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Decline in atmospheric sulphur deposition and changes in climate are the major drivers of long-term change in grassland plant communities in Scotland[☆]

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ABSTRACT

The predicted long lag time between a decrease in atmospheric deposition and a measured response in vegetation has generally excluded the investigation of vegetation recovery from the impacts of atmospheric deposition. However, policy-makers require such evidence to assess whether policy decisions to reduce emissions will have a positive impact on habitats. Here we have shown that 40 years after the peak of SO_x emissions, decreases in SO_x are related to significant changes in species richness and cover in Scottish Calcareous, Mestrophic, *Nardus* and Wet grasslands. Using a survey of vegetation plots across Scotland, first carried out between 1958 and 1987 and resurveyed between 2012 and 2014, we test whether temporal changes in species richness and cover of bryophytes, Cyperaceae, forbs, Poaceae, and Juncaceae can be explained by changes in sulphur and nitrogen deposition, climate and/or grazing intensity, and whether these patterns differ between six grassland habitats: Acid, Calcareous, *Lolium*, *Nardus*, Mesotrophic and Wet grasslands. The results indicate that Calcareous, Mesotrophic, *Nardus* and Wet grasslands in Scotland are starting to recover from the UK peak of SO_x deposition in the 1970's. A decline in the cover of grasses, an increase in cover of bryophytes and forbs and the development of a more diverse sward (a reversal of the impacts of increased SO_x) was related to decreased SO_x deposition. However there was no evidence of a recovery from SO_x deposition in the Acid or *Lolium* grasslands. Despite a decline in NO_x deposition between the two surveys we found no evidence of a reversal of the impacts of increased N deposition. The climate also changed significantly between the two surveys, becoming warmer and wetter. This change in climate was related to significant changes in both the cover and species richness of bryophytes, Cyperaceae, forbs, Poaceae and Juncaceae but the changes differed between habitats.

1. Introduction

Grasslands are among the most extensive ecosystems in the world. Depending on the definition used, grasslands cover between 20 and 40% of the terrestrial area of the earth (Food and Agriculture Organization of the United Nations, 2005). Grasslands provide high levels of ecosystem services and are commonly managed to maximise their supply, particularly production services, for human benefit. Although many grasslands were created, and are currently being maintained, by human activities human-induced environmental perturbations are acknowledged threats to their biodiversity and functioning, with atmospheric pollution, climate change and land management being three of the most influential drivers (Millennium Ecosystem Assessment, 2005; UK National Ecosystem Assessment, 2011). These drivers operate over local to global scales and from short to decadal time-periods, with progressive change reflecting, amongst other factors, changing policies, regulation and

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global weather patterns. Therefore, while experiments can assess short-term impacts of these drivers, long-term and large-scale repeated surveys are required to fully assess the impact of spatial and temporal changes in these drivers.

Atmospheric pollution, particularly nitrogen (N) deposition, is well known as a major driver of change in many habitats around the world (Barron et al., 2014; Bobbink et al., 2010; Phoenix et al., 2006) and was identified as a major threat in the conservation of grasslands by European policy-makers (Stevens et al., 2011b). Most studies have focused on acid grasslands where N deposition has been shown to decrease species richness and diversity, increase the cover of grasses and other competitive species and decrease the cover of diminutive species such as some forbs (Damgaard et al., 2011; Dupre et al., 2010; Field et al., 2014; Stevens et al., 2011a, 2016). Increased N deposition has also been shown to increase the abundance of N-demanding plants; as shown by an increase in plants with high Ellenberg N scores (Maskell et al., 2010; Smart et al., 2003).

N deposition occurs in two forms, NO_x and NH_y. In the UK, NO_x emissions have decreased from a peak of around 900 Gg-N yr^{-1} in 1990 to about 350 Gg-N yr^{-1} in 2010 resulting in a significant decline in NO_2 concentration over the UK of about 50% and a 24% decline in wet deposition (RoTAP, 2012). Emissions of NH_y in the UK peaked in the 1980s and have decreased by about 15% since then, with around 250 Gg-N being emitted in 2010 (RoTAP, 2012). Despite the declines in emissions, however, NH_y deposition in the UK has changed little over the last 20 years due to continued transboundary movement of NH_y from overseas (RoTAP, 2012). Overall there have been small increases in NH_y in remote regions of the UK and small declines in regions in which pig and poultry emissions dominate the sources (RoTAP, 2012). Although there are differences in responses between species and habitats different forms of nitrogen deposition (NO_x or NH_y) have been shown to impact plant communities in different ways. Nitrogen deposition can directly affect the plant community via the phytotoxic effects of NO_x and NH_y and indirectly affect the plant community via eutrophication, soil acidification and increased availability of toxic metals in the soil caused by NH_y (Bobbink et al., 2010; Bobbink and Hicks, 2014; Dorland et al., 2013; Pannek et al., 2015). NO_x is associated with higher energy costs for the plants, as it is not so readily taken up as NH_y, but NO_x can counteract the acidification effects of NH_y (Dorland et al., 2013; Pannek et al., 2015).

Like N deposition, sulphur (S) deposition can impact plant communities both directly through phytotoxic effects and indirectly via increased soil acidity and increased availability of toxic metals resulting in a decline in grassland species richness and an increase in the grass:forb ratio (Damgaard et al., 2013; Henrys et al., 2011; McGovern et al., 2011). Sulphur emissions in the UK have significantly decreased, from a peak of around 3200 Gg-S in 1970, to 203 Gg-S in 2010; this has resulted in a significant decline in S deposition across the UK. Wet deposition of anthropogenic S in 2008 was 85 Gg-S compared to 252 Gg-S in 1986, a reduction of approximately 70% (RoTAP, 2012). Dry deposition of S has declined from 390 GgS yr^{-1} in 1986 to 32 Gg-S yr^{-1} in 2008 (RoTAP, 2012). Following the decrease in S emission, soils in the UK started to recover from acidification, with long-term monitoring showing soil pH increasing across a range of habitats (Morecroft et al., 2009). For many years there appeared to be a lag effect in recovery of the vegetation (McGovern et al., 2011; Morecroft et al., 2009) with the vegetation not responding significantly to the decrease in soil acidity. However, more recent work (Rose et al., 2016) across the same network of sites as Morecroft et al. (2009) reported significant increases in species richness and increases in species characteristic of less acid soils, which the authors concluded were likely to be driven by the large reductions in acid deposition in recent decades.

Atmospheric pollution is not the only driver affecting grasslands across Europe, with agricultural management (both intensification and abandonment) and climate change being listed in the top five drivers by European policy-makers (Stevens et al., 2011b). The impact of climate change on grasslands depends on which climatic factors alter and where the grasslands are located. In perennial grassland in the French Massif Central, taxonomic diversity showed no response to climate treatments (warming, summer drought and elevated CO_2) but the relative abundance of grasses decreased under both warming and simultaneous application of warming, summer drought and elevated CO_2, and legume relative abundance increased in all warmed treatments (Cantarel et al., 2013). In calcareous grasslands in Southern England, simulated climate change of warmer winters with increased summer rainfall resulted in plant cover and species richness significantly increasing (Sternberg et al., 1999). In contrast, experiments with the same levels of simulated climate change on calcareous grasslands in Northern England concluded that compositional changes were less than short-term fluctuations in species abundances driven by inter-annual climate fluctuations (Grime et al., 2008). Pakeman et al. (2015) also found very limited evidence of climate change driven species change for coastal grasslands in Scotland.

Grasslands are nearly always maintained in a pre-climax vegetation state by grazing, but the intensity, timing, duration and type of grazing animals present have all been shown to influence the plant community composition and the sward structure (Ball, 1974; Bullock et al., 1994; Grant et al., 1996; Marriott et al., 2009; Moore et al., 2015; Smith and Rushton, 1994; Stewart and Pullin, 2006). Heavy grazing can result in the dominance of grazing-tolerant species such as *Nardus stricta* and *Molinia caerulea* while light grazing can result in smaller forbs being shaded out by competitive grass species and ultimately, if seed sources are available, the establishment of woody species. In the EU, the Common Agricultural Policy (CAP), particularly in relation to agri-environment schemes, has heavily influenced the intensity and timing of grazing by domestic livestock in grassland systems (Corbelle-Rico et al., 2015; Dobrev et al., 2014; Mouysset, 2014; Pe'er et al., 2014; Schulz, 2015; Trubins, 2013). In the 1990's there was an increase in livestock numbers but, following the decoupling of livestock numbers from payment within CAP, livestock numbers have declined with destocking and abandonment occurring in many areas within Europe (Acs et al., 2010; SAC, 2008).

The impacts of changes in climate, pollution and grazing on grasslands will interact and their effects may take decades to be seen. Only long-term repeat survey work over a large area can enable us to explore and identify how grasslands respond to these different drivers and the relative importance of these drivers. Using a survey of grassland vegetation plots across Scotland, first carried out between 1958 and 1987 and resurveyed between 2012 and 2014, we test: 1) whether changes in species richness and cover of bryophytes, Cyperaceae, forbs, Poaceae, and Juncaceae over 26–55 years can be explained by changes in: a) S, NO_x and NH_y deposition; b) climate; and/or: c) grazing intensity; 2) whether different grassland habitats respond differently to changes in pollution deposition, climate and grazing; and: 3) whether the relative importance of pollution, climate and grazing in explaining variation in grassland species composition has changed between the two surveys.

2. Method

2.1. Vegetation surveys

Between 1958 and 1987 Birse and Robertson compiled 1980 records of vegetation composition in grasslands across Scotland