a CP for spreading and also the options for extending this period over a “shoulder” period may be, in practical terms, restricted by the ability of farmers to store slurry in the wetter months for a longer period of time, which should lead in turn to policy recommendations for additional funding through grants (such as the Targeted Agricultural Modernisation Scheme in Ireland) or loans to increase slurry storage capacity on livestock farms. Farms should have an additional four weeks’ spare capacity based on the length of the current CP (approximately 16 weeks), especially as in reality, with poor management practices such as dirty water from dairy operations, silage effluent and rainwater entering the slurry tanks, this excess capacity may be reduced significantly in practice. The situation of the farmers then having full tanks when the CP ends and having to spread slurry on waterlogged fields at the start of the OP irrespective of rainfall and SMD constraints is clearly undesirable. There may also be extended periods of bad weather in February or early October where cattle will have to remain housed indoors that will also lead to fuller tanks at the start of the OP and start of the CP, respectively.

5 Conclusions

The use of a physically based model, Surphos, to predict P losses following slurry applications has been trialled in Irish hydrological conditions and found to perform satisfactorily compared against field data obtained from two contrasting sites. There was considerable variability in runoff at the second site where only one calendar year of data was available for testing the model. This highlights the spatial variability in runoff from drained agricultural soils due to local factors, which varied across even a very small distance. The Surphos model has been applied to investigate multiple scenarios of different timings and rates of slurry P applications. These scenarios showed that, in general, the model predicted that changes in soluble P export would be proportional to any changes in P inputs.

The current NAP regulations in NI are effective in reducing soluble P lost post slurry application to temperate grasslands. The current evidence base supports the use of a closed period as the most effective strategy for minimizing the risks associated with slurry spreading from 15 October to 31 January. Removal of the closed period and its replacement with the current NAP regulations (i.e. restricting applications based on soil moisture and rainfall conditions) will not sufficiently mitigate the risk associated with slurry applications during this period. Such information is not currently available to farmers and would require a significant improvement in the current resolution of meteorological data across the whole of Ireland. Mitigation strategies such as restrictions on application rates and reducing the P content of slurry will reduce losses during high-risk periods without the need to extend the current closed period any further.

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References

Barry, C.D. and Foy, R.H., 2016. Assessing the success of regional measures for lowering agricultural nutrient pollution in headwater streams. *Journal of Environmental Quality*, 45, 1329–1343. doi:10.2134/jeq2015.04.0184

Bechmann, M. and Stålnacke, P., 2005. Effect of policy-induced measures on suspended sediments and total phosphorus concentrations from three Norwegian agricultural catchments. *Science of the Total Environment*, 344, 129–142. doi:10.1016/j.scitotenv.2005.02.013

Benskin, C.M.H., *et al.*, 2014. Review of the annual phosphorus loss estimator tool - a new model for estimating phosphorus losses at the field scale. *Soil Use and Management*, 30, 337–341. doi:10.1111/sum.12128

Bishop, P.L., *et al.*, 2005. Multivariate analysis of paired watershed data to evaluate agricultural best management practice effects on stream water phosphorus. *Journal of Environmental Quality*, 34, 1087–1101. doi:10.2134/jeq2004.0194

Cassidy, R., Doody, D.G., and Watson, C.J., 2017. Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils. *Science of the Total Environment*, 575, 474–484. doi:10.1016/j.scitotenv.2016.07.063

Collick, A.S., *et al.*, 2016. Improved simulation of edaphic and manure phosphorus loss in SWAT. *Journal of Environmental Quality*, 45, 1215–1225. doi:10.2134/jeq2015.03.0135

Cruickshank, J.G., 1997. *Soil and Environment: northern Ireland*. Belfast, UK: Agricultural and Environmental Science Division, DANI.

DAERA, 2019. *Nutrients Action Programme 2019-2022* [online]. Available from: https://www.daera-ni.gov.uk/nutrientsactionprogramme2019-2022 [Accessed 15 Feb 2021].

DOE-DARD, 2004. *The protection of water against agricultural nitrate pollution regulations (Northern Ireland) 2004. Statutory rules of Northern Ireland 2004 No. 419*. [online]. Available from: http://www.legislation.gov.uk/nisr/2004/419/pdfs/nisr_20040419_en.pdf [Accessed 15 Feb 2021].

DOE-DARD, 2005. *Nitrates directive consultation document: proposed action programme measures for the protection of northern ireland water section 4*. Belfast, UK: Department of Agricultural and Rural Development.

Doody, D.G., *et al.*, 2012. Approaches to the implementation of the Water Framework Directive: targeting mitigation measures at critical source areas of diffuse phosphorus in Irish catchments. *Journal of Environmental Management*, 93, 225–234. doi:10.1016/j.jenvman.2011.09.002

Doody, D.G., *et al.*, 2010. Overland flow initiation from a drumlin grassland hillslope. *Soil Use and Management*, 26, 286–298. doi:10.1111/j.1475-2743.2010.00279.x

Ferris, C.P., *et al.*, 2010. Effect of offering dairy cows diets differing in phosphorus concentration over four successive lactations: 1. Food intake, milk production, tissue changes and blood metabolites. *Animal: An International Journal of Animal Bioscience*, 4, 545. doi:10.1017/S1751731109990929

Higgins, A.J., Cassidy, R., and Bailey, J.S., 2020. The relative impacts of dairy and non-dairy ruminant sectors on the Olsen-P status of grassland soils and hence water quality in Northern Ireland. *Soil Use and Management*, 37, 900–905. doi:10.1111/sum.12618

Holden, N.M., *et al.*, 2004. Rainfall climate limitation to slurry spreading in Ireland. *Agricultural and Forest Meteorology*, 122, 207–214. doi:10.1016/j.agrformet.2003.09.008

Jordan, C., McGuckin, S.O., and Smith, R.V., 2000. Increased predicted losses of phosphorus to surface waters from soils with high Olsen-P concentrations. *Soil Use and Management*, 16, 27–35. doi:10.1111/j.1475-2743.2000.tb00168.x

Jordan, P., *et al.*, 2012. The seasonality of phosphorus transfers from land to water: implications for trophic impacts and policy evaluation. *Science of the Total Environment*, 434, 101–109. doi:10.1016/j.scitotenv.2011.12.070

Kleinman, P.J., *et al.*, 2015. Implementing agricultural phosphorus science and management to combat eutrophication. *Ambio*, 44, 297–310. doi:10.1007/s13280-015-0631-2

O'Rourke, S.M., *et al.*, 2010. Effect of varying the phosphorus content of dairy cow diets on losses of phosphorus in overland flow following surface applications of manure. *Journal of Environmental Quality*, 39, 2138–2146. doi:10.2134/jeq2010.0205

O'Rourke, S.M., *et al.*, 2021. Effect of increasing the time between slurry application and first rainfall event on phosphorus concentrations in runoff. *Soil Use and Management*, 38, 611–621. doi:10.1111/sum.12732

Rothwell, S.A., *et al.*, 2020. Phosphorus stocks and flows in an intensive livestock dominated food system. *Resources, Conservation and Recycling*, 163, 105065. doi:10.1016/j.resconrec.2020.105065

Rozemeijer, J.C., *et al.*, 2014. Water quality status and trends in agriculture-dominated headwaters; a national monitoring network for assessing the effectiveness of national and European manure legislation in The Netherlands. *Environmental Monitoring and Assessment*, 186, 8981–8995. doi:10.1007/s10661-014-4059-0

Schulte, R., *et al.*, 2010. Modelling soil phosphorus decline: expectations of Water Framework Directive policies. *Environmental Science and Policy*, 13, 472–484. doi:10.1016/j.envsci.2010.06.002

Schulte, R.P.O., *et al.*, 2006. Agriculture, meteorology and water quality in Ireland: a regional evaluation of pressures and pathways of nutrient loss to water. *Biology and Environment: Proceedings of the Royal Irish Academy*, 106B, 117–133. doi:10.1353/bae.2006.0031

Shore, M., *et al.*, 2016. Characterisation of agricultural drainage ditch sediments along the phosphorus transfer continuum in two contrasting headwater catchments. *Journal of Soils and Sediments*, 16, 1643–1654. doi:10.1007/s11368-015-1330-0

Thompson, J.J., *et al.*, 2012. Dynamics of critical source areas: does connectivity explain chemistry? *Science of the Total Environment*, 435-436, 499–508. doi:10.1016/j.scitotenv.2012.06.104

Tuohy, P., *et al.*, 2016. Rainfall and subsurface drain response from mole and gravel mole drainage across episodic rainfall events. *Agricultural Water Management*, 169, 129–139. doi:10.1016/j.agwat.2016.02.020

Ulén, B. and Fölster, J., 2007. Recent trends in nutrient concentrations in Swedish agricultural rivers. *Journal of Environmental Quality*, 373, 473–487.

Vadas, P.A., Bolster, C.H., and Good, L.W., 2013. Critical Evaluation of models used to study agricultural phosphorus and water quality. *Soil Use and Management*, 29, 36–44. doi:10.1111/j.1475-2743.2012.00431.x

Vadas, P.A., *et al.*, 2007. A model for phosphorus transformation and runoff loss for surface-applied manures. *Journal of Environmental Quality*, 36, 324–332. doi:10.2134/jeq2006.0213

Vadas, P.A., *et al.*, 2017. Quantifying the impact of seasonal and short-term manure application decisions on phosphorus loss in surface runoff. *Journal of Environmental Quality*, 46, 1395–1402. doi:10.2134/jeq2016.06.0220

Vadas, P.A., *et al.*, 2011. The effect of rain and runoff when assessing timing of manure application and dissolved phosphorus loss in runoff. *Journal of the American Water Resources Association*, 47, 877–886. doi:10.1111/j.1752-1688.2011.00561.x

Vero, S.E., *et al.*, 2014. Field evaluation of soil moisture deficit thresholds for limits to trafficability with slurry spreading equipment on grassland. *Soil Use and Management*, 30, 69–77. doi:10.1111/sum.12093

Watson, C.J., *et al.*, 2000. Inorganic nitrogen in drainage water from grazed grassland in Northern Ireland. *Journal of Environmental Quality*, 29, 225–232. doi:10.2134/jeq2000.00472425002900010029x

Watson, C.J. and Matthews, D.I., 2008. A 10-year study of phosphorus balances and the impact of grazed grassland on total P redistribution within the soil profile. *European Journal of Soil Science*, 59, 1171–1176. doi:10.1111/j.1365-2389.2008.01083.x

Watson, C.J., Smith, R.V., and Matthews, D.I., 2007. Increase in phosphorus losses from grassland in response to Olsen-P accumulation. *Journal of Environmental Quality*, 36, 1452–1460. doi:10.2134/jeq2006.0207

Withers, P.J.A., *et al.*, 2020. Towards resolving the phosphorus chaos created by food systems. *Ambio*, 49, 1076–1089. doi:10.1007/s13280-019-01255-1

Withers, P.J.A., *et al.*, 2014. Agriculture and eutrophication: where do we go from here? *Sustainability*, 6, 5853–5875. doi:10.3390/su6095853

Withers, P.J.A., *et al.*, 2003. Incidental phosphorus losses–are they significant and can they be predicted? *Journal of Plant Nutrition and Soil Science*, 166, 459–468. doi:10.1002/jpln.200321165