

RESEARCH ARTICLE

Evaluating the success of upland hay meadow restoration in the North Pennines, United Kingdom, using green hay transfer

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Abstract

1. Traditionally managed mesotrophic species-rich upland hay meadows conforming to the National Vegetation Classification (NVC) MG3b are one of the rarest grassland types in the United Kingdom, with substantial declines in botanical diversity over the last 50 years. Intensive spring grazing, earlier cut dates and increases in soil fertility cause a decline in characteristic positive indicator species in MG3b meadows, shifting communities from species-rich MG3b, to NVC MG6 meadows, and finally to species-poor NVC MG7 meadows.
2. The North Pennines Area of Outstanding Natural Beauty (AONB) Partnership's Hay Time project aimed to improve the knowledge of upland hay meadows, and to investigate the success of seed addition of key positive indicator species. A landscape-scale restoration programme was undertaken between 2006 and 2012, harvesting seed from 82 species-rich donor meadows and spreading seed onto 89 receptor meadows (222.82 ha). Seed was harvested as green hay, using two types of donors: MG6 (classed as restoration, with species such as *Rhinanthus minor*) and MG3b (classed as enhancement, with species such as *Geranium sylvaticum*). All 89 meadows were monitored, with a baseline botanical survey and a repeat survey 3–5 years after seed addition. In addition, 41 meadows that did not have seed addition were monitored (controls).
3. Species richness, diversity and floristic composition improved in 77 meadows 3–5 years after seed addition. Eighteen plant species had an increase in frequency in the receptor meadows but did not increase in frequency in the control meadows. The most successful were eight positive indicators which were annuals or fast-growing perennial plants (*Anthoxanthum odoratum*, *Euphrasia* spp., *Myosotis discolor*, *Plantago lanceolata*, *Ranunculus acris*, *R. minor*, *Trifolium dubium* and *Trifolium pratense*). However, rarer characteristic MG3b plants such as *Alchemilla* spp., *G. sylvaticum* and *Cirsium heterophyllum* showed little signs of establishing.
4. Botanical evidence is demonstrating that seed addition using green hay is a successful way of restoring meadows to an MG6 community. What is now needed is an effective method to establish characteristic MG3b plants. Hand-collecting seeds

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and establishing plug plants, alongside seed addition and maintaining traditional management practises, is one possible way forward.

KEYWORDS

Geranium sylvaticum, green hay, MG3b, MG6, restoration, *Rhinanthus minor*, seed addition, species-rich grassland

1 | INTRODUCTION

There have been extensive declines in the species richness and diversity of upland hay meadows over the last 50 years, and these are now one of the rarest grassland types in the United Kingdom (Bullock et al., 2011; Jefferson, 2005; Pacha & Petit, 2008; Rodwell et al., 2007). Typical mesotrophic upland hay meadows conforming to the National Vegetation Classification (NVC) community *Anthoxanthum odoratum* L.—*Geranium sylvaticum* L., sub-community *Briza media* L. (MG3b), are the most species rich, having an average of 35 species per 4 m² (Rodwell, 1992). MG3b meadows are UK Biodiversity Action Plan (BAP) priority habitats and are listed under the European Habitats Directive as Annex 1 (6520) mountain hay meadows. There are approximately 870 ha of species-rich MG3b meadows remaining in northern England, UK, but this is likely to be an over-estimation (Bullock et al., 2011; Rodwell et al., 2007). Upland hay meadows tend to be restricted to the upland dales of northern England, in the counties of Northumberland, County Durham, Cumbria, Lancashire and North Yorkshire, between 180 and 500 m altitude (Jefferson, 2005; O'Reilly, 2010; Pacha & Petit, 2008). In the North Pennines, the MG3b meadows in the valleys of Teesdale, Allendale and Weardale are particularly notable with many meadows designated as Sites of Special Scientific Interest (SSSI). These ancient meadows have characteristic northern-montane species such as *G. sylvaticum*, *Alchemilla* L. spp., *Cirsium heterophyllum* (L.) Hill and *Trollius europaeus* L. (O'Reilly, 2010; Rodwell, 1992; Table 1).

Long-term traditional management of upland hay meadows has been in place in the North Pennines for centuries and involves sheep grazing in spring and autumn, no grazing between late May–July (shut-up period), hay making from mid-July to August, aftermath grazing with cattle, and low applications of farmyard manure (maximum 12 t/ha⁻¹/year) (Critchley et al., 2007; Jefferson, 2005). These traditional methods are essential to maintain the botanical diversity of upland hay meadows. The recent widespread declines in botanical diversity have been related to high stocking densities in spring, earlier cutting times, chemical fertilizer use, a switch from hay making to silage production, re-seeding with *Lolium perenne* L. and *Trifolium repens* L., and loss of meadows to pastures (Critchley et al., 2007; Jefferson, 2005; Rodwell et al., 2007; Starr-Keddle, 2014; Smith et al., 2008, 2017). *G. sylvaticum* declined in 40% of meadows over a 20-year period in the Yorkshire Dales National Park (Pacha & Petit, 2008) and over a 30-year period in Teesdale (Starr-Keddle, 2014). These declines were mainly attributed to intensive spring grazing and increases in soil fertility (Pacha & Petit, 2008; Starr-Keddle, 2014). Many studies show that increases in soil

fertility from farmyard manure and chemical fertilizer inputs causes grassland species-richness and diversity to decline. A rise in soil fertility favours competitive, fast-growing species which dominate the sward and inhibits the establishment of less competitive species. These studies have demonstrated that higher species-richness occurs within a narrow band of low soil extractable phosphate levels between 4–15 mg/L (Critchley et al., 2002; Janssens et al., 1998; Kirkham et al., 2008, 2014; Smith et al., 2003, 2008). Since the late 1980s, farmers in the North Pennines have been entering agri-environment schemes which aim to maintain high biodiversity and promote land management for the environment. Payments are made to farmers for following management prescriptions maintaining traditional low intensity farming practices, such as low applications of farmyard manure, a restriction on the use of chemical fertilizers and a later hay cut date. Regardless of how well farmers have been adhering to these schemes, the botanical diversity of upland hay meadows has continued to decline into the 21st century (Critchley et al., 2007; Rodwell et al., 2007).

When botanical diversity declines, the plant communities shift from MG3b to MG6 meadows (conforming to the NVC community *L. perenne* – *Cynosurus cristatus* L. (MG6) mesotrophic grassland) as the longer-lived perennials are lost. MG6 and MG3b meadows share a number of positive indicator species such as *Rhinanthus minor* L., *Plantago lanceolata* L. and *Trifolium pratense* L., however, MG6 meadows are missing the rarer plants such as *G. sylvaticum* and *Alchemilla* spp. A further shift occurs as the commoner wildflowers disappear due to agricultural intensification: MG7 meadows (conforming to the NVC community *L. perenne* (MG7) leys) have a range of grasses with few positive indicators, often found where the meadows are cut for hay earlier, re-seeded or soil fertility is increasing (Kirkham et al., 2008; O'Reilly, 2010; Rodwell, 1992; Smith et al., 2003) (Table 1 shows a list of main species found in each NVC community). Once positive indicators have disappeared, traditional upland hay meadow management alone is unlikely to result in botanical diversity increasing in an MG7 meadow. This is due to several reasons including an absence of appropriate seeds within the seed-bank, the soil is too fertile, or because the meadows have become isolated from other species-rich grasslands (Kirkham et al., 2008; Pacha, 2004; Pacha & Petit, 2008; Smith et al., 2003).

To restore the botanical composition of species-rich grasslands, the introduction of seed is often needed. Several methods have been used in other studies, such as strip seeding or over-seeding with purchased seed mixes; brush harvesting, hay strewing and green hay harvesting from donor grasslands; or planting plug plants (Edwards et al., 2007; Hopkins et al., 1999; Kirkham et al., 2013; Smith et al.,

TABLE 1 List of main indicator species often found in MG3b, MG6 and MG7 NVC meadow communities with their indicator species score. These species were not always in every meadow and are a selection of plants listed in Rodwell (1992) and O'Reilly (2010)

Main indicator species of upland hay meadow NVC communities			
MG3b meadows	MG6 meadows	MG7 meadows	Indicator Species Score
<i>Alchemilla</i> spp.			+3
<i>Cirsium heterophyllum</i>			+3
<i>Geranium sylvaticum</i>			+3
<i>Sanguisorba officinalis</i>			+3
<i>Trollius europaeus</i>			+3
<i>Caltha palustris</i>	a		+2
<i>Conopodium majus</i>	a		+2
<i>Leontodon hispidus</i>	a		+3
<i>Euphrasia arctica</i>	<i>Euphrasia arctica</i>		+2
<i>Myosotis discolor</i>	<i>Myosotis discolor</i>		+1
<i>Plantago lanceolata</i>	<i>Plantago lanceolata</i>	a	+1
<i>Prunella vulgaris</i>	<i>Prunella vulgaris</i>		+2
<i>Ranunculus acris</i>	<i>Ranunculus acris</i>		+1
<i>Rhinanthus minor</i>	<i>Rhinanthus minor</i>	a	+2
<i>Trifolium dubium</i>	<i>Trifolium dubium</i>		+1
<i>Trifolium pratense</i>	<i>Trifolium pratense</i>	a	+1
<i>Agrostis capillaris</i>	<i>Agrostis capillaris</i>	<i>Agrostis capillaris</i>	+1
<i>Anthoxanthum odoratum</i>	<i>Anthoxanthum odoratum</i>	a	+1
<i>Cynosurus cristatus</i>	<i>Cynosurus cristatus</i>	a	+1
<i>Dactylis glomerata</i>	<i>Dactylis glomerata</i>	<i>Dactylis glomerata</i>	−1
<i>Festuca rubra</i>	<i>Festuca rubra</i>	<i>Festuca rubra</i>	+1
<i>Holcus lanatus</i>	<i>Holcus lanatus</i>	<i>Holcus lanatus</i>	0
<i>Lolium perenne</i>	<i>Lolium perenne</i>	<i>Lolium perenne</i>	−1
<i>Trifolium repens</i>	<i>Trifolium repens</i>	<i>Trifolium repens</i>	−1
<i>Trisetum flavescens</i>	<i>Trisetum flavescens</i>		+2

^aThese species are found occasionally in these meadows: +, positive indicator species; 0, neutral indicator species; −, negative indicator species.

2000, 2003, 2008; Sullivan et al., 2020). A field trial conducted by Smith et al. (2000, 2003, 2008) on an MG6 upland hay meadow at Colt Park, Yorkshire, UK, revealed that the highest plant diversity was found in plots with a late cut date, no nutrient additions (either farmyard manure or chemical fertilizer) and with seed addition from a commercial seed mix (Smith et al., 2000, 2003, 2008). Studies have shown that introducing plants such as *Euphrasia* L. spp., *R. minor* and *T. pratense* through seed addition to agriculturally improved swards, can modify soil microbial communities, altering soil conditions to be more comparable to traditional upland hay meadows (De Deyn et al., 2011; Pywell et al., 2004; Smith et al., 2000, 2003, 2008). These studies suggest that adding seed could be a crucial step in restoring the botanical diversity of upland hay meadows (Edwards et al., 2007; Kirkham et al., 2013; Smith et al., 2000, 2003, 2008; Sullivan et al., 2020).

Several studies have also demonstrated the importance of investigating abiotic factors and ground preparation beforehand to make sure that seed addition is successful. It is important to create as much bare ground as possible, using scarification or harrowing before seed

addition; the more the ground is scarified the greater the establishment of seeds (Edwards et al., 2007; Kirkham et al., 2013; Sullivan et al., 2020; Westbury, 2004). High residual soil fertility from long-term farmyard manure and chemical fertilizer use can inhibit the effectiveness of seed addition. Studies have shown that grassland restoration is most successful on sites with low soil fertility. Where grasslands sites have had previous agricultural improvement with high soil fertility, methods such as turf removal or repeated cutting have been implemented to reduce concentrations of the plant-available soil phosphate (P) (Critchley et al., 2002; Hopkins et al., 1999; Janssens et al., 1998; Kirkham et al., 2008; Marrs, 1993).

The aim of this paper is to present the results of the impact of seed addition using green hay transfer on the botanical composition of 89 receptor meadows and to assess whether seed addition has been successful. The results presented are from the comparison of baseline botanical surveys undertaken just before seed addition, compared with repeat monitoring surveys undertaken 3N5 years after seed addition.

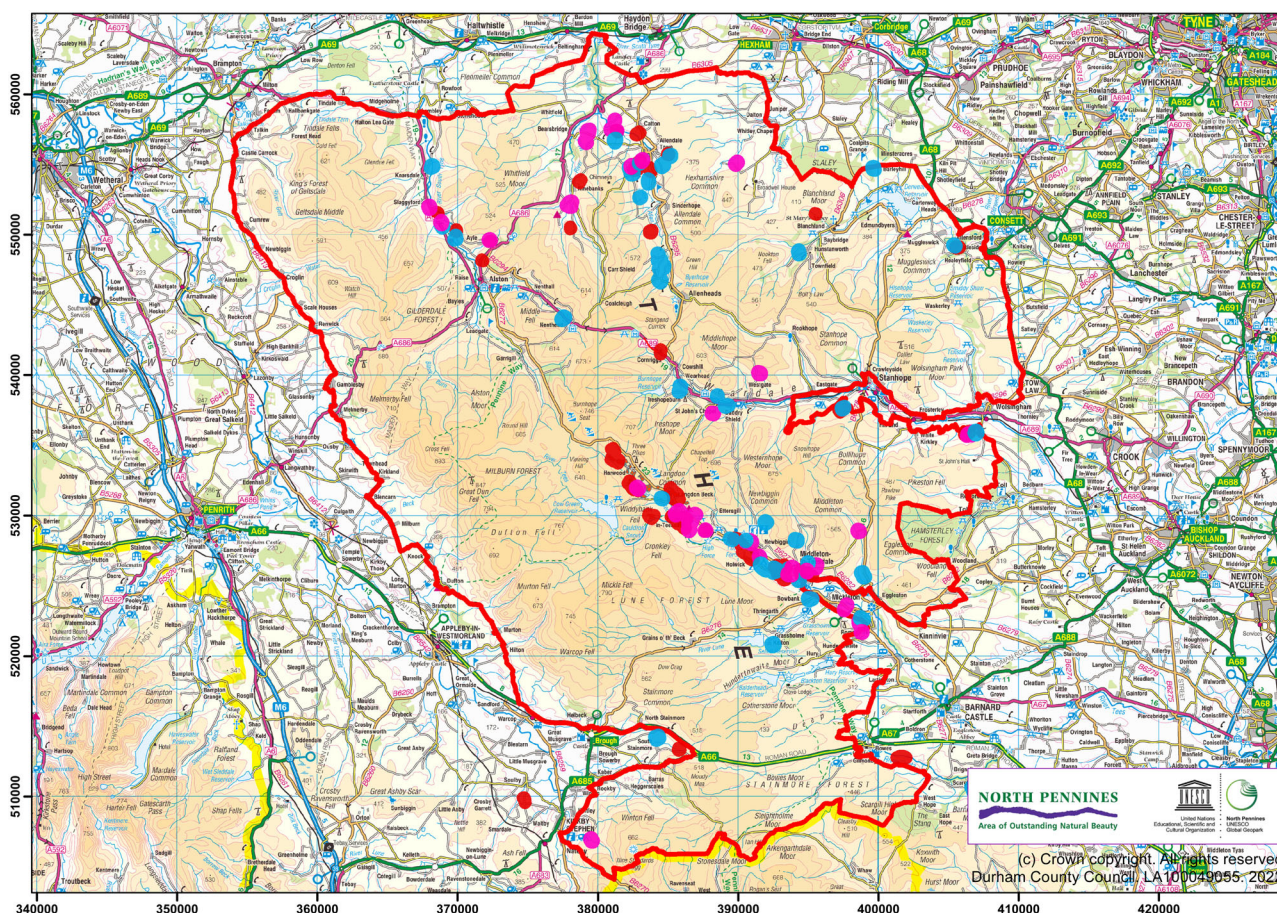


FIGURE 1 Map showing the locations of the 89 receptor meadows and 82 donor meadows, with the North Pennines AONB, UK, boundary in red. Blue circles, meadows restored with a MG6 donor; pink circles, meadows enhanced with an MG3b donor; red circles, donor meadows

2 | MATERIALS AND METHODS

2.1 | Hay time project and receptor meadow selection

The North Pennines AONB Partnership's Hay Time project ran from 2006 until 2012. The project aimed to improve knowledge of upland hay meadow extent, management, and to investigate the impacts of seed addition. Over the 6 years of the project, a landscape-scale restoration programme was undertaken across the North Pennines, UK, harvesting seed from 82 donor meadows and spreading seed onto 89 receptor meadows (222.82 ha) (Figure 1).

The majority of the 89 receptor meadows have been managed in a traditional way for centuries and very few have had historical chemical fertilizer use. Previously the receptor meadows have been in agri-environment schemes from the 1980s with the requirement to make hay and restrictions of chemical fertilizer inputs (as part of the Pennine Dales Environmentally Sensitive Area (ESA)). The receptor meadows were in Higher Level Stewardship (HLS) agri-environment agreements being managed under the HK7 option (restoration of species-rich semi-natural grassland). Farmers in the HK7 option are usually required to cut their meadows for hay after the 15th of July and only apply farmyard manure (maximum 12 t/ha⁻¹/year). Chemical fertilizer use

is prohibited (Critchley et al., 2007; Jefferson, 2005; Natural England, 2010).

Botanical surveys were undertaken across the whole farm to assess the suitability of the meadows for restoration, with permission from the farmers or landowners for access and data collection. Receptor meadows were chosen that had low frequencies of negative indicator species such as *L. perenne*, *Bromus hordeaceus* L. and *Ranunculus repens* L., few injurious weeds and low soil fertility (Natural England, 2010; O'Reilly/North Pennines AONB Partnership, 2006). Once agreed with the receptor farmer, the capital costs for the agricultural contractors to implement the work and payment to the donor farmers for their hay crops were calculated and included in the conditions of the receptor farmer's agri-environment agreement, arranged with Natural England advisors who gave SSSI consent and permissions where needed (approximately £800 per hectare) (Natural England, 2010).

2.2 | Baseline soil sampling

Twenty-three meadows were sampled for extractable soil phosphate (P). During the botanical survey at each site, 20 pellets (0–7.5 cm depth, 2.5 cm width) were collected using a pot corer and sent to Lancrop laboratories combined as one sample. Natural England require the

receptor meadows to be below P Index 2 (Natural England, 2010). The meadows tested were between P Index 0 and 1 (0–15 mg/L), so were below the recommended fertility levels (Appendix, Table 1).

2.3 | Botanical surveys and monitoring

Botanical surveys consisted of a W-shaped walk-through the meadow, taking approximately 1 h to complete. All vascular plants were recorded (nomenclature according to Stace, 2010) and allocated a DAFOR frequency score, between 1 and 5 (1 = rare, 2 = occasional, 3 = frequent, 4 = abundant, 5 = dominant) (O'Reilly/North Pennines AONB Partnership, 2006; Starr-Keddle, 2018). All 89 receptor meadows were surveyed just before seed addition, with a repeat monitoring survey undertaken 3–5 years later. Forty-one meadows that did not have seed addition were monitored (controls), with a baseline survey and repeat monitoring survey undertaken 3–5 years later. The control meadows were often on the same farm as the receptor meadows. Monitoring surveys were undertaken from mid-June to mid-July, between the years 2009–2017. Monitoring surveys were undertaken close to the same day as the previous baseline survey.

2.4 | Donor selection

Two types of donor meadows were used; a MG6 donor which had good populations of species such as *A. odoratum*, *Euphrasia* spp., *R. acris*, *R. minor*, *Trifolium dubium* Sibth. and *T. pratense*; or a MG3b donor which had good populations of these species plus later-flowering, longer-lived perennials such as *G. sylvaticum*, *Alchemilla* spp., *Sanguisorba officinalis* L. and *C. heterophyllum*. MG6 donors with the more widespread annuals and faster-growing perennials were spread onto 47 species-poor MG7 receptor meadows (classed as restoration meadows) with a grass sward and scarce wildflowers. The aim here was to restore the MG7 receptor meadows to a MG6 meadow community. Whereas MG3b donors were spread onto 42 MG6 receptor meadows which already had good populations of *R. minor* and *T. pratense* (classed as enhancement meadows). It is hoped that by introducing the characteristic plants of MG3b meadows, the MG6 receptor meadows will be returned to a species-rich MG3b meadow community (O'Reilly/North Pennines AONB Partnership, 2006; Starr-Keddle, 2018).

Great attention was given to the selection of species-rich donor meadows to make sure they would complement and improve the botanical composition of the receptor meadow. The species-lists of the receptor meadow were matched with the donor meadow to make sure that additional species would be introduced. Donor meadows were surveyed and assessed for negative indicator species such as *Ranunculus repens* L., *Juncus effusus* L. and *B. hordeaceus*. Areas were chosen with high positive indicator species and low negative indicator species and marked-out. A maximum of a third of a donor meadow was marked-out and was not used again for another 4 years to prevent over-harvesting seeds. On average, the receptor meadows were between 2 and 3 ha in size, with approximately 0.6 ha of donor area marked-out for a 3-ha

meadow (a ratio of 1:5). The farmer was paid £500 per hectare of green hay. The donor areas were checked before harvesting to make sure that the plants had fully set-seed (O'Reilly/North Pennines AONB Partnership, 2006; Starr-Keddle, 2018).

2.5 | Harvesting and spreading methods

Harvesting and spreading was undertaken on the same day in early to mid-August, as soon as the receptor meadows were cut, and the hay removed. The weather was checked beforehand, and the work carried out on dry days. Occasionally harvesting and spreading occurred later in August if wet weather had prevented work. Green hay was harvested from donor meadows and spread onto nearby receptor meadows within the same dale, within a maximum of 10 miles. This ensured the seed was of local provenance and preserved genetic variation, whilst also ensuring that seed was spread within 1 h of harvesting (Sackville Hamilton, 2001; O'Reilly/North Pennines AONB Partnership, 2006; Starr-Keddle, 2018).

A forage harvester called the Amazone Groundkeeper was used to harvest green hay, taking all of the standing vegetation. The forage harvester cut the vegetation close to the ground, collecting the green hay into a bucket and tipping the green hay into the spreader. The receptor meadows were scarified using a spring-tine harrow, scarifying approximately 50% of the meadow, creating lines of exposed soil, whilst also preserving the original meadow vegetation. The green hay was spread using a conventional muck spreader, following the scarified lines. Afterwards the farmer was asked to let cattle or other livestock into the meadow to graze the aftermath and trample in the seeds (O'Reilly/North Pennines AONB Partnership, 2006; Starr-Keddle, 2018).

2.6 | Calculating meadow variables

For each meadow, the botanical survey data were used to calculate the species richness (total number of species found) and Shannon Diversity Index (H') (Shannon, 1948). At the beginning of the Hay Time project, grassland plant species recorded in the North Pennines were assigned an indicator score ranging from –2 through to +4. Positive indicator species are plants that are typical of upland hay meadows. Positive indicator species in MG3b meadows were given +3 scores, whereas MG6 plants were given +1 or +2 scores. Neutral indicator species are plants that are common to all grasslands, and these were given 0 scores. Negative indicator species are plants that are competitive, injurious weeds or invasive, and these were given negative scores (Table 1). Positive Indicator Species Scores and Negative Indicator Species Scores were calculated by multiplying the frequency on a 1–5 scale (DAFOR) with the species score and summing all species per meadow (O'Reilly/North Pennines AONB Partnership, 2006; Starr-Keddle, 2018). Ellenberg Fertility Index (N) was similarly calculated by multiplying the species frequency with the species fertility score and summing all species per meadow, then averaged (weighted means)

TABLE 2 Comparison of mean calculated variables and number of meadows with an increase or decrease, between baseline surveys and repeat monitoring surveys undertaken 3–5 years after seed addition (89 meadows in total)

Calculated variables	Baseline survey (mean)	SE	Repeat survey (mean)	SE	No. of meadows inc/dec	Statistical significance
Species richness	26.26	±0.60	30.2	±0.59	+64	$t_{88} = -7.431, p < 0.001$
Shannon Diversity Index (H')	3.12	±0.02	3.28	±0.02	+70	$t_{88} = -9.483, p < 0.001$
Positive Indicator Species Score	43.79	±2.07	59.39	±2.14	+77	$t_{88} = -9.977, p < 0.001$
Ellenberg Fertility Score (N)	4.9	±0.03	4.77	±0.02	-51	$t_{88} = 5.573, p < 0.001$
Best fit to MG3b	49.55	±2.10	53.89	±2.28	+28	$t_{88} = -2.108, p = 0.038$

Number of meadows increased (+) or decreased (–).

(Hill et al., 1999). TABLEFIT was used to calculate the goodness of fit to MG3b for each meadow survey (Hill, 1996). This was calculated in order to ascertain whether the receptor meadows had improved in botanical composition similar to an MG3b meadow.

2.7 | Data analysis

Baseline surveys and repeat monitoring surveys were compared for 89 receptor meadows that had seed addition, and 41 control meadows without seed addition, using paired sample *t*-tests, with the function *t.test* in the R-package *stats* with the option 'paired = TRUE' in R-3.4.3. (R Core Team, 2017). Paired sample *t*-tests were used where the data were normally distributed, checked by a Shapiro–Wilk normality test, otherwise a Wilcoxon's signed rank test (nonparametric test) was used. The differences between species-richness, Shannon Diversity Index (H'), Positive Indicator Species Score, Negative Indicator Species Score, Ellenberg Fertility Score (N), goodness of fit to MG3b and the key indicator species were compared between baseline surveys and repeat monitoring surveys. In addition, the 89 receptor meadows were analysed using the community ecology package Canoco 5. The 'species' data, 'environment' data (categorized as baseline surveys, repeat surveys, restoration [using MG6 donors, 47 sites], enhancement [using MG3b donors, 42 sites]) were input into Canoco 5 and a constrained Redundancy Analysis (RDA) was performed as the lengths of gradient were under three (Leps & Smilauer, 2014).

3 | RESULTS

3.1 | Meadows with seed addition (89 meadows)

Comparing baseline surveys with repeat monitoring surveys undertaken 3–5 years after seed addition, led to the increase of species-richness in 64 meadows (mean = 3.93, $p < 0.001$), Shannon Diversity Index (H') in 70 meadows (mean = 0.16 H' , $p < 0.001$), Positive Indicator Species Score in 77 meadows (mean = 15.59, $p < 0.001$) and the goodness of fit to MG3b in 28 meadows (mean = 4.34, $p = 0.038$), while Ellenberg Fertility Score (N) reduced in 51 meadows (mean = -0.13 N , $p < 0.001$) (Table 2). A total of 109 species were recorded in the base-

line surveys and 117 species were recorded in the repeat monitoring surveys. Nineteen positive indicator species and one negative indicator species increased in frequency (DAFOR) after seed addition. Nine positive indicator species found in both MG6 and MG3b meadows showed the greatest increases, with three characteristic MG3b positive indicator species showing signs of establishing in some meadows (Table 3).

The bi-plot (Figure 2) associates many positive indicator species with the repeat monitoring surveys to the right side of the graph. Several negative indicator species are found on the left side of the graph, associated with the baseline surveys. Key positive indicator species found in MG6 meadow communities are associated in the top right corner, where these meadows had been restored with a MG6 seed donor, and key positive indicator species found in MG3b meadows are associated in the bottom right corner, where these meadows had been enhanced with a MG3b seed donor (Table 4 and Figure 2).

3.2 | Meadows without seed addition (41 control meadows)

Comparing baseline surveys to repeat monitoring surveys undertaken 3–5 years later on meadows without seed addition, led to an increase in Shannon Diversity Index (H') in 27 meadows (mean = 0.06 H' , $p = 0.034$), Positive Indicator Species Score in 23 meadows (mean = 7.24, $p = 0.002$), while Ellenberg Fertility Score (N) decreased in 26 meadows (mean = 0.07, $p = 0.038$) (Table 5). Two positive indicator species increased, and one negative indicator species declined, between the baseline and repeat monitoring surveys (Table 6).

4 | DISCUSSION

The results from botanical monitoring showed that seed addition through the harvesting and spreading of green hay was an effective way of introducing species or improving botanical composition in 86% of cases (77 meadows). Whether seed addition worked was not just about the number of species establishing – in some meadows the species-richness stayed the same but diversity and positive indicators increased, while Ellenberg N decreased. These changes showed there was an encouraging improvement in the floristic composition of

TABLE 3 Comparison of mean species frequency (DAFOR) and number of meadows with an increase or decrease, comparing baseline surveys and repeat monitoring surveys undertaken 3–5 years after seed addition (89 meadows in total)

Plant species	Baseline botanical surveys			Repeated monitoring surveys				Statistical significance
	DAFOR (mean freq.)	SE	No. of meadows recorded	DAFOR (mean freq.)	SE	No. of meadows recorded	No. of meadows inc/dec	
<i>Anthoxanthum odoratum</i>	2.88	±0.19	74	3.32	±0.13	90	+36	$t_{88} = -2.2945, p = 0.024$
<i>Caltha palustris</i>	0.34	±0.09	15	0.48	±0.10	21	+12	$V = 21, p = 0.01$
<i>Cynosurus cristatus</i>	3.12	±0.17	78	3.54	±0.15	83	+38	$t_{88} = -2.2603, p = 0.026$
<i>Dactylorhiza</i> spp.	0.05	±0.03	4	0.15	±0.05	10	+9	$V = 11, p = 0.037$
<i>Euphrasia</i> spp.	0.97	±0.15	34	2.09	±0.15	74	+54	$t_{88} = -6.9752, p < 0.001$
<i>Geranium sylvaticum</i>	0.13	±0.05	9	0.24	±0.05	18	+12	$V = 22.5, p = 0.02$
<i>Hypochaeris radicata</i>	0.13	±0.04	10	0.27	±0.07	17	+15	$V = 36, p = 0.01$
<i>Leontodon hispidus</i>	0.10	±0.03	8	0.16	±0.05	11	+8	$V = 11, p = 0.066$
<i>Myosotis discolor</i>	0.79	±0.09	50	1.24	±0.11	64	+38	$t_{88} = -3.8751, p < 0.001$
<i>Plantago lanceolata</i>	2.17	±0.18	65	3.17	±0.14	87	+52	$t_{88} = -6.4062, p < 0.001$
<i>Prunella vulgaris</i> ^a	0.62	±0.1	34	1.20	±0.13	52	+39	$t_{88} = -4.6872, p < 0.001$
<i>Ranunculus acris</i>	3.20	±0.15	87	3.70	±0.12	90	+47	$t_{88} = -3.4783, p < 0.001$
<i>Ranunculus repens</i>	2.53	±0.12	87	3.16	±0.09	92	+44	$t_{88} = -4.3305, p < 0.001$
<i>Rhinanthus minor</i>	1.93	±0.18	62	3.38	±0.13	90	+64	$t_{88} = -7.1871, p < 0.001$
<i>Rumex acetosa</i>	2.84	±0.15	82	3.20	±0.12	89	+41	$V = 625, p = 0.018$
<i>Sanguisorba officinalis</i> ^a	0.15	±0.06	9	0.30	±0.08	14	+10	$V = 0, p = 0.004$
<i>Trifolium dubium</i>	0.76	±0.12	35	1.38	±0.14	57	+41	$V = 183, p < 0.001$
<i>Trifolium pratense</i>	2.02	±0.12	83	2.92	±0.1	92	+57	$t_{88} = -7.2366, p < 0.001$
<i>Trisetum flavescens</i>	0.55	±0.1	30	1.00	±0.13	45	+29	$V = 143.5, p < 0.001$
<i>Vicia cracca</i>	0.11	±0.04	8	0.22	±0.06	13	+8	$V = 7, p = 0.036$

^aTwo species that also had a significant increase in frequency in the control meadows.
Number of meadows increased (+) or decreased (–).

TABLE 4 Summary constrained RDA output. Total variation is 12,134.739, explanatory variables account for 4.61% (adjusted explained variation is 3.56%). Permutation test results: on all axes, pseudo- $F = 4.4, p = 0.002$

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.0375	0.0086	0.1305	0.0724
Explained variation (cumulative)	3.75	4.61	17.66	24.9
Pseudo-canonical correlation	0.5435	0.4537	0	0
Explained fitted variation (cumulative)	81.25	100		

TABLE 5 Comparison of mean calculated variables and number of meadows with an increase or decrease, between baseline surveys and repeat monitoring surveys undertaken 3–5 years later, without seed addition (41 meadows in total)

Calculated variables	Baseline survey (mean)	SE	Repeat survey (mean)	SE	No. of meadows inc/dec	Statistical significance
Shannon Diversity Index (H')	3.22	±0.03	3.28	±0.02	+27	$t_{40} = -2.588, p = 0.034$
Positive Indicator Species Score	65.25	±3.45	72.49	±3.46	+23	$t_{40} = -3.317, p = 0.002$
Ellenberg Fertility Score (N)	4.82	±0.03	4.75	±0.03	-26	$t_{40} = 2.144, p = 0.038$

Number of meadows increased (+) or decreased (–).

TABLE 6 Comparison of mean species frequency (DAFOR) and number of meadows with an increase or decrease, between baseline surveys and repeat monitoring surveys undertaken 3–5 years later, without seed addition (41 meadows in total)

Plant species	Baseline botanical surveys			Repeat monitoring surveys				Statistical significance
	DAFOR (mean)	SE	No. of meadows recorded	DAFOR (mean)	SE	No. of meadows recorded	No. of meadows inc/dec	
<i>Prunella vulgaris</i> ^a	0.37	±0.1	12	0.98	±0.17	21	+18	$V = 14, p = 0.005$
<i>Sanguisorba officinalis</i> ^a	0.34	±0.11	9	0.49	±0.14	12	+7	$V = 4.5, p = 0.041$
<i>Trifolium repens</i>	3.63	±0.19	40	3.15	±0.13	41	-22	$V = 320.5, p = 0.023$

^aTwo species that also had a significant increase in frequency in the control meadows.

Number of meadows increased (+) or decreased (–).

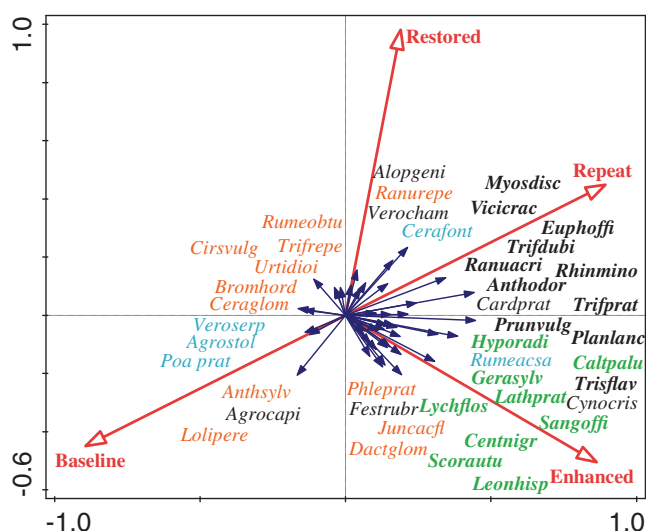


FIGURE 2 Constrained Redundancy analysis (RDA) bi-plot, showing the associations between 43 plant species. Key: Species names in: orange, negative indicator species; blue, neutral indicator species; black, positive indicator species; black in bold, key positive indicator species in MG6 meadows; green in bold, key positive indicator species in MG3b meadows. Baseline, baseline surveys; Repeat, repeat monitoring surveys; Restored, those meadows that had MG6 donor (47 sites); Enhanced, those meadows that had MG3b donor (42 sites). Species: *Agrostis capillaris*; *Agrostis stolonifera*; *Alopecurus geniculatus*; *Anthoxanthum odoratum*; *Anthriscus sylvestris*; *bromhord*, *Bromus hordeaceus*; *Cathpalu*, *Caltha palustris*; *Cardprat*, *Cardamine pratensis*; *Centnigr*, *Centaurea nigra*; *Cerafont*, *Cerastium fontanum*; *Ceraglom*, *Cerastium glomeratum*; *Cynocris*, *Cynosurus cristatus*; *Ceraglom*, *Cerastium glomeratum*; *Cirsulg*, *Cirsium vulgare*; *Dactglom*, *Dactylis glomerata*; *Euphoffi*, *Euphrasia arctica*; *Festrubr*, *Festuca rubra*; *Gerasylv*, *Geranium sylvaticum*; *Hyporadi*, *Hypochaeris radicata*; *Juncacfl*, *Juncus acutiflorus*; *Lathprat*, *Lathyrus pratensis*; *Lolipere*, *Lolium perenne*; *Leonhis*, *Leontodon hispidus*; *Lychflos*, *Silene flos-cuculi*; *Myosdisc*, *Myosotis discolor*; *Phleprat*, *Phleum pratensis*; *Planlanc*, *Plantago lanceolata*; *PoaPrat*, *Poa pratensis*; *Prunvulg*, *Prunella vulgaris*; *Ranurepe*, *Ranunculus repens*; *Ranuacri*, *Ranunculus acris*; *Rhinmino*, *Rhinanthus minor*; *Rumeacsa*, *Rumex acetosa*; *Rumeobtu*, *Rumex obtusifolius*; *Sangoffi*, *Sanguisorba officinalis*; *Scorautu*, *Scorzonera autumnalis*; *Trifdubi*, *Trifolium dubium*; *Trifprat*, *Trifolium pratense*; *Trifrepe*, *Trifolium repens*; *Trisflav*, *Trisetum flavescens*; *Verocham*, *Veronica chamaedrys*; *Veroserp*, *Veronica serpyllifolia*; *Vicicrac*, *Vicia cracca*; *Urtidioi*, *Urtica dioica*.

receptor meadows, rather than just an addition of the total number of species. The most consistent finding was the clear increase in the Positive Indicator Species Scores. Using these calculated scores has been a good tool to assess whether seed addition has been successful (O'Reilly/North Pennines AONB Partnership, 2006). Three other studies have looked at comparable harvesting methods on upland hay meadows and have concluded that seed addition using green hay transfer was a successful means of reintroducing plants into meadows (Kirkham et al., 2013; Smith et al., 2000, 2003, 2008; Sullivan et al., 2020).

Eighteen plant species had an increase in frequency in the receptor meadows but did not increase in frequency in the control meadows, showing that it is likely that they were successfully established due to seed addition. Seventeen plant species were positive indicators (of which three were grasses) and one was a negative indicator (*R. repens*). Eight positive indicator species found in both MG6 and MG3b meadows repeatedly established with seed addition: *A. odoratum*, *Euphrasia* spp., *M. discolor*, *P. lanceolata*, *R. acris*, *R. minor*, *T. dubium* and *T. pratense*. These species are either annual plants or fast-growing perennial plants that tend to flower in June and set-seed at the same time in mid-July, with numerous seeds in their seed-head. Several other studies have investigated restoration of grasslands and have found similar patterns with the faster growing annuals and perennials establishing (De Deyn et al., 2011; Edwards et al., 2007; Hosie et al., 2019; Hopkins et al., 1999; Pywell et al., 2004).

Rhinanthus minor is a hemiparasite with a reduced root system that uses haustoria connections to attach to a host plant for growth. *R. minor* is an important species to introduce during restoration as it reduces the vigour of its host and creates gaps in the sward. This can facilitate the colonization and persistence of slower-growing species by reducing competition from faster-growing grasses (Pywell et al., 2004; Westbury, 2004). Smith et al. (2003), suggests that the restoration of plant communities to their target community may be assisted by the introduction of key species that have a crucial influence on vegetational change. At the Colt Park experiments, the increase in *R. minor* and legumes was associated with a corresponding increase in fungal:bacterial ratios and may be useful in returning vital ecosystem functions in these meadows. A combination of *R. minor* as a hemiparasite, and legumes with their nitrogen-fixing ability, may be able to facilitate grassland diversification (De Deyn et al., 2011; Pywell et al., 2004;

Smith et al., 2003). Interpreting the results in combination with findings from other studies, suggest that *Euphrasia* spp., *P. lanceolata*, *R. minor* and *T. pratense* could be useful target species to assess whether seed addition has been successful, to improve botanical diversity, and to enhance soil and microbial functioning (De Deyn et al., 2011; Edwards et al., 2007; Hopkins et al., 1999; Hosie et al., 2019; Kirkham et al., 2013; Pywell et al., 2004; Smith et al., 2000, 2003, 2008). An additional benefit (from the author's personal observations) was an increase in bumblebees with the establishment of these nectar-rich wildflowers, which was also investigated by Edmonson et al. (2017), who observed a similar pollinator response. These results show that finding a green hay donor with these target plant species and harvesting in early to mid-August is an effective way in shifting the plant communities from a species-poor MG7 meadow to a MG6 meadow community.

The receptor meadows have been in agri-environment agreements since the 1980s and the farmers follow prescriptions such as a late hay cut-date after the 15th of July and restrictions on the use of chemical fertilizers. This has prevented these traditionally managed upland hay meadows becoming silage fields and has slowed the increases in soil fertility observed in other intensively managed grasslands (Critchley et al., 2002, 2007; Jefferson, 2005). However, several studies have shown that even low applications of farmyard manure at the rate of 12 t/ha⁻¹/year will still be enough to increase soil fertility to the point where species-richness is reduced (Kirkham et al., 2014; Smith et al., 2003). In addition, each year farmers favour cutting their meadows as close to their prescribed cut-date as possible if the weather is warm and sunny. Even these traditionally managed meadows are frequently spring grazed until the end of May and cut around the 15th of July; a 7–8-week shut-up period. Modern machinery can cut meadows within a few days, whereas traditional machinery would have taken longer, with more variable cutting times (Critchley et al., 2007; O'Reilly, 2010; Petit & Pacha, 2008). This prescriptive management is favouring MG6 plants, especially annuals and fast-growing perennial plants which can grow, flower and set-seed before or around the 15th of July. A uniform suite of wildflowers (such as *Euphrasia* spp., *P. lanceolata*, *P. vulgaris*, *R. acris*, *R. minor*, *T. dubium* and *T. pratense*) are found in MG6 meadows across the North Pennines, and this botanical composition is also being boosted by the introduction of these species from green hay. Studies by O'Reilly (2010) and Starr-Keddle (2018) have shown that these species are now a frequent component of meadows in comparison to surveys that were undertaken in the 1980s (O'Reilly, 2010; Starr-Keddle, 2018).

Species-rich donors were found with good populations of characteristic MG3b plants, introduced with the purpose of enhancing MG6 receptor meadows to an MG3b community. Twenty-eight meadows showed an improvement in the goodness of fit to MG3b but the increase was small. There were a few MG3b species that were showing slight increases in frequency, which was also supported by the bi-plot (Figure 2) where the species more associated with MG3b communities were clustered towards the repeat surveys (i.e., *C. nigra*, *L. hispidus*, *L. pratensis*, *S. autumnalis* and *S. flos-cuculi*). The botanical monitoring data were showing that some meadows are beginning to shift from an MG6 community to an MG3b community. However, what has been missing in most of the receptor meadows were plants such as *Alchemilla*

spp., *C. heterophyllum*, *G. sylvaticum*, *S. officinalis* and *T. europaeus* (Rodwell, 1992). This pattern was also observed by Sullivan et al. (2020), where *Alchemilla xanthochlora* Rothm. and *G. sylvaticum* did not establish in 19 meadows that had seed addition using green hay transfer (Sullivan et al., 2020). In Kirkham et al. (2013) *G. sylvaticum* was found frequently in the donor meadow but was not found in the receptor meadow (Kirkham et al., 2013). Similarly, in the trial plot experiments at Colt Park, *G. sylvaticum* was only found in a few plots with low soil fertility and with a late-cut date (Smith et al., 2000, 2003, 2008). In the North Pennines, *G. sylvaticum* slightly increased in 12 meadows with seed addition which is encouraging, and *S. officinalis* increased in 10 (but also increased in seven control meadows). These plants take time to mature and only start flowering 3N4 years after germination, so it may be possible that younger plants are hidden in the sward and may become more noticeable as the plants grow bigger.

From the author's personal observations, *G. sylvaticum* is a slow-growing, later-flowering, longer-lived perennial wildflower which needs a lengthier shut-up period and sets-seed after the 15th of July cut-date. Petit and Pacha (2008) have shown that *G. sylvaticum* was lost from 40% of upland hay meadows in the Yorkshire Dales over a 20-year period. Pacha (2004) observed that the declines were due to high soil fertility, high grazing pressure, plus isolation and fragmentation from suitable seed sources, with the larger flowering plants on roadside verges rather than in the meadows (Pacha, 2004). Persistent residual soil fertility is a problem, particularly in the case of phosphorus, and is likely to enable competitive grasses to dominate at the expense of longer-lived perennial wildflowers (Janssens, et al., 1998; Marrs, 1993; Smith et al., 2003). Another factor to consider is the impact of climate change on montane communities, with warmer, wetter winters increasing in the uplands. *G. sylvaticum* is an alpine plant with a northern distribution, requiring vernalization of the seeds to break dormancy (Pacha, 2004). Whereas *S. officinalis* has a southern distribution and may be increasing due to warmer winters (Berry et al., 2003). *G. sylvaticum* can be used as a good indicator for high quality upland hay meadow habitat where it is found, however these MG3b meadows are fast disappearing (Pacha, 2004; Petit & Pacha, 2008; Starr-Keddle, 2018). As the principal characteristic plant of MG3b meadows, an effective method to successfully re-establish this species would be valued. Plug planting of species that are difficult to establish has been suggested as a supplement to seed addition (Hopkins et al., 1999; Sullivan et al., 2020). Early signs from hand-collecting seeds of the characteristic MG3b wildflowers and plug planting undertaken during the North Pennines AONB Partnership's Nectarworks and Plugging the Gaps projects, are showing promising indications that plug planting may be a way to boost MG3b plant populations into the future (Starr-Keddle, 2018).

5 | CONCLUSIONS

Over a 6-year period, the North Pennines AONB Partnership's Hay Time project spread seed using green hay transfer on 89 receptor meadows (222.82 ha). This is a substantial area considering the rarity of species-rich upland hay meadows which is estimated to be 870 ha

in Northern England (Bullock et al., 2011; Rodwell et al., 2007). Eighty-two MG3b and MG6 meadows were used as a seed donor, which is a considerable number of the suitable seed donor sites. The restoration undertaken in other studies have been on a small-scale, on a smaller number of sites (Hosie et al., 2019; Kirkham et al., 2013; Sullivan et al., 2020). A restoration programme of this magnitude, with many donor and receptors meadows, across a large-scale, has not been investigated previously so these encouraging results are important to communicate.

These monitoring results have demonstrated that harvesting and spreading using green hay transfer is an effective way of increasing botanical diversity, but these approaches are only able to shift the botanical composition of MG7 to MG6 communities, rather than return these meadows to species-rich MG3b communities. Botanical surveys in the North Pennines have shown that MG3b communities are often found in remnant populations in less fertile, uncut edges, steep banks and road verges where the characteristic later-flowering, longer-lived perennial plants can grow bigger, flower and set-seed (O'Reilly, 2010; Starr-Keddle, 2018). It is likely that changes in management such as intensive spring grazing, shorter growing seasons, increases in soil fertility and the prescriptive 15th of July cut-date are causing the disappearance of MG3b species with a shift to MG6 communities (Kirkham et al., 2008; Pacha & Petit, 2008; Rodwell et al., 2007; Smith et al., 2003, 2008, 2017; Starr-Keddle, 2018). What is now needed is an effective method to establish MG3b plants into MG6 meadow communities.

As Smith et al. (2008) pointed out, restoration can take a minimum of 20 years, so these results are only showing the beginning of a lengthy changeable process. What is most important is that the low intensity traditional management of these meadows are maintained going forwards which will support the positive outcomes of seed addition and help to address the botanical declines in these meadows (Smith et al., 2008, 2017). Lessening spring grazing, extending the shut-up period, easing farmyard manure usage, restricting chemical fertilizers, and more flexible hay cutting times would be desirable, alongside a green hay and plug planting regime to maintain and increase species richness, diversity and positive indicators to further enhance the MG3b upland hay meadow target community into the future (Critchley et al., 2007; Smith et al., 2017).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The substantial part of the botanical survey work was undertaken by Dr. Ruth Starr-Keddle. Some botanical surveys were undertaken by John O'Reilly and Fiona Corby whilst they worked at the North Pennines AONB Partnership so they have been acknowledged. All data were analysed by Dr. Ruth Starr-Keddle with no additional supervision. Dr. Ruth Starr-Keddle wrote the manuscript with no additional supervision. A few North Pennines AONB Partnership staff members read the paper but made no edits.

PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1002/2688-8319.12134>.

DATA AVAILABILITY STATEMENT

All data are available through the Dryad Digital Repository <https://doi.org/10.5061/dryad.gmsbcc2q5> (Starr-Keddle, 2020). Original species records were shared with Botanical Society of the British Isles (<https://database.bsbi.org/>).

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SUPPORTING INFORMATION

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