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INTRODUCTION

Phosphorus in soils and its transfer to water: from fine-scale soil processes to models and solutions in landscapes and catchments

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Phosphorus (P) is an essential fertilizer element in support of plant growth, and it is also a non-renewable resource that is consumed at a rate of 23.5 Tg/yr (Carpenter & Bennett, 2011). Some estimates project that the global demand for P is expected to increase annually at the rate of 1.5%, suggesting that P could be exhausted in 100–250 yr, with the peak in mining activity being reached by around 2030 (Cordell *et al*., 2009). This, combined with the imperative of feeding an increasing world population, makes P a key element for underpinning global agriculture and food production.

However, food production based on P comes at a cost. It is estimated that the riverborne flux of P to oceans has increased threefold since pre-industrial times (Bennett *et al*., 2001), and it is reasonable to hypothesize that this is correlated with the use of P in agriculture. Unfortunately, when P leaks to water, it also has a profound negative influence on water quality (Haygarth *et al*., 2005; Ryan *et al*., 2012). At a global scale, the agronomic input of P as fertilizer or recycled manure (23.8 Tg/yr) exceeds P removal by harvested crops (12.3 Tg/yr), but a P deficit in the agricultural system is estimated to occur for almost 30% of the global crop area (MacDonald *et al*., 2011). The rational use of P reserves that involve efficient management of soil and fertilizer P and recycling, which focuses on the improvement of water quality, is essential.

The European Union (EU) Cooperation in Science and Technology (COST) Action 832 'Quantifying the agricultural contribution to eutrophication' (1997–2003) involved researchers from 18 countries (Chardon & Withers, 2003) and provided probably the first integrated view of the problem of P transfer from agricultural land to water in Europe. EU COST Action 832 was linked in its origin to a series of International Phosphorus Workshops (IPW), where P scientists met every 3 years (Wexford, Ireland, 1995; Antrim, Northern Ireland, 1998; Plymouth, UK, 2001; Wageningen, The Netherlands, 2004; Silkeborg, Denmark, 2007; and Seville, Spain, 2010). IPW7 is planned in Uppsala, Sweden, 9–13 September 2013. The IPW meetings have contributed to increasing and sharing of knowledge on the transfer of P from agricultural land and how impacts can be mitigated; the result has been the creation of a European and international network of researchers on this topic. A more recent EU COST Action 869 'Mitigation options for nutrient reduction in surface water and ground waters' started in November 2006, as a follow-up of COST 832, and focused on assessing the suitability and cost-effectiveness of different options for reducing nutrient loss to water at a river basin scale. COST Actions and IPW meetings were interrelated and contributed to the integration of the P research community into a European network capable of analysing environmental P problems and proposing actions to all stakeholders.

The sixth IPW meeting (IPW6) was held in Seville from 27 September to 1 October 2010. The 149 researchers (from 31 countries) who attended the meeting discussed a variety of topics. These included P dynamics/cycling at the pedon scale, P mobilization processes (measurement, monitoring and modelling of soil P loss and transport), water quality and ecology in relation to P status and technical evaluation and cost/benefit analysis of mitigation options. In addition, particular attention was paid to P as a non-renewable resource affecting global food security in a changing world. As part of IPW6, a joint meeting with EU COST Action 869 members was organized resulting in shared session entitled 'P mobilization and modelling at the field and catchment', with 45 presentations. This supplement has been assembled as an output arising from the joint COST 869 and IPW6 Meeting in Seville.

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The soil science of P transfer to water is complex, involving multiple scales from the molecular, through the soil ped and soil profile, to hillslope, catchment and even regional scale. One attempt to rationalize scale is the P transfer continuum approach devised by Haygarth *et al.* (2005), which proposes the source (P into farm), mobilization (from soil, by solute or solid), delivery (hydrological flows across landscapes) and eventual impact (ecological effect in streams), in a spatially nested conceptual framework. Scaling up involves multiple disciplines (chemistry, biology, physics, hydrology, mathematics, statistics and pedology) as well as inevitable changes in the inherent scientific methodology. At the small scale, the soil lends itself easily to replication and manipulation, but when considering the larger sizes at the field, hillslope or catchment scale, it is inevitable that inductive reductive replicated and controlled experimental designs cannot be applied across a complex landscape framework. It is simply not possible to replicate fields and certainly not so for catchments (Haygarth *et al.*, 2005, 2012). Initially, this might seem uncomfortable for a discipline like soil science, where tight hypotheses-led reductionist studies have led and dominated the paradigm of the last 30 years. Challenges for soils and the environment, such as P and water quality, need to involve much more than simply what is 'in soil', but also require techniques for understanding the impacts in fields, hillslopes, catchments and regions that contribute to lakes, seas and oceans. In this volume, there are 19 papers of which perhaps only four can be classified as being small scale, reductionist and in-soil focused, with the remainder focus on field hydrology and regional scales, often using modelling to overcome the issues of complexity. This is in itself interesting and revealing in terms of the development of the subject.

Specifically, Djodjic & Mattsson (2013) presents a study of changes in P solubility and plant availability, and similarly, Ahlgren *et al.* (2013) focuses on soil organic P, reflecting the increasing interest in these P forms as started by others (Chardon *et al.*, 1997; Turner *et al.*, 2002, 2006). De Bolle *et al.* (2013) presents a study on the distribution of P to deeper soil layers in P saturated acid sandy soils. Three papers use small-scale biogeochemistry on soil processes and attempt to set the results into a regional context; this is challenging and not without difficulties, such as extrapolation to the larger scale. Examples are provided by Horta *et al.* (2013), who considers sorption processes in soils of the Mediterranean; Eriksson *et al.* (2013), who attempts to develop lab P indices for use in the context of P in agricultural soils of the Baltic Sea; and Renneson *et al.* (2013), who considers P in deep horizons under various cropping soils in Belgium. Three papers focus on mitigation of delivery/hydrological transport modification at the hillslope/field scale: Noij *et al.* (2013) considers unfertilized buffer strips, and Smith & Livingston (2013) focuses on the use of hillslope depression areas with a study from the USA. McGrath *et al.* (2013) has a focus on the design of *in-situ* drainage filters.

Modelling approaches seem to be increasingly prevalent in the subject area, a trend reflected in the papers in this issue. Models provide a means to rationalize and attempt to overcome the complexities of the larger scale land–water connections. Vadas *et al.* (2013) provides a useful overview on his critical evaluation of models, with Dechmi *et al.* (2013) and Troitiño *et al.* (2013) developing the classic P – index approach started by Lemunyon & Gilbert (1993), but here for local European conditions. Farkas *et al.* (2013) uses the INCA model to determine soil erosion and P losses under variable land use, whilst Schoumans *et al.* (2013) proposes a simple model that focuses on P leaching. Wall *et al.* (2013) attempts to forecast the decline in excess soil P in agricultural catchments; this is certainly novel and addresses some long-standing questions about the hysteresis of soil P availability following years of application. Panagopoulos *et al.* (2013) models diffuse pollution mitigation at zero cost, using a multi-objective optimization approach.

Uncertainty is inevitably highly prevalent, and needs to be given due consideration when trying to find solutions that may guide policy; three papers in particular address these issues in attempts to model and mitigate P transfers. Litaor *et al.* (2013) uses uncertainty analysis as part of a study that focuses on the assessment of P application practices in altered wetland soils. Finally, a pair or related papers, Scholefield *et al.* (2013) and Zhang *et al.* (2013) postulate a fuzzy and thus uncertainty-based decision approach to aid prediction of P hydrological delivery modification, raising the debate around some realities about the uncertainty of hydrological flows and its modelling. The realities of uncertainties are certainly uncomfortable when seen from the traditional reductionist viewpoint, but open debate of the issues is necessary if progress is to be made in the science and the provision of solutions.

This collection of papers points a way forward through some new and difficult science involving the complexities and 'uncomfortable uncertainties' of scale. It seems from the papers in this supplement of *Soil Use and Management* that we are beginning to move towards an exciting new era in P research, that may not always be perfect or couched in traditional methodologies, but certainly raises the debate to help with the evolution of studies from fine-scale soil processes to models and solutions in landscapes and catchments.

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