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A tool for cost-effectiveness analysis of field scale sediment-bound phosphorus mitigation measures and application to analysis of spatial and temporal targeting in the Lunan Water catchment, Scotland

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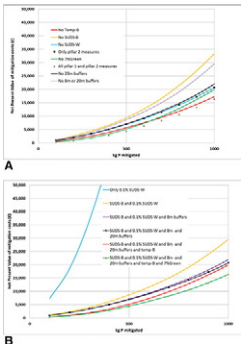
HIGHLIGHTS

- Cost-effectiveness of 6 measures to mitigate sediment P loss from fields analysed.
- Some measures (e.g. buffers, bunds and wetlands) were eligible for government grants.
- Some measures (e.g. sediment fences) were not eligible for government grants.
- Costs vary (£9–48/kg P) with target catchment scale impact (500–2500 kg P).
- Restricting available measures to only those funded by grants increases costs.

GRAPHICAL ABSTRACT



Effect on Net Present Value of optimised mitigated costs of (a) omitting (b) adding to the suite of measures available. In (a) measures are successively removed from the suite. In (b), measures are successively added to the suite.

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ABSTRACT

The cost-effectiveness of six edge-of-field measures for mitigating diffuse pollution from sediment bound phosphorus (P) runoff from temperate arable farmland is analysed at catchment/field scales. These measures were: buffer strips, permanent grassland in the lowest 7% of arable fields, dry detention bunds, wetlands, and temporary barriers such as sediment fences. Baseline field P export was estimated using export coefficients (low risk crops) or a modified Universal Soil Loss Equation (high risk crops). The impact of measures was estimated using simple equations. Costs were estimated from gross margin losses or local data on grants. We used a net cost:benefit (NCB) factor to normalise the costs and impacts of each measure over time. Costs minimisation for target impact was done using PuLP, a linear programming module for Python, across 1634 riparian and non-riparian fields in the Lunan Water, a mixed arable catchment in Eastern Scotland.
With all measures in place, average cost-effectiveness increases from £9 to £48/kg P as target P mitigation increases from 500 to 2500 kg P across the catchment. Costs increase significantly when the measures available are restricted only to those currently eligible for government grants (buffers, bunds and wetlands). The assumed orientation of the average field slope makes a strong difference to the potential for storage of water by bunds and overall cost-effectiveness, but the non-funded measures can substitute for the extra expense incurred by bunds, where the slope orientation is not suitable. Economic discounting over time of impacts and costs of measures

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favours those measures, such as sediment fences, which are strongly targeted both spatially and temporally. This tool could be a useful guide for dialogue with land users about the potential fields to target for mitigation to achieve catchment targets.

1. Introduction

The Water Framework Directive (WFD) requires EU member states to work towards achieving Good Ecological Status (GES) of surface fresh water bodies (EU, 2000). The chemical standards for water quality to achieve GES (UKTAG, 2012) need to be implemented at catchment scale. This has led to research effort to develop tools to identify cost-effective diffuse pollution measures at catchment and national scale (e.g.; Newell Price et al., 2009; Gooday et al., 2014, 2015). These often deal with multiple pollutants, and generally use "model farm" scenarios to identify the impact of farming and the mitigation of diffuse pollution from it. Sediment bound phosphorus eroding from arable fields is a principal contributor to ecological downgrading of water quality of lakes, and, more indirectly, of rivers in Scotland (Stutter et al., 2009; SEPA, 2015). It is widely recognised that much sediment related pollution from arable farming is the result of erosion from high risk areas (e.g. Bracken et al., 2013), which cannot readily be identified if diffuse pollution models are run at "model farm" scale. Although the hillslope is the natural hydrological scale at which to understand such processes (e.g. Lane et al., 2009), in the arable agricultural landscape field boundaries play a major part in delineating the combinations of crop/slope/riparian connectivity which lead to high risk, and this is also the scale at which most management information and practical intervention occurs. So in considering the analysis of costs of mitigation alongside effectiveness of potential measures, the field scale is the most tractable scale at which to specify the targeting of measures. It also lends itself to scaling up to devise plans for catchment scale management, a scale at which grants for integrated action are increasingly becoming available (e.g. Scottish Government, 2016). The Ecological Focus Area (EFA) measure in Scotland places a requirement for businesses with arable areas over 30 ha to have "greening" of at least 5% of their land within a recognised EFA option (fallow, buffer strips, field margins, catch crop/green cover, N-fixing crops). From the perspective of diffuse pollution mitigation, targeted use of these funds to areas of arable fields which could assist mitigation of soil erosion by being converted to unfertilised permanent grassland would be welcome.

A wide variety of mitigation measures has been identified for preventing loss of sediment and sediment bound P from arable fields to water associated with soil erosion. The first line of defence in the "treatment train" includes improved in-field methods, such as reduced tillage, cover cropping and seedbed management (Maetens et al., 2012; Rickson, 2014). However edge-of-field methods, such as those shown in Fig. 1 are also required (Rickson, 2014; Ockenden et al., 2012, 2014). Potential methods include the use of vegetated buffer strips and grass margins (Dosskey et al., 2010), conversion of arable land to unfertilised permanent grassland ("greening"), as well as physical barriers such as contour bunds, detention/retention basins, ponds and wetlands. Many of these are outlined in recent guidance documents for farmers in Scotland (Duffy et al., 2016) and have been shown to be effective in a rural context by other work (e.g. Braskerud, 2002; Braskerud et al., 2005; Wilkinson et al., 2014; Ockenden et al., 2012, 2014). In addition, physical methods that are receiving increased attention include the use of temporary barriers such as sediment fences (Keener et al., 2007; Farias et al., 2006; Stevens et al., 2007; McCaleb

Fig. 1. Clockwise from top left (a) 2 m regulatory buffer strip for protection of water course from sediment runoff from adjacent potato field, which also shows infield measure of contour furrows on end rig of the field (b) targeted sediment fence constructed in Dec 2014 at margin of field in aftermath of Brussels sprouts (c) detention bund constructed at base of gully running through field currently in grass. The site was chosen as high risk after large erosion losses after the field was in potatoes.

and McLaughlin, 2008; Vinten et al., 2014) or compost socks (Keener et al., 2007) made of geotextiles.

Apart from their overall costs and effectiveness, measures can be classified according to the extent to which they are implemented in either (a) a spatially targeted way (e.g. all field margins, riparian margins or low corners of fields) and/or (b) a temporally targeted way (e.g. always present, only present when an erodible crop is being grown or only present when an erodible crop is being grown and the year in question is high risk).

These factors influence the economically optimal combination of measures to be employed at the scale of regulation (e.g. WFD water body scale) and at the hydrological scale (catchment scale), to achieve target levels of mitigation of sediment P loads. There is a need to develop design methodology and guidelines at appropriate scale for practitioners and farmers, as well as to demonstrate more widely the potential for practical (i.e. cost-effective) application of such measures. This will enable farmers and catchment managers to make informed choices and obtain the mitigation of water quality and management impacts of sediment and sediment bound P, sought by WFD and other relevant policies.

In this paper, the cost-effectiveness of six generic measures, with different spatial and temporal attributes, are compared at catchment/field scales using simple field scale costing and effectiveness rules. We assume that buffer strips of at least 2 m width (Buff2 m) are implemented in all fields where other measures are not employed and they deliver some mitigation impact. The cost of this measure is considered zero, as it is a regulatory requirement. Other government-funded generic measures are: buffer strips on riparian margins of 8 m or 20 m width (Buff8 m, Buff20 m); non-fertilised permanent grassland in the lowest 7% of each arable field (7%Green); rural sustainable drainage systems consisting of either dry detention bunds (rSUDS-B) or wetlands (rSUDS-W); temporary barriers such as sediment fences or compost socks (Temp-B) installed without taking land out of arable production.

Government funding has recently been announced (Scottish Government, 2015) in Scotland for competitive Pillar 2 support under the EU Common Agricultural Policy (CAP) for several of these measures (Buff8 m, Buff20 m, rSUDS-B, rSUDS-W), while the other measures (7%Green, Temp-B) help achieve regulatory compliance ensuring receipt of the EU Pillar 1 support for agriculture, locally termed the single farm payment (SFP).

The cost-effectiveness of these alternative approaches to edge-of-field mitigation of P pollution associated with sediment loss from arable agricultural land has been analysed across 1634 fields in the Lunan Water catchment in Eastern Scotland. Mitigation impacts are defined relative to a modelled prediction of sediment bound P loss. These losses are estimated using either look up tables based on crop risk and slope risk or, for high risk crops, using the Universal Soil Loss Equation (USLE) combined with phosphorus enrichment/depletion ratios for erosion and entrapment of sediment. Each field/land use/mitigation measure combination is given a unique sediment P mitigation cost and mitigation impact depending on erosion and sediment P loss risk, land use, topography, simplified field geometry and design features of the mitigation measures. The information displayed on maps could readily be used as an aid to stakeholder and farmer engagement, alongside assessment of multiple benefits of these measures to facilitate more effective and responsive rural landscape planning.

2. Methods

2.1. Maximum potential for P mitigation for each agricultural field

The annual baseline field P export with the potential for mitigation by edge-of-field measures, P_{max} (kg P/ha), depends on crop risk (allocated a risk class of 1 to 5), slope risk (allocated a risk class of 1 to 3) and the fraction of P export linked to sediment runoff, and therefore amenable to entrapment by surface measures. For all but the highest risk class crops, P_{max} values were based on a lookup table taken from Balana et al. (2012). As an option, they were then modified by connectivity to water ($f_{connectivity}$, allocated a default value of 1):

$$P_{max} = C_{slope\ risk,crop\ risk}\ f_{connectivity} \quad (1)$$

Observations of sediment and P entrapment by temporary barriers in our study catchment (Vinten et al., 2014) showed that the values of P_{max} in Balana et al. (2012) for highest risk (risk class 5) crops, especially in high risk years, were too low. This is not surprising, as they are mean export coefficients, and therefore not taking into account year-to-year variation. As these values are critical to the overall analysis of targeted sediment P mitigation, we took a different approach to estimation of P_{max} in crop risk class 5 fields. This class is only used for crops such as potatoes and other vegetable crops grown in beds, where the risk of concentrated flows of runoff to form rills and gullies is enhanced, and for which post harvest cultivations make a big difference to erosion risk. The thinking is that in high risk years, such cultivations may be delayed, curtailed or omitted, thus exposing bare soil and ridge/furrow topography to winter rainfall. For crop risk 5 only, we assume:

$$P_{max} = ER\ [P]_{soil} SL\ f_{connectivity}\ f_{post\text{-}harvest\ management} \quad (2)$$

where ER = enrichment ratio of eroded soil = $[P]_{mobilised\ sediment}/[P]_{soil}$, which reflects selective mobilisation of fine sediment (see Sharpley, 1980); $[P]_{soil}$ = soil P content (g/kg); $[P]_{mobilised\ sediment}$ = mobilised sediment P content (g/kg); SL = eroded soil (kg/ha).

We used a calibration of the Universal Soil Loss Equation (USLE) developed by Stone and Hilborn (2012) for arable soils from Ontario, Canada, an area of similar agro-climatic conditions, to define soil loss:

$$SL = \left[0.163 + 0.114\alpha + 0.0164\alpha^2\right] \cdot (L/k)^N \quad (3)$$

where SL = soil loss in tonnes/ha, α = slope steepness (%), L = slope length in m, k = constant with a value of 22.1, N = 0.2, 0.3, 0.4 or 0.5 for slopes of <1%, 1–3%, 3–5%, and >5% respectively. The erosivity factor used was 100, the crop factor used was 0.5 and the soil erodibility factor used was 0.27 tonnes/ha. Both the tillage factor and the support factors were assumed to be 1. These factors are defined in Stone and Hilborn (2012) and Wischmeier and Smith (1978). It was assumed that all soil erosion takes place during the post-harvest winter months.

For the highest risk crops, year-to-year variation in climatic factors has been allocated an additional risk factor, $f_{post\text{-}harvest\ management}$, of 1 or 3, depending on whether the year in question is "normal" or "high" risk, especially with regard to the potential to carry out regulatory post-harvest cultivation management after row crops such as potatoes, which can be curtailed in difficult years, leaving a much higher risk of erosion by autumn and winter rainfall. Over the last ten years, we have observed two years when such post-harvest management was particularly challenging, so we have assumed this occurs one year in 5. Note also that there is limited variation in rainfall across the catchment, so risk factors do not need to vary either.

2.2. Effectiveness of measures

We classified the potential measures (see Fig. 2) into 3 broad types:

a. Measures that are weakly targeted both spatially and temporally. This type includes measures which form part of the requirements for regulatory compliance, such as 2m buffer strips on riparian margins of fields. It also includes buffer strips 2 to 20m wide (Buff8m and Buff20m), which are pillar 2 measures for improving water quality specified in the 2015-2020 Scotland Rural Payments Scheme (Scottish Government 2016).
b. Measures that are strongly targeted spatially, but not temporally. This type includes pillar 2 measures targeted to wet corners of fields,

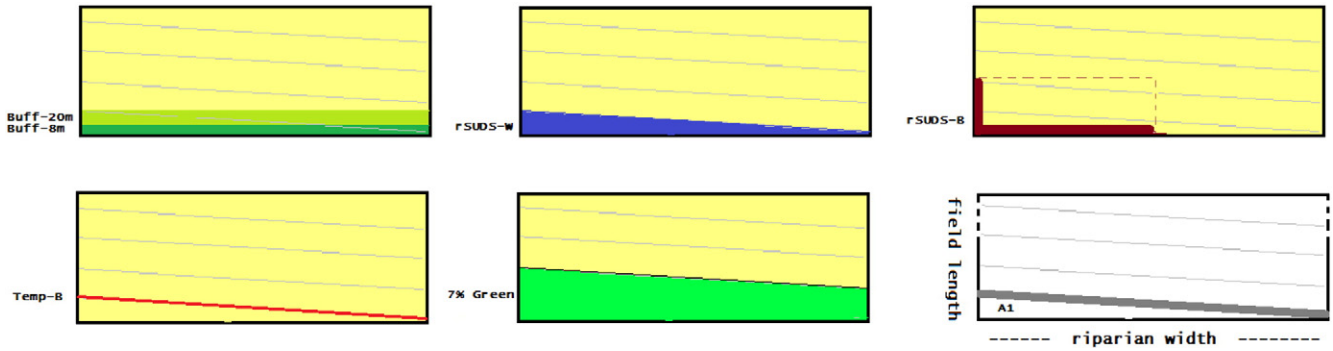


Fig. 2. Schematic representation of the positioning of different measures in a rectangularised field, relative to field edges and contours, for mitigation of sediment and sediment bound P pollution from arable fields.

such as ponds or wetlands (rSUDS-W) which take land out of production and dry sediment traps and bunds (rSUDS-B), which do not (apart from the area required for the bund and excavated trap (typically 3 metres width along the upslope edge of the bund). These measures are also specified in the 2015-2020 Scotland Rural Payments Scheme.

This type also includes the concept of "greening" for arable farmers. New EU rules require a percentage of arable land to be converted to low productivity grassland or subject to diversification. From a water quality perspective, if such land were targeted to the lowest, say, 7% of riparian arable fields, in which only unfertilised grass were grown and managed, the efficiency of these areas in mitigating sediment pollution would be high, perhaps > 90%. We term this measure "7%Green". This measure is not eligible for pillar 2 funding but is a measure which would aid compliance for pillar 1 single farm payments.

c. Measures that are strongly targeted both spatially and temporally. This type includes the use of temporary barriers, such as sediment fences or compost socks. They are likely to be targeted to high risk fields in high risk years, especially where post-harvest cultivation (e.g. tine cultivation or "grubbing" of potato land) has proved impossible to achieve due to wet conditions. This measure is also not eligible for pillar 2 funding but can be used to aid compliance for pillar 1 single farm payments. We term this measure "Temp-B".

The efficiency of sediment entrapment by a given mitigation measure X, $E_{X,\ mobilised\ sediment}$ (%) depends strongly on the design of the measure and the local field conditions (see below). In addition, sediment bound phosphorus (P) entrapment efficiency, $E_{X,\ P}$ (%), can be characterised by a typical depletion ratio, DR, which reflects the less efficient capture of mobilised finer sediment:

$$E_{X,P} = E_{X,mobilisedsediment}\ DR \quad (4)$$

where DR = depletion ratio of entrapped sediment = $[P]_{trapped\ sediment}/[P]_{mobilised\ sediment}$.

Our observations of the P content of intact soil and entrapped sediment by temporary barriers in arable fields (Vinten et al., 2014) suggest that the value of the term ER × DR × $[P]_{soil}$ ≈ 1.0 kg P/tonne of eroded soil. As $[P]_{soil}$ ≈ 1.0 kg P/tonne in this study, it follows that ER × DR ≈ 1.0 and we make this assumption for estimating sediment P mitigation in this paper. This ties in well with some other observations (e.g. Ockenden et al., 2014; Braskerud, 2002), but more work is needed to compare enrichment ratios across sites and depletion ratios across soil types and mitigation measures.

The details of how effectiveness and costs of each of these measures was estimated are contained in Supplementary Material A1. Table 1 contains a summary of the characteristics of each of the measures considered and default values used.

2.3. Discounting of costs and benefits for economic comparison between measures

We model mitigation of P export over 5 years, 2005–2009. The costs of each measure and their mitigation impacts are distributed in different ways through time. To capture this, we calculate a factor, termed the net cost:benefit factor, to normalise the costs and impacts of each measure:

$$NCB_X = (NPV(i_{costs}, 1, 1, 1, 1, 1)/NPV(i_{benefits}, 1, 1, 1, 1, 1) \quad (5)$$

where NCB_X = net cost:benefit factor for measure X, NPV = Net Present Value of costs or benefits, i_{costs} = discount rate for costs and $i_{benefits}$ = discount rate for environmental benefits. The values 0 or 1 are indices which show whether costs or benefits are incurred in any given year. All the calculations of costs of Buff8 m, Buff20 m, rSUDS-W, rSUDS-B, Temp-B and 7%Green in previous equations were multiplied by the appropriate NCB factor, before carrying out cost-effectiveness analysis. In our base case analyses, we assume a default discount rate of 7% for both costs and benefits. For the cost flows, the discount rate can be interpreted as the opportunity cost of capital (OCC) and 7% is equivalent to the average long term UK OCC i.e. interest rate (see http://data.worldbank.org/country/united-kingdom). For benefit flows, the discount rate can be interpreted as the social discount rate (SDR) which is a reflection of society's valuation of the benefits of social projects. This rate is however typically difficult to discern because of the risk associated with measuring benefits. To account for this uncertainty on the cost effectiveness of the measures, we conduct sensitivity analyses of the benefit discount rate at 0% and 14%, as well as 7%. We assume discounting of one off construction costs and benefits takes place over 5 years, and discounting of recurrent annual costs occurs each year.

2.4. Catchment

The Lunan water catchment (Figs. 3 and 6) is a typical mixed arable farmland catchment that drains an area of 134 km^2 from its source near the town of Forfar to the North Sea at Lunan Bay, in Angus, Eastern Scotland. The main crops grown in the catchment are spring and winter barley (26% of cultivated area in 2005), winter wheat (12%), potatoes (7%) and winter oil seed rape (7%) and grassland (15%). The cultivated area is 96% of the catchment. The remainder of the non-arable land use is mainly grassland and forestry with only a few small settlements within the catchment. Average annual rainfall is around 820 mm and is quite uniformly distributed throughout the year. Estimated annual evapotranspiration is around 400 mm. The maximum elevation in the catchment is 250 m, but most of the area lies along a flat broad valley and includes two lochs, Rescobie and Balgavies, covering 1.78 km^2. The catchment is dominated by arable farming on sandy soils (≈5% clay) of mainly the Forfar Association (water sorted drifts, derived from Old Red Sandstone). There are large arable areas in the catchment with significant slopes, which makes the growing of potatoes and other erodible crops,

Table 1
Measures considered and their characteristics of field location, cost and effectiveness.

Measure	Targeting	Crop	Duration	Cultivations	Recurrent costs	Capital costs	Position in field	P mitigation impact (see supplementary material A1 for equations)
2 m regulatory buffer	None	All risks	5 years	Normal	Nil	Nil	Riparian margin	Eqs. (S1) and (S2)[a]
8 m buffer (BUFF8 m)	None	All risks	5 years	Normal	£495/ha for 6 m buffer	Nil	Riparian margin	Eqs. (S1) and (S2)
20 m buffer				(BUFF20 m)	None	All risks	5 years	Normal
£495/ha for 18 m buffer	Nil	Ripari-an	margin	Eqs. (S1) and (S2)				
Wetland (rSUDS-W)	Spatial	All risks	5 years	Normal	Nil	£5/m^2 SUDS plus £5.5/m perimeter fence	Rectangle of 0.5% of field in lowest part of field	Eqs. (S3)
Detention bund (rSUDS-B)	Spatial	All risks	5 years	Normal	Nil	£7/m bund, plus £10.5/m^2 excavation plus £5.5/m perimeter fence[b]	Rectangle of 0.5% of field in lowest part of field	Eqs. (S11) and (S12)
7% Green	Spatial	All risks	5 years	Normal	Crop gross margin loss[c]	Nil	Lowest 7% of field	90% efficiency
Temporary barrier (Temp-B)	Spatial and temporal	Crop risk class 5	high risk year only (2009)	± Post-harvest cultivation for regulatory compliance	£5.5/m	Nil	On contour giving catchment area/fence length = 300	Eq. (S6)

[a] Dosskey et al., 2010.
[b] https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/environmental-co-operation-action-fund/catchment-management-for-water-quality/.
[c] Determined by local crop records or assuming local average (Lunan Water £680/ha).

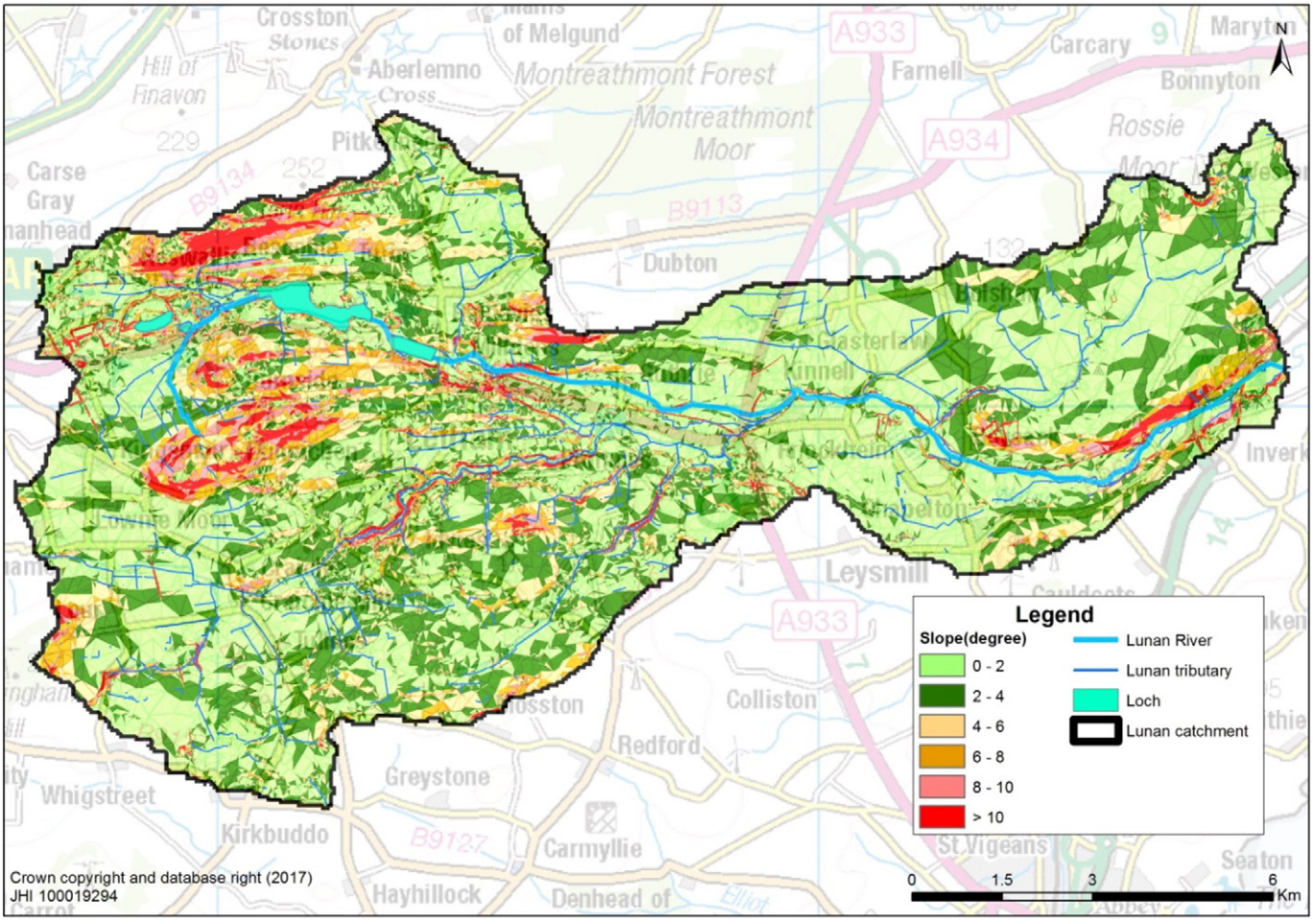


Fig. 3. Map showing average slope per 10 m pixel in the Lunan Water catchment, Eastern Scotland. Boundaries of fields used in optimisation process are also shown.

an important risk factor for sediment and diffuse P pollution losses in the catchment (Fig. 3). The model described above estimates export of P with a potential for mitigation by the measures considered, of 4380 kg (average of years 2005–2009). A number of the water bodies are currently at less than Good Ecological Status under the WFD and the lochs suffer from over-enrichment with P, leading to serious eutrophication in summer. This also affects the Lunan Water downstream, with an annual average Soluble Reactive Phosphorus (SRP) of 58 μg P/L (2011–2014, at Kinnell Mill, grid reference NO 59120 49660) and Moderate Ecological Status under the revised WFD standards (UKTAG, 2012). It is worth noting that 1000 kg P mitigation, if converted into an impact on the average total P concentration of the Lunan Water (mean annual flow 34.8 Mm^3) would reduce the annual average total P concentration by 29 μg/L. Impacts on soluble P concentrations would, of course, be lower, and depend on the extent of P desorption during sediment residence in the surface water environment.

2.5. Spatial data

For administration of the Common Agricultural Policy (CAP) in Scotland, the Integrated Administration and Control System (IACS) provides an annual field scale register of land use and agricultural activity at a detailed field scale. These data have been made available for the Lunan Water catchment by the Scottish Government from 2005 to 2009 and cover all areas where agricultural support is provided through CAP. Each crop was classified according to erosion risk (5 classes), and according to gross margin (5 classes) using the same categorisation as employed by Balana et al. (2012).

A 50 m resolution Digital Elevation Model (DEM) was used to determine the average slope in each field, and fields were categorised into 3 slope classes, as described by Balana et al. (2012). The DEM was also used to identify the lowest 5, 10 and 20% of each field by area and the length of the contour line defining the upper bound of this area. These values were used in the calculations to estimate costs of sediment fences.

For the stream network, the Ordinance Survey (OS) MasterMap dataset was used to distinguish riparian versus non-riparian fields, assuming riparian fields were all those within 20 m of a watercourse.

2.6. Cost-effective optimisation of placement of measures

Costs estimates and effectiveness/impacts data were integrated in an optimization model where the objective function being minimized was the aggregate cost of measures at sub-catchment scale to achieve target nutrient load reductions. The total cost function, C, is given by

$$C = \sum_s \sum_X \lambda_{X,s} C_{X,s} \quad (6)$$

where $C_{X,s}$is the cost of measure X in field s and $\lambda_{X,s}$is a binary variable which takes value 1 when measure X is implemented in field s and 0 otherwise. We want to calculate the minimum value of C, subject to a constraint on the total effectiveness:

$$\sum_s \sum_{X,s} \lambda_{X,s} R_{X,s} \geq R_{tot} \quad (7)$$

where $R_{X,s}$is the absolute amount of mitigation achieved by measure X in field s and R_{tot} is the total amount of pollutant mitigation required to achieve the water quality target. The total load *delivered* to the stream should then be:

$$\sum_s (E_s - \sum_X \lambda_{X,s} R_{X,s}) \leq Pload \quad (8)$$

where $E_s$is the total pollutant load coming from field s assuming no measures are in place and *Pload* is the maximum acceptable total load (from the catchment area of interest) before the waterbody fails to meet the desired water quality standard.

We solved the optimisation problem across 1634 riparian and non-riparian fields for a five year period in the Lunan Water catchment using PuLP (https://github.com/coin-or/pulp), a linear programming module for Python. The problem was formulated as a Binary Linear Program, which was used to minimise the cost for a specified effectiveness, subject to the condition that each field could have a maximum of only one measure.

3. Results

The modelled P losses with potential for mitigation across the catchment based on the above approach varied from 3477 to 4326 kg in "normal" years and were 10,520 kg for the "high risk" year. We carried out the cost-effectiveness analysis (CEA) of mitigation measures for a number of options, to help us identify which measures were important in delivering mitigation and in driving down costs, and which assumptions were critical to the model.

3.1. Availability of measures

We used two main default options for use of mitigation measures:

A. Assuming mitigation is achieved using only the key edge of field measures for improving water quality funded under pillar 2 in the 2015–2020 Scotland Rural Payments Scheme. These are buffer strips (Buff8 m and Buff20 m, of which 6 m and 18 m are funded by grants), rural SUDS wetlands (rSUDS-W), and rural SUDS bunds (rSUDS-B);
B. Assuming mitigation is achieved using the above measures, and also measures identified as relevant under pillar 1 arrangements for receipt of single farm payments in Scotland. These are 7% greening (7%Green) and temporary barriers (Temp-B).

The outcomes of the CEA for the default conditions (Table 1) are shown in Fig. 4a and b. We see that the average cost-effectiveness of mitigation, per kg P, increases strongly with increasing target P mitigation. We also see that in the absence of pillar 1 measures, rSUDS-B is the most important form of mitigation at all levels of mitigation. Only at higher levels of total mitigation do buffer strips play a significant role, and some of these need to be 20 m wide to contribute to the target mitigation. rSUDS-W is not cost-effective over the whole range of levels of mitigation. The presence of pillar 1 measures changes the picture, reducing costs at all levels of P mitigation and reducing dependency on rSUDS-B for delivery of mitigation. Temp-B, used in year 5 only, offers a cost-effective solution in that year. 7%Green, being less well targeted, offers cost-effective mitigation at higher levels, which substitutes for rSUDS-B.

3.2. Orientation of average field slope

The assumed orientation of the average field slope makes a strong difference to the potential for storage of water by rSUDS-B and hence treatment efficiency. For the above default options, A and B, we assumed the slope runs wholly up the non-riparian field boundary. As a variant to this we assumed that the slope was shared between two field boundaries, so equal length bunds for each side of the nominal rectangular field result, but with much less capacity for storage of water and therefore mitigation of sediment. The results for this variant are shown for pillar 2 measures only (Fig. 4c) and with pillar 1 and pillar 2 measures included (Fig. 4d).

The orientation of the slope has a strong effect on costs where only pillar 2 measures are employed, but to a significant extent, the pillar 1 measures, especially 7%Green, can substitute for the extra expense incurred by rSUDS-B, where the slope orientation is not suitable. This is

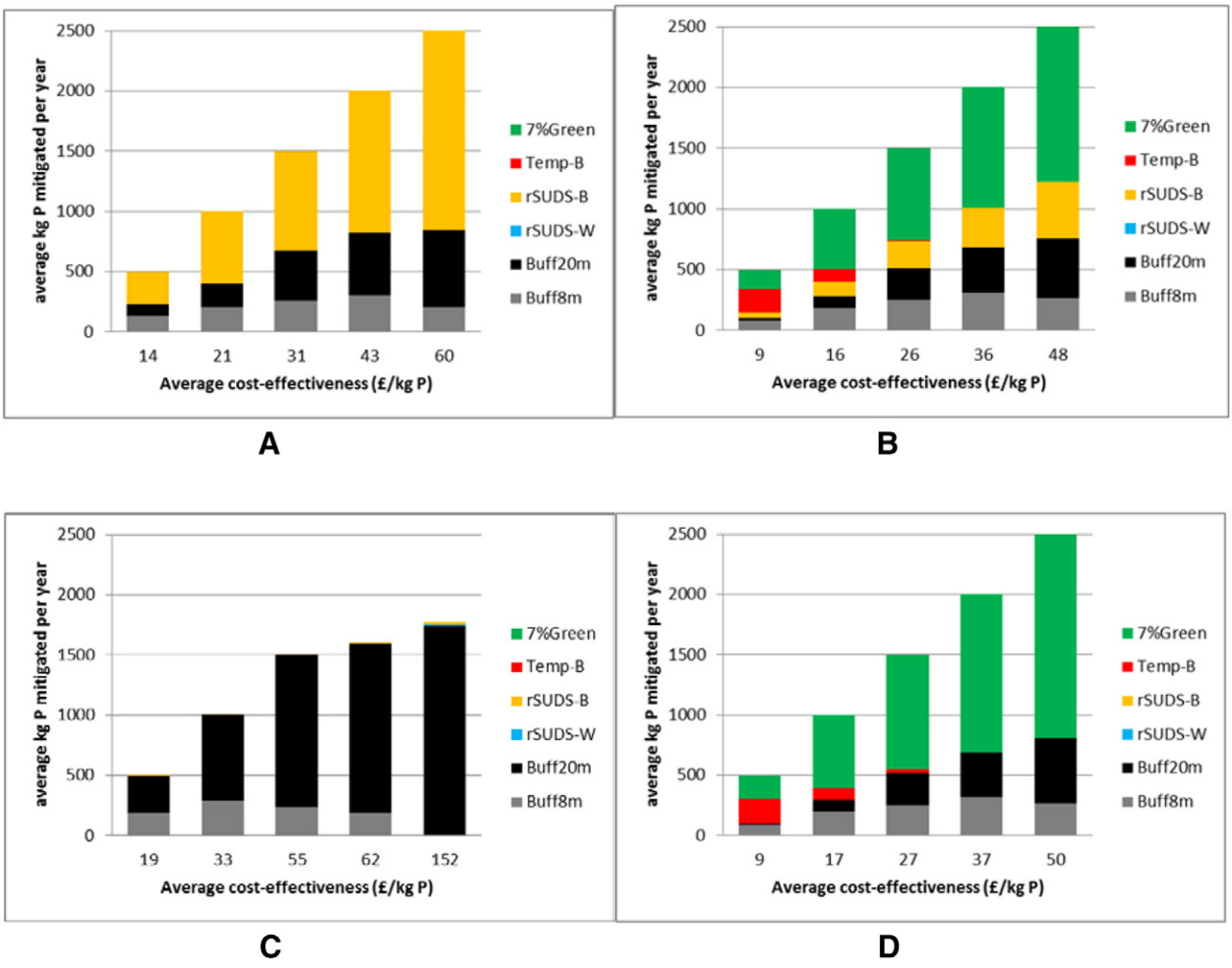


Fig. 4. Relationship between annualised costs and impacts. Default options. A. Assuming mitigation is achieved using only the key edge of field measures for improving water quality funded under pillar 2 in the 2015–2020 Scotland Rural Payments Scheme. These are buffer strips (Buff8 m and Buff20 m, of which 6 m and 18 m are funded by grants), rural SUDS wetlands (rSUDS-W), and rural SUDS bunds (rSUDS-B). B. Assuming mitigation is achieved using the above measures, and also measures identified as relevant under pillar 1 arrangements for receipt of single farm payments. These are 7% greening (7%Green) and temporary barriers (Temp-B). Impact of allocating average field slope equally between the riparian and non-riparian field boundaries, instead of default allocation to non-riparian field boundary. C. Assuming mitigation is achieved using only the key edge of field measures for improving water quality funded under pillar 2 in the 2015–2020 Scotland Rural Payments Scheme. D. Assuming mitigation is achieved using the above measures, and also measures identified as relevant under pillar 1 arrangements for receipt of single farm payments.

a useful result to be borne in mind for application when detailed surveys are done on individual fields to assess suitability.

3.3. Assumptions used for SUDS-W

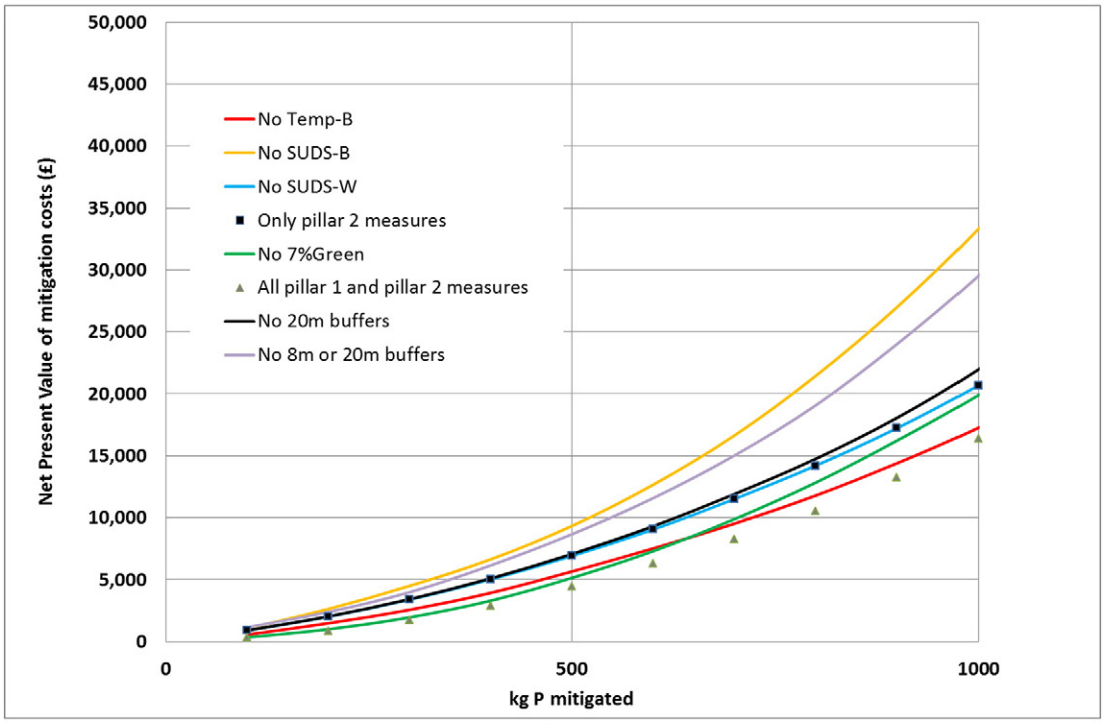
With the default assumptions (Table 1) presented in Fig. 4, we assumed efficiency will vary according to the criterion of the maximum load treated not exceeding 30 kg P/ha of SUDS-W, and wetland area of 0.5% of the total field area. When we decreased the effective wetland area to 0.1% SUDS-W was still not cost-effective. Only when the constraint of the maximum mitigation rate of 30 kg P/ha wetland/year was removed and the assumption of 0.1% instead of 0.5% land take was made, did rSUDS-W contribute, and even then it was only at the higher mitigation rates (74 kg of a total 2500 kg P mitigation, or 3%). We included this modification for consideration of the impact of omission and addition of measures.

3.4. Omission of individual measures

This has a potentially strong effect on overall costs as shown in Fig. 5. The effect of stepwise addition (Fig. 5a) and stepwise removal (Fig. 5b) is shown, over the range from 0 to 1000 kg P mitigation. This shows that rSUDS-W is not cost-effective, but that all the other options (with the possible exception of Buff20 m) have an important role to play in driving down costs at a catchment scale. As we have seen, including the pillar 1 measures, as well as pillar 2, in the CEA, leads to significantly lower costs. For comparison, Vinten et al. (2012) assumed septic tank and sewage treatment works P mitigation had costs of £35/kg P and £15/kg P respectively, so these field measures are competitive with point source treatment in many cases, with 43 fields having a marginal mitigation cost <£15/kg P and delivering 516 kg P mitigation and a further 101 fields having a marginal mitigation cost <£35/kg P, delivering a further 484 kg P mitigation.

3.5. Severity of erosion losses

We assumed post-harvest erosion in high risk crops depends on whether post-harvest cultivations are possible. In field studies on use of sediment fences as Temp-B measures in the Lunan Water catchment (Vinten et al., 2014), we found that there was a threefold increase in sediment captured on potato field plots that were not cultivated by post-harvest tine cultivation (or "grubbing", as required under the



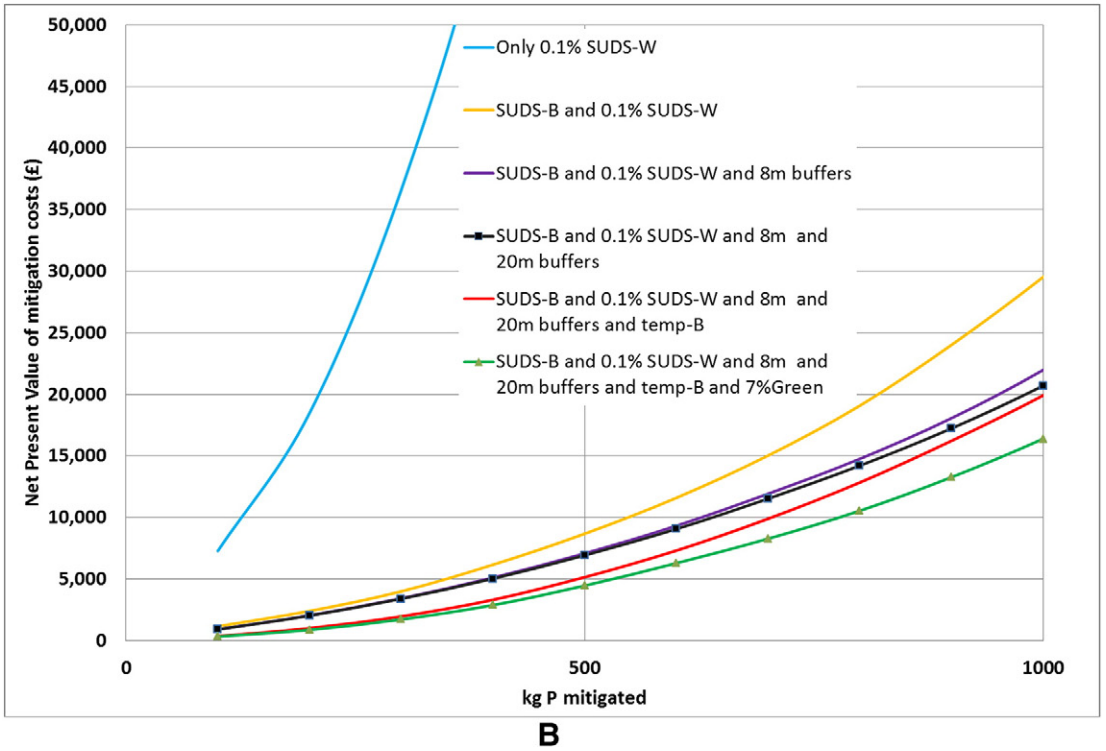
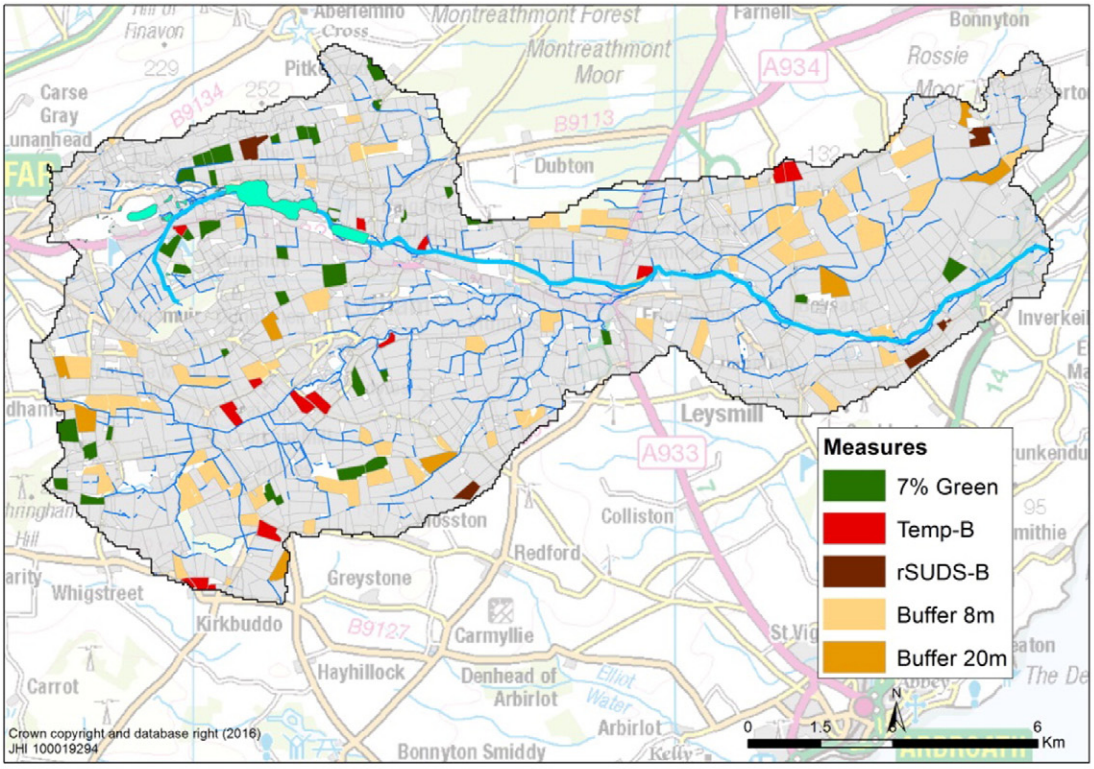


Fig. 5. Effect on Net Present Value of optimised mitigated costs of (a) omitting (b) adding to the suite of measures available. In panel a, measures are successively removed from the suite. In panel. b, measures are successively added to the suite.

Good Agricultural and Environmental Condition (GAEC) rules for receipt of pillar 1 single farm payments by farmers). In the default case presented in Fig. 4, we increased the value of P_{max} by a factor of 3 in the analysis for 2009, to simulate one high risk year in five, when post-harvest cultivations required in autumn are not possible, due to wet conditions, or when they are ineffective. The use of Temp-B was limited to this year. However, it may be that they could be cost-effectively used in all risk class 5 crops and all years, even when this additional post-harvest risk is not present. When we assumed no high risk years and that Temp-B was available in all years (results not shown), costs

were higher than the default case, because of lower soil erosion rates. We also find that, as before, other measures can substitute effectively for rSUDS-B, with little additional costs, where the slope allocation limits storage volume of the bunds. With the lower erosion rates, the increased availability of Temp-B (i.e. in all years) is offset by lower cost-effectiveness.



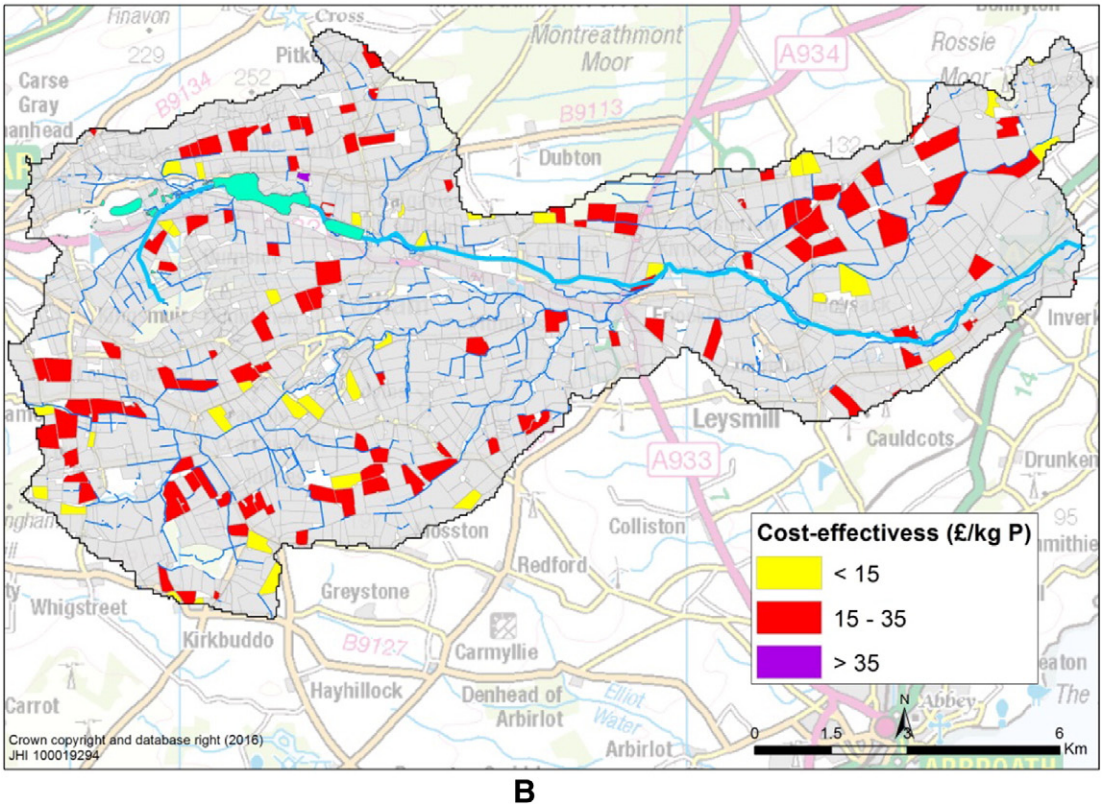


Fig. 6. Example of allocation of measures to fields in the Lunan Water to achieve 500 kg P mitigation from erosion of sediment. A. Preferred measures B. Cost-effectiveness of these measures for each field.

3.6. Riparian connectivity

Our default assumption was that $f_{connectivity} = 1$ for all fields. If we define riparian fields as those <20 m from watercourses and allocate them $f_{connectivity} = 1$, and assume all other fields (35% of total arable area) are non-riparian and have $f_{connectivity} = 0.06$, as was done in Balana et al. (2012), this decreases the average potential for P mitigation from 4380 to 3035 kg P, a 31% reduction. The cost of achieving 500 kg P mitigation is however only increased by 12% by this assumption.

3.7. Discussion and conclusions

The purpose of this paper is to describe the development of a simple and versatile tool, using readily obtainable spatial data at field scale, to assess cost-effectiveness of sediment P mitigation at catchment scale. Without considering multiple benefits, the most competitive options from a suite of six regulatory, SRDP funded and privately funded options for mitigation of P losses from arable land to water were identified. This has been done for riparian fields and cropping conditions showing a range of source strengths (soil erosion losses) and design criteria, such as area requirements for SUDS measures. Fig. 6 shows an example of how the results of a CEA can be displayed spatially. Such displays will form a useful tool for dialogue with land users and stakeholders about the potential fields to target for mitigation, in the next phase of the work.

The overall analysis shows that cost-effectiveness of P mitigation is higher, where erosion risk is higher. Depending on assumptions about discount rates for costs and benefits, this is strongly enhanced by temporal targeting of measures instead of using spatially fixed measures. It also suggests that pillar 1 measures to support erosion control (7%Green, Temp B), are more cost-effective than the pillar 2 measures in many circumstances, especially where risk of soil erosion is high. Such measures need to be financed directly by farmers, but protect their statutory single farm payment, and so may well be implemented without costs to government, increasing their attractiveness to policy-makers. It is noteworthy that a significant increase in fallow land has been recorded (http://www.gov.scot/Topics/farmingrural/Agriculture/CAP/regulations/Meetings-2015) in 2015 in Scotland:, following the release of the new greening measures, 23,600 ha (4% of arable area) were given over to fallow, compared with 11,900 ha the previous year. If this were targeted to lower field corners instead of whole fields, it would have a substantial impact on diffuse pollution losses from suitably targeted fields, while not jeopardising agricultural production. The contra-argument is however, that as with buffer strips, such areas will eventually become sources of soluble P, whereas with measures such as temporary barriers or SUDS detention bunds, the sediment and P associated with it, has a much better prospect of physical recovery and return to fields (Stutter et al., 2009).

At lower erosion risk, the importance of spatially fixed Buff8 m and Buff20 m measures is greater. When aiming at high levels of sediment P loss mitigation, rSUDS-B are also cost-effective. It is also worth noting that the funding of the rSUDS-B and rSUDS-W measures includes an element of funding for fencing. If this is the case, it would make sense for the area allocated to a sediment bund to have an upper boundary in the field that was set along a contour and lined by sediment fencing. Even if the area used was small, such a layout would significantly aid the retention of eroded sediment in the field, rather than in the rSUDS feature, where recovery and re-use might well be more difficult.

Considering comparative costs of materials for potential Temp-B measures, typical sediment fence costs are £1–2/m while typical compost sock costs are £5–10/m. Installation costs for sediment fences, which are dug in to the ground and pinned to temporary fence posts, are probably higher than for compost socks, which may provide an effective seal with the land surface with only rudimentary staking and no digging. Both measures are in use in trials and commercial contexts in the UK, and a comparative study looking at both costs and effectiveness of these alternatives would be worthwhile.

The discount rate of the benefit flows can be interpreted as the social discount rate (SDR) and is typically difficult to discern hence the need for sensitivity analyses of this parameter on the cost effectiveness of measures. If we expect the risk premium of the SDR to be higher than that of the opportunity cost of capital, OCC (i.e. discount rate of the cost flows), then the SDR would be higher than the OCC, and vice versa. Hence we set the SDR at 0% (i.e. 7% lower than the default discount rate of 7%) and the higher benefit discount rate at 14% (i.e. 7% higher than the default discount rate of 7%). A higher SDR of 14% implies society places a higher risk premium on the benefits of the measures, leading to a reduced valuation of those benefits and hence higher 'discounted cost-benefit ratio'. The implication is that for every benefit, there is a higher cost than the default. Similarly, a lower SDR of 0% implies society places a lower risk premium on the benefits of the measures, leading to a higher valuation of those benefits and hence lower 'discounted cost-benefit ratio'. The implication is that for every benefit, there is a lower cost than the default results.

Evidently these results depend on the assumptions about relative efficiency of the various methods and their costs – a topic about which there is a great deal of uncertainty, given the diversity of variables which contribute to the outcome of the mitigation. Now that the CEA framework is established, more exploration of these uncertainties would be warranted, across a range of arable catchments, with differing land use and topography.

The analysis described could be enhanced by several methods, such as:

(a) by improvement of spatial methods to include analysis of the topography of field corners for all fields in the catchment. Use of LIDAR data may enable more accurate representation of the dimensions of rSUDS-B, in particular, which would greatly enhance assessment of costs and effectiveness; it would also be better to be able to draw the line of a sediment fence on an accurate contour, and to use the topographic data to identify catchment areas within fields more closely;
(b) by improved modelling of erosion risk as a function of field topography, crop, soil type, rainfall intensity and timing, and enrichment ratios of sediment entrained. A key area to be considered in this modelling is the relationship between post-harvest cultivation and erosion losses, especially for late harvested row crops;
(c) by improved modelling of entrapment efficiency for spatially targeted measures and for temporary barriers on high risk crops and years;
(d) The choice of method adopted depends on many factors other than economic costs and mitigation of sediment P, although this is the principal reason for these edge-of-field measures being available for grant support in the first place. However, the analysis methods used here are quickly applicable across a range of catchments and scales, and so allow a first assessment of the likely costs and effectiveness of measures that are being supported by the Scottish Government under the 2015–2020 rural payments strategy. This could then help inform applications for funds which need to include multiple criteria analysis as well.
(e) The analysis does not consider variations in the total P content of soils in the catchment. This would be valuable, but compared with plant available P, such data is normally hard to obtain, although Lumsdon et al. (2016) report total, plant available and water soluble P for 66 fields in the Lunan catchment. The CV for Total P (28%) was relatively low, and hence a mean value was considered appropriate for this study. Moreover, it was difficult to relate total P to plant available soil P ($r^2 = 0.28$) or water extractable P ($r^2 = 0.22$).

(f) There are many factors, such a soil texture and stability, the concentration of phosphorus in hotspots associated with livestock, and the formation of gullies and rills leading to concentrated flows of water and sediment, which would influence both source strength and mitigation by the measures considered. Many of these are factors can best be considered by on the ground inspection by local agri-environment advisors, once the initial appraisal using the cost-effectiveness tool has been done at catchment scale.

(g) Improved knowledge of landscape connectivity. Non-riparian fields can deliver sediment through field gates or road drains, and riparian fields can be weakly connected. Such considerations require detailed knowledge of field-by-field structures, which, as with item (f) above, can better be dealt with on the ground by field advisors.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.02.034.

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