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Anthropocene environmental change in an internationally important oligotrophic catchment on the Atlantic seaboard of western Europe

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ABSTRACT

Oligotrophic catchments with short spatey streams, upland lakes and peaty soils characterise northwest European Atlantic coastal regions. These catchments are important biodiversity refuges, particularly for sensitive diadromous fish populations but are subject to changes in land use and land management practices associated with afforestation, agriculture and rural development. Quantification of the degree of catchment degradation resulting from such anthropogenic impacts is often limited by a lack of long-term baseline data in what are generally relatively isolated, poorly studied catchments. This research uses a combination of palaeolimnological (radiometrically-dated variations in sedimentary geochemical elements, pollen, diatoms and remains of cladocera), census, and instrumental data, along with hindcast estimates to quantify environmental changes and their aquatic impacts since the late 19th century. The most likely drivers of any change are also identified. Results confirm an aquatic biotic response (phyto- and zooplankton) to soil erosion and nutrient enrichment associated with the onset of commercial conifer afforestation, effects that were subsequently enhanced as a result of increased overgrazing in the catchment and, possibly, climate warming. The implications for the health of aquatic resources in the catchment are discussed.

Introduction

Oligotrophic headwater drainage systems are of fundamental importance in terms of global freshwater resources. In the north east Atlantic region, these systems often constitute the majority of pristine reference lakes and rivers (Bennion et al., 2004; Leira et al., 2006; Kelly et al., 2009), and support internationally important salmonid populations. Atlantic salmon are an Annex II species under the 1992 European Habitats Directive, and member states are required to conserve its habitat and protect the stock status (O'Keeffe and Dromey, 2004). The sensitivity of oligotrophic waters and their catchments to climate change and the potential reduction in freshwater biodiversity necessitate ongoing scientific focus (Ormerod et al., 2010; Strayer and Dudgeon, 2010). Their remote location has enabled some relative protection from more obvious anthropogenic disturbances, such as intensive agriculture and industry. However, the isolation of headwater catchments often results in their being relatively poorly studied and data poor, deficiencies that can compromise understanding of the risk posed by environmental change and effective management responses.

In western Ireland, headwaters are generally found in acid sensitive catchments in which hydrology and flood regimes are dependent on climate while surface waters are oligotrophic with relatively low primary productivity. Catchment degradation, attributed to land use and land management policies associated with afforestation, agriculture and rural development (Moriarty and Dekker, 1997; Hendry et al., 2003; Crozier et al., 2003) have impacted freshwater quality, quantity and habitat. Since the 1950s, agriculturally unproductive, generally poorly-drained, upland catchments across Ireland were targeted for commercial coniferous afforestation (Black et al., 2008) generally planted without riparian buffer strip protection. Thus the commercial benefits of

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afforestation have been associated with environmental costs, ranging from acidification (Allott et al., 1990, 1997; Kelly-Quinn et al., 1996, 1997; Cruikshanks et al., 2008; Feeley et al., 2011), sediment release (Rodgers et al., 2010), nutrient enrichment (Rodgers et al., 2010; Drinan et al., 2013a) to hydrological changes (Drinan et al., 2013b). For example, many studies have highlighted the exacerbating effect of forestry on water draining forested peatlands (Allott et al., 1990, 1997; Dalton, 2000) and episodic acidifying events (Kowalik et al., 2007; Evans et al., 2008; Ormerod and Durance, 2009; O'Dwyer and Taylor, 2010; Feeley et al., 2011). Many headwaters occur in naturally acidic peatland catchments, where forestry practices can increase the loading of allochthonous dissolved organic carbon (DOC) and lead to fundamental changes in trophic status and biological processes in lakes (Cole et al., 2011). For example, reduction in water clarity can restrict autotrophic production while DOC can fuel microbial metabolism (Jasser and Arvola, 2003; Sucker and Krause, 2010). Anthropogenically-exacerbated acidification at these sites can greatly increase aquatic effects, including changes in the quality of primary producers, extirpation of macroinvertebrates and decreased fish spawning efforts and survival rates (Kowalik et al., 2007; Kroglund et al., 2007).

Drainage works associated with afforestation (Carling et al., 2001) have precipitated changes in hydrological regimes and increased erosion risk (Müller, 2000). Nutrient-poor peat soils with thin vegetation cover in upland catchments are susceptible to damage from such erosion (Gordon et al., 2001; Watts et al., 2003), leading to increased sediment loads in downstream receiving waters and changes in ecological quality (e.g. elimination of species or switch in species dominance) (Kowalik and Ormerod, 2006; Drinan et al., 2013a). Excessive erosion has also been associated with overgrazing by sheep (Soulsby et al., 2001a; Allott et al., 2005). Stocking levels of sheep in the west of Ireland increased sharply from the early 1970s as a result of EU subsidies (Gillmor and Walsh, 1993; Weir, 1996; O'Connor, 2000) with degradation of upland areas in particular commonplace. Erosion of peat in headwater catchments results in excess levels of suspended sediment entering receiving waters (Wood and Armitage, 1997; Heaney et al., 2001; Mainstone et al., 2008). This leads to legacy sediment or rates of sediment accumulation in downstream lakes far in excess of those expected in the absence of anthropogenic disturbance (James, 2013). Excess sediment loads can have major ecological impacts on resident fish populations, for example, by reducing visibility in streams and hence affecting predation, or by modifying habitats and suffocating spawning beds and thereby reducing egg survival of salmon and trout (Soulsby et al., 2001b; Suttle et al., 2004). In addition, particulate forms of phosphorus (P), nitrogen (N) and carbon (C) are carried along with eroded material causing enrichment effects in receiving waters. The sources of nutrients under such circumstances may be anthropogenic fertilisation of commercial forestry or agricultural lands (P and N), forest harvest operations, or peat degradation leading to erosion of the terrestrial C pool (Cummins and Farrell, 2003; Rodgers et al., 2010; Drinan et al., 2013b) with aquatic impacts extending downstream.

Climate variability can also influence the nature and magnitude of aquatic effects of catchment disturbance, in addition to being a driver of change in its own right (Jennings et al., 2000; Battarbee et al., 2002). Future climate projections for catchments along the north east Atlantic coast include increases in air and water temperatures, frequency of storm events, and rate of DOC loss (Fealy et al., 2010; Jennings et al., 2010; Naden et al., 2010). Future management of these types of catchments requires sound understanding of how multiple drivers have shaped current ecological conditions and are projected to do so in coming years.

A cause–effect relationship between catchment degradation and declines in water quality is plausible but questions remain about the relative strengths of climate and land use effects. Moreover, little research has focused on understanding the consequences of aquatic risks of climate and land use changes acting in unison. In the absence of long-term datasets, evidence of past drivers of aquatic ecosystem changes and their effects preserved in lake sediments and recovered through palaeolimnological techniques can potentially provide a useful source of proxy evidence (Battarbee et al., 2002; Dalton et al., 2009; Smol, 2010). Sediment-based archives represent datable accumulations of autochthonous and allochthonous material, in the form of biological, chemical and physical components. Research presented in this paper tests the null hypothesis (H_0) that there is no relationship between changing environmental conditions in an upland peat catchment on the Atlantic seaboard of western Europe and aquatic responses during a period (beginning in the late 19th century) that accommodates a large part of the Anthropocene. The Burrishoole catchment in the west of Ireland, a nationally and internationally important index site for monitoring stocks of diadromous fish (Whelan et al., 1998; ICES, 2012, 2013), is the focus of the study.

Materials and methods

Study site

The Burrishoole catchment (53°56′ N, 9°35′ W), a sparsely populated area (c. 100 km^2) of generally extensively grazed upland peat soils and coniferous plantation forestry (Fig. 1), is climatically influenced by the Atlantic Ocean (Allott et al., 2005). Catchment bedrocks are quartzites and schists/gneiss overlain by poorly drained soils. The headwater lake Bunaveela and a downstream lake, Feeagh, are both deep, oligotrophic and coloured (respectively, maximum depths of 23 m and 45 m; 12 and 8 μg l^{-1} TP; and 68 and 80 mg l^{-1} PtCo), the latter because of high levels of DOC, and have low alkalinity and pH (see Supplementary Data (SD) Table 1). For the purposes of the EU Water Framework Directive (WFD), Feeagh is currently classified as being of 'Good' ecological status (McGarrigle et al., 2010), and is assigned to the risk category 2a (expected to achieve good ecological status) (Anon., 2005).

Historical and instrumental data

Climate data (air temperature and precipitation) were available for the Newport meteorological station, located within the catchment (1968 to present) and for Belmullet synoptic station, 40 km northwest of the catchment (1956 to present). Data were also obtained for the Arctic multidecadal oscillation (AMO), the North Atlantic Oscillation Index (NAO) and the Gulf Stream North Wall Index (GSI). The AMO and NAO are related to large-scale weather events (NAO is thought to be a function of the larger scale AMO) while the GSI is related to a measure of the latitude of the Gulf Stream current. The NAO Index is based on the pressure difference at locations representative of the strength of the Azores high and of the Icelandic low (Hurrell, 1995). Highly positive values are associated with an increase in the occurrence of westerly winds and increased wind speeds, temperatures and rainfall in northern Europe (Jennings et al., 2000). There are several versions of the NAO index: here the winter version (average values for the months of December, January, February, and March: Hurrells Index) for the period 1864–2009 is used. The index provided a proxy for local and regional climate for the full time period, especially the earlier period when meteorological data were unavailable.

Population data from 1970 were available from the Central Statistics Office (CSO) in Ireland for district electoral divisions (DEDs), while pre-1970 data are estimates based on rural district data from paper records. Changes in land use were compiled from