



The phosphorus transfer continuum: Linking source to impact with an interdisciplinary and multi-scaled approach

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Abstract

This critical review introduces a template that links phosphorus (P) sources and mobilisation processes to the delivery of P to receiving waters where deleterious impact is of concern. It therefore serves as a key introductory paper in this special issue. The entire process is described in terms of a 'P transfer continuum' to emphasise the interdisciplinary and inter-scale nature of the problem. Most knowledge to date is derived from mechanistic studies on the sources and mobilisation of P using controlled experiments that have formed the basis for mitigation strategies aimed at minimising transfer from agricultural fields. However, our ability to extrapolate this information to larger scales is limited by a poor knowledge base while new conceptual advances in the areas of complex systems and fractal dynamics indicate the limitations of past theoretical frameworks. This is compounded by the conceptual and physical separation of scientists working at different scales within the terrestrial and aquatic sciences. Multi-scaled approaches are urgently required to integrate different disciplines and provide a platform to develop mechanistic modelling frameworks, collect new data and identify critical research questions.

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1. Introduction

Phosphorus (P) transfer from agricultural soil to water has attracted increased attention in the last decade, but it remains difficult to achieve a balanced

consensus on critical issues. The amounts of P transferred from agricultural soils are small compared with those added to soil as mineral fertilizer and manure. For example, total P losses from soil are in the order of $1 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Haygarth and Jarvis, 1999), whereas annual fertilizer and manure inputs are typically between 20 and $50 \text{ kg P ha}^{-1} \text{ year}^{-1}$ (Cameron et al., 2002; Haygarth et al., 1998b). In

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terms of the mechanisms of P transfer, several studies highlighted the importance of soil erosion and physical transfer of P with soil particles from land to water, for example on arable soils in the mid-western USA (Sharpley, 1985; Sharpley and Smith, 1990). Other studies stressed the importance of fertilizer inputs, soil P concentrations (Heckrath et al., 1995), and manure inputs (Greatz and Nair, 1995; Lanyon, 1994). Added complexity arises from confusing terminology for the forms of P and the processes and pathways of their mobilisation and transfer: Table 1 provides a reference for key terms and definitions: it goes beyond that provided by Haygarth and Sharpley (2000).

This paper presents a critical review of P transfer research, outlining why we believe progress is being stifled and offering ways that this can be remedied. There is insufficient interaction between scientists in different disciplines, with the result that views become confined to the scale of focus and the methodology of each individual discipline. In particular, debate about control of P transfer is currently based mainly on data from soil science and agronomy, yet the problem is manifested, explicitly, in limnology. This presents a difficulty, because soils scientists tend to favour reductionist approaches that test hypotheses, dissecting processes at increasingly finer scales. In strong contrast, limnologists favour observational and empirical approaches, identifying patterns in lotic and lacustrine systems that, by their very nature, are integrated and ‘lumped’ at the large scale. The result is that the current research questions that drive the subject forward are inadequate because they do not cross disciplinary boundaries.

A coalition of disciplines within the land–water continuum is required, aimed at producing a truly integrated approach to the problem. This is in part the aim of this special issue and also of this introductory overview paper. If this can be achieved, new and critical research questions will emerge to define a more effective approach to P transfer. Here, a template for linking P transfer from source to impact is provided using an interdisciplinary and multi-scaled approach. This simple conceptual framework involves selected (but by no means complete) use of representative citations from soil scientists, agronomists, hydrologists, chemists, ecologists, limnologists, modellers,

policy makers and regulators. By presenting and discussing the problem in an interdisciplinary context, we hope to evolve a coherent structure for synthesising research and understanding of this complex issue.

2. The phosphorus transfer continuum

We adopt a simple source-mobilisation-delivery-impact structure to organise the discussion. This is similar to classical ‘source-pathway-receptor’ models that are well proven. Its evolution can be traced back to indexing approaches (Lemunyon and Gilbert, 1993), the arrangement of a European Research Programme (Withers, 1997), conceptual models (Haygarth and Jarvis, 1998, 1999), the structure for an international conference (Haygarth et al., 2001), and approaches which also formed the focus of modelling frameworks (Heathwaite et al., 2003). This four tiered framework is called the ‘P transfer continuum’ to emphasise the interdisciplinary and interconnected nature of the science (Fig. 1).

2.1. Sources

The input of P to soil creates the potential for an increase in transfer to the wider environment. Phosphorus sources can be natural (indigenous soil P and atmospheric deposition) and anthropogenic (fertilizers and animal feed input to the farm, fertilizers and manure applied to the soil). Most research examining diffuse P sources has been conducted in intensively managed agro-ecosystems, where continued inputs of P as mineral fertilizers and imported animal feed result in the accumulation in topsoil (Condon, 2004; Haygarth et al., 1998a). Imported feed is particularly important in areas of intensive livestock production where large quantities of manure are applied to land (Sharpley and Tunney, 2000). The spatial distribution of the various source inputs of P across the landscape creates a complex and dynamic mosaic of potential P sources, because the inputs vary within the ‘agricultural year’ (e.g. timing of manure and fertilizer applications) and over longer timescales (e.g. in response to economic drivers such as reform of European Union Common Agricultural Policy) (Heathwaite et al., 2003).

Table 1
Suggested definitions for terminology commonly associated with phosphorus transfer from land to water

Term	Definition	Example reference
Transfer/transport	Generic term that describes phosphorus movement through the land–water continuum.	Haygarth and Jarvis (1999)
Loss	Specific term often used to describe phosphorus ‘loss’ from soil. This term is discipline specific and can cause confusion (i.e. loss from soil can equal gain in water). Not recommended unless the context is made explicit.	Withers and Jarvis (1998)
Source	Refers to the raw inputs of phosphorus to the agricultural system, such as fertilizer, feed, mineralised from soil or atmospheric deposition.	Haygarth et al. (1998b)
Mobilisation	This describes the start of the phosphorus transfer, the process by which phosphorus molecules begin movement from soil. May be either solubilisation or detachment.	Haygarth and Condron (2004)
Solubilisation	Biological or chemical process of mobilisation.	Turner and Haygarth (2001)
Detachment	Physical process of mobilisation that involves phosphorus attached to soil particles and colloids.	Fraser et al. (1998)
Incidental	A mobilisation process that occurs when rain and runoff interact directly with fresh applications of phosphorus on the soil surface, such as those from fertilizer, manure or excreta.	Haygarth and Jarvis (1999), Withers et al. (2003)
Delivery	Describes the linkage from the spatial and temporal point of mobilisation to the point of channelised flow.	Beven et al. (2005)
Impact	Describes the biological and ecological effect that results from the presence of phosphorus in running and standing fresh waters.	Moss (1996)
Phosphorus transfer continuum	Describes the four-tiered source-mobilisation-delivery-impact structure in an interdisciplinary way to help break down disciplinary boundaries	This paper

Developed and revised from some of the original definitions published by Haygarth and Sharpley (2000).

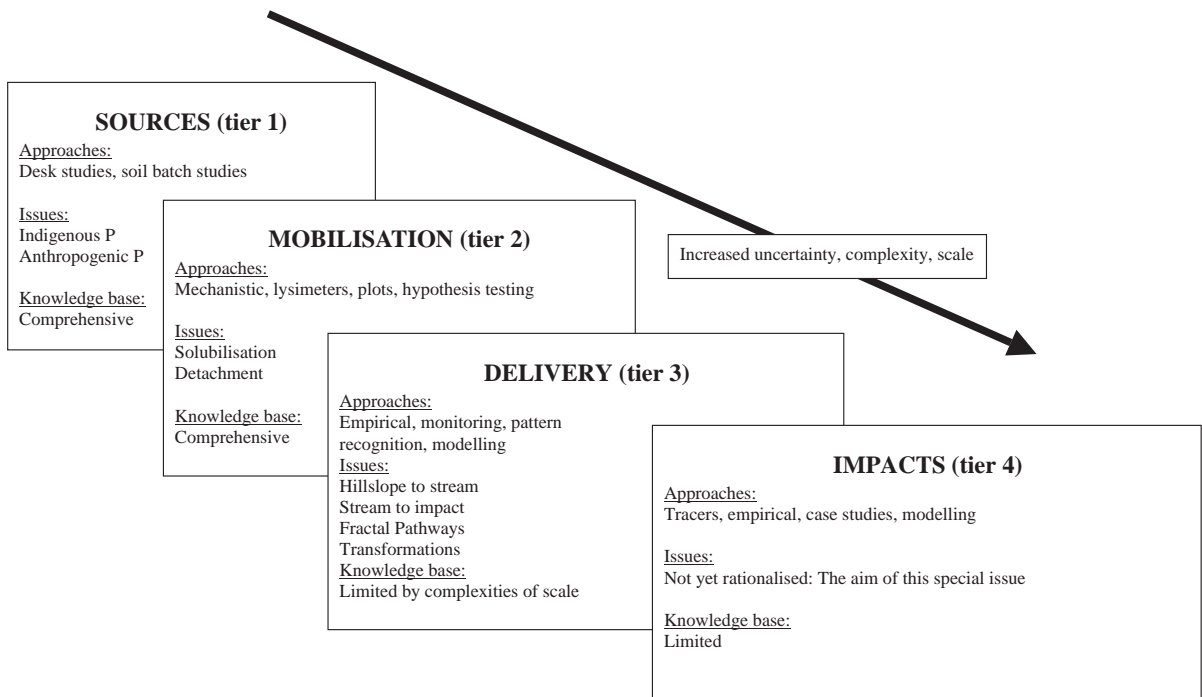


Fig. 1. The 'Phosphorus Transfer Continuum', a simple four-tiered model to describe the research approaches and needs for the continuum of phosphorus transfer from source to impact.

2.2. Mobilisation

Mobilisation describes the initial separation of P molecules from their source. It operates at the soil profile scale, and includes chemical, biological and biochemical processes. These processes group into either solubilisation or detachment mechanisms, defined by the physical size of the P compounds that are mobilised. Solubilisation reflects long-term management history. There is strong evidence to suggest that the potential for solubilisation increases with increasing concentrations of extractable soil P. In particular, there has been substantial interest in threshold soil P concentrations, above which transfer in drainage water increases at a much greater rate (Heckrath et al., 1995). These threshold concentrations have been termed 'change points', and may be used to assess the potential for P transfer from soil in runoff water (Blake et al., 2002; Daly et al., 2001; Maguire and Sims, 2002). These findings indicate that soil test P concentrations and the degree of saturation can be used to predict the risk of transfer by surface or subsurface hydrological flow paths. Other studies

suggest that organic P has an important, but little understood role in determining solubilisation, especially in soils with low fertility (Chardon et al., 1997; Ron Vaz et al., 1993; Turner, 2005; Turner and Haygarth, 2001).

Detachment of soil particles and associated P is often linked to soil erosion, which provides a physical mechanism for mobilising P from soil into waters (Haygarth and Jarvis, 1999). Soil erosion per se has been described many times (Quinton, 1997) and in the context of P transfer is important for particulate loss (Catt et al., 1994; Fraser et al., 1998). Some studies showed that soil solution and river water contain a continuum of sub-0.45 μm sized particles, often smaller than 10,000 Da molecular weight (Haygarth et al., 1997; Heathwaite et al., in press). Such work shows that categorising P into dissolved or particulate forms based on membrane filtration is an analytical convenience and, apart from implications for downstream bioavailability, may or may not have limited environmental or mechanistic relevance.

Virtually all the research reported above was conducted using variations on the controlled plot

experimental approach. Such work is rarely examined in the context of the location of the plots in the landscape or the implications of severing hydrological flow paths by introducing bounded plots. In addition to these experimental and up-scaling challenges are timescale issues. There is a major research need to understand the relative importance of different P detachment mechanisms. To do this requires untangling the contribution to P transfer in high magnitude but usually short-timescale erosion events (Haygarth et al., 2005), perhaps associated with larger sized particles, from long-term and more continuous detachment of soil colloids (i.e. smaller particles and macromolecules). Much of the evidence and mechanistic understanding of detachment at the landscape scale is, at best, anecdotal and many fundamental scientific hypotheses remain untested. Further, there are issues of atmospheric cycling and deposition of P that has hardly been covered (Neal et al., in press).

2.3. Delivery

The routing of P from the point of mobilisation to the point of delivery to channelised flow is complex. It embraces (i) differences in the relative importance of the controls on P transfer at different scales from point to plot, field, hillslope and catchment (Brazier et al., 2005; Harris and Heathwaite, 2005); (ii) temporal variations and dynamics (Haygarth et al., 2004); and (iii) differences in the relative contribution from different P fractions according to the pathway of transfer and the environmental controls on movement. Recent analyses of the movement of contaminants in catchments indicate that the flow paths may be fractal in nature and that there are some paradoxical properties of delivery mechanisms to streams (Kirchner, 2003; Kirchner et al., 2000, 2004). Most of the data have not been collected at the correct scale and lack the resolution to clarify many of these issues (Harris and Heathwaite, 2005; Kirchner et al., 2004). Further complexity arises because P is usually deposited and entrained during transport (Jarvie et al., 2002c; Neal et al., 2002) and can change form in space and time. While some plot scale work has examined the controls on the transport at scales up to 1 ha (Haygarth et al., 1998a), scaling-up this work to delivery to surface and groundwater at the hillslope or catchment scale is complex (Beven et al., 2005) and

cannot be easily be quantified because of the nature and complexity of the flow paths (Heathwaite et al., 2005). During delivery, the extent, nature, and dynamics of interactions between soluble and particulate forms in water and sediments play a critical role, and are an important consideration in developing effective strategies for mitigation of accelerated P transfer (Baldwin, 1996; McDowell et al., 2001, 2004).

2.4. Impact

‘Impacts’ relate to an actual change or perturbation in a receiving water body resulting from the P transfer. The overriding impact is eutrophication, a process defined as “an increase in the fertility status of natural waters that causes accelerated growth of algae or water plants” (Pierzynski et al., 2000). Elevated concentrations of P in streams, rivers and lakes may contribute to eutrophication. Relationships between P concentrations and phytoplankton growth have been established for lakes (Vollenweider, 1968), but the impacts on riverine plant ecology are less clear. Eutrophication has important health and financial implications, limiting water use for drinking, fishing, industry and recreation (Carpenter et al., 1998). Dissolved P concentrations have increased markedly in recent decades in Europe, New Zealand, and the USA (Cameron et al., 2002; Crouzet et al., 1999). Such changes are linked to large-scale fish kills in some estuaries caused by increased populations of the dinoflagellate *Pfiesteria piscicida*, which in turn has the potential to adversely affect human health (Burkholder et al., 1992). The protection of water quality is an important environmental issue in many countries. For example, the European Union Water Framework Directive (2000/60/EC) aims to restore all waters to ‘good ecological status’ by 2015, which will require specific action to reduce and control diffuse pollution from agriculture including P transfer. However, there is considerable uncertainty surrounding the concentrations of P that limit aquatic plant growth. Recent studies of large-scale reductions in river P concentrations have shown no significant improvement in ecological quality (Jarvie et al., 2002a, 2004). However, more information is required to assess the long-term ecological impacts and lags associated with reducing concentrations in rivers, and the potential

importance of within-river processing linked to interactions between river sediments and dissolved P (House, 2003; House and Denison, 2002) and between species and aquatic plants (Jarvie et al., 2002b).

Although such impacts might at first appear obvious, new evidence from high-frequency monitoring of water quality in receiving waters (rivers, lakes and coastal waters) indicates similar degrees of complexity there. Analyses of high-frequency data in such waters (at least daily; preferable hourly or at scales of minutes) have revealed multi-fractal scaling properties and the presence of information buried in the correlation structures (Harris, 2003; Harris and Heathwaite, 2005; Seuront et al., 1999). So ‘noisy’ water quality data, which are often collected at weekly intervals or longer, should not be averaged to reduce the ‘noise’, and traditional statistical and empirical approaches to limnology may be also missing much important fine scale information (Harris, 2003; Harris and Heathwaite, 2005).

The challenge for the future (and in part the aim of this special journal issue) is to trace backwards through the P transfer continuum (delivery through mobilisation to source) to link actual processes in farms and agricultural soils to specific impacts in waters. We are able to identify, with reasonable confidence, (i) the sources and mechanisms of P accumulation in soils and some of the likely pathways of transfer from agricultural land to water, and (ii) some aspects of P-associated deterioration of water quality. However, the hard evidence needed to quantify the linkage between source, the types of source, and impact requires significantly more investigation (McDowell et al., 2004) and to take this forward, research is starting within a new 5-year project PARIS (Phosphorus from Agriculture: Riverine Impacts Study) to link agricultural land use and practices with high risk of P loss to chemical and ecological impacts in rivers (Defra, 2003). Some of the key research questions are how to determine the causal link between perturbation in the agricultural landscape (e.g. slurry spreading before rainfall) and its associated impact on ecological quality of a water body that is separated from the original perturbation in space (perhaps hundreds of km) and time (perhaps tens of years) and is connected through dynamic processes distributed over fractal flow paths. There

are few examples of such linkages, but three approaches may progress research in this area further:

1. Sediment tracking and fingerprinting techniques to demonstrate a direct physical link (Walling and He, 1999).
2. Detailed case studies that integrate across scales (e.g. www.lec.lanacs.ac.uk/cswm/research; Haygarth et al., 2005; Wood et al., in press).
3. Mechanistic and empirical modelling at all scales (Heathwaite et al., 2003; Whitehead et al., in press).

3. Reductionism and complexity: the need for different methodologies

Table 2 summarises the range of disciplines involved in the P transfer continuum and the associated scales of focus and methodology. It demonstrates that both reductionist-based (usually small scale, replicated hypothesis testing) and complexity-based (usually large scale, field observation, empirical patterns) (Coveney and Highfield, 1995) approaches are both integral and essential to the development of the overall P transfer discipline. To a large extent the key messages from the table are self-evident, but there are three important issues that we wish to emphasise.

1. There is a need to recognise the relative strengths and weaknesses of reductionism and complexity. The strength of small scale reductionism is that it allows us to replicate and test hypothesis and reach conclusions that help isolate mechanisms with a relatively high degree of certainty. The weakness is that, if conducted in isolation, there is no means of gauging how relevant or connected the reductionist experiment is to the wider world (or catchment, river or lake). Conversely, complexity based approaches observe patterns that are relevant to (and indeed are part of) the wider world and integrate the fine-scale processes into a manifest emergent pattern. The weakness, of course, is that it is difficult to explain the observed patterns and there is great contingency and uncertainty.

Table 2
Different methodologies associated with disciplines and scales for studying the phosphorus transfer continuum

Scale of study	Methodology	Connection to impact (i.e. 'applicability' and 'relevance to society')	Associated uncertainty with methodology	Associated disciplines
Rivers, lakes, catchments	Complexity based. Deductive, empirical observation, integrated lumping, hypothesis forming pattern recognition approaches.	High	High	Limnology, hydrology; basis of regulatory decisions on water quality
Hillslope		↕	↕	Hydrology, soil science
Field, plot				Agronomy, soil science, hydrology; opportunity for some agronomic advice to farmers
Lysimeter, macro/mesocosm	Reductionism based. Inductive mechanistic, replicated hypothesis testing approaches.	Low	Low	Soil science, hydrology
Batch, soil ped, molecular				Soil science, biochemistry

2. It is critically important to recognise and exploit the cyclical interaction between complexity and reductionist approaches (Kuhn, 1962). Patterns observed in complexity-based approaches can be viewed as 'hypothesis forming' and help guide fine-scale hypothesis testing. In turn, conclusions from these hypotheses reduce the uncertainty in explanations of complex patterns. If this critical interaction between the two extremes is achieved and maintained, it will clarify research priorities and provide a strong basis for a team based interdisciplinary approach to P transfer science. One of the great uncertainties in this work is the possibility of cross-scale emergence in these very complex systems (i.e. differences in small scale pathways and processes which we do not understand may have large scale emergent impacts). This is very likely to be important in landscapes and waterscapes which are complex and fractal across a wide range of time and space scales. At this stage we simply do not know how important this is likely to be (Harris and Heathwaite, 2005) and the cross-comparison of the two approaches both on land and in the water is the only way to test for these effects.

3. There are some similarities to the concept of 'decoherence' suggested by Addiscott and Mirza

(1998) originally used in context for nitrogen emissions from soil. Therefore, different properties seem to dominate their control at different scales.

4. Conclusions and the future

As we cascade through the four tiers of the P transfer continuum, and scale-up from point sources to catchment impacts, our knowledge of critical processes decreases and uncertainty in the linkages increases. Clearly we have conducted much research in tiers 1 and 2 on source and mobilisation, which has been largely characterised by reductionist hypothesis-testing approaches. At these scales our understanding is sufficiently comprehensive for building conceptual models of our understanding, but there are limits to which our knowledge can be extrapolated to other scales. However, we are currently undergoing a change in research emphasis from mobilisation to delivery, which involves a large step in discipline from controlled mechanistic experiments to observation of complex empirical patterns that are integrated or 'lumped' at the large scale. This new approach will take the discipline forward, with complexity based approaches arising from high resolution data collection. This is certainly the case for water quality in

general (Kirchner et al., 2000, 2004), although for P per se, the degree of progress will be constrained by our development of electrodes and appropriate technologies (Le Goff et al., 2004). One particularly novel and exciting development is described in Scholefield et al. (2005) who demonstrated concerted diurnal patterns in riverine nutrient concentrations and physical conditions.

In ‘jumping the gap’ between reductionism and complexity we must accept that our understanding becomes increasingly incomplete. Approaches to the assessment of P delivery and its impact on water quality are characterised by empiricism that attempts to integrate information from a range of scales, but in doing so often becomes disconnected from the mechanistic information contained in tiers 1 and 2. To advance our science and ensure sound policy advice we must urgently seek mechanisms to connect and integrate these tiers of understanding. Bringing together disciplines in this special issue may help us do this.

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References

- Addiscott TM, Mirza NA. New paradigms for modelling mass transfers in soils. *Soil Tillage Res* 1998;47:105–9.
- Baldwin D. The phosphorus composition of a diverse series of Australian sediments. *Hydrobiologia* 1996;335:63–73.
- Beven KB, Heathwaite L, Haygarth PM, Walling D, Brazier R, Withers P. On the concept of delivery of sediment and nutrients to stream channels. *Hydrol Process* 2005;19(2):551–6.
- Blake L, Hesketh N, Fortune S, Brookes PC. Assessing phosphorus ‘change-points’ and leaching potential by isotopic exchange and sequential fractionation. *Soil Use Manage* 2002;18:199–207.
- Brazier RE, Heathwaite AL, Lui S. Scaling issues relating to phosphorus transfer from land to water in agricultural catchments. *J Hydrol* 2005;304(1–4):330–42.
- Burkholder JM, Noga EJ, Hobbs CW, Glasgow Jr HB, Smith SA. New “phantom” dinoflagellate is the causative agent of major estuarine fish kills. *Nature* 1992;358:407–10.
- Cameron KC, Di HJ, Condron LM. Nutrient and pesticide transfer from agricultural soils to water in New Zealand. In: Haygarth SC, Jarvis SC, editors. *Agriculture, Hydrology and Water Quality*. Wallingford: CAB International; 2002. p. 373–94.
- Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol Appl* 1998;8:559–68.
- Catt JA, Quinton JN, Rickson RJ, Styles P. Nutrient losses and crop yields in the Woburn erosion reference experiment. In: Rickson RJ, editor. *Conserving Soil Resources: European Perspectives*. Wallingford: CAB International; 1994.
- Chardon WJ, Oenema O, del Castilho P, Vriesema R, Japenga J, Blaauw D. Organic phosphorus solutions and leachates from soils treated with animal slurries. *J Environ Qual* 1997;26:372–8.
- Condron LM. Phosphorus—surplus and deficiency. In: Schjøning P, Christensen BT, Elmholt S, editors. *Managing soil quality—challenges in modern agriculture*. Wallingford: CAB International K; 2004. p. 69–84.
- Coveney P, Highfield R. *Frontiers of Complexity*. New York: Fawcett Columbine; 1995.
- Crouzet P, Leonard J, Nixon S, Rees Y, Parr W, Laffon L, et al, editors. *Nutrients in European Ecosystems*. Copenhagen: European Environment Agency; 1999.
- Daly K, Jeffrey D, Tunney H. The effect of soil type on phosphorus sorption capacity and desorption dynamics in Irish grassland soils. *Soil Use Manage* 2001;17:12–20.
- Defra. Review of Defra’s Research Programme on Phosphorus Emissions from Agriculture; 2003. London SW1P 3JH.
- Fraser AI, Harrod TR, Haygarth PM. The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils. In: SEPA, editor. *3rd International Conference on Diffuse Pollution*. Edinburgh, Scotland: IAWQ; 1998. p. 106–10.
- Greatz DA, Nair VD. Fate of phosphorus in Florida spodosols contaminated with cattle manure. *Ecol Eng* 1995;5:163–81.
- Harris GP. Ecological paradigms, change detection and prediction. In: Post DA, editor. *Integrative modelling of biophysical, social and economic systems for resource management solutions* Proceedings of MODSIM 2003 international conference on modelling and simulation, vol. 1. Townsville: MODSIM; 2003. p. 1–10.
- Harris GP, Heathwaite AL. Inadmissible evidence: knowledge and prediction in land and riverscapes. *J Hydrol* 2005;304(1–4):3–19.
- Haygarth PM, Condron LM. Background and elevated phosphorus release from terrestrial environments. In: Valsami-Jones E, editor. *Phosphorus in Environmental Technology Principles and Applications*. London: IWA Publishing; 2004;ISBN 1843390019:512.
- Haygarth PM, Jarvis SC. Phosphorus transfers from agricultural soils described by a conceptual model. In: SEPA SC, editor. *3rd*

- Conference on Diffuse Pollution. Edinburgh, Scotland: IAWQ; 1998. p. 2–5.
- Haygarth PM, Jarvis SC. Transfer of phosphorus from agricultural soils. *Adv Agron* 1999;66:195–249.
- Haygarth PM, Sharpley AN. Terminology for phosphorus transfer. *J Environ Qual* 2000;29:10–5.
- Haygarth PM, Warwick MS, House WA. Size distribution of colloidal molybdate reactive phosphorus in river waters and soil solution. *Water Res* 1997;31:439–42.
- Haygarth PM, Hepworth L, Jarvis SC. Forms of phosphorus transfer in hydrological pathways from soil under grazed grassland. *Eur J Soil Sci* 1998a;49:65–72.
- Haygarth PM, Jarvis SC, Chapman P, Smith RV. Phosphorus budgets for two contrasting grassland farming systems in the UK. *Soil Use Manage* 1998b;14:160–7.
- Haygarth PM, Condron LM, Butler PJ, Chisholm JS. Connecting Phosphorus Transfer from Agriculture to Impacts in Surface Waters. Okehampton: Institute of Grassland and Environmental Research; 2001.
- Haygarth PM, Turner BL, Fraser AI, Jarvis SC, Harrod TR, Nash D, et al. Temporal variability in phosphorus transfers: classifying concentration–discharge event dynamics. *Hydrol Earth Syst Sci* 2004;8:88–97.
- Haygarth PM, Wood F, Heathwaite AL, Butler P. Phosphorus dynamics observed through increasing scales in a nested headwater-to-river channel study. *Sci Total Environ* 2005;344:83–106.
- Heathwaite AL, Fraser AI, Johnes PJ, Hutchins M, Lord E, Butterfield D. The phosphorus indicators tool: a simple model of diffuse P loss from agricultural land to water. *Soil Use Manage* 2003;19:1–12.
- Heathwaite AL, Quinn PF, Hewett CJM. Modelling and managing critical source areas of diffuse pollution from agricultural land by simulating hillslope flow connectivity. *J Hydrol* 2005;304(1–4):446–61.
- Heathwaite AL, Haygarth PM, Matthews R, Preedy N, Butler P. Evaluating colloidal phosphorus delivery to surface waters from diffuse agricultural sources. *J Environ Qual* in press.
- Heckrath G, Brookes PC, Poulton PR, Goulding KWT. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk Experiment. *J Environ Qual* 1995;24:904–10.
- House WA. Geochemical cycling of phosphorus in rivers. *Appl Geochem* 2003;18:739–48.
- House WA, Denison FH. Exchange of inorganic phosphate between river waters and bed sediments. *Environ Sci Technol* 2002;36:4295–301.
- Jarvie HP, Lycett E, Neal C, Love A. Patterns in concentrations and biological quality indices across the upper Thames river basin, UK. *Sci Total Environ* 2002;282/283:263–94.
- Jarvie HP, Neal C, Warwick A, White J, Neal M, Wickham H, et al. Phosphorus uptake into algal biofilms in a lowland chalk river. *Sci Total Environ* 2002;282/283:353–73.
- Jarvie HP, Neal C, Williams RJ, Neal M, Wickham HD, Hill LK, et al. Phosphorus sources, speciation and dynamics in a lowland eutrophic chalk river: the River Kennet, UK. *Sci Total Environ* 2002;282/283:175–203.
- Jarvie HP, Neal C, Williams RJ. Assessing changes in phosphorus concentrations in relation to in-stream plant ecology in lowland permeable catchments: bringing ecosystem functioning into water quality monitoring. *Water Air Soil Pollut Focus* 2004;4:641–55.
- Kirchner JW. A double paradox in catchment hydrology and geochemistry. *Hydrol Process* 2003;17:871–4.
- Kirchner JW, Feng X, Neal C. Fractal stream chemistry and its implications for contaminant transport in catchments. *Nature* 2000;403:524–7.
- Kirchner JW, Feng X, Neal C, Robson AJ. The fine structure of water quality dynamics: the (high frequency) wave of the future. *Hydrol Process* 2004;18:1353–89.
- Kuhn TS. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press; 1962.
- Lanyon LE. Dairy manure and plant nutrient management issues affecting water quality and the dairy industry. *J Dairy Sci* 1994;77:1999–2007.
- Le Goff T, Braven J, Ebdon L, Scholefield D. Phosphate-selective electrodes containing immobilised ionophores. *Anal Chim Acta* 2004;510:175–82.
- Lemunyon JL, Gilbert RG. The concept and need for a phosphorus assessment tool. *J Prod Agric* 1993;6:483–6.
- Maguire RO, Sims JT. Soil testing to predict phosphorus leaching. *J Environ Qual* 2002;31:1601–9.
- McDowell RW, Sharpley AN, Condron LM, Haygarth PM, Brookes PC. Processes controlling soil phosphorus release to runoff and implications for agricultural management. *Nutr Cycl Agroecosyst* 2001;59:269–84.
- McDowell RW, Biggs BJF, Sharpley AN, Nguyen L. Connecting phosphorus loss from agricultural landscapes to surface water quality. *Chem Ecol* 2004;20:1–40.
- Moss B. A land wash with nutrients—the problem of eutrophication. *Chem Ind* 1996;11:407–11.
- Neal C, Jarvie HP, Wade AJ, Whitehead PG. Water quality functioning of lowland permeable catchments: inferences from an intensive study of the River Kennet and upper River Thames. *Sci Total Environ* 2002;282/283:471–90.
- Neal C, Neal M, Wyatt R, Turner H, Hill L, Hewett N. Rainfall and runoff water quality of the Pang and Lambourn, tributaries of the River Thames, south eastern England. *Hydrol Earth Syst Sci* in press.
- Pierzynski GM, Sims JT, Vance GF. *Soils and Environmental Quality*. Boca Raton: CRC Press; 2000.
- Quinton JN. Reducing predictive uncertainty in model simulations: a comparison of two methods using the European Soil Erosion Model (EUROSEM). *Catena* 1997;30:101–17.
- Ron Vaz MD, Edwards AC, Shand CA, Cresser MS. Phosphorus fractions in soil solution: influence of soil acidity and fertilizer additions. *Plant Soil* 1993;148:179–83.
- Scholefield D, Le Goff T, Braven J, Ebdon L, T. L., Butler M. Concerted diurnal patterns in riverine nutrient concentrations and physical conditions. *Sci Total Environ* 2005;344:201–10.
- Seuront L, Schmitt F, Lagadeuc Y, Schertzer D, Lovejoy S. Universal multi-fractal analysis as a tool to characterise intermittent patterns: example of phytoplankton distributions in turbulent coastal waters. *J Plankton Res* 1999;21:877–923.

- Sharpley AN. The selective erosion of plant nutrients in runoff. *Soil Sci Soc Am J* 1985;49:1527–34.
- Sharpley AN, Smith SJ. Phosphorus transport in agricultural runoff: the role of soil erosion. In: Boardman J, Foster LDL, Dearing JA, editors. *Soil Erosion on Agricultural Land*. Chichester: John Wiley & Sons; 1990. p. 351–66.
- Sharpley AN, Tunney H. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. *J Environ Qual* 2000;29:176–81.
- Turner BL. Organic phosphorus transfer from terrestrial to aquatic environments. In: Turner BL, Frossard E, Baldwin DS, editors. *Organic Phosphorus in the Environment*. Wallingford: CAB International; 2005. p. 269–95.
- Turner BL, Haygarth PM. Phosphorus solubilization in rewetted soils. *Nature* 2001;411:258.
- Vollenweider, RA. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors of eutrophication. Rep. No. GP OE/515. Organisation for Economic Co-operation and Development, Paris; 1968.
- Walling DE, He Q. Improved models for estimating soil erosion rates from ¹³⁷Cs measurements. *J Environ Qual* 1999;28:611–22.
- Whitehead PG, Heathwaite AL, Flynn N, Snook D, Quinn PF. Evaluating the risk of nonpoint source pollution from sewage sludge: modelling nutrient losses at a range of scales from plot to catchment. *Hydrol Earth Surf Syst Sci* in press.
- Withers PJ. COST 832: Quantifying the Agricultural Contribution to Eutrophication. EU; 1997. <http://www.alterra-research.nl/pls/portal30/docs/folder/cost832/cost832/index.htm>.
- Withers PJA, Jarvis SC. Mitigation options for diffuse phosphorus loss to water. *Soil Use Manage* 1998;14:186–92.
- Withers PJA, Ulen B, Stamm C, Bechmann M. Incidental phosphorus losses—are they significant and can they be predicted? *J Plant Nutr Soil Sci* 2003;166:459–68.
- Wood FL, Heathwaite AL, Haygarth PM. Evaluating the contribution of diffuse agricultural phosphorus contributions to river fluxes at different scales in the Taw catchment, Devon, UK. *J Hydrol* in press.