Modelling Nutrient Export from Agricultural Land: Approaches, Scales and End-Users

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Abstract: In parts of Australia and much of the UK, increased inputs of nitrogen and phosphorus to land in the form of fertilisers, manures and biosolids means that agricultural runoff now comprises a greater share of these nutrients in rivers and lakes and associated water quality problems. While numerous site-specific field studies have quantified the potential export of nutrients in agricultural runoff, it is clear that to meet the requirements of end-users, the research effort needs to shift towards developing generic models of non-point source pollutant export from land that are based on expert knowledge but remain simple to use and easy to apply. Data-hungry process-based models, while elegant and all-encompassing, may not be suitable for the simple decision support frameworks required by end users such as government agencies, water utilities and farmers.

Keywords: *Nitrogen; Phosphorus; Empirical modelling; NPS pollution; Agriculture*

1. INTRODUCTION

Significant advances have been made in recent years to improve knowledge on the sources and cycling of nutrients, especially nitrogen (N) and phosphorus (P) within agricultural systems through, for example, the UK DEFRA R&D on *Phosphorus Loss from Agriculture to Water*, the USDA *P Index* Planning Tool and the Australian *National Eutrophication Management Programme*. The seriousness of water quality deterioration as a consequence of the export of nutrients in agricultural runoff has been documented recently for both the UK [Environment Agency, 2000] and Australia [Davies and Koop, 2001]. Phosphorus in particular limits the biological productivity of freshwaters; if present in excess it can accelerate the eutrophication of freshwaters. Eutrophication has been identified as the most ubiquitous water quality impairment in the US [USEPA, 1996; USDA/EPA, 1999].

Empirical nutrient export models may be used to develop predictors or indicators of loss at the small catchment through to regional or national scale. These so-called 'black-box' models have long been used to provide simple budgets of, for example, nutrient loads entering waterbodies [e.g. Johnes and Heathwaite, 1997]. Such models make no attempt to explain the processes involved in generating nutrient outputs from a set of input parameters but allow some evaluation of the impact of changing inputs or managing outputs within, for example, agricultural systems.

While it is recognized that agriculture is an important contributor to P loading on water bodies in England and Wales it is clear that current estimators of P loss are crude and there is little consensus on the most appropriate indicators of P loss. To meet this knowledge gap a number of empirical phosphorus export models are currently being evaluated in the UK under a DEFRA research programme: *Towards a National Consensus on Indicators of P Loss to Water from Agriculture*. A prototype of a new tool, able to produce a best expert assessment of the most appropriate single indicator or set of indicators of P loss from land to water, is being developed. Such consensus is necessary to meet DEFRA requirements to provide national indicators of agricultural sustainability with regard to NPS P loss to water. Parallel research on P export from land to water is being undertaken in the US, where simple nutrient indexing approaches have been developed [e.g. Gburek et al., 2000; Weld and Beegle, 2001] and applied on a farm-by-farm basis in selected study areas. This work is being undertaken in response to USDA/EPA proposals that all Animal Feeding Operations (AFOs) have a comprehensive nutrient (P and N) management plan in place by 2008 in order address water quality concerns related to nutrient management. Interim results [Beegle et al., in prep] suggest even simple P indices may not be time or cost-effective when utilised as field assessment tools. The implications of such conclusions in developing a balance between the research product and the needs of the end-user will be evaluated in this paper in the context of empirical P modelling tools.

2. BACKGROUND

2.1 The Problem: Non-Point Source (NPS) Nutrient Export to Water

On a global scale, less than 10% of surface waters may be classified as pristine [Heathwaite et al., 1996]. There is strong evidence to implicate NPS loading of P and N on surface waters as the causal factor [Carpenter et al., 1998; Sharpley and Rekolainen, 1997]. Phosphorus is typically the key limiting nutrient in freshwater ecosystems but N is important in hypertrophic waters - particularly standing waters - with a large excess of P [EEA, 1999] because freshwater cyanobacteria can fix atmospheric N. In estuarine ecosystems, P tends to be the limiting nutrient at the freshwater extreme, grading through to N-limitation at the seaward end, although other factors (light, turbidity, residence time) may limit algal growth.

As work to reduce nutrient loads from point sources (e.g. sewage treatment works) progresses, the agricultural contribution is increasing in importance [Withers et al., 2000]. In many developed countries, elevated NPS loads result from the shift towards specialised and intensive farming systems that import a lot more nutrients in feed and fertilizer than are output in produce. In intensively cultivated areas, nitrate in groundwater is increasing by 1-2mg l^{-1} per year [Burt et al., 1993]; with the average nitrate concentration in European rivers at 4.5mg NO_3-N l^{-1} compared with 0.25 mg NO_3-N l^{-1} outside Europe. Similar trends are recorded for P: the national balance sheet in UK agriculture shows a net surplus of 10 kg P ha^{-1} a^{-1} [Withers, 1997] and is largely a consequence of changes in land management, which have enhanced the potential for P transport [Heathwaite et al., 2000a].

2.2 The Need: Enabling End-Users to Make Appropriate, Effective and Economically-Viable Mitigation Decisions

The assessment of nutrient enrichment on both terrestrial and aquatic ecosystems is extremely difficult with respect to the scale of impact or the likely costs involved [Edwards et al., 2000]. Whereas most ecosystems respond in a similar way to an increase in N supply, which causes a reduction in species diversity and an increase in productivity, it is difficult to isolate the effects of N because other nutrients, such as P, are commonly enhanced. As a consequence, many of the effects of nutrient enrichment are chronic in nature and substantial lags are likely between implementation of restrictions and some reduction in nutrient loss.

In meeting the complexity of nutrient dynamics and NPS pollution issues, research efforts have commonly taken one of two key routes: (i) small-scale process studies conducted at the lysimeter, field plot or small (up to 1km^2) catchment scale, and (ii) physically-based process models. The two routes are sometimes interlinked with (i) 'feeding' (ii). Field experimental research has made some inroads in understanding the mechanisms of nutrient transport and delivery from agricultural land to receiving waters. Such data is invaluable in elucidating the processes of nutrient cycling and identifying the potential for nutrient loss. However, the temporal and spatial complexity of NPS catchment sources means it is difficult to see how NPS mitigation can be developed strategically without recourse to predictive models. The available research on NPS nitrogen pollution, for example, highlights the need for an improvement in predictive capacity in order to test various proposals for changes to, for example, agricultural land use and fertiliser management [Edwards et al., 2000]. A number of process-based models have been developed to predict changes in N loss as a result of specific changes in land use and management. These include NCYCLE (grassland), SUNDIAL (arable), MANNER (manures), INCA (hydrochemistry) and LEACHN (soils). The INCA [Whitehead, 1990] and LEACHN [Hutson and Wagenet, 1992] models are less-agriculturally biased but include realistic in-river processes and groundwater/surface water interactions, respectively.

But are such process-based models what end-users need? Or is the information generated and are the tools developed too complex and demanding to be applicable across a wide-range of geoclimatic regions where the instruments of mitigation (e.g. buffer zones, reduced nutrient inputs in feedstuffs) are themselves 'blunt'? Is there are role here for simple, empirical models based on process knowledge but which are not in themselves process-based?

In current nutrient modelling research, there appears to be a move from sophisticated, data-hungry models towards simple semi-distributed models that estimate nutrient loss on the basis of the limited data available. Such models commonly operate with a spatial resolution around 1km and are driven by data availability, which in most developed countries includes land cover, livestock numbers, crops grown, climate, and physical properties of soils. Examples of approaches used in the UK are described below. Clearly, 'research-providers' and 'research-users' need to reach a point at which common research goals can be identified. At this point it should be possible to define the level of complexity needed in field experimentation to derive data to run generic models that meet the requirements of end-users, so that land may be managed more effectively and NPS nutrient export minimised.

3. AN OVERVIEW OF EXISTING AND NEW APPROACHES

3.1 Existing Black-Box Models

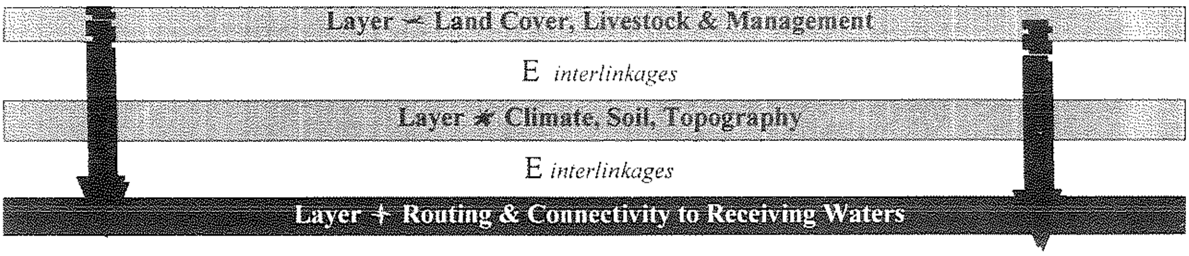
Existing empirical modelling approaches used in the UK include the simple but well-tested Export Coefficient Model [Johnes, 1996], which has an implicit water quality bias and the P-Expert System [Fraser and Harrod, 1998], which has a soils bias but includes hydrological drivers. In the US, the modified P Index [Gburek et al., 2000] has been refined for use in a number of states where legislation relating to AFOs requires nutrient management planning for P [Weld and Beegle, 2001]. Heathwaite et al. [2000b] describe an integrated N and P Index based on US research.

Simple empirical nutrient models, usually based on deriving export coefficients for known model input parameters, posses a number of advantages over more complex physically-based models. They enable the regulation of a number of data sources into a coherent system of evaluation that is readily translated into GIS format using digitised databases. They also enable policy-based decisions to be made for longer-term management of agricultural land where NPS nutrient export generates environmental risk [Heathwaite et al., 2000b]. For example, mitigation to reduce the proportion agricultural soils with high soil P could take decades to filter through to reduced P loss; using empirical modelling approaches such as the hindcasting/forcasting feature in the Export Coefficient Model [Johnes, 1996] enables some estimation of the timescales involved without having to resort to complex, physically-based models. Similarly, it is possible vary the weighting applied to nutrient losses on the basis of new field data and to re-evaluate the potential outcome.

3.2 A New Tool to Derive Indicators of P Loss From Agricultural Land to Water

The ongoing DEFRA R&D on *Phosphorus Loss from Agriculture* is addressing water pollution problems associated with P loss from agricultural land. As part of this R&D, the P Indicators project (PE0105: *Towards a National Consensus on Indicators of P Loss to Water from Agriculture*) is currently developing a prototype of a simple model tool to derive environmentally-sensitive indicators to predict P loss to water from agriculture based on the best components of existing approaches. The project is steered by the University of Sheffield and the project working team consists of the expert groups in this research area: AERC (Reading) who developed the original Export Coefficient Model [see Johnes, 1996], NSRI (Cranfield University) who developed the P-Expert System [see Fraser and Harrod, 1998], and the ADAS research group who have developed a phosphorus catchment accounting system [see Hutchins et al., 2001]. An overview of the initial stages of this project is given in this paper. The P Indicators project will report to DEFRA at the end of November 2001.

In developing the new tool, the working group identified 3 interlinked modules or layers that may be used to describe key 'indicators' of P loss from land to water, these are referred to as: (Layer 1) loss-potential indicators (livestock, land cover and land management), (Layer 2) transfer indicators (climate, soil and topography), and (Layer 3) delivery indicators (routing and connectivity to watercourses). The prototype of the tool will use a simple lumped/semi-distributed approach on an annual time-step. It will be designed to have low data requirements and to be applicable at national, regional and catchment scales. The three-layer structure of the new tool is shown in Figure 1. The ArcView™ platform will be used to construct the tool because it is well-suited to the extrapolation and presentation of spatial data and will allow future refinements and integration of revised datasets. A small number of complex calculations may require processing external to the GIS but this will be achieved using customised compiled C^{++} programmes. The databases available for each layer of the new tool vary in their quality and resolution. In the UK, DEFRA-funded research has generated reliable estimates of nutrient loss from agricultural land through empirical work at the plot scale, and has identified many of the non-point sources of nutrients in agricultural catchments. This database provides high quality, high resolution input to Layer 1 of the new tool (Loss-Potential Indicators) but it is important to recognise that the data is largely derived from site-specific field experiments. New work has started to resolve



LAYER	KEY INDICATORS	KEY DRIVERS
⤙ P loss-potential indicators @ 1km² scale	Soil nutrient status Fertilizer inputs Manure inputs	Land Cover (major arable crops, permanent/temporary grass, rough grazing, woodland, non-agricultural sources) Management (livestock numbers/type, livestock waste timing/method of application/source), bag fertiliser input/type.
✯ P-transfer indicators @ geoclimatic regional scale	Hydrologically Effective Rainfall Erosion vulnerability Potential for lateral and vertical water discharge Topsoil P concentration	Climate (mean annual runoff, HER, rainfall duration/timing, intensity) Soil (structure, texture, infiltration capacity; organic matter, calcium status; cohesion) Topography (slope angle, proximity to waterbody).
✢ P-delivery indicators @1km scale if possible	Delivery ratio (water volume, P/sediment delivery from edge-of-field Surface flow/drainflow P loss from farm infrastructure	Hydrology (drainage density, drainage status, stream order, return period, degree of connectivity) 'Artificial' Flow Routing (field drainage, routing along roads and tracks, direct runoff from farmyards, presence/absence of exit pathways)

Figure 1. Prototype of the new phosphorous indicators tool DEFRA PE0105 [after Heathwaite et al., 2001a].

the potential pathways of P mobilisation and transportation but again this is at plot to hillslope scales. For the present, the new tool utilises generalized geoclimatic scale data in Layer 2 (Transfer Indicators), this is commonly of low resolution but enables some regional parameterization of the tool. The data available to parameterize Layer 3 (Delivery Indicators) is very limited but where available is generally of high resolution but of limited spatial extent. It is clear that because the pathways of loss are not straightforward there is a long way to go before P sources may be linked to P <u>delivery</u> to watercourses.

The new tool is currently being applied to a number of test catchments representing different geoclimatic regions in Layer 2. The test catchments have been evaluated in the initial sensitivity analysis phase of the project [Heathwaite et al., 2001a] using the original models developed by the project working group.

4. SCALING

We need to develop tools to allow the application of our understanding of small-scale processes to patterns of nutrient loss at the farm or catchment scale because it is at the larger scale that nutrient management strategies are applied and legislation invoked. However, in order to develop a generic P indicators tool it is necessary to upscale the loss potential indicators (layer 1 of the new tool), which are often derived from small-scale field experiments, to different geoclimatic regions (represented by transport indicators in the new tool) through verification, validation and testing in representative catchments. While small-scale field experiments are good for budgeting the relative importance of different P inputs to land or different land use practices (layer 1), they are less effective at tracking P delivery to water (layer 2), or in predicting P export to receiving waters at the catchment scale (layer 3). Uncertainty is also implicit in upscaling both in association with the model parameters or indicators themselves, and with the application of parameter values to catchments or ecoregions outside the original study catchments.

Environmental measurements cannot be scaled-up directly; different information is generated at different research scales. The types of measurements taken at a point ($1 m^2$) differ from measurements made at the hillslope scale (1 ha), in small catchments ($1 km^2$) or in large catchments ($1000 km^2$). Research examining NPS nutrient export has commonly focused on the soil lysimeter or plot scale to derive the processes of nutrient mobilisation, but quantification of nutrient loss is commonly investigated at the catchment scale where nutrient loads and water quality changes in streams and rivers are evaluated [Heathwaite et al., 2000a]. Quinn [2001] suggests that some environmental measurements can be made accurately at all scales (e.g. water and nutrient balances) and may be used to design combined monitoring and modelling strategies for addressing scale issues [Heathwaite and Quinn, in prep]. When dealing with NPS nutrient fluxes from land to receiving waters, scale-specific (e.g. point, plot, hillslope or catchment scale) physical or quasi-physical models always yield a time series of water and nutrient fluxes over time; these time series form a common denominator at all scales for both physically-based models and simplistic models such as the export coefficient model [Johnes, 1996] or later versions of the new tool. The effect of scaling-up can, therefore, be observed where application of the simple model over a range of scale produces a change in the calibrated model parameter values. Johnes & Butterfield (in press) used the export coefficient model to evaluate error propagation when upscaling from small catchment to regional scales. Their analysis suggests that nutrient flux modelling at the regional scale needs to account for the impact of landscape heterogeneity on nutrient cycling processes.

It is clear that scaling must form a key part of future research programmes attempting to integrate different indicators on NPS P export. Research currently underway on the EPSRC SEAL project (www.shef.ac.uk/seal) has shown that it is possible to set-up a multi-scaling field and modelling approach that goes beyond edge-of-field modelling to include delivery to receiving waters from non-point sources at the catchment scale [Heathwaite et al., 2001b]. Such approaches are necessarily multidisciplinary and need to combine process-driven field experimentation with spatially-sensitive predictive modelling.

5. MEETING THE NEEDS OF END-USERS

End-users of predictive nutrient models include, for example, Government agencies (in the UK, DEFRA and the Environment Agency), landowners and managers and conservation bodies. The instruments of mitigation available to end-users dealing with NPS nutrient export from land are blunt. By contrast, the tools developed and information generated by research-providers is often too complex and/or cost and time-demanding to be widely applicable and readily used. Clearly there is a role here for simple, empirical models based on process knowledge but which are not in themselves process-based. This is particularly the case with regard to NPS pollution control strategies that require a holistic approach to be effective because environmental problems unfortunately interact. For example, buffer zones decrease nitrate leaching but they also enhance nitrous oxide emissions.

A holistic approach to NPS pollution is implicated in the recent EU Water Framework Directive, and requires integrated nutrient management strategies that are applicable at the catchment scale. Such strategies need to operate within the controls imposed on end-users by legislation, which is often targeted at the quality of receiving waters. For N, health risk concerns prompted a Maximum Contaminant Level (MCL) for nitrate-N in drinking water set at 10 mg l^{-1} [USEPA, 1996]. Setting standards for P are less clear-cut than for N because there is no direct impact on human health. A number of organisations [e.g. Environment Agency, 2000] suggest the critical P concentrations for eutrophication control are in the range 0.01-0.02 mg P l^{-1}, which is an order of magnitude lower than those in agricultural soils (0.20-0.30 mg l^{-1}), demonstrating the sensitivity of surface waters to P loss from agriculture.

Most best management practices (BMPs) designed by end-users focus on controlling the nutrient sources implicit in Layer 1 of the new tool (loss-potential indicators) [Heathwaite and Sharpley, 1999]. Here the main objective is to achieve a balance between nutrient inputs and outputs, often at the farm scale using, for example, controls on fertilizer and manure applications or the nutrient content in feedstuffs. A number of BMP options exist to manipulate nutrient loss through transport controls (layer 2 of the new tool). Transport indicator BMPs are commonly based on the assumption that landscape features that slow surface runoff or encourage infiltration or sediment trapping can reduce nutrient loss; the aim is to delay or store agricultural runoff using terracing, contour tillage, cover crops, buffer strips, riparian zones and settling ponds. The difficulty lies in devising combined BMPs for both N and P control. One important feature of nitrate leaching that separates it from P is related to its limited retention by the solid phase of the soil and hence its greater mobility. This necessitates differences in approach for mitigation options for each nutrient. To reduce N losses at source the designation of large areas of land is considered the most appropriate option [e.g. the UK Nitrate Sensitive Areas scheme; Lord et al., 1999]. Many of the field based options for P have a greater degree of spatial focus, tending to concentrate on reducing the risk of erosion from land adjacent to the drainage network [Heathwaite et al., 2000b].

6. LESSONS TO BE LEARNED FROM A US EXAMPLE: HOW MUCH 'DUMBING-DOWN' OF PROCESS-KNOWLEDGE IS POSSIBLE?

The US P Index is a simple screening tool based essentially on empirical research and is designed to assist end-users in identifying agricultural areas or practices vulnerable to P loss [Sharpley et al., 1998; Weld et al., 1999]. The P Index is used to target mitigation strategies and prevent further build-up of soil P. The Index works by accounting for and ranking the source (soil P, applied P type, rate, method) and transport (runoff, erosion, contributing distance to water) factors controlling P loss in surface runoff. By ranking these factors, the P index aids identification of sites where the risk of P movement is expected to be higher than at other sites, based on site hydrology, soil P, and field management.

Although the P Index is viewed by the research-providers [e.g. Gburek et al., 2000] as a highly simplified version of the factors controlling NPS P loss from agricultural land, testing of various prototypes of the P Index has highlighted several practical limitations, primarily related to the length of time required to evaluate the soil parameters used in estimating erosion and surface runoff potential. Currently, research using the P Index at the farm scale is underway to determine how much information required by the index could be predetermined from existing soil survey, topographic maps, stream channel network, and other GIS databases [Beegle et al., 2001]. It is clear that there is still a considerable way to go before the products of NPS pollution modelling research match the practical needs of end-users.

7. CONCLUSIONS

Empirical P export models constitute a fairly sophisticated black-box approach that is able to make good use of expert knowledge and spatial data. The danger lies in extrapolating these simple models beyond their (limited) powers and the difficulty is in recognising their errors and limitations. Simple empirical models cannot, for example, quantify environmental impact because they are at present only capable of predicting potential loss to water, which is an indirect measure. Nor are the models meant to be process-based; rather they are process-informed. Thus, at present existing coefficient-based models cannot distinguish the relative importance of different transport or delivery pathways, which remains a critical NPS research issue.

Evaluating nutrient loss from non-point sources is complex. For P, it is unlikely that a single indicator or set of indicators will be sufficient to accurately predict export from land to water. Progress is needed to evaluate the interlinkages between different indicators in the agricultural system such as N loss indicators; manure use indicators and livestock housing indicators.

8. ACKNOWLEDGMENTS

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