Monitoring single-species *Sphagnum* plug growth on blanket bog

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Summary

Reintroduction of *Sphagnum* to eroding upland moorland sites following peat stabilisation works can halt the loss of peat through erosion on the moors and, in turn, reverse the loss of carbon to the atmosphere. *Sphagnum* restoration works create a wetter environment on the moorlands, which is beneficial for improving water quality derived from the area as well as improving peatland biodiversity. One of the key aims of the MoorLIFE 2020 project is to reintroduce *Sphagnum* mosses into vegetated areas where it has been lost. *Sphagnum* has been brought in predominantly as commercially-grown plug plants. Current mixes include a combination of between 5 and 11 species in fixed ratios.

In this study, change in area cover of the 11 *Sphagnum* species was assessed after 16 months following application of single-species *Sphagnum* plugs in aggregate sized 'samples', each comprising of 36 plugs in a 6 x 6 configuration. Blanket bog sites dominated by three different moorland species were chosen for the study: *Eriophorum, Molinia* and *Calluna*.

Sphagnum sample growth was recorded at all sites at the time of the summer 2020 survey. The mean area increase of all samples was almost eight-fold, expanding from 144 cm^2 to 1137 cm^2 over the 16-month period.

Sphagnum samples showed increased success in growth of area cover in the *Eriophorum*-dominated study area, than in the *Molinia*-dominated area and in the mixed-moorland reference area. All *Sphagnum* species have grown well in the time period across all sites. Furthermore, targeted planting of *S. cuspidatum* into pools at the surface of the bog yielded significantly larger expansion in cover of plug samples, supporting our current recommendation for planting *S. cuspidatum* into semi-permanent pools. However, the increased growth in area cover is likely a direct result of the lawn spreading out in the water, therefore additional measures of growth are recommended for future single-species *Sphagnum* growth studies.

It was concluded that the dominant vegetation type on upland moorland blanket bog might affect growth of single-species *Sphagnum* plug samples, however potential effects of altitude and different climatic conditions (particularly total monthly rainfall, which was variable between sites) requires consideration for this and for any further studies.

Our current guide to planting mixed plugs can be tailored to reflect the success of the larger starting sample size of plugs, which was successful for all species across all study sites and resulted in more rapid growth in area cover than the (mixed plug) planting density trialled previously by MFFP on Kinder Scout.

To be able to further target the plug planting in order for single-species planting to be feasible across the SAC, a literature review is recommended to find out more about individual species' niches.

1. Introduction

The Active Blanket Bog of the South Pennine Moors Special Area of Conservation (SAC) have been formed predominantly by *Sphagnum* moss species (Lindsay 2010). Peatlands cover approximately 12 % of the UK (Evans *et al.* 2017) but currently only 22 % of peatlands in the UK are in a near natural or rewetted condition (ONS, 2019). Reintroduction of *Sphagnum* to eroding upland moorland sites following peat stabilisation restoration works can halt the loss of peat through erosion on the moors and, in turn, reverse the loss of carbon to the atmosphere. This resilience is important in the face of climate change: The Centre for Ecology and Hydrology estimated that UK peatlands are emitting around 23,100 kt CO2e yr^{-1} greenhouse gas in total (ONS, 2019). Over 50 % of UK soil carbon is stored in peatland systems and 75 % of these peatlands are upland blanket bog (Evans *et al*. 2010). *Sphagnum* restoration works, importantly, create a wetter environment on the moorlands, which is also beneficial for improving water quality derived from the area (a key Water Framework Directive objective). The works are essential towards moving Sites of Special Scientific Interest (SSSI) into favourable condition, improving biodiversity. As well as habitat condition, specialist species and key species trends are used to assess peatland biodiversity. These species have specialised to thrive in the waterlogged, nutrient-poor and acidic peatland conditions, including a rich breeding bird assemblage (Littlewood *et al.* 2010).

One of the key aims of the MoorLIFE 2020 (ML2020) project is to reintroduce *Sphagnum* mosses into vegetated areas where it has been lost. Despite significant development in recent years involving Moors for the Future Partnership (MFFP), there is currently no 'best practice' for re-establishing *Sphagnum* mosses on blanket bog. Approaches investigated by MFFP so far include *Sphagnum* enriched brash, *Sphagnum* fragments, *Sphagnum* beads (BeadaMoss™), *Sphagnum* gel (SoluMoss™); *Sphagnum* plugs (BeadaHumok™) and translocated *Sphagnum* clumps. Crouch (2018) assessed four *Sphagnum* propagule types on Kinder Scout over a period of three years and three months and found that *Sphagnum* plugs were the most successful propagule type in terms of increase in coverage. Topography (i.e. hagg tops vs undulating ground) had a dramatic effect on the growth of *Sphagnum* plugs. There was a greater expansion in area coverage of *Sphagnum* on undulating ground where the plugs were better protected from dessication. Caporn *et al*. (2018) found that plugs had a 99 % survival rate into *Eriophorum angustifolium*-dominated blanket bog after 14 months, which was much greater than the survival of beads (maximum 12 % survival on stabilised peat surfaces). The authors reported that "the advantage of *Sphagnum* plugs is most likely due to the larger plant mass being better able to withstand extreme fluctuations in environmental conditions (notably desiccation and waterlogging) and crowding by other vegetation". As we know that these larger plants potentially have the ability to survive very well, *Sphagnum* has been brought in predominantly as commercially-grown plug plants, under the ML2020 project. The commercial plug plants were supplied as a mix of species. Throughout the life of the project MFFP have refined these mixes and tailored them to specific site conditions, as our knowledge has developed, primarily through trial and error/field observation. Current mixes include between 5 and 11 species, in fixed ratios (Appendix A).

In addition to traditional site-scale vegetation surveys that are undertaken on the ground, aerial imagery was used as part of the ML2020 project to monitor vegetation across the project area in order to assess the impact of blanket bog conservation at a landscape scale. Blanket bogs that have become dominated by single species, such as *Eriophorum* (cotton-grass), *Molinia* (purple moor grass) and *Calluna* (heather) were a focus of monitoring for the project. Imagery collected from manned aircraft and UAVs has been analysed to produce maps showing the type and extent of vegetation and other land covers[1]. Part of the analysis required the identification of pure pixels of moorland species to train the classifiers in the image classification process. Since naturally occurring *Sphagnum* is rare or absent in the project area and it does not tend to grow as single species, field identification of areas of extant pure 'stands' of each species was not possible on the study sites. Instead, single-species plugs were sourced to be introduced alongside re-introduction planting so that they could be used additionally to ensure that all the required spectral information was gathered for the image classification process.

Whilst the aim of the plug planting was to identify the different *Sphagnum* species occurring on the moors via aerial imagery capture and image classification, the planting also provided an opportunity to continue with learning and development of the existing approaches and methods for *Sphagnum* reintroduction. The planting design was tailored to gain more insight into the establishment and growth of the single-species *Sphagnum* plugs in the traditional 'Moorland mix'. The aim of the study was to increase knowledge of the growth of single-species *Sphagnum* plug plants on blanket bog restoration sites to inform best practice for planting. Change in cover of 11 *Sphagnum* species was assessed over a 16-month period and also the change in cover of *Sphagnum* plugs on blanket bog sites dominated by three different moorland species: *Eriophorum, Molinia* and *Calluna.*

[1] Further information about monitoring conservation using aerial imagery is available on the MFFP website: [MoorLIFE 2020: using aerial imagery to monitor vegetation | Moors for the Future]

2. Methods

The majority of *Sphagnum* plugs that have been applied to upland moorland sites so far by MFFP are a mix of 12 *Sphagnum* species in the traditional 'Moorland Mix' (Appendix A). One of the species, *S. russowii*, was too difficult/slow growing to bring on as a single species, so the 11 species that were planted for this study are: *S. capillifolium, cuspidatum, fallax, fimbriatum, papillosum, palustre, denticulatum, medium, squarrosum, subnitens,* and *tenellum*.

Table 1 details the five ML2020 project survey sites used in the study, comprising 11 experimental catchments.

Table 1. Study site description and mini-catchment ID

Survey site	Dominant vegetation	Experimental catchments
Birchinlee (BRCH)	*Eriophorum*	Eriophorum (Con); Eriophorum (Spha)
Derwent & Howden (DWHW)	*Calluna*	Calluna (Con); Calluna (Spha); Calluna (Spha GB)
Moss Moor (MOSS)	*Molinia*	Molinia (Con); Molinia (Spha)
Featherbed Moss (PENG)	None - mixed moorland	P (Ref)
Kinder (KIND)	Previously bare peat	F (Con); N (Veg Spha GB); O (Veg)

Intervention: Con = control; GB = gully blocking; Ref = intact reference; Spha = Sphagnum; Veg = revegetation

A 50 m buffer was created around each ML2020 project mini-catchment (Figure 1) for the single-species *Sphagnum* plug planting, which were planted in the buffers in March 2019 (Figure 2). The reason for planting within a buffer was to avoid affecting on-going experiments within the mini-catchments, whilst ensuring that the *Sphagnum* plugs were captured within the aerial imagery during the aerial survey.

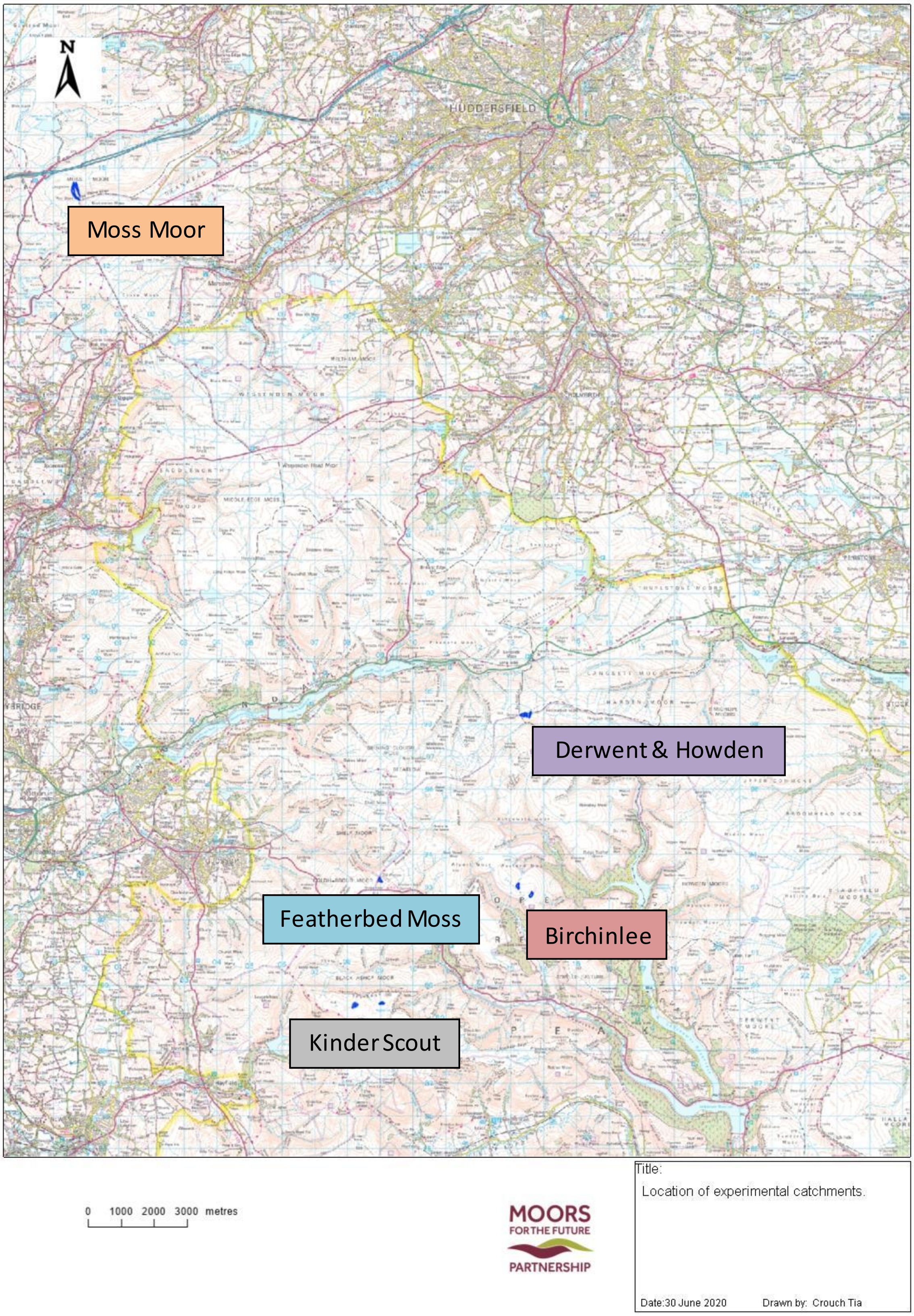

Figure 1. Map showing the 11 experimental mini-catchment areas on the five study sites: Moss Moor, Derwent & Howden, Featherbed Moss, Birchinlee and Kinder

2.1. Plug planting design

Whilst individual plugs are too small to differentiate in the image classification process within the study and control areas, a larger 'sample' size of plugs were planted together. Each sample consisted of 36 plugs in a 6 x 6 configuration. Within each mini-catchment buffer, one 'sample' of each species was planted in each of the five replicate areas (Figure 2). A *Sphagnum* plug consists of several plants forming a bouquet of around 3 cm in diameter. This created a sample size of approximately 12 x 12 cm on day zero, which is equivalent to 1.5 pixels of the multi-spectral camera that was used to collect the imagery for the image classification process. A 12 x 12 cm wooden 'planting frame' was provided into which the plugs were planted by MFFP staff and volunteers following the MFFP planting specification for plugs.

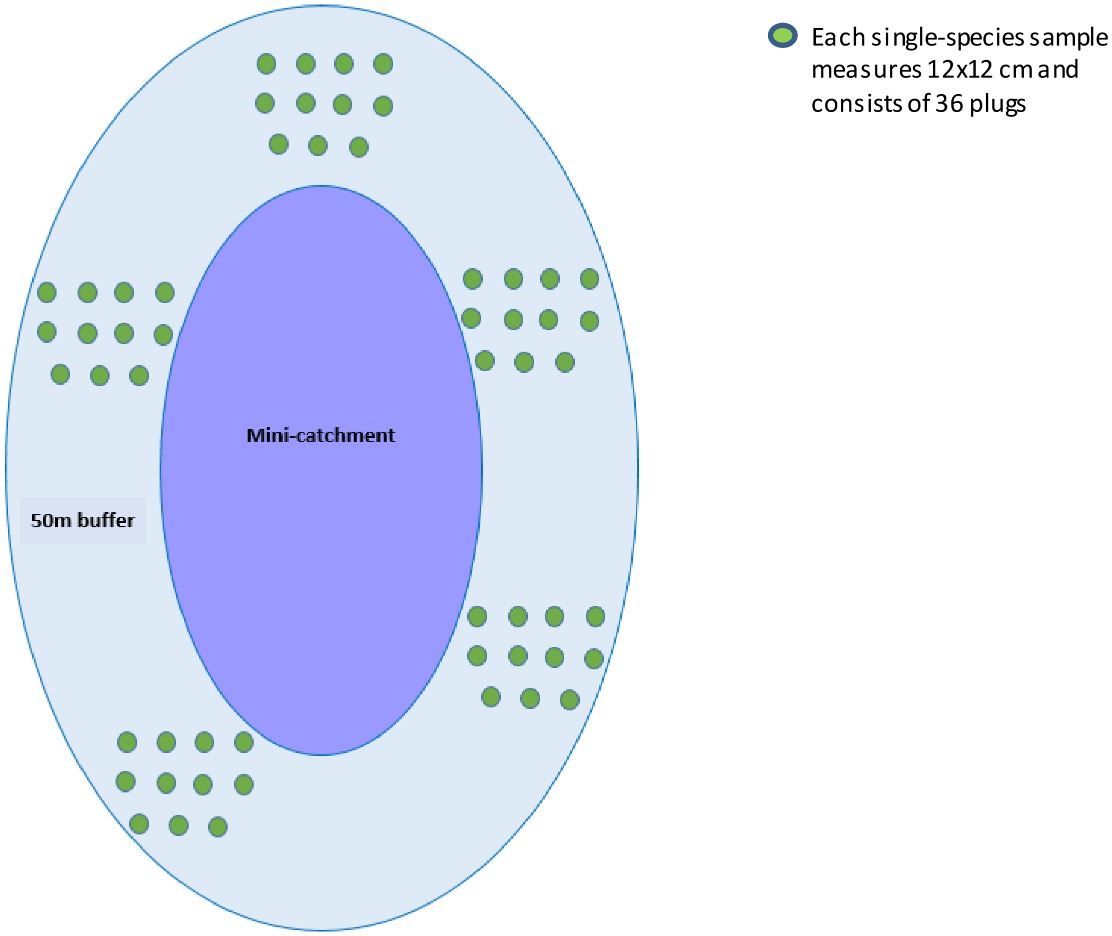

Figure 2. Plug planting design

The five replicate areas were selected within each mini-catchment buffer based on their perceived suitability for *Sphagnum*. The centre of the five replicate areas was marked with a stake. Bare peat areas were avoided to ensure the provision of some shelter for the plugs, as were areas with existing *Sphagnum*. In line with our existing protocol for spreading/planting *Sphagnum,* we did so in where there is accessibility to the peat in the areas of vegetation. Lower topographical areas in the buffer were chosen, with hagg tops avoided, as, although it appears that moisture from precipitation and cloud cover is sufficient for *Sphagnum* to survive and grow slowly, much faster growth is observed when *Sphagnum* plugs are located in areas with a higher water table and better protection from desiccation (Crouch, 2018).

Sphagnum plugs were supplied in bundles of 20, with 20 bundles per bag. Once on site, four people were responsible for planting 2-3 species each. The location of the centre of each *Sphagnum* sample was marked with a Trimble Geo 7x GNSS. At each replicate location an area of 30 x 30 m was marked out on the ground using tape measures before planting one sample of each species into the area. All planters worked on the same area at the same time, before moving onto the next replicate area. The planters identified the species of the sample using plant markers. At the same time the marker marked the location and species of each sample with the Trimble and collected in the plant marker to return to the relevant planter.

No permanent markers were left in place, only the stake marking the centre of the 30 x 30 m area. Using data from the GNSS, maps were created to help locate the *Sphagnum* samples in repeat surveys. These maps were also used to ensure that all samples were located and the correct *Sphagnum* species were recorded in the annual project vegetation survey. Within each mini-catchment buffer 55 *Sphagnum* samples were planted, consisting of 1980 plugs. In total across the 11 mini-catchments 605 *Sphagnum* samples were planted, totalling 21,780 plugs for the whole study.

2.2. Field measurements

A suite of different methods that have been trialled for *Sphagnum* growth monitoring in the literature were reviewed in the introduction of MFFP's report to Natural England 'Harvesting *Sphagnum* from donor sites: pilot study report' (Benson *et al.* 2019). In light of the limitations of the methodologies presented in that report, the monitoring methods considered for the study were those that are non-destructive to the site, to assure minimal damage and to enable repeat surveys of the established *Sphagnum* plug samples to take place over time. Of these methods, area measurements were deemed to be the simplest repeatable measure of growth for use in the study.

In March 2019, a wooden 12 x 12 cm planting frame was used to ensure a fairly uniform size of samples on day zero. A survey took place in the summer of 2019 to assess the initial progress of the *Sphagnum* on the five sites. Length (cm) and width (cm) of the established samples were measured to be able to calculate the area of *Sphagnum* cover (cm^2). Photographs were taken of the samples to illustrate change over time (Figure 3). A repeat survey was undertaken in 2019 and a further repeat survey was undertaken in a short time-frame between 16th July and 5th August 2020.

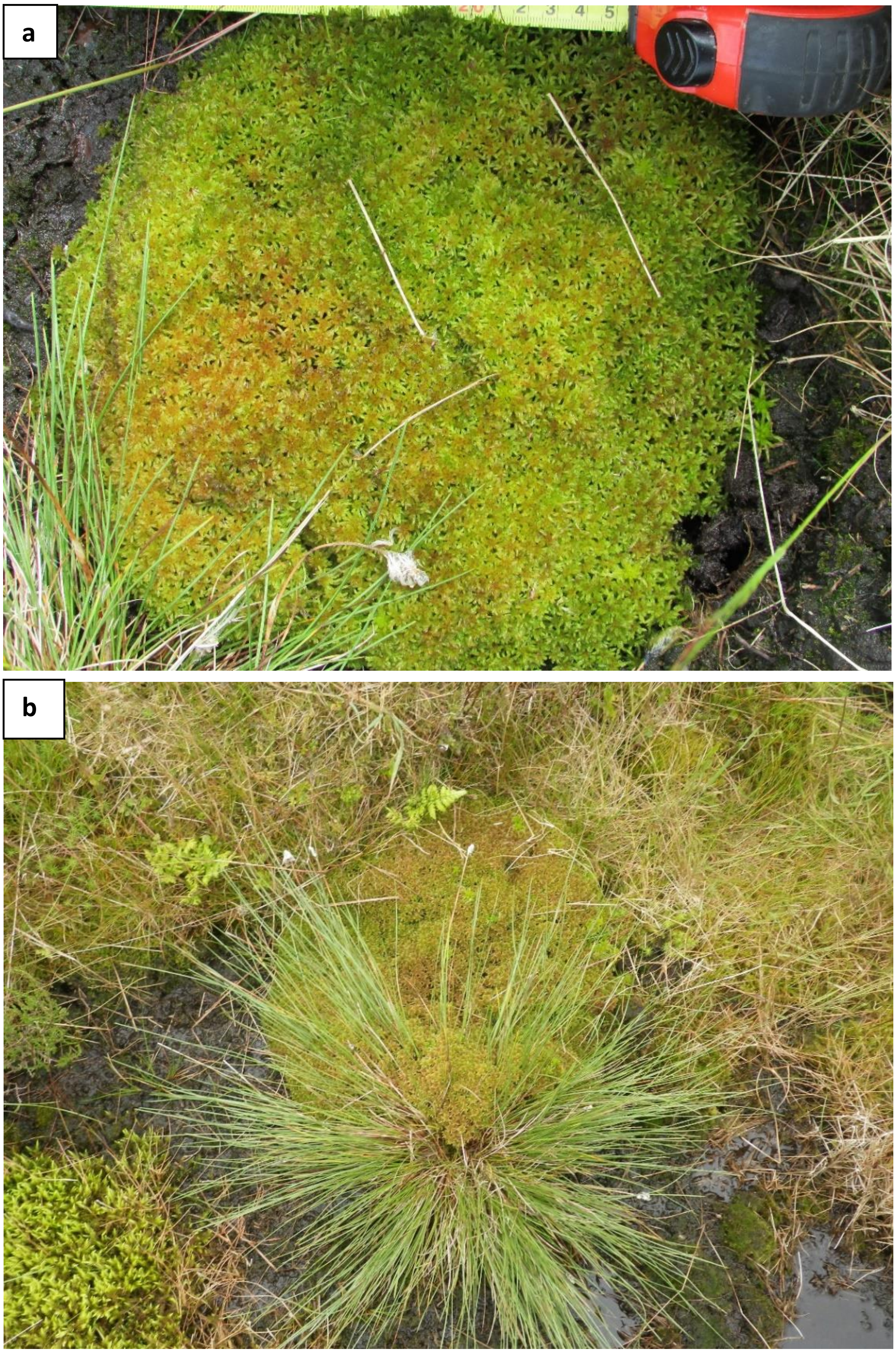

Figure 3. ***S. capifollium*** **sample on Kinder Scout (a) 4 months after planting, (b) 16 months after planting**

3. Results

Sphagnum sample growth since planting was recorded at all sites at the time of the summer 2020 survey. The mean area of samples across all five sites was 1137 cm^2, which represents an approximate eight–fold increase in *Sphagnum* cover from the estimated cover at day zero, which was 144 cm^2. The fold change in cover at each survey site is detailed in Table 2. Similarly, an increase in the cover of the *Sphagnum* samples was recorded for each individual species assessed across all five sites together (Table 3).

Table 2. Fold change in mean area cover of *Sphagnum* 'samples' in the different dominant species areas, 16 months after planting

Survey site	Dominant vegetation	Fold change in mean area cover*
Birchinlee	*Eriophorum*	9-fold increase
Derwent & Howden	*Calluna*	8-fold increase
Moss Moor	*Molinia*	7-fold increase
Kinder	Previously bare peat	8-fold increase
Featherbed Moss	None – Mixed moorland	7-fold increase

*to the nearest whole number

Table 3. Fold change in mean area cover of *Sphagnum* 'samples' across all survey sites, 16 months after planting

Sphagnum species	Fold change in mean area cover*
S. capillifolium	7-fold increase
S. cuspidatum	14-fold increase
S. denticulatum	6-fold increase
S. fallax	9-fold increase
S. fimbriatum	7-fold increase
S. medium	7-fold increase
S. palustre	8-fold increase
S. papillosum	8-fold increase
S. squarrosum	7-fold increase
S. subnitens	7-fold increase
S. tenellum	6-fold increase

*to the nearest whole number

A two-way ANOVA test carried out in Minitab statistics package showed that there was no significant interaction between the effects of species and site on mean area of single-species *Sphagnum* samples ($F(40, 477) = 1.32$, $p = 0.099$) (Table 4).

Table 4. ANOVA summary table

Source	DF	F	P
Site	4	5.20	0.000
Species	10	6.68	0.000
Site*Species	40	1.32	0.099
Error	477		
Total	531		

Simple main effect analysis showed that the mean area cover of *Sphagnum* samples at Birchinlee was significantly greater than the mean area at Moss Moor and at Featherbed Moss ($P < 0.01$, $P < 0.01$, respectively) (Table 5 and Figure 3).

Table 5. Simple main effect analysis of mean area cover – differences between sites and differences between species

Difference	P
Area of *Sphagnum* in BRCH greater than area in MOSS	< 0.01
Area of *Sphagnum* in BRCH greater than area in PENG	< 0.05
Area of *S. cap* less than area of *S. cus*	< 0.001
Area of *S. cus* greater than area of *S. den*	< 0.001
Area of *S. cus* greater than area of *S. fal*	< 0.05
Area of *S. cus* greater than area of *S. fim*	< 0.05
Area of *S. cus* greater than area of *S. med*	< 0.001
Area of *S. cus* greater than area of *S. pal*	< 0.001
Area of *S. cus* greater than area of *S. pap*	< 0.001
Area of *S. cus* greater than area of *S. squ*	< 0.001
Area of *S. cus* greater than area of *S. sub*	< 0.001
Area of *S. cus* greater than area of *S. ten*	< 0.001
Area of *S. den* less than area of *S. fal*	0.07, marginal

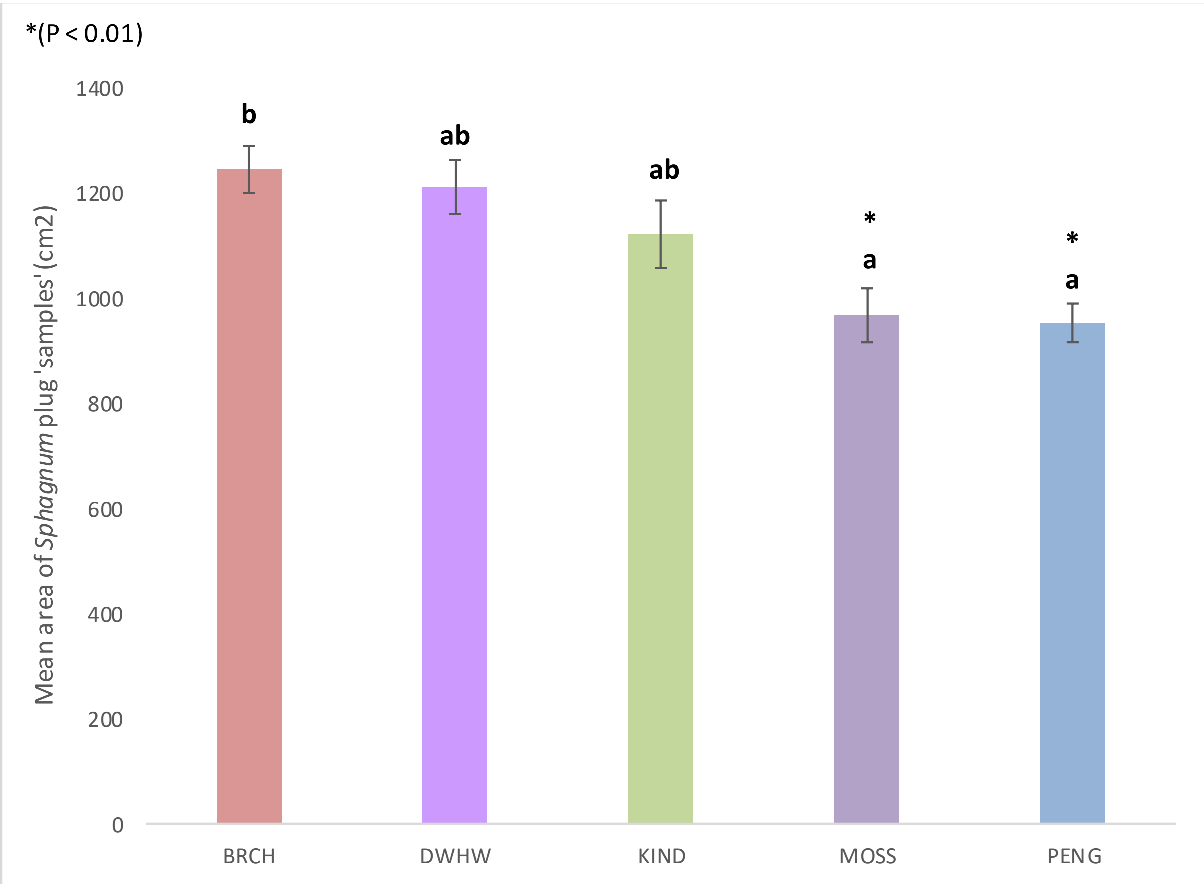

Figure 4. Mean area of established single-species *Sphagnum* plug 'samples' (11 species) at the study sites in summer 2020, 16 months after planting

Simple main effect analysis also showed that the mean area cover of *S. cuspidatum* samples was significantly greater than mean area cover of all other single-species *Sphagnum* samples (Table 5 and Figure 4).

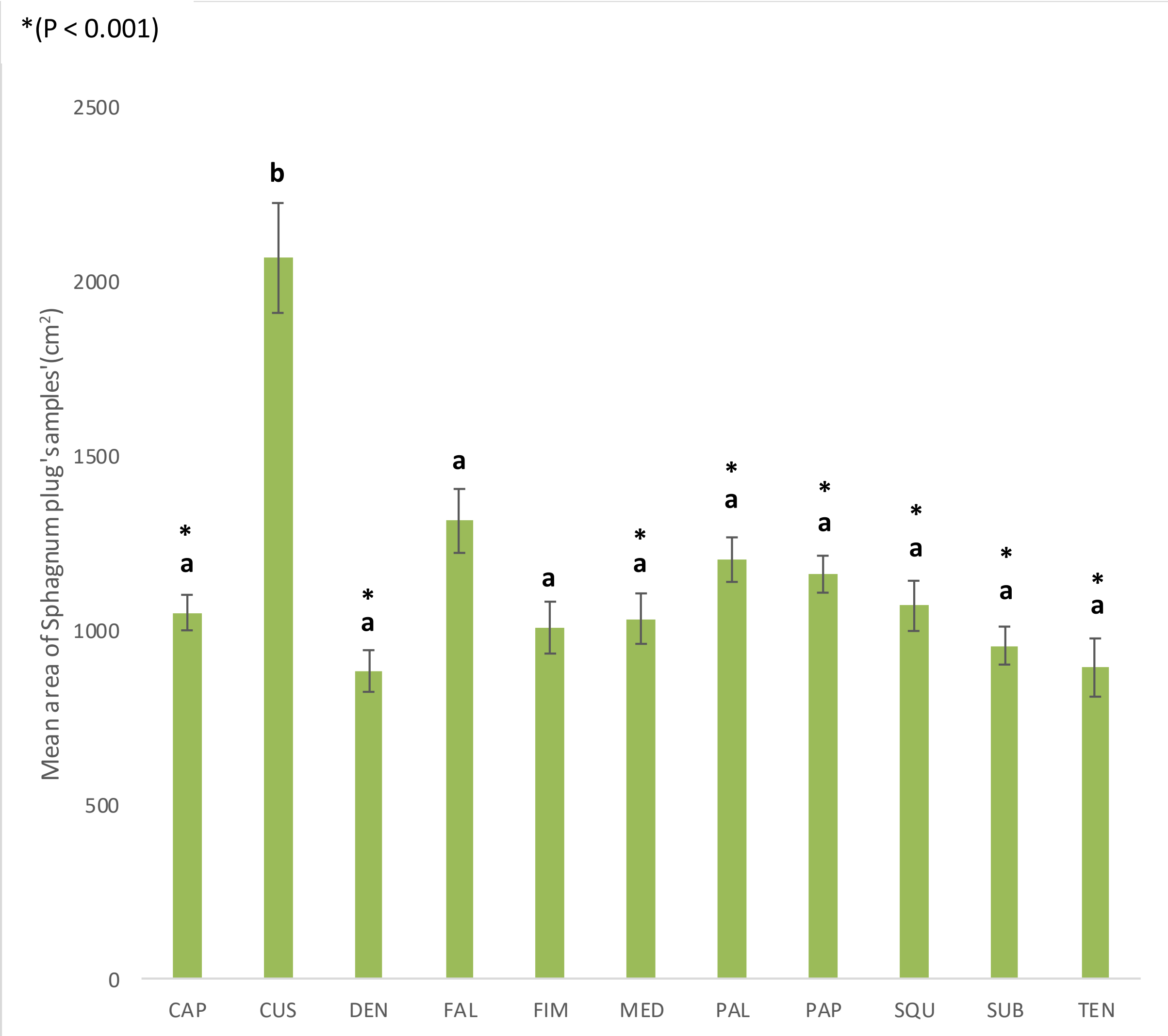

Figure 5. Mean area of established single-species *Sphagnum* plug 'samples' across all five study sites in summer 2020, 16 months after planting

4. Discussion

Growth in area coverage of *Sphagnum* samples was recorded at all sites in the summer 2020 survey. This supports our existing knowledge that these larger plants potentially have the ability to flourish (Crouch, 2018; Caporn et al. 2018).

The fact that *Sphagnum* plug samples grew to cover larger areas on the *Eriophorum*-dominated site (BRCH), than on the *Molinia*-dominated and mixed-moorland reference sites (MOSS and PENG) indicates that the different conditions of the site are important to the success of *Sphagnum* inoculation. Where blanket bog is dominated by grass and/or sedge, unless subject to drainage, water tables are generally high and there is therefore high potential for *Sphagnum* establishment (MFFP, 2017). The higher *Sphagnum* cover on the *Eriophorum*-dominated site than on the *Molinia*-dominated site, which are both classed as 'State 4' blanket bog (Natural England, 2015; MFFP, 2017), suggests that the dominant vegetation type could impact *Sphagnum* growth. *Sphagnum* samples planted in the more 'open' *Eriophorum*-dominated areas may have been less restricted in their growth than those planted in-between tussocks of *Molinia.* Caporn *et al.* (2018) observed that *Sphagnum* became pale and drawn out where *E. angustifolium* growth was most dense. This was observed in the present study on the *Molinia*-dominated site, where *Molinia* cover is dense across the whole site. It was also most difficult to find and see the extent of the *Sphagnum* on the *Molinia*-dominated site for this reason. Whilst Pilkington & Walker (2020) concluded that the establishment of *Sphagnum* colonies from plugs on *Molinia*-dominated blanket bog is successful, a cover in *Molinia* that was higher than 85 % and which increased in successive survey years was associated with declines in the established *Sphagnum* cover over time, following initial establishment and expansion of cover of plugs at 16 months in the dense *Molinia*. In the present study the mean cover of *Molinia* recorded in vegetation quadrats on the *Molinia*-dominated site was 93 % (summer 2020 survey), indicating that the *Molinia* area was too dense to expect any further continued growth in *Sphagnum* area cover after the initial 16-month study period; therefore there may be a decline in area cover of the established plug samples in successive surveys years. A repeat survey is recommended to check for any positive effects of the larger aggregate plug sample size on this predicted growth trajectory.

A limitation of the study is that whilst the study areas are located some distance apart (Figure 1) there are likely differences in rainfall, occult precipitation and temperature fluctuations between sites, which can be an important factor where water table is spatially variable (Allott *et al.* 2009, cited by Caporn *et al.* 2018). Whilst the average monthly air temperature recorded at the *Calluna* site (DWHW) was consistently higher than at both the *Molinia* and *Eriophorum*-dominated sites, average air temperature between the three species dominated sites remained within a narrow 1.6 degrees Celsius range over the 16-month period. No air temperature data was recorded at the previously bare or mix moorland reference sites (KIND and PENG). Monthly total rainfall however was more variable between sites over the study period - no clear trend over time. The *Calluna* site and previously bare peat site often recorded the greatest total monthly rainfall. In the absence of a clear rainfall trend, the fact that *Sphagnum* plug samples grew to cover larger areas on the *Eriophorum*-dominated site than on the *Molinia*-dominated site indicates that the conditions provided in the open cotton-grass areas may have been more favourable for *Sphagnum* reintroduction, where there may also be less interspecific competition for resources than in the mixed moorland area, due to both lower species diversity and abundance across the *Eriophorum*-dominated study site.

The 'State 5' intact mixed-moorland reference site has a high water table, yet the plugs planted on the 'State 4' *Eriophorum*-grass dominated site showed significantly greater growth. This suggests that whilst the water table is important for *Sphagnum* area cover growth, altitude may be a limiting factor. At different altitudes, the study areas may have been subjected to the aforementioned different climatic conditions. Peatland altitude is known to be an important factor in net primary productivity (Worrall, F. 2021 pers. comms., 3 February); peat accumulation is positively associated with warming and negatively associated with cloudiness (Charman *et al.* 2013, cited by Gallego-Sala and Prentice, 2013). However, high temperatures (greater than 15^{o}C) are damaging to *Sphagnum* species (Bragazza, 2008, cited by Gallego-Sala and Prentice, 2013) and blanket bog occurrence is subject to certain controlling processes, for example maintenance of water table by year-round moisture (Gallego-Sala and Prentice, 2013). Whilst average monthly air temperature did not exceed 15^{o}C at the *Eriophorum-grass* site, unfortunately, no temperature data is available for the intact mixed-moorland site to enable a direct comparison. Vegetation surveys undertaken for aerial photography classification identified almost twice as many records of natural *Sphagnum* patches on the 'State 5' mixed-moorland blanket bog site however than on the *Eriophorum*-dominated site, suggesting that climatic conditions for *Sphagnum* have been favourable. Due to a higher level of existing natural *Sphagnum* patches, there may have been a bias towards less-favourable areas for *Sphagnum* planting chosen on the reference site because of the requirement to avoid existing *Sphagnum,* which will naturally colonise the most favourable areas in the buffer zone. Rogers (2014, cited in Caporn *et al.* 2018) found that *Sphagnum* occurred naturally "only where near surface water flow was common in surface depressions or gullies" on the intact mixed-moorland reference site.

All 11 species samples have grown well in the time period, expanding between 6 and 14 times their size on day zero, by mean area cover measurement. This suggests that all of the species are suitable for planting as single-species plug samples initially on the study sites at the aggregate size. Previously, Crouch (2016) found that the mean total area cover of single mixed species *Sphagnum* plugs that had been planted individually at a set density increased three-fold, from 179 cm^2 to 550 cm^2 in a 12 month-period. By comparison, the aggregate size of plug plants in the present study yielded a mean eight-fold increase in area cover of

Sphagnum samples over 16 months. This provides some evidence that the larger aggregate sample size of *Sphagnum* results in a more rapid growth in area cover than the (albeit mixed plug) density trialled in quadrats in the previous MFFP study. It is thought that the aggregate size of reintroduced *Sphagnum* is important for performance (Robroek et al. 2009), with larger patches better able to supply the capitula with water (Robroek et al. 2007).

Additionally, *S. cuspidatum* grew significantly larger on all sites than all of the other *Sphagnum* species. Whilst planting of *S. cuspidatum* was targeted into areas where the water was visibly pooling at the surface of the bog, due to the species' tendency to grow in pools (Appendix A), the other species were also targeted into wetter areas. A consideration about this result however is that any *Sphagnum* species may measure larger in pools, especially in the summer survey when other *Sphagnum* patches are likely under stress due to high temperatures and low water availability. Furthermore, the *S. cuspidatum* lawn tends to be 'open' in structure due to the capitula being lax (Clymo, 1970) and its nature to spread out in the water would have directly impacted the area cover measurement, making it larger. Also to note that during propagation it was likely that *S. squarrosum* was contaminated with *S. fallax*. A further assessment of how *S. squarrosum* grows as a single-species at the aggregate size on species-dominated blanket bog areas is therefore recommended.

A limitation of the study is that growth was measured in one plane and changes in growth in height were not investigated, meaning that hummock-forming species' growth could have been under-represented by the area measurements. There can be substantial variation in habitat within a peatland ecosystem, characterised according to pH and other cations, as well as the variation in ground water due to micro-topography (Rydin and Jeglum, 2013, cited in Johnson *et al*. 2014) and *Sphagnum* species are known to differentiate into narrow micro-habitats, for example according to pH (Andrus, 1986, cited by Johnson *et al*. 2014). Hollow species maximise photosynthesis by concentrating growth in the capitulum, while remaining sparsely packed at the water table. Whilst species with small capitula grow in densely packed hummocks to maintain water availability higher above the water table (Rice et al., 2008, cited in Johnson *et al.* 2014).

A further limitation of the study is that soil moisture in the buffer zone was not measured. The main focus of the planting design was for the aerial surveys – visibility from the air was an important factor. The ML2020 Technical Application states that "by far the most important factor in re-establishing *Sphagnum* back successfully onto the damaged Active Blanket Bogs of the SAC is to target those areas which retain high soil moisture for most of the year." Wetness was tested for by depression of the planter's boot into the ground (worn on the foot), which enabled identification of suitable planting areas in the buffer zone at the time of planting. Lees *et al.* (2021) developed a method for monitoring peatland resilience to drought using Sentinel-1 Synthetic Aperture Radar data as a proxy for water table depth and soil surface moisture. A further piece of work would be to use satellite data to indicate surface wetness to assess the suitability of the moors for *Sphagnum*.

In conclusion, this study suggests that the dominant vegetation type on upland moorland blanket peat might affect growth of single species *Sphagnum* plug samples, in addition to any effects of altitude and rainfall. *Sphagnum* samples showed higher cover increase in the *Eriophorum*-dominated study area, than in the dense *Molinia*-dominated area and mixed-moorland reference area.

Whilst all *Sphagnum* species have grown well in the time period, targeted planting of *S. cuspidatum* into pools at the surface of the bog has yielded significantly larger expansion in cover of plug samples on the study sites, supporting our current recommendation for MFFP's single-species plug planting of *S. cuspidatum* (Appendix A). However, the increased success in growth for this species may be partly due to the capitula spreading out in the lawn in the water. This uncertainty highlights the need for more additional measures of growth, tailored to the individual species' structure and form in future studies, which were out of scope in the present study. It would be useful to undertake a literature review to learn more about other individual species' niches to be able to further target the plug planting in order for single-species planting to be feasible across the SAC. It is also desirable to know more about how species interactions affect growth. For example vigorous growth of *S. magellanicum* on damaged peatlands has been shown to be dependent on the presence of other species, such as *S. fuscum* (Chirino *et al.* 2006, cited in Johnson *et al.* 2014).

Our current guide to planting mixed plugs can be tailored as a result of this study to reflect the success of the larger aggregate starting sample size of plugs, which was successful for all species across all sites. The larger aggregate sample size of *Sphagnum* resulted in more rapid growth in area cover than the (mixed plug) density trialled previously by MFFP on Kinder Scout.

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6. Appendix A - A guide to planting the different mixes

1. **Moorland Mix –** a mix of 11 species (this is the traditional mix that we plant the most) and includes a broad mix of different types of species including both flush and hummock or chunky species.

   As this is a 'generalist' mix, the concept is that no matter where the plug is planted following the guidelines above, one or some of the species present will thrive and grow. This type of mix is ideal for a site with variation in micro-habitats and lacking in any *Sphagnum* species in general. This is especially the case for large areas of newly revegetated areas of bare peat including a lot of blocked erosion gullies.

2. **Chunky Mix –** a mix of 5 hummock or chunky species.
   This mix is being targeted for areas that are in unfavourable condition, but are largely vegetated and not heavily eroded by gullying. These areas are more typical and are more hydrologically intact and therefore may have areas of *Sphagnum*, in particular flush species, already present to a degree in the wetter flushes and gullies. In order to move these areas into more favourable condition, diversification is key, and in particular, the introduction of *Sphagnum* species associated with functioning blanket bogs because of their ability to form peat layers.

   It is also worth noting that Natural England are moving towards the type of key *Sphagnum* species present on site, as opposed to general *Sphagnum* presence when assessing condition.

3. **Yorkshire Mix –** a mix 5 species that is mainly hummock or chunky mix, but also includes *S. fallax*. This is a mix used by Yorkshire Peat Partnership across their sites. A surplus led us to try out this mix on a handful of MFFP's restoration sites. As with the Chunky Mix above, these are species more associated with peat forming (but also have *S. fallax* included). It is likely that this is a one-off for 2018-19 planting.

4. **Single species –** Bags containing 200 plugs of a single species, but with different bags containing different species.
   Flush species e.g. *S. fallax* & *fimbriatum* – prefer wetter, flush areas such as gullies.
   Hummock or chunky species e.g. *S. medium* (prev. *magellanicum*), *papillosum*, *capillifolium* – still require wet areas, but can tolerate the drier tops. Suitable for planting in larger, flatter cotton-grass dominated areas.
   S. cuspidatum – this is a species of Sphagnum that thrives in pools and should always be planted or placed in or on the edge of semi-permanent pools such as behind gully blocks (plastic piling or peat dams).

5. **Pool Mix –** We are trialling a mix consisting of *S. cuspidatum* (30 % of the mix), *S. denticulatum* (25 %), *S. fallax* (15 %), *S. medium* (10 %), *S. palustre* (10 %) *and S. papillosum* (10 %). These are species that thrive in pools and on land and can be planted on to the edge of semi-permanent pools behind gully blocks.