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Modelling the long-term response of stream water chemistry to forestry in Galloway, Southwest Scotland

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ABSTRACT

The role of forestry in acidification of soils and surface waters under historic and contemporary acidic deposition was assessed using a process-based soil hydrogeochemical model incorporating Bayesian calibration and uncertainty propagation. The five study sites were acid impacted headwater catchments in the Galloway region of southwest Scotland, with between 0 and 65% forest cover. A 'no forestry' scenario was compared to future 'Forest Design Plans' provided by the Forestry Commission to assess the relative effects of forestry and acidic deposition. Biological impacts were assessed using a critical chemical threshold of 20 μeq l^{-1} for annual acid neutralising capacity (ANC). During the peak of acidic deposition in the 1970s, simulated ANC declined by an average of 37 μeq l^{-1} across all sites from background values in 1860, but the threshold was breached only at the moorland (no forest cover) site. Conifer planting enhanced pollutant scavenging and increased base cation uptake but did not strongly impede the widespread chemical recovery of surface waters from the mid 1980s to present in response to ~80% reduction in sulphur dioxide emissions (and associated decreases in sulphate deposition). Current ANC values are above the critical ANC threshold at all five sites and >50 μeq l^{-1} at three of the four forested sites; however, ecological surveys show that the response of fish and aquatic invertebrates has generally been small, albeit improving. Continued chemical recovery was predicted in response to agreed reductions in acidic deposition to 2020 but thereafter at a much slower rate; no site is expected to return to the original pristine chemical conditions of 1860 by 2100. Differences in the ANC response post 2010 under the planned forest scenario and the 'no forest' scenario were small (ranging from 0.7 to 6.3 μeq l^{-1}), suggesting that future changes in forest cover are unlikely to have a major impact on the recovery process. Future emissions reductions may therefore be required to promote biological recovery in affected catchments.

1. Introduction

Historically, anthropogenic sulphur (S) emissions were the main component of 'acid rain', causing widespread acidification of soils and waters, and biological damage in acid sensitive regions (Harriman et al., 1987). Although S deposition has decreased greatly from its peak during the 1970s (Harriman et al., 2001; Fowler et al., 2005) ecosystem recovery has been slow, and some of the most acid sensitive waters remain acidified (Monteith et al., 2005). In concert, atmospheric emissions of nitrogen (N = nitrogen oxides [NOx] and reduced nitrogen [NHy]) have increased (Fowler et al., 2004), contributing to acidification, and nutrient enrichment of semi-natural ecosystems. In the United Kingdom (UK), forestry is acknowledged to exacerbate the acidification of surface waters in acid sensitive regions (Harriman et al., 2003; Malcolm et al., 2014a,b; Monteith et al., 2014), owing to enhanced interception of atmospheric pollutants by aerodynamically rough forest canopies (Forestry Commission, 2003; Miller et al., 1991). In addition, the removal of base cations (Bc = Ca^{2+}, Mg^{2+} and K^{+}) by forest harvesting reduces the neutralising capacity of soils (Department of Environment and Forestry Commission, 1991; Kirchner and Lydersen, 1995). The influence of forestry on water quality therefore depends not only on acidic deposition but also on the forest cycle.

The critical loads approach has been widely accepted (and used) by policy makers to guide emissions controls for surface water

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protection at UK and European levels. In 1993, the Forestry Commission adopted the critical loads approach to identify sites that were potentially sensitive to anthropogenic acidification (Forestry Commission, 1993). Catchment-based critical load assessments are required where new planting or forest restocking exceed certain forest cover thresholds, with restrictions imposed where critical loads are found to be exceeded (Forestry Commission, 2003). However, the role of forest management in acidification and recovery processes continues to be debated, with the fisheries sector expressing scepticism regarding the suitability of critical load thresholds for surface waters in forested catchments (McCartney et al., 2003; Bridcut et al., 2004). The critical load concept assumes steady state conditions between acidic deposition, water chemistry and biological effects. In reality, the response of surface water chemistry to changes in acidic deposition is not instantaneous but, entails lag times of years to decades, depending upon the processes involved and the natural characteristics of vegetation, soils and waters. Similarly, the biological response to changes in water chemistry is lagged owing to recruitment and re-colonisation.

Predicting the future recovery of soil and freshwater ecosystems requires dynamic process-oriented models. These models have been developed during the past 30 years to explain observed trends in water quality and to predict future changes in response to emission reductions and land use management (e.g., Cosby et al., 1985a,b).

The combined effects of acidic deposition and forestry have been studied across Europe and North America with a range of outcomes relating to catchment characteristics, forest management and more recently climate change (Aherne et al., 2012; Wright et al., 2006; Oulehle et al., 2007). A common modelling protocol was used at 14 intensively studied sites in Europe and eastern North America and the results showed a mixed response to forestry, but the effects on ANC, NO_3 and soil base saturation were relatively small compared to other climate induced changes (Wright et al., 2006). In contrast, the response of soil solution chemistry to long term changes in acid deposition and forest practices in a Norway spruce monoculture and a natural European beech forest concluded that forest management practices influenced soil acidification with notable affects at the spruce dominated site.

The objectives of the current study were to (a) simulate the historical effects of increased acidic deposition and forestry in selected acid impacted headwater catchments; and (b) assess if further reductions in forest cover would aid the recovery process. The impacts of acidic deposition and land management were evaluated at five headwater catchments in Galloway, Southwest Scotland using the process-based Model of Acidification of Groundwater in Catchments (MAGIC), incorporating Bayesian calibration and uncertainty propagation. Many studies have evaluated the impacts of increased harvest removals (i.e., use of harvest residues for bioenergy (e.g., Aherne et al., 2012) on soil and surface water acidification; in contrast, this study focused on the influence of reduced forest cover, density, and harvest removals under future emission reductions.

2. Methods

The Model of Acidification of Groundwater in Catchments (Cosby et al., 1985a,b, 2001) was combined with a stochastic model for output data, to estimate all unknown model parameters by Bayesian calibration using a Markov Chain Monte Carlo (MCMC) technique. This involved specifying prior probability distributions for the input parameters and likelihood functions for the output data based on observed site-specific data. The approach allowed for a formal management of parameter uncertainties and the impact of uncertainty on model predictions to be explicitly shown (Larssen et al., 2006; MacDougall et al., 2009; Helliwell et al., 2011).

2.1. Site selection

The five study sites represent acid impacted headwater catchments in the Galloway region of southwest Scotland, including three sub-catchments in the Black Water of Dee (Dargall Lane, Green Burn and Cuttie Shallow); Cardoon Burn in the Big Water of Fleet and Waterside on the River Bladnoch. Four were partly forested and one (Dargall Lane) a moorland site, with similar characteristics in terms of slope, size, and climate to the nearby forested Green Burn catchment (Table 1); however, the moorland site has been shown to have a substantial geological source of sulphate ($SO_4{}^{2-}$; Giusti, 1999). Additional information on the study sites, data sets and methods used to generate model parameters are described in Helliwell et al. (2011). A geographic information system (GIS) and high resolution digital elevation model (DEM) were used to identify catchment boundaries, and generate catchment area and altitude for the five sites.

2.2. Data sources for model parameterisation

2.2.1. Deposition chemistry

Observed deposition chemistry from Loch Dee, southwest Scotland (part of the UK Acid Deposition Monitoring Network (UKADMN), Grid reference NX 468779) was used to estimate pollutant deposition loads of S, NOx and NHy to the study sites during the period 1988–2008. Longer-term historic trends were modelled by scaling current deposition to reconstructed emission sequences (Bettelheim and Littler, 1979; Warren Spring Laboratory 1987; Simpson et al., 1997). The future deposition scenarios were based on projections from the FRAME model (Fournier et al., 2004) and represent current legislation (Gothenburg protocol [multi-pollutant multi effects protocol]) under Updated Energy Projections (UEP30; Malgorzata et al., 2009), which aims to reduce emissions of S, N and ozone to achieve critical load targets for acid sensitive areas (Fig. 1a).

Sulphate deposition from Loch Dee was modified to account for dry deposition to the forest canopy based on the assumption that $SO_4{}^{2-}$ was conservative and in balance with observed output in surface water. On the whole, the rate and magnitude of change in observed S deposition compared well with FRAME modelled data, with a slight deviation in the early record (Fig. 1b). Trend analysis for the period 1986–2006 exhibited a statistically significant ($p < 0.001$) decline in non-marine $SO_4{}^{2-}$ of 0.52 μeq l^{-1} yr^{-1} (change per year of −2.7%) and in nitrate of −0.06 μeq l^{-1} yr^{-1} (change per year of −0.6%).

2.2.2. Rainfall and discharge

Rainfall volume data were also obtained from Loch Dee, and discharge data derived from the National River Flow Archive for the nearest river gauging station downstream of each site (Table 2). Daily mean flow values were converted to total daily discharge depth and verified against the Scottish Environment Protection Agency's (SEPA) discharge records. In instances where the nearest gauging station was a significant distance down river, the total discharge was downscaled to match the study catchment drainage area.

2.2.3. Forestry

Forest information was extracted from the Forestry Commission's spatial databases, including the extent of current plantations, proportion of open ground, tree species composition, planting dates, harvest removal volumes and yield class per species (Table 3).