Europ. J. Agronomy 57 (2014) 52–61

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Contrasting the spatial management of nitrogen and phosphorus for improved water quality: Modelling studies in New Zealand and France

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ARTICLE INFO

Article history:
Received 27 January 2013
Received in revised form 6 September 2013
Accepted 18 September 2013
Available online 14 November 2013

Keywords:
Buffer
Cost-effectiveness
Critical source area(s)
Grassland
Mitigation strategy

ABSTRACT

Critical source areas (CSAs) define areas of a farm or catchment that emit the majority of water quality contaminants but account for a minority of the area at a field, farm or catchment scale. Using process based modelling we tested the hypothesis that the definition and management of CSAs would decrease losses of phosphorus (P) in two New Zealand catchments and nitrogen (N) in a French catchment. In the New Zealand catchment, CSAs of P loss were isolated to small areas within fields commensurate with surface flow pathways, while in the French catchment, CSAs for N loss were influenced by factors (inputs and land use) relevant at a field (or multiple field) scale. Scenarios were tested that examined the management of CSAs versus whole field management for P, and decreasing N loss within CSAs by increasing the proportion of grassland fields and changing their location relative to cropland. The results showed that N losses decreased by up to 25% as more grassland was incorporated into the catchment, especially in wet areas near valley bottoms due to a longer growth period and better utilisation/storage of N than cropland. For P, focusing mitigation on CSAs decreased catchment losses to a similar degree as mitigations applied across the whole catchment, but was on average 6–7 times more cost-effective. Therefore, the definition and management of CSAs at an appropriate scale is recommended to improve water quality and minimise the impact on farm profitability.

1. Introduction

Diffuse pollution of surface and groundwater by nitrogen (N) and phosphorus (P) has been the subject of much research over several decades. Efforts in mitigating N and P losses at a catchment scale have utilised methods that range from changing land use according to likely losses (e.g. as estimated from simple lookup tables; Johnes and O'Sullivan, 1989), to sophisticated models that estimate event-based losses and processes (e.g. ICECREAM; Liu et al., 2012). Whichever approach is used, one focus over the last decade has been the concept of critical source areas (CSAs). These account for a majority of N or P loss which tend to originate from a minority of a field, farm or catchment's area. Commensurate with CSA theory is that a map of CSAs will allow for optimisation of water quality and profitability by placing land use or mitigation strategies at small scales which can significantly decrease N or P loss at a lower cost than mitigation strategies applied at a larger scale (i.e. whole farm).

Originally, CSA theory was applied to a farm as a means to rank fields according to their potential to supply N or P for loss (Gburek et al., 1996; Heathwaite et al., 2000). However, little consideration of hydrologic pathways that dictate whether or not a high N or P loss potential will translate into stream-enrichment was included. For P, recent work has looked at incorporating factors such as average or annual hydrologic response units (HRUs) to predict surface runoff (Schneiderman et al., 2007). However, less attention has focused on how HRUs vary in space in time. For instance, variable source area hydrology dictates that saturated zones near streams, which contribute saturation-excess surface runoff, will expand and contract in response to rainfall and soil moisture (Ward, 1984). Hence, the frequency and size of storms will change the size of a CSA considerably, often resulting in a CSA that is much less than a field.

For N, losses are a function of surplus N and the dominant flow pathway – sub-surface flow (Heathwaite et al., 2000). Hydrologic response units for N therefore transport N from the plant root zone via the vadose zone to either groundwater and/or the stream channel. Critical source area theory at a field or catchment scale can be used to identify any surplus of N via a mass balance within a single or at a multiple field scale. This can then be used to identify where to best incorporate mitigation strategies to intercept losses in surface

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http://dx.doi.org/10.1016/j.eja.2013.09.011

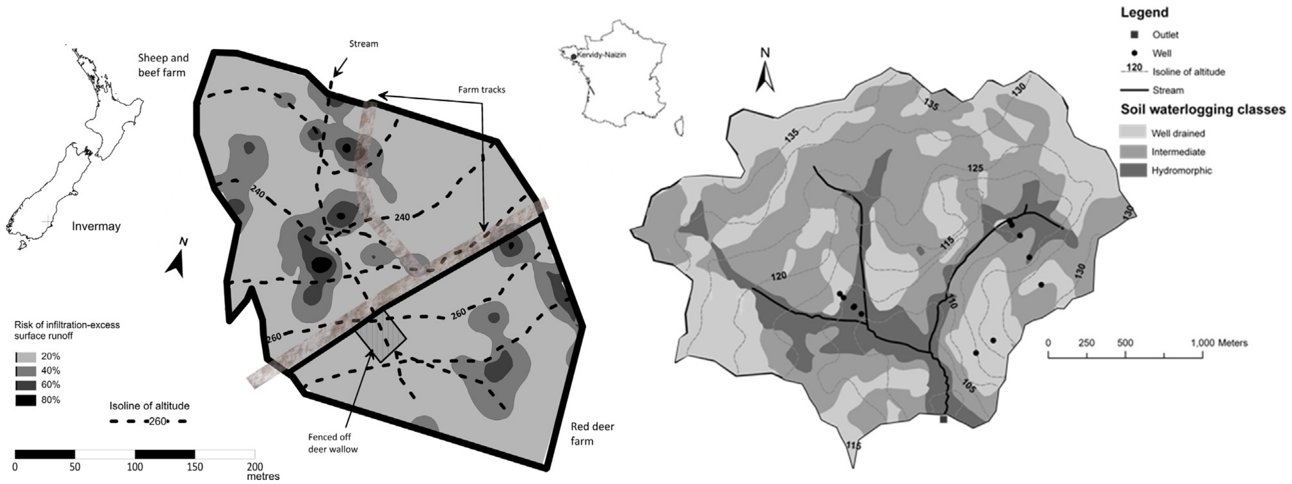

Fig. 1. On the left is a map of the Invermay catchment showing the red deer and sheep and beef farms, 20 m contours (msl), the location of farm tracks, the stream and an area used prior to 2006 by red deer for wallowing and grey shading showing the risk of infiltration excess runoff (data from McDowell and Srinivasan, 2009), while on the right is a map of the Kervidy catchment showing 5 m contours (msl), the location of wells, the stream and outlet and soil drainage classes.

and sub-surface flow. One popular mitigation approach in Europe has been to modify land use by the incorporation of grassland fields that act as buffer zones to alter the N surplus and sequester N (Haycock et al., 1997).

This paper examines CSA theory for N and P. Our hypothesis is that the identification of CSAs and targeting CSAs with remedial strategies (including land use change if appropriate) will result in less N and P being lost to water, and cost less, than applying strategies or land use change across a whole catchment. Two catchments were used in this study. In a New Zealand catchment, we aimed to decrease P losses as periphyton growth, like many New Zealand streams and Rivers, was likely to be P-limited (McDowell et al., 2009). In contrast, in northwest France, the main social and environmental issue is nitrate-N contamination of surface and groundwater and the associated impact on drinking water and eutrophication of coastal waters. In the mixed land use French catchment, we used CSA theory to optimise where grasslands could be best placed (*viz.* buffer zones) compared to cropland. This was done at a field scale, whereas in the New Zealand catchment, large differences in catchment factors like slope, soil type or rainfall, isolated much smaller CSAs and also meant that a range of mitigation strategies were assessed (instead of land use change) to decrease P export.

2. Materials and methods

2.1. Catchment descriptions and management

The New Zealand catchments were located at the AgResearch-Invermay Agricultural Centre, thereafter called Invermay, about 10 km west of Dunedin in Otago, New Zealand (Fig. 1). The catchments collectively covered 10 ha, with the 5-ha of the headwater catchment forming part of a red deer farm that flowed into a second 5 ha catchment that was part of a sheep and beef farm. Catchments were situated at an elevation between 220 and 280 msl and had a moderate slope (10–15°) and annual rainfall of 850 mm. The predominant soil type was a Warepa silt loam (NZ soil Classification, mottled fragic Pallic soil; USDA Taxonomy, Typic Hapludalf) with outcrops of Cargill hill soils (acidic mafic Brown soil; USDA Taxonomy, Umbric Dystrochrept) at higher elevations (Otago Regional Council, 2004).

As part of managing both farms, the Invermay catchments received about 26 kg P ha^{-1} as superphosphate applied each year by aeroplane in early summer. Additional applications of lime were made in early summer when soil tests indicated pH had dropped below 5.8. All animals grazed a mixed ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) pasture with a rotation of 21–56 days, depending on pasture growth during the year. Every 3–4 years one field in each catchment was utilised for a winter forage crop, usually a Brassica, whereby stock grazed the crop in situ during winter thereby avoiding pugging damage to grassland and mitigating the need for large amounts of silage. The forage cropped fields were resown in grassland in spring. When not grazing a forage crop in winter, animals were allowed open access to fields. The average annual stocking rate for the red deer and sheep and beef farms were 14 and 14.6 stock units ha^{-1} (one stock unit equates to 1 ewe at 55 kg live-weight, from which a 15–27 month old red deer and a 450 kg cattle beast equate to 1.8 and 7.1 stock units respectively; Fleming, 2003).

The French study was performed in the 5 km^2 catchment of Kervidy in Brittany, Western France (Fig. 1). The area is included in a French long-term ecological research site (https://www.inra.fr/ore_agrhys, Cheverry, 1998). The region has a mild oceanic climate, with a mean annual temperature of 11.8 °C. The mean annual rainfall (1993–2002) is 883 mm, with strong inter-annual variations. The mean annual potential evapotranspiration is 705 mm and annual runoff ranges from 195 to 820 mm. Soils include loams that are well drained on hillslopes (distric and aquic eutrochrepts), but waterlogged near the channel network (glossaqualfs and fluvents). Waterlogged soils occupy 15% of the catchment area. The bedrock is Brioverian (Late Proterozoic) schist, while the thickness of weathered bedrock is highly variable, ranging from 1 to more than 30 m. A shallow and perennial groundwater table develops in the soil and the weathered bedrock. Close to the river the water table fluctuates within the first metre below the surface, while upslope, the water table is between 3 and 8 m below the soil surface.

Some 90% of the land surface is used for agriculture, mainly dairy and pig production. Land-use is composed of 30% corn (mainly corn silage sown in April and harvested in October), 30% winter cereals sown in November and harvested in July, and 30% grasslands. With about 3000 cattle and 33,000 pigs, the average stocking rate of the farms operating in the catchment was 10 livestock units (LSU) ha^{-1}. Using a conversion factor (see Pain and Menzi, 2003; European Commission, 2012) this equates to between 55 and 65 stock units ha^{-1} i.e. an animal density that is 4.5–5 times more than the New Zealand catchment. The higher livestock density in the Kervidy Catchment is mainly due to indoor pig farming.