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Research article

Change to ecosystem properties through changing the dominant species: Impact of *Pteridium aquilinum*-control and heathland restoration treatments on selected soil properties

G. Milligan, K.E. Booth, E.S. Cox, R.J. Pakeman, M.G. Le Duc, L. Connor, S. Blackbird, R.H. Marrs*

School of Environmental Sciences, University of Liverpool, Liverpool, UK

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A B S T R A C T

It is well known that soils are influenced by the plant species that grow in them. Here we consider the effects of management-induced changes to plant communities and their soils during restoration within a 20-year manipulative experiment where the aim was to change a late-successional community dominated by the weed, *Pteridium aquilinum*, to an earlier-successional grass-heath one. The ecological restoration treatments altered the above- and below-ground components of the community substantially. Untreated plots maintained a dense *Pteridium* cover with little understory vegetation, cutting treatments produce significant reductions of *Pteridium*, whereas herbicide (asulam) produced significant immediate reductions in *Pteridium* but regressed towards the untreated plots within 10 years. Thereafter, all asulam-treated plots were re-treated in year 11, and then were spot-sprayed annually. Both cutting and asulam treatments reduced frond density to almost zero and resulted in a grass-heath vegetation. There was also a massive change in biomass distribution, untreated plots had a large above-ground biomass/necromass that was much reduced where *Pteridium* was controlled. Below-ground in treated plots, there was a replacement of the substantive *Pteridium* rhizome mass with a much greater root mass of other species. The combined effects of *Pteridium*-control and restoration treatment, reduced soil total C and N as and available P concentrations, but increased soil pH and available N. Soil biological activity was also affected with a reduction in soil N mineralization rate, but an increased soil-root respiration. Multivariate analysis showed a clear trend along a pH/organic matter gradient, with movement along it correlated to management intensity from the untreated plots with low pH/high organic matter and treated plots with to a higher pH/lower organic matter in the sequence asulam treatment, cut once per year to cut twice per year. The role that these changed soil conditions might have in restricting *Pteridium* recovery are discussed.

1. Introduction

Bracken *Pteridium aquilinum* (L.) Kuhn, hereafter referred to as *Pteridium*), originally a woodland species, invades sub-seral communities in many parts of the word (Marrs and Watt, 2006). During this invasion *Pteridium* often produces stands of dense fronds with a deep litter layer (Marrs and Watt, 2006), which combine to cause problems for agriculture and forestry where such *Pteridium* stands can inhibit crop growth (Aguilar-Dorantes et al., 2014; Levy-Tacher et al., 2015; Pakeman and Marrs, 1992; Roos et al., 2011). It also poses problems for conservation where invasion can suppress important understorey plant communities (Cox et al., 2008), leaving a much impoverished community with less conservation value than the pre-*Pteridium* state (Pakeman and Marrs, 1992). Where dense *Pteridium* occurs in long-established stands a steady-state should be reached with respect to productivity, litter dynamics and soil processes (Pakeman and Marrs, 1996).

Given its importance as a world-wide weed, there have been many experimental attempts to control *Pteridium* and replace it with either an earlier-successional plant communities or forest cover. In Great Britain, various approaches have been tested: cutting and herbicide use (Cox et al., 2007), cutting, bruising and

* Corresponding author.
E-mail address: calluna@liverpool.ac.uk (R.H. Marrs).

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repeated herbicide use (Milligan et al., 2016), and in Italy initial cutting followed by ploughing or harrowing and thereafter sowing of a forage mixture (Argenti et al., 2012). For neo-tropical *Pteridium*, various approaches have been tested, for example in Mexico, repeated selective cutting (Aguilar-Dorantes et al., 2014) and initial cutting coupled with overstorey canopy competition from Balsa trees (*Ochroma pyramidale* (Cav. ex Lam.) Urb.), and in Ecuador, a range of mechanical and herbicidal approaches (Roos et al., 2011). Some of these studies have been of relatively short-term duration, concentrating on initial treatment responses, and this is unfortunate as *Pteridium* is well known to recover quickly, at least in northern Europe (Marrs et al., 1998). It is also important to note that there are taxonomic differences in *Pteridium* between these different geographical locations (Marrs and Watt, 2006), and it is possible that the different species/sub-species react differently to control treatment as they have differing annual growth cycles (Silva Matos et al., 2014.)

It is well known that ecosystem function including soil processes can be influenced by the plant species that grow in them (Connell and Slatyer, 1977; Jenny, 1980) and *Pteridium* should be no exception. Recent research in this area has focused on the mechanisms involved in this process, where plant species diversity is the major control (Dybzinski et al., 2008; Fornara and Tilman, 2008) or whether the majority of processes are controlled primarily by the traits of the dominant species, the “mass-ratio effect” (McLaren and Turkington, 2010). The transition between dense *Pteridium* and an earlier-successional community is an in ideal model system to investigate whether (a) changes in soil processes occur, and (b) they are likely to assist or hinder ecological restoration efforts. In Great Britain, the ideal conservation management\restoration objective is to reduce *Pteridium,* a perennial geophyte, to a low level and then create an alternative stable state (ASS) dominated by perennial species with a mixture of life-histories/traits, that might include: dwarf shrubs (chamaephytes; *Calluna vulgaris (*L.) Hull, *Vaccinium myrtillus* L.), grasses (geo-cryptophytes; *Agrostis capillaris*, L., *Deschampsia flexuosa* (L.) Trin.) and forbs (hemi-cryptophytes; *Galium saxatile*, L. *Potentilla erecta* (L.) Räusch) (Alday et al., 2013). This new ASS would maintain itself and prevent *Pteridium* re-invasion. This change in the balance of traits would be predicted to modify ecosystem function including soil processes (Diaz et al., 2007; Cortois et al., 2016), although soil processes have also been shown to be affected by soil microbial community composition (Wubs et al., 2016), interacting with climatic factors such as drought (Kaisermann et al., 2017). Here, we hoped that management action that created and maintained the stable state would enforce soil change.

In this paper, therefore, we report the results of such an enforced change within a former *Pteridium*-dominated community under experimental conditions over a twenty-year period. In this experiment, previous analyses over a ten-year period showed that *Pteridium* was reduced and a grass-heath developed. Alday et al. (2013) described this as an Alternative State (AS) because it was achieved by continuous application of a pulse treatment and hence there could be no guarantee of stability in the absence of treatment application. The early-successional grass-heath community is preferred from a conservation viewpoint because it has a greater value than the later-successional, *Pteridium*-dominated one (Pakeman and Marrs, 1992), meeting local and national Habitat Action Plan targets (Anon, 2016). Grass-heath communities tend to occur on nutrient-poor soils (Marrs, 1993; Mitchell et al., 1997) and it was hoped that soil changes induced by this newly-created community would maintain itself and prevent *Pteridium* re-invasion. Such modified soil regimes, brought about through a changed community structure, have been demonstrated elsewhere (Diaz et al., 2007).

To investigate this, the effects of a series of *Pteridium*-control and grass-heath ecological restoration treatments on soil properties were measured over a 20-year period (1993–2013). We hypothesized that the management applied would reduce *Pteridium* cover and create a more diverse community made up of species with markedly different traits and this transformation would modify some soil properties, reduce total soil carbon and nitrogen and increase in soil pH, available nutrients and soil biological activity.

2. Methods

The experiment is located at Hordron Edge site in the Peak District, Derbyshire, UK (Latitude and Longitude: 53°23′N, 1°41′W). The starting condition was a community with a dense *Pteridium* fronds (1–2 tall) and a deep litter layer (ca. 30 cm) and an extremely species-poor understory vegetation. *Pteridium* has been present for at least 100 years (N. Taylor, pers. comm.). Currently, the site is grazed by sheep at a low stocking density, ca. 0.5 sheep ha^{-1} (Pakeman et al., 2000).

The experiment was set up in 1993 using a randomized block, split-split-plot design with three blocks (60 m × 40 m) each with six main plots (10 m × 36 m) initially (1993–2003) receiving one of six *Pteridium*-control treatments: no treatment (experimental control, Untr), cut once yearly (Cutx1), cut twice yearly (Cutx2) and three treatments using the herbicide asulam applied by knapsack at 4.4 kg ai ha^{-1}, 11 L Asulox in 400 L water ha^{-1} (Manufacturers, Bayer CropScience Ltd, Cambridge, UK and United Phosphorus Ltd, Warrington, UK). The three herbicide treatments were: a single treatment in 1993 (Asulam), a single treatment in 1993 followed by a single cut in 1994 (AsuCut), and a single cut in 1993 followed by a single spray in 1994 (CutAsu). Restoration treatments were applied to sub-plots (10 m × 18 m) and sub-sub-plots (10 m × 5 m). The sub-plot treatments tested sheep-grazing *versus* no sheep-grazing (grazed *versus* ungrazed) and the sub-sub-plot treatments received one of three *Calluna vulgaris* (L.) Hull seeding treatments (no seeding, seed applied in brash, and seed applied in litter). All treatments were applied randomly within each experimental stratum.

In 2004, it was apparent that *Pteridium* was recovering in the three herbicide treatments (Cox et al., 2007). Accordingly the Asulam, AsuCut and CutAsu treatments were resprayed with asulam (as above) in August 2004, followed up annually with spot-spraying until 2012, with the asulam applied individually by knapsack sprayer to all emergent fronds at a rate of 1 ml solution/frond of 6% vol:vol Asulox:water (Robinson, 2000). Both cutting treatments were continued. For clarity, the original treatment codes have been retained.

2.1. Assessing trends in vegetation

In 1993, species composition was measured in five sub-samples within each of three selected sub-plots in each block to ensure that the “visually uniform” vegetation and *Pteridium* variables were similar at the start (Cox et al., 2007). Thereafter, vegetation composition was then monitored in all experiments in June (i.e. before the application of the first cutting treatment) from 1994 to 2008 and 2013. Each year, two quadrats (1 m × 1 m) were placed at random co-ordinates on 1 m × 1 m grids within each sub-sub-plot and the cover (%) of all vascular plant, bryophyte and lichen species recorded visually as well as an estimate of *Pteridium* litter cover. Within the central 0.5 m × 0.5 m of the quadrats all fronds were counted and their length measured. Mean frond length and frond density (number m^{-2}) were then calculated.

In late-July 2013, at frond peak biomass (Lowday et al., 1983;