Integrating Economic and Biophysical Data in Assessing Cost-Effectiveness of Buffer Strip Placement

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The European Union Water Framework Directive (WFD) requires Member States to set water quality objectives and identify cost-effective mitigation measures to achieve "good status" in all waters. However, costs and effectiveness of measures vary both within and between catchments, depending on factors such as land use and topography. The aim of this study was to develop a cost-effectiveness analysis framework for integrating estimates of phosphorus (P) losses from land-based sources, potential abatement using riparian buffers, and the economic implications of buffers. Estimates of field-by-field P exports and routing were based on crop risk and field slope classes. Buffer P trapping efficiencies were based on literature metadata analysis. Costs of placing buffers were based on foregone farm gross margins. An integrated optimization model of cost minimization was developed and solved for different P reduction targets to the Rescobie Loch catchment in eastern Scotland. A target mean annual P load reduction of 376 kg to the loch to achieve good status was identified. Assuming all the riparian fields initially have the 2-m buffer strip required by the General Binding Rules (part of the WFD in Scotland), the model gave good predictions of P loads (345–481 kg P). The modeling results show that riparian buffers alone cannot achieve the required P load reduction (up to 54% P can be removed). In the medium P input scenario, average costs vary from £38 to £176 kg^{-1} P at 10% and 54% P reduction, respectively. The framework demonstrates a useful tool for exploring cost-effective targeting of environmental measures.

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The European Union's Water Framework Directive (WFD) requires Member States to set water quality objectives or standards and to identify cost-effective mitigation measures to achieve "good status" in all waters in Europe in 2015 (EC, 2000; WATECO, 2003). Evidence suggests that diffuse agricultural pollution such as phosphorus (P) is a key contributor affecting water quality (Fezzi et al., 2008; Haygarth et al., 2009; Johnsen, 1993; Vinten, 2009; Vinten et al., 2008). Surface runoff and erosion represent the major, but not exclusive, paths of diffuse P loss from many agricultural systems (Bailey et al., 2007; Kronvang et al., 2005). Because P is less soluble than, for example, nitrate, the main loss process of P involves particulate loss associated with the eroding soil particles. Thus, edge of field controls, such as buffer strips (Collins et al., 2009; Maguire et al., 2009; Liu et al., 2008), are among the principal options for P pollution mitigation. One reason that buffers are strongly favored is the relative ease of blanket legislation for narrow buffer strips to be placed on all watercourses. In Scotland, for example, the requirements of the WFD have been transposed into the national Controlled Activities Regulations [The Water Environment (Controlled Activities) (Scotland) Regulations 2005 No. 348; Environmental Protection: Water]. Diffuse pollution is regulated by the General Binding Rules (GBRs), whereby activities posing a risk, such as cultivation of land, need to follow rules to protect the water environment. Examples include the statutory requirement for a 2-m buffer between watercourses and cultivated land (part of GBR20-cultivation of land [see http://www.sepa.org.uk/water/diffuse_pollution.aspx]). In addition, economic measures, such as payments for the establishment of up to 6 m grass margins around the perimeter of fields to provide "beetle banks" also offer the opportunity to mitigate diffuse pollution (Scottish Government, 2006). Such application of buffers in complex agricultural landscapes is envisaged to partly meet erosion control and P load reduction requirements.

Our premise is that better targeting of buffers in terms of buffer width and spatial placement in key locations (e.g., widening certain buffer areas) may be more cost-effective than uniform installations. However, this targeting approach requires an integrated economic–biophysical framework. The key aim

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Abbreviations: GBR, General Binding Rule; LMO, land management options; MC, marginal cost; PLUS, Phosphorus Land Use Slope; SAC, Scottish Agriculture College; SEPA, Scottish Environment Protection Agency; TP, total phosphorus; WFD, Water Framework Directive.

of this study is to develop such a framework and demonstrate it in a case study on optimizing the size and placement of riparian buffer strips for mitigating P entering into Rescobie Loch in the Lunan water catchment, eastern Scotland. While some dynamic P export models such as INCA-P (Wade et al., 2002) can provide useful detail on the export and transformations between different forms of P, their semidistributed structure means that the field-by-field analysis of placement of buffer strips is difficult to achieve. Other field plot–scale models, such as MACRO (Larsson et al., 2007; McGechan et al., 2002), require too much parametrization to be efficient at catchment scale and do not deal with landscape-based transport. For analysis of the baseline P export to standing water with turnover time of several months, a simple annual export model, as used by many other works (e.g., Johnes and Heathwaite, 1997; Fozzard et al., 1999), was considered the most appropriate. This is readily applicable, through risk-based coefficients, to consideration of the effects of riparian buffers on a field-by-field basis across a landscape of varying topography. However, it should be recognized that the lack of a process base in such models means that key sensitivities to soil, crop, and livestock management attributes such as high P status soils, hotspots of pollution due to placing of feeders close to streams, or inadequate manure storage may be overlooked. Moreover, soil texture and soil stability are not considered. However, we believe that for the development of cost curves to describe the effectiveness of buffer strips in an agricultural landscape, the export coefficient approach is adequate.

Based on scenarios of crop and land uses allocations generated using the LandSFACTS (Landscape Scale Functional Allocation of Crops Temporally and Spatially) model (Castellazzi et al., 2010) and geographical information system (GIS) tools, P export coefficients and buffer P trapping efficiencies were estimated for each field. Average gross margins for various farm activities were obtained from the Scottish Agriculture College (SAC) Farm Management Handbook 2008/09 (SAC, 2008). An integrated optimization model of cost minimization was developed and solved for different P reduction targets using the "Risk Solver Platform" optimization tool in Excel (Frontline Systems, 2011). The optimization model identifies optimal buffer widths for each of the riparian fields to achieve specified water quality targets at minimum economic cost.

Materials and Methods

Characterization of Rescobie Loch and Catchment

Rescobie Loch is a shallow, eutrophic loch in Angus, eastern Scotland. It has an area of 0.59 km^2, mean depth of 3.3 m, catchment area of 19.6 km^2, and a turnover time estimated as 0.35 yr. The mean catchment excess rainfall has been modeled as 279 mm yr^{-1} using the hydrological approach developed by Dunn et al. (2004) (see also SNIFFER, 2006), and mean catchment rainfall is 771 mm. The soils of the catchment are mainly freely draining podzols with some brown earths. Alluvial soils are found along the main drainage channels. These soils are a combination of sorted and unsorted drifts derived from Old Red Sandstone and fluvio-glacial deposits derived from acid rocks. Much of the area is underlain by groundwater bodies in Old Red Sandstone. The area of fluvio-glacial sands and gravels borders the river channel network and in groundwater terms is classified as a high productivity drift aquifer. The maximum elevation is 251 m (Turin Hill), and most of the topography is undulating hills.

The catchment is dominated by mixed arable farming, much of it on moderate to steep slopes. A number of small streams (e.g., Baldardo Burn, Burnside Burn) and ditches drain into the loch. Much of the riparian land around these streams and ditches is poorly buffered mixed arable farmland, which leads to significant quantities of sediment and nutrients (N and P) being transported into the loch from surface runoff. In addition there are external inputs from septic tanks, from a small caravan site with a private sewage treatment works, from birds, and from fish stocking. Phosphorus is the nutrient often considered to be limiting undesirable growth of cyanobacteria and green algae in freshwater lochs, and the loch specific standard for achieving the WFD "good status" is a total P (TP) concentration of 27 μg L^{-1} (I. Fozzard, personal communication, 2008). The observed annual geometric mean TP concentration in 2003 to 2006 ranged from 59 to 84 μg L^{-1}. The loch often suffers from severe cyanobacterial blooms in late summer (e.g., *Aphanizomenon* spp., an important genus of cyanobacteria that inhabits freshwater lakes and can cause choking blooms).

Field Characteristics and Crop Allocations

The export of soluble and sediment associated P into Rescobie Loch from overland flow for each field is assumed here to be driven by slope, crop type, and cultivatable area. Each of the cultivated fields, major streams, and ditches were identified and extracted from Ordnance Survey (Southampton, UK) Master Map topographic vector layer, and the three required parameters were generated. The riparian fields were identified as those where one or more boundaries were intersected by a 20-m riparian buffer generated around the water courses. The average slope of each field was defined by using zonal statistics on the slope raster generated from a smoothed 10-m Ordnance Survey Land-Form PROFILE Digital Terrain Model. Ten independent cropping scenarios for the Rescobie Loch catchment were generated using the LandSFACTS model (Castellazzi et al., 2010) based on Scottish Integrated Administration and Control System (SIACS) census data.

Export Coefficients for Phosphorus

Average field slope, crop type, and cultivatable area were used to allocate P export coefficients to each of the fields (Table 1). The three slope classes (<4, 4–13, and >13 degrees), and the default multipliers are those used in the export model Phosphorus Land

Table 1. P export coefficients (kg/ha) as a function of crop risk class and slope risk class.

Slope risk class	1	2	3
Avg. field slope	<4°	4–13°	>13°
Slope descriptor	Low	Medium	High
Crop risk class	P export coefficient		
	kg ha^{-1}		
1 (very low)	0.01	0.02	0.03
2 (low)	0.06	0.10	0.14
3 (moderate)	0.3	0.5	0.7
4 (high)	0.7	1.1	1.5
5 (very high)	1.3	2.2	3.1

Use Slope (PLUS) (Fozzard et al., 1999), which has been widely used for estimating trophic status of lochs based on land use in Scotland. For each slope risk class, field-by-field land use is separated into five risk classes. Arable crops are separated into three classes: moderate, high, and very high (Table 2). This differs from PLUS (which only has one class for arable crops) to reflect the observation that winter cereals are more vulnerable to soil erosion than are spring cereals (e.g., Speirs and Frost, 1985) and that there is much greater soil erosion observed from vegetables and potatoes due to the fine seedbeds and ridge and furrow cultivation up- and downslope. Land used for these crops is also often left bare during the vulnerable autumn–winter periods, leading to increased erosion risk and P loss. The P export coefficients used for the low (2) and high (4) crop risk classes are the median figures for rough grazing and arable classes in PLUS. We used the export value for rough grazing from Johnes and Heathwaite (1997) for the low crop risk class.

Drawing on the results of Norwegian experiments on plots of varying erosion risk (Kronvang et al., 2005), we assumed that the proportion of particulate P in the export from fields increased from 0.5 to 0.9 with increase in crop risk class 1 to 5 (see Table 3). Using results from the same paper, which showed an increasing proportion of P transported via surface runoff, rather than subsurface drainage, as the erosion risk increased, we assumed the proportion of P transported by surface runoff increased from 0.6 to 0.8 from erosion risk class 1 to 3. Combining these two assumptions gave estimates of the ratio of soluble P from surface runoff to total P exported from the field for each crop/slope risk combination from Table 1. These are given in Table 3.

Modeling Phosphorus Input into Rescobie Loch

To test the export coefficient approach, total P input was modeled for the Rescobie Loch catchment. The P export (P_{land}) from cultivatable land (m fields) to the loch is given by Eq. [1] where we assume that the fraction that is amenable to buffer strip mitigation is the particulate P traveling in surface runoff:

$$P_{\text{land}} = \sum_{i=1}^{m} (P\text{s}, r_i f_{\text{buffer}_i} + P\text{p}, r_i + P\text{s}, d_i + P\text{p}, d_i) f_{\text{connectivity}_i} f_{\text{stream\_to\_loch}} \quad [1]$$

where $P\text{s},r_i$, $P\text{p},r_i$, $P\text{s},d_i$, and $P\text{p},d_i$ = soluble (s) and particulate (p) P losses through surface runoff (r), and subsurface drainage (d), respectively, $f_{\text{buffer}i}$ = 1 – buffer trapping efficiency of the ith field, $f_{\text{connectivity}i}$ is the proportion of P reaching the stream from a given field, and $f_{\text{stream\_to\_loch}}$ is the proportion of P entering the stream that reaches the loch. We assume that there is no buffering on nonriparian fields ($f_{\text{buffer}i}$ = 1) and that all the P leaving riparian fields reaches the water course ($f_{\text{connectivity}i}$ = 1). We expect that connectivity between nonriparian fields and watercourses is relatively low because most of the flow will be diverted by field margins to run down the edges of fields, where coarse vegetation will act to provide for relatively efficient filtration, deposition and infiltration, and deposition of runoff sediment along the field margin. The value of $f_{\text{connectivity}i}$ (set at 0.06) for the nonriparian fields and the value of $f_{\text{stream\_to\_loch}}$ (set at 0.85) were chosen to help tune the P export model so that total delivery was in line with estimates based on loch total P status. The various buffer efficiency figures used in this paper and the loch's P mass balance are presented in Tables 4 and 5, respectively. The detailed descriptions of the Rescobie Loch P mass balance and connectivity estimates are provided in the separate online supplemental material.

Potential for Mitigation by Buffer Strips

We identified three policy-relevant buffer widths, as mitigation options (Table 4):

1. 2 m: the minimum width required by current regulations for arable agriculture in Scotland under the so-called General Binding Rules (GBRs) (see SEPA, n.d.).
2. 8 m: a typical buffer width (6 m) receiving payment for grass margins and beetle banks under the Scottish government Land Management Options (LMO) scheme in arable fields (see Scottish Government, 2011), plus the 2 m minimum requirement. The subsidy requires a margin to be established around the whole perimeter of the field.
3. 20 m: a buffer width expected to be near 100% efficient in removing sediment from runoff except where concentrated rill or gully flows occur.

The mitigating effect of buffer strips was estimated using the metadata set of Collins et al. (2009), who summarized the efficiency of sediment and nutrient removal by buffer strips as a function of width, slope, and soil texture from over 40 papers. In the medium-slope class, the efficiency of P removal was determined by the exponential model fit between sediment or TP removal and buffer width from these data. The coefficients and 95% confidence intervals thus determined were 0.3 (upper bound 0.34, lower bound 0.24) for 2-m buffers, 0.75 (upper bound 0.82, lower bound 0.67) for 8-m buffers, and 0.97 (upper bound 0.99, lower bound 0.94) for 20-m buffers. In the other slope classes, we assumed higher or lower efficiencies than the medium class, based on expert judgment. The buffer efficiencies generated by this process agreed reasonably well with another metadata analysis by Liu et al. (2008). Note that variability in buffer performance cannot be explained by buffer width and slope alone, being a complex

Table 2. Crop risk classes assumed for the crop types within the Rescobie Loch catchment.

Crop risk class	Land use/crop types
1	Rough grazing
2	Grass over 5 yr, fallow land, set aside
3	Spring barley, grass under 5 yr, spring oats, spring wheat, fodder leaf, grass for mowing, fruit
4	Winter barley, winter wheat, peas/beans, winter oats
5	Turnips/swedes, bulbs/flowers, fodder roots, ware potatoes, seed potatoes, other vegetables

Table 3. Fraction of P export from fields which is amenable to removal by buffer strips.

Crop risk class	Proportion particulate P	Slope risk class 1	Slope risk class 2	Slope risk class 3
		Proportion of P traveling as runoff		
		0.6	0.7	0.8
1	0.5	0.3	0.35	0.4
2	0.6	0.36	0.42	0.48
3	0.7	0.42	0.49	0.56
4	0.8	0.48	0.56	0.64
5	0.9	0.54	0.63	0.72

Table 4. Buffer strip efficiency factors as a function of width and slope.

Buffer widths	Slope risk class		
	1	2	3
	Buffer strip efficiency factor		
2 m (GBRs)†	0.5	0.3	0.1
6 m +2 m (LMOs +GBRs)‡	0.9	0.75	0.5
20 m	1	0.97	0.94

† GBRs = General Binding Rules (regulatory standard) (SEPA, n.d.)

‡ LMOs = land management options (economic option) (Scottish Government, 2011).

function of the soil type, catchment area, microtopography, soil cover and management, and so on, which cannot be reasonably incorporated into a simple export model.

Integration of Biophysical and Economic Data

Buffer trapping efficiencies were combined with economic data on farm gross margins and integrated into the geo-database. This enabled the calculation of P input, P reduction, and the economic costs of P mitigation as a function of buffer width (Fig. 1). To calculate this loss of area the vector field boundaries and streams were manipulated in ArcGIS. The cultivatable area of fields with whole-perimeter buffers was calculated by applying a simple internal buffer to each field. For the case with buffers on just the riparian margins, field boundaries along the major streams and ditches were first identified by buffering the water courses by 20 m. Field boundaries lying within this buffer zone were considered "riparian," and these margins alone were subsequently buffered (by 2, 8, and 20 m) to create riparian buffer strips. The buffer strip areas were then subtracted from the original field areas to estimate the area of cultivatable land remaining.

Cost estimates were based on the gross margins obtained from the SAC Farm Management Handbook (SAC, 2008) based on 2007 prices. The handbook is claimed to be a comprehensive and up-to-date source of information for farm business in Scotland. Each year, it provides estimates of gross margins for various farm business and activities in the United Kingdom. From the results of crop rotation simulations, we identified the cropping sequence in each of the 90 riparian fields under consideration (accounting for 95% of land-based loch P inputs). Based on the size of field area allocated to buffers and cropping sequences, average gross margin per field and loss of farm income from each field were obtained. As buffer zones are assumed to be established merely from abandoning land from agricultural activities, other costs such as construction or capital investment costs were not considered.

Economic Optimization Model Framework

A cost-effective selection of buffer strips requires that the cost of pollutant abatement be minimized, provided that at least the predetermined pollutant concentration into a loch is satisfied. Following Azzaino et al. (2002), this can be presented as an integrated optimization model (Eq. [2]):

$$\left.\begin{array}{l} \text{Min } C = \sum_i B_i C_i \\ \text{subject to} \\ \sum_i (X_i - X_i^B) \geq Q \end{array}\right\} \quad [2]$$

where B_i is a binary variable taking the value of 1 if buffer strip of a certain width is established in the *i*th field and 0 if it is not; C_i is the cost of establishing a buffer strip in the *i*th field; X_i denote P loadings entering the loch without buffer from field *i*; X_i^B is the P loadings entering into the loch after establishing a buffer strip in field *i*; and Q denotes the minimum required P input reduction into the loch to achieve the WFD good status standard for P.

Following Eq. [2], we built the following empirical model for identifying cost-effective selection of buffer widths across the riparian fields in the Rescobie Loch catchment (Eq. [3]).

Table 5. Loch and catchment P mass balance used for cost-effectiveness analysis

			Notes†
Rescobie Loch			
	Loch total P concentration μg/L	71	A
	Implied total P load to loch (kg)	604	B
Non-land-based inputs			
	Septic tanks	98	C
	Sewage treatment works	20	D
	Fish stocking	7	E
	Birds	16	F
	Internal load	30	G
	Total non-land-based inputs to loch	172	H
Land-based inputs to streams			
	From riparian fields with no buffers	593	I
	From riparian fields with default 2-m buffers	484	J
	From nonriparian zone	22	K
Delivery from land to stream		506	L
Delivery from stream to loch	Estimate of land-based total P load to loch	432	M
	Implied proportion of P entering the stream that reaches the loch ($f_{stream\_to\_loch}$)	0.85	N

† A: mean of 2003–2006 annual geomeans; B: Using Vollenweider and Kerekes (1982); C: 0.3 kg total P/person/yr, 4 persons per septic tank, and 82 septic tanks; D: 0.44 kg total P/person/yr, 90 per caravan site sewage treatment works, operating 50% of year; E: Using mean stocking and catch rates for loch (2000–2009), assuming P content of 0.23%; F: Assuming deposition rates per unit loch area the same as for Loch Leven; G: Assuming 5% of total load per year; H = C+D+E+F+G; I: Export model; J: = export corrected using Tables 3 and 4; K: Using nonriparian $f_{connectivity}$ = 0.06; L: = J + K; M = B – H, which implies $f_{stream\_to\_loch}$ = 0.85; N = M/L.

A. Objective Function

$$\text{Min } C = \sum_i \sum_j (\text{GM})_{ij} B_{ij} \quad [3]$$

where i = 1, …, 90 (the 90 riparian fields considered in the model), j = buffer width j in the field i, B_{ij} = a binary variable (B_{ij} = 1 if buffer of width j is established in field i and 0 otherwise), and GM = farm gross margin foregone in putting buffer of width j in field i.

B. Constraints

1. Environmental constraint: This constraint specifies that P reduction from all fields considered should be greater than or equal to a specified proportion (k) of the 10-yr mean overall TP load reduction required to comply with the desired water quality standard (Eq. [2]). For Rescobie Loch, we estimated an annual TP loading of 604 kg, out of which about 432 kg (71.5%) comes from land-based sources and the remaining 172 kg (28.5%) from various other sources such as septic tanks, sewage treatment works, and loch internal loads (see Table 5). Using the loch-specific Scottish Environment Protection Agency (SEPA_ good/moderate boundary of 27 μg L^{-1} P, we estimated that to achieve SEPA's good/moderate loch quality status, the total P loading of the loch should not be more than 228 kg TP. Assuming that the 172 kg P cannot be treated by riparian buffer strips, this implies that to achieve the desired loch quality status, the required P input reduction to the loch is 376 kg P. A mean P load reduction from land-based sources of 440 kg P is required to achieve this, assuming only 85% of what enters the stream reaches the loch (Table 5). In Eq. [4], this required P reduction to achieve the WFD requirement for P is denoted as Q_p:

$$\sum_i \sum_j (PR)_{ij} B_{ij} \geq \left(\frac{k}{100}\right)(Q_p); \text{for } 1 \leq k < 100 \quad [4]$$

where $(PR)_{ij}$ = the amount of P reduction from field i if buffer of size j is installed in field i. The model was solved for k = 10, …, 100 P reductions percentages.

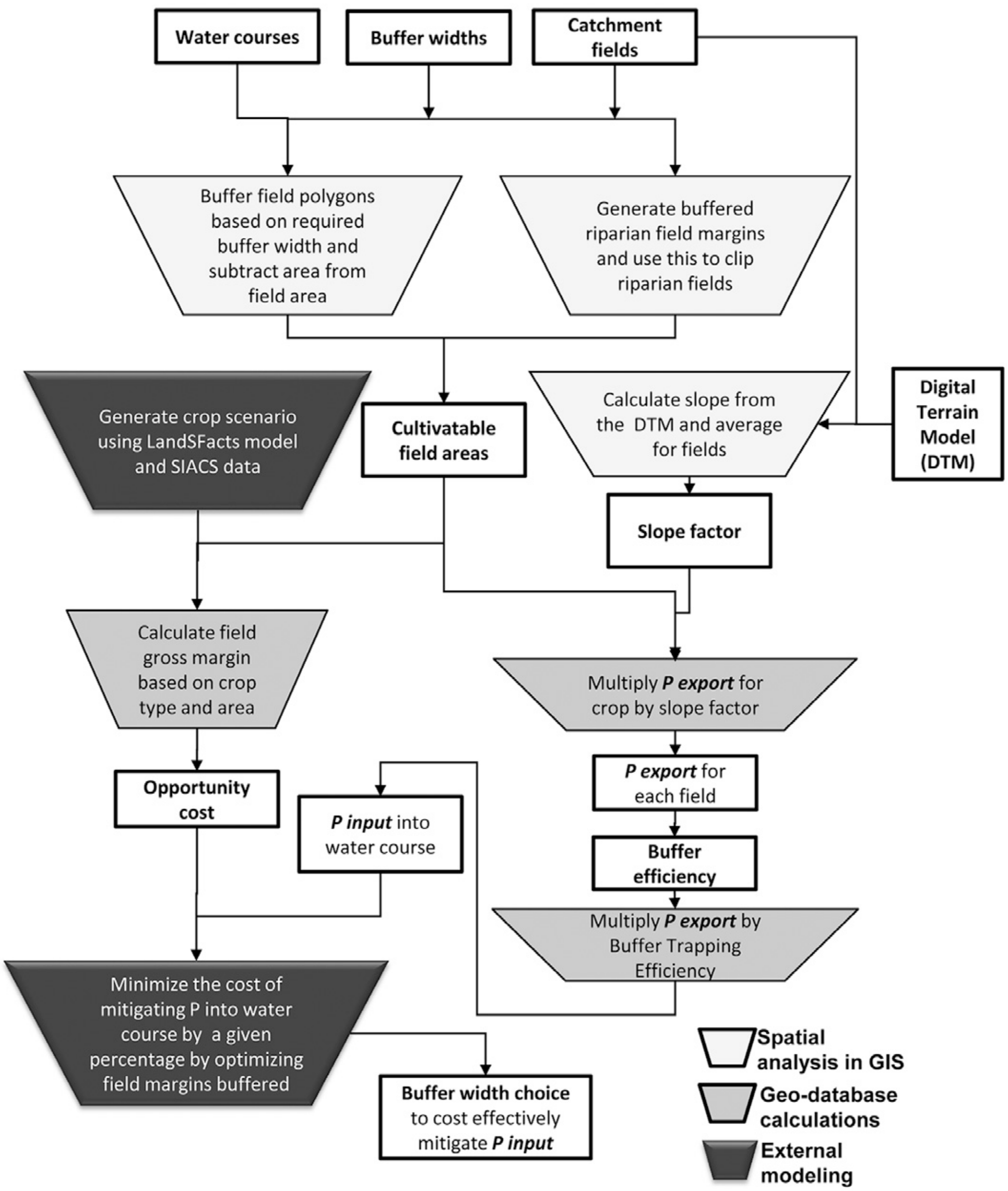

Fig. 1. Conceptual diagram showing the framework to integrate the spatial, biophysical, and economic data used for cost-effectiveness analysis.

2. Buffer width constraint: A field can have one of the three discrete buffer widths. Mathematically,

$$\sum_j B_{ij} = 1; \forall i$$

where j = 2 m, 8 m, 20 m. and B_{ij} = binary (0 or 1); for all i's. A similar approach was pursued by others; see, for instance, Yang and Weersink (2004).

3. Policy constraint: All fields must have a minimum of a 2-m buffer as required by the GBR for arable agriculture in Scotland. Therefore, a given field can operate just at the GBR condition (2 m) or an 8-m or a 20-m riparian buffer.

Results

Simulation Outcomes

For the 10 simulated crop arrangement scenarios, the median predicted P load to Rescobie Loch associated with the 90 riparian fields with a 2-m buffer was 421 kg P (range 345–481 kg P). Without any riparian buffer, the median predicted P load was 515 kg P (range 417–592 kg P), lower than the export model P prediction (i.e., 593 kg P from land-based sources, Table 5). We assumed that the regulatory 2-m buffer was the default condition, and this figure was used to estimate the small nonriparian contribution to the catchment mass balance in Table 4, by difference. Results from the 10 simulated rotations show that buffer strips can achieve up to 54% of the required P load reduction. From the 10 crop rotation simulation results, three scenarios with low (345 kg P), median (421 kg P), and high (481 kg P) loads were selected. Compared with the mandatory 2-m buffers, if 20-m buffers were applied across all riparian fields with the low P loads scenario, the maximum loading reduction would be 158 kg P (about 36% of the required reduction); if 20-m buffers were applied with high P loads scenario, the maximum loading reduction would be 238 kg P (about 54% of the mean required reduction). Thus, any combinations of the default 2-m buffers, with some 8-m and some 20-m buffers, would not achieve more than 54% of the mean P reduction required for good status of the loch; i.e., P reduction required for good loch status cannot be achieved by buffer strips alone.

Sensitivity Analysis

We undertook a sensitivity analysis of the export model to changes in key values. Doubling export coefficients for risk classes 1 and 2 led to only a 1% increase in predicted export to the loch, but doubling export coefficients for risk classes 3 to 5 led to a 71% increase. Increasing the multiplier for slope class 3 from 1.4 to 1.8 led to only a 2% increase in predicted export to the loch, while decreasing the multiplier for slope class 1 from 0.6 to 0.2 led to a 12% decrease. Halving the multiplier for crop risk class 3 from 0.5 to 0.25 led to a 13% decrease in predicted export to the loch, while doubling the multiplier for crop risk class 5 from 2 to 4 led to a 23% increase. Decreasing the default 2-m buffer strip efficiency factor by 0.1 led to a 5% increase in predicted export to the loch. Doubling the nonriparian connectivity factor led to a 3% increase in predicted export to the loch, but doubling the efficiency of P removal by streams and loch riparian area led to a 13% decrease. Finally, Brett and Benjamin (2007) reviewed seven models used to describe the relationship between P loads and loch TP concentration. Depending on choice of model, the implied export of P to the loch varied from 73 to 132% of the load calculated using Eq. [5]. This analysis suggests that improving our local understanding of risk factors for high-risk crops at moderate slopes would do most to improve the estimates of loading from fields. The use of average slope to define the slope risk class could also be improved, as this limits the number of fields exhibiting high risk of soil erosion. Moreover, an improved local knowledge of the deposition of P in streams and the loch riparian zones, and of the response of loch TP concentration to P loads, would also be helpful.

Economic Optimization

The optimization modeling framework outlined in Eq. [3] and [4] seeks to minimize the foregone value of economic returns of crop production as a result of land allocation to buffer strips, subject to achieving a certain percentage of P reduction in Rescobie Loch. The model determines the selection of either of the 2-, 8-, or 20-m riparian buffer widths for each of the agricultural fields across the riparian areas. The selection is jointly determined by the economic costs of foregone crop returns and the P trapping efficiency of buffer strips in each of the fields.

Figures 2a and 2b indicate the cost-effective combination of buffer widths for various levels of P load reduction relative to the target mean P load reduction requirement under low P loss of the 10 crop rotations (low scenario) and high P loss of the 10 crop rotations (high scenario), respectively. Figure 3 shows the spatial distribution of the results for 30% of the mean required P load reduction under the low P input scenario. As the set P reduction level increases, more fields are under the 20-m buffer in the low scenario than in the high scenario. For instance, to achieve P reduction by 30% of the mean required P load reduction cost effectively, 34 riparian fields should be with 20-m buffer under the low scenario, whereas only 8 fields need to be with the 20-m buffer under the high scenario. The explanation for this is that under the low scenario, there is less opportunity to mitigate P loading than with the high scenario (see Fig. 2).

Table 6 presents the abatement costs (total and average costs) to achieve various levels of P reduction at low, median, and high P input scenarios. For instance, with a 30% P reduction, the total gross margin loss will be £15,489, £9901, and £7472 in the three scenarios, respectively. As with the increase in the number of fields with larger buffer widths under the low P input scenario, larger cost is incurred to fix the problem if the P input is already at low level. On the other hand, even if one can afford larger economic costs, in reality not all land-based P inputs can be removed with buffer strips. For instance, under the low P input scenario, with a uniform buffer width of 20 m in all the 90 riparian fields, the maximum physical P reduction potential would be 158 kg P yr^{-1} (i.e., 36% of the desired reduction) with a total foregone annual crop return value of about £32172. To achieve the required P reduction, other abatement measures should be implemented in both the land- and non-land-based sources to account for the P input unabated by buffer strips. Under all the three P input scenarios, 100% P removal using buffer strips is not feasible (see Table 6). Various studies on buffer P trapping efficacy documented different findings. Uusi-Kämppä and Kilpinen (2000; cited in Iho, 2004) reported that a buffer strip of 10-m width removes 30 to 40% of TP in surface runoff. In his numerical analysis of the cost-effective reduction of P runoff into the Ylane River (Finland), Iho (2004) indicated that a buffer strip of 10 m traps 17.5% TP runoff originating from agricultural fields. From the buffer zone experiments conducted in Nordic countries, Uusi-Kämppä et al. (2000) reported that buffers decreased 27 to 97% of TP loads from agricultural runoffs (the experiments include buffers with widths ranging from 1.5 to 16 m on different soil textures such as loam, clay and sandy soils).

From the point of view of cost-effective P reduction, field-by-field targeting of buffer widths would achieve a given P reduction at a much lower cost. For instance, the median P input scenario, with uniform 8-m buffers across all the 90 riparian fields, would result in a reduction of 129 kg P (i.e., 30% of the required reduction), with a total cost of £12,326. The same 30% P reduction can be achieved at a lower overall cost of £9901 (about 20% cost saving) by placing 8-m buffers in only 37 fields, and the remaining 16 fields with 20-m buffers and 37 fields in 2-m GBR condition. For 30% P reduction, the most cost-effective combinations of buffer widths under low P input scenario would be 46 riparian fields with 8-m buffers, 34 fields with 20-m buffers, and 10 fields remaining at 2-m GBR. For the same 30% P reduction, if the high P input scenario is considered, the combination of widths is 29 fields with 8-m buffers, 8 fields with 20-m buffers, and 53 fields with 2-m GBR condition.

Discussion

Achieving water quality targets at minimum economic cost is one of the underlying principles driving the selection of mitigation measures. Agro-environmental management can involve a variety of strategies to reduce diffuse pollution such as phosphorus. By reducing surface runoff and trapping incoming sediments and nutrients, buffer strips along agricultural fields can offer important environmental services including as filters for agricultural phosphorus (Iho, 2004; Uusi-Kämppä et al., 2000; Yang and Weersink, 2004). However, the trapping efficacy of buffers and the associated economic returns foregone vary across space. Considering the variation in both biophysical capacity and economic productivity at field-by-field level in riparian agricultural lands across a given catchment could lead to achieving specified water quality targets at minimum economic cost. As can be seen from Table 6, the abatement costs increase significantly with increases in the P reduction levels

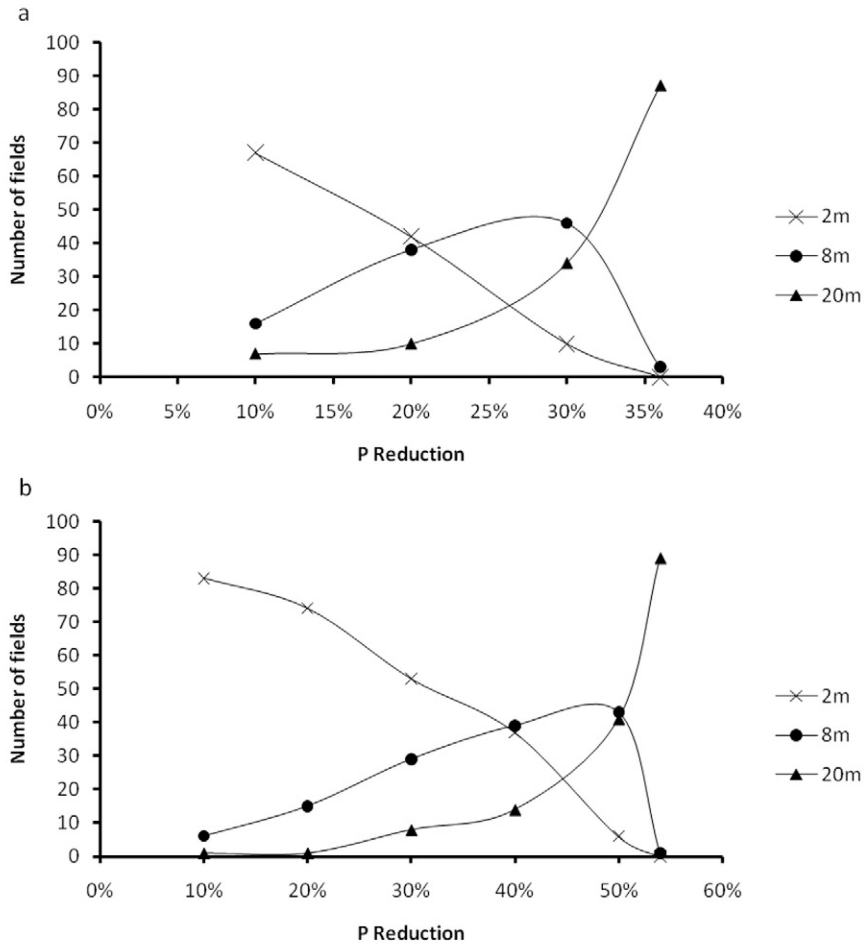

Fig. 2. Optimum buffer width combinations to achieve various proportions of the mean target P load reduction under different P input scenarios: (a) low P input scenario and (b) high P input scenario.

Fig. 3. Optimal spatial distribution of fields with various buffers widths to achieve 30% of the mean P loading reduction under low P input scenario. (Field boundaries and water courses from Ordnance Survey Master Map Topographic Layer; Ordnance Survey, Southampton, UK).

Table 6. Total cost (TC) and average cost (AC)† under low, medium, and high P input scenarios.

P Reduction	Costs under low P input		Costs under medium P input		Costs under high P input	
	TC	AC	TC	AC	TC	AC
10%	1,990	45	1,666	38	1,425	33
20%	5,970	68	4,498	51	3,585	41
30%	15,489	117	9,901	75	7,472	57
36%	32,172	204	14,914	94	11,080	70
40%	n.a.‡	n.a.	20,426	116	14,329	81
45%	n.a.	n.a.	36,877	184	19,409	97
50%	n.a.	n.a.	n.a.	n.a.	26,366	120
54%	n.a.	n.a.	n.a.	n.a.	41,890	176

† All costs are in £ (TC in £/total P reduced/yr; AC in £/kg P removed/yr).

‡ n.a. = not applicable. Depending on the P input scenarios (low, medium, and high), the maximum potential P reduction if 20-m buffers placed in all the riparian fields is 36, 45, and 54% respectively of the required P removal.

for all three P input scenarios. If, for instance, we move from 20 to 30% P reduction under all three P input scenarios (low, median, and high), the corresponding costs increase much more than proportionately, i.e., from £5970 to £15,489, £4489 to £9901, and £3585 to £7472, respectively.

Although land-based activities are the major P source in the study catchment, future cost-effectiveness research should also consider the P mitigation options for other sources, such as septic tanks and sewage treatment works. In the case study presented here, for instance, about 28% of P input is contributed from other non-land-based sources. Attention should also be paid to mitigation options other than riparian buffers, such as constructed wetlands and reduced use of fertilizer (Uusi-Kämppä et al., 2000; Withers and Jarvis, 1998). Considering multiple sources and examining alternative mitigation options could result in an enhanced cost-effective solution for achieving the environmental objective. The results reported in this study show the limitations of riparian buffers when considered as the sole mitigation measure for agricultural P removal. For example, if the sewage derived P were mitigated at a cost of £15 kg^{-1} P and the septic P at a cost of £35 kg^{-1} P (based on data from Ove Arup, 2005), the cost of mitigating P from these sources (118 kg P, Table 5) would be £3,604. If, for example, we intend to remove 50% of the required P reduction (i.e., 220 kg P), an additional 102 kg P need to be removed from land-based sources. The cost (for the high P input scenario in this study) of mitigating the 102 kg P using buffer strips would be £5404, making a total of £9008. For the same 50% P reduction, total cost would be £26366 using buffer strips alone (the former cost is only 34% of the latter).

Figure 4 shows the marginal cost (MC) curves (i.e., the rate of changes in total costs to the changes in P reduction levels) and the relative rate of increase of MC in the three P input scenarios. The MC curve and its rate of increase are the highest in low P input scenario compared with the other two cases. The implication is that the cost of reducing each additional P input to the loch increases at a higher rate at the margin when the current P input level is already low. In all the three scenarios, the MC curves are negatively sloped. This is consistent with the microeconomic production theory of diminishing marginal returns or increasing marginal cost, which states that within the production process with some inputs held fixed, each additional unit of a variable input provides a smaller benefit (diminishing return/increasing cost) at the margin. Although the case under study is not a production process as described in neoclassical microeconomic theory, the same principle applies in the economics of pollution abatement (Kolstad, 2000; Perman et al., 2003), i.e., the abatement potential of a measure decreases or its cost increases when the level of the abatement activity of that measure increases.

It is worth considering whether the existing policies for management of riparian areas in Scotland provide an efficient means of achieving the funding required to meet these costs. Measures such as payments for the establishment of up to 6-m grass margins around the perimeter of fields to provide "beetle banks" also offer the opportunity to mitigate diffuse pollution. These currently attract a payment of £500 ha^{-1}, but all field margins must be so managed. From the case study, we found that riparian buffers could not achieve 100% P mitigation from the riparian fields. The implication is that considering ways to trap P traveling in drainflow, and soluble P (e.g., by establishment of riparian wetlands through blocking drains), as well as addressing point sources could enhance the cost-effectiveness of achieving the environmental objective. Hence, we suggest

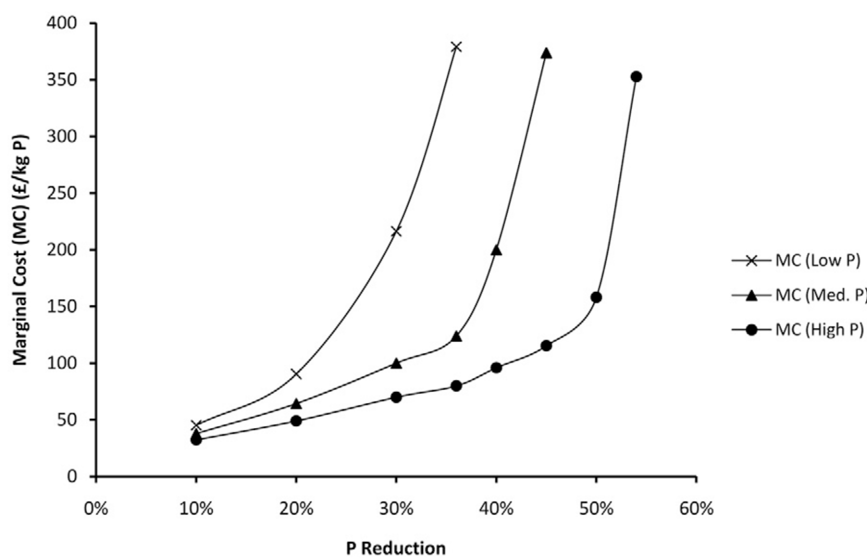

Fig. 4. Marginal abatement cost curves (to achieve a percentage of the mean P loading reduction target) under the low, medium, and high P input scenarios.

future cost-effectiveness studies to explore multiple sources of pollutants and alternative mitigation options. We also suggest that instead of focusing on a single benefit of buffer strips (such as P trapping benefit as in this study), future studies need to explore the multiple benefits of buffer strips such as biodiversity and wildlife corridors for better decision support. Implementing a measure for reducing a particular pollutant may generate unintended impacts (e.g., pollution swapping). Thus, ranking and choice of measures based on cost-effectiveness analysis findings should be further supplemented by assessment of these wider cobenefits and costs.

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