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Sustainable nutrient management at field, farm and regional level: Soil testing, nutrient budgets and the trade-off between lime application and greenhouse gas emissions

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ABSTRACT

Pollution from agriculture has environmental consequences at local and global scales. Managing this pollution is challenging because of diffuse sources and complex relationships between aquatic and atmospheric emissions. We illustrate this for a UK county that has suffered outbreaks of microbial pollution and eutrophication. We surveyed 49 livestock farms covering 12% of total agricultural grazed land. Soil nutrient status and whole-farm nutrient balances were determined, and the environmental impact of alleviating sub-optimal soil pH by liming was estimated at the county level. Only 37% of fields contained more P than was required for satisfactory grass growth, and soil acidity and available K were often limiting production. The mean farm N, P and K balances were similar to a modelled farm in England & Wales and EU indicators for the majority of North West Europe. This suggests that local eutrophication events linked to agriculture are more likely to relate to improper timing of nutrient application rather than over-application. None of the surveyed farmers used nutrient decision support tools, largely due to a lack of awareness and competing sources of information. Liming soils to pH 6.0 was estimated to both reduce N-leaching and N_2O emissions; however, the net climate-change impact would be negative as the direct CO_2 emissions would exceed CO_2 equivalent emissions of not liming by 394% (95% CI 201–21,232). Although liming currently presents a net cost to farmers, a sensitivity analysis suggests that reduced lime cost could lead to economic benefit to farmers but still increased greenhouse gas emissions. The results are applicable to all pasture-based agricultural systems where there is a drive to maintain or increase production through optimal soil and nutrient management. The findings demonstrate an important trade-off between reducing aquatic and atmospheric pollution and agricultural productivity, and the need to improve communication of this trade-off to farmers.

1. Introduction

Maintaining agricultural production, while minimising diffuse pollution to water and air, is a global problem. Direct emissions from agriculture comprise roughly 11% of global greenhouse gas emissions and these emissions are projected to rise by 20% by 2030 (US-EPA, 2011). Including indirect emissions increases the total emissions from agriculture to 19–29% of the global total (Vermeulen et al., 2012). Anthropogenic activities have profoundly altered the global nitrogen and phosphorus cycles and will continue to do so (Bouwman et al., 2009). Net anthropogenic nitrogen inputs in China, US & Northern Europe are estimated at between 2 and 3.5 t ha^{-1} of which 15–30% is exported in rivers (Swaney et al., 2012). Indeed, studies across the globe have shown agriculture to be amongst the largest contributor of annual nitrate and phosphate loads to river waters (Defra, 2007; Puckett et al., 2011; Liu et al., 2012).

To advance sustainable agricultural production requires considering the management activities at the scale of farm and field, in the context of policy at the regional or catchment level. In this paper, we consider the management of agricultural inputs and the consequent impact on diffuse pollution at three different scales: field, farm and region. Common field and farm management activities affecting diffuse pollution include the over-application of fertilizer (Lord and Mitchell, 1998; Withers et al., 2001), the inappropriate application of manure or slurry to land (Smith et al., 1998; Shepherd

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et al., 2001; Shepherd and Chambers, 2007), or poor management of soil leading to erosion and surface runoff on both livestock and arable farms (Quinton et al., 2010). However, although such activities are often very localized and spatially explicit, monitoring programmes and policy to reduce emissions are largely applied at the catchment and regional scale. For example, regulations such as the Water Framework Directive, which requires all surface waters in the European Union (EU) to be of 'good ecological status' by 2015 (WFD, 2000). Also in the EU, policy-makers have endeavoured to reward farmers for reducing the risk of diffuse pollution such as by managing land under 'Good Agricultural and Environmental Condition' to benefit from the Single Payment Scheme. The European Commission has adopted 28 indicators of agri-environment status to assess the interaction between the Common Agricultural Policy and the environment at EU, national and regional level. A subset of these indicators are directly related to the risks and impacts of diffuse emissions to water and air *viz.* nitrogen and phosphorus surpluses, greenhouse gas emissions and nitrate leaching.

While indicators provide guidance on levels of emissions, effective management of diffuse pollution requires both that farmers are able to connect their management activity with diffuse pollution outcomes and that there are incentives to adopt sustainable management. A frequently used approach to quantify whether a farm is managing nutrients efficiently, and identify ways to improve nutrient-use efficiency, is to construct a nutrient budget (e.g. Koelsch, 2005; Kettering et al., 2012; Langeveld et al., 2007; Cherry et al., 2012) which is a powerful tool for raising awareness and stimulating action (Goulding et al., 2008). Voluntary best management practice supported by nutrient budgets have been shown be more effective in reducing diffuse pollution than regulation (Koelsch, 2005). On livestock farms a 'farm-gate' nutrient budget (e.g. PLANET; Defra, 2005) is generally considered the most versatile method of doing this, which takes into account nutrient loads coming in and going out of the farm-gate. Further, a farm-gate budget is deemed to be a suitable environmental performance indicator (Oenema et al., 2003). Whilst uncertainties exist in all budget methodologies, they are usually smaller for a farm-gate budget and these are therefore preferred over, e.g., soil surface budgets, as a policy instrument (Oenema et al., 2003). The result, usually a surplus of N or P, is compared against calculated benchmarks. The surplus nutrient is thus used to indicate the relative risk of diffuse pollution (Lord et al., 2002; Oborn et al., 2003) and can be used to derive farm-level nutrient-use efficiency. Nutrient budgeting has been employed by policy-makers (e.g. PARCOM, 1988; EEA, 2001; OECD, 2001) as an agri-environmental indicator and to raise awareness of nutrient use efficiency. Levels of N and P surplus are two indicators in the EU set of 28 and they have also been used as a regulatory policy instrument, e.g. in the Netherlands (MINAS) where it has been shown that by reducing whole-farm surpluses, surface and groundwater concentrations of N and P decline over time (Oenema et al., 1998). Given the current high cost of fertilizers, nutrient budgeting can also be valuable in highlighting to farmers potential imbalances and, when combined with standard field soil testing (for pH, P, K and Mg), quantify incentives for reducing inputs. However, uptake by farmers of decision support systems in general has been poor (Matthews et al., 2008; Hochman and Carberry, 2011) and there seems to be little evidence that nutrient management is an exception.

Some nutrient budgeting programs (e.g. PLANET; Defra, 2005) do not consider soil pH, although it is well documented that sub-optimal levels of pH (<6.0) prevent optimal plant nutrient-use efficiency and can increase surplus soil N (Stevens and Laughlin, 1996) which could exacerbate N leaching. The mechanism for increased growth and N uptake is complex, arising both from the alleviation of toxicity (from Al and Mn) and the alleviation of nutrient deficiency (of Ca, Mg and Mo). Liming is the most common method of raising the pH of acidic soil (Goulding et al., 1989; Viade et al., 2011); however, recent data (British Survey of Fertiliser Practice, 2010; AIC, 2011) show that there has been a considerable decrease (20–30%) in lime applications to agricultural grassland in the UK since the mid-1990s. Similarly, in Ireland the amount of lime used on grassland has dropped greatly in recent years (Tunney et al., 2009). This reduction in the use of lime, together with the acidifying effects of high rates of N fertilizer application, may therefore be limiting crop production and exacerbating N losses. Whilst the limited existing research indicates that lime extraction and application to agricultural soils can lead to greenhouse gas (GHG) emissions (IPCC, 2006), it is well known that fertilizer production and application also increases GHG emissions (IPCC, 2006), as well as the loss of nutrients to surface and ground waters described previously. The application of lime may enable farmers to reduce fertilizer application rates whilst still maintaining crop productivity due to better utilization of the nutrients applied and stimulation of nutrient cycling from native soil organic matter reserves. This may have multiple benefits in reducing both on-farm costs and nutrient losses through leaching and GHG emissions. Such information is needed by industry and policy-makers to stimulate 'win-win' management practices that deliver truly sustainable farm systems (Goulding et al., 2008).

The aims of this study were to explore sustainable nutrient management at the field, farm and regional level for one rural UK county in terms of: (i) variation amongst farms in field level nutrients; (ii) whether current levels of surplus N, P and K are likely to lead to on-farm economic losses and risk of environmental pollution; (iii) the regional-level environmental trade-off (nutrient leaching versus GHG emissions) and economic costs of reducing nutrient application through increasing lime application. The work was done as part of the 'CEFN Conwy' project, which aimed to reduce diffuse nutrient and microbial pollution from agriculture by assisting farmers in the sustainable on-farm management of nutrients and soils (CEFN Conwy, 2011).

2. Materials and methods

2.1. Study area and farmer recruitment

The fieldwork was carried out during November 2009 and February 2010 within the county of Conwy in north-west Wales, UK (Fig. 1). The county's area is 1130 km^2 (Conwy Council, 2012), and is typical of many parts of the UK, with land types ranging from relatively unproductive waterlogged mineral soils and organic peat soil moorland in upland areas, which predominantly support extensive sheep farming and commercial forestry, to fertile lowland areas that support a variety of livestock farming. Its drainage is dominated by two large river systems fed by a number of smaller catchments and sub-catchments (Fig. 1). In general, Conwy has very few water bodies designated as 'poor' in water quality status relative to Water Framework Directive targets (EA, 2009), but several are classified as 'moderate' and are potentially at risk from diffuse pollution. The region is not currently in a Nitrate Vulnerable Zone (in such regions farmers must follow restrictions designed to reduce nitrate losses). The estuary area of the River Conwy is important for the commercial harvesting of shellfish and has several public beaches with designated EU bathing waters, and these have in the past been affected by contamination with faecal coliforms (Thorn et al., 2012).

Farmers across the county were recruited by a combination of awareness-raising events and local press, and through the two largest farmers' unions. Forty-nine farmers from across the county agreed to undertake a farm survey in return for free soil testing of at least two fields of their choice. Farm types were representative