Going native, going local: revegetating eroded soils on the Falkland Islands using native seeds and farmland waste

Running head: Revegetating remote islands using native seeds

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## AUTHOR CONTRIBUTIONS

SWS, BB, RU, AD conceived and designed the study; SWS, KR, SK established trials and collected data; BB and SWS analyzed the data; SWS and SK wrote the first draft of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

## ABSTRACT

Remote island ecosystems are vulnerable to human disturbance and habitat destruction, yet they often have limited capacity to revegetate degraded habitats, especially with native species. To revegetate degraded island habitats practitioners often rely on importing non-native species, thereby increasing the number of introduced species on islands. In this study, we investigated the effectiveness of sowing wild collected native seeds and locally sourced treatments for revegetating different eroded soil types (clay, peat and sand) across the Falkland Islands. A seed mixture of 15 native species was sown with different supportive treatments (sheep dung, sheep dags (woolly off-cuts) and geotextile matting (coir)) and their combinations. After one year, native seeds provided up to 70% plant cover and accrued 1.98 kg $m^{-2}$ in biomass. Three key native species *Elymus magellanicus*, *Poa flabellata* and *Poa alopecurus* occurred in 64, 50 and 50% of all sown plots. However, supportive treatments equally facilitated the colonization and establishment of non-native species. At the same time, there was no difference in native plant cover and biomass across different treatments or soil types, although in the absence of supportive treatments there was little to no revegetation. Thus, locally sourced treatments (i.e. sheep dung and dags) may provide an equally effective but low-cost alternative to imported treatments (i.e. geotextiles). We further discuss challenges of integrating revegetation using native seeds and livestock grazing on the Falkland Islands. Our study demonstrates that native species and local treatments can provide a rapid approach to revegetating degraded island habitats.

Keywords: Falkland Islands, introduced species, revegetation, seeds, sheep grazing, soil erosion

## IMPLICATIONS FOR PRACTICE

- Sowing native seeds can provide rapid plant cover across major eroded soil types (clay, peat and sand) on the Falkland Islands
- Sown native seeds do not establish without supportive treatments
- Local farmland waste (i.e. sheep dung and dags) provides low-cost treatments that are as effective as imported treatments (i.e. geotextiles)
- Use of farmland waste facilitates colonization and establishment of non-native species, thus this approach may be inappropriate on oceanic islands where mitigating the spread of non-native species is important
- Using native seeds is limited by seed supply. However, large tussock-forming grasses were the most successful colonizers and may potentially be sown at lower seeding densities, thus optimizing wild collected seed supply

## INTRODUCTION

Island ecosystems are biodiversity hotspots of global significance, yet they are also highly vulnerable to human disturbance and habitat destruction. In recent decades habitat loss on islands has exceeded that of adjacent mainlands (Sax & Gaines 2008). In addition, many remote island communities have limited capacity to restore degraded or eroded habitats, whether, for example, by planting seedlings or sowing local or native seeds (Ruiz-Jaen & Aide 2005; CBD 2010; RGB KEW 2016). Due to this, practitioners have commonly relied on the use of imported non-native plant species at the cost of developing local restoration approaches (Hobbs et al. 2006; Schlaepfer et al. 2011). Some practitioners may view non-natives as an effective tool to restore degraded habitats, because seeds are readily available and typically strong colonizers and competitors with high growth rates (Grant et al. 2011; Hagen et al. 2014). Alternatively, practitioners could perceive the use of non-natives for restoration as problematic because introduced species could endanger local nature and the economy (Chapin et al. 2000; Van der Wal 2015). At the same time, many native species have similar colonizing and invasibility traits as non-natives (Thompson et al. 1995; Vilà & Weiner 2004; Kuester et al. 2014) and thus may present an underutilized tool for habitat restoration. This may be particularly true for native species on islands, which typically are adapted to recolonizing frequently disturbed habitats, for example following tidal surges. Against this background, in our study we trialed revegetation approaches that use native seeds and locally sourced treatments on degraded habitats in a remote island system.

The Falkland Islands is an archipelago in the South Atlantic Ocean consisting of two mainlands, East Falkland and West Falkland, and several hundred smaller islands. Due to historic and current land use practices, mainly livestock rearing, the islands have been subject to widespread soil erosion (Strange et al. 1988; Wilson et al. 1993). Natural recovery of eroded habitats on the islands is further hindered by strong winds that quickly remove topsoil and are also likely to remove the buried seed bank. Loss of topsoil is common, exposing underlying mineral clay and sand-rich soil horizons (Wilson et al. 1993). Clay soils on the islands are particularly dense, often above 40% clay and occasionally over 60% clay with no internal structure (Cruickshank 2001). Heavy clays are vulnerable to further disturbance via compaction, prone to waterlogging and drying and have limited pore spaces for plants to root and access water and nutrients. Given the extent of erosion, the harsh soil environment and the climatic conditions, human assistance is often required to restore eroded habitats. Yet, problematically, there is a limited number of effective approaches to address this issue on the islands. The main method using a local species to restore habitats is to plant grass tillers of *Poa flabellata* (Tussac). This approach has been successful only on peat and sand soils, and establishment rates even on these soil types have been inconsistent (Cris et al. 2011; Smith & Karlsson 2017). Using non-natives has rendered similar results on peaty and sandy soils, with, for example, *Ammophila arenaria* widely used to stabilize sand dunes (Davies 1939; Kerr 1994), yet non-natives have also been unsuccessful in revegetating clay-rich soils. Thus, in order to be effective, any approach to restoration on the islands would need to establish across multiple soil types and in challenging climatic conditions.

In 2013, a pilot study was established on a single eroded clay patch on East Falkland to test establishment rates of different sown native species. A mixture of 15 native species was selected based on observational evidence that in some locations these species successfully colonize eroded sites across the archipelago (A. Davey, R Upson unpublished). As part of the pilot, seeds rather than plantlets were used for several reasons including: inconsistent rates of establishment of grass tillers, to establish multiple species simultaneously and increase genetic heterogeneity. Furthermore, seeds were applied in combination with locally sourced treatments, namely sheep dung and dags (woolly off-cuts) and wood pallets, thus avoiding importing material that could otherwise be sourced locally. Importing materials has logistical difficulties such as in the 1930s large-scale pasture improvement trials across the islands involved shipping sheep dung – with embedded non-native seeds – 8,000 miles from the UK to the Falklands (Davies 1939). Additionally, any imported organic material typically involves biosecurity risks and increased likelihood of introducing alien species. Overall results from the pilot were promising with the most successful treatment increasing plant cover by 70% after one year. Nevertheless, to comprehensively test the effectiveness of sowing native species with local treatments required a larger trial across multiple soil types and microclimatic conditions on the Falkland Islands.

Building on the pilot, in this study we established an island-wide restoration trial sowing a mixture of 15 native plant species to restore three major eroding soil types (clay, peat and sand) across the Falkland Islands. Using the trial we aimed to (1) identify the most effective revegetation approach across soil types when sowing native species in combination with local treatments (sheep dung, dags and geotextile matting); (2) identify the most successful native species within the mixture; (3) quantify colonization by non-native species across treatments and soil types; and (4) determine whether the effectiveness of specific treatments is due to alteration of the soil surface microclimate (soil moisture, temperature, surface windspeed and soil movement rates). By undertaking this trial we aimed to provide information for land managers on the most effective approach to revegetating different eroded soil types with native seeds on the Falkland Islands.

## MATERIALS AND METHODS

### SITE SELECTION

We established a revegetation trial across the mainland of East Falkland on the Falkland Islands, between December 2014 and January 2015 (Fig 1). The islands have a southern cool-temperate oceanic climate with mean summer (January) and winter (July) temperatures of 9.4°C and 2.2°C respectively, and annual precipitation of 640 mm (1961-1990 averages from Stanley; see Jones et al. 2013). The islands have a windy climate with average wind speeds of 8.5 m $s^{-1}$ (16.5 knots) and frequent gale force winds over 70 days per year (Jones et al. 2013, 2015). The underlying geology of the islands is comprised of mudstone, quartzite and sandstone (Aldiss & Edwards 1999) overlain predominantly by organic soil types, dominated by histosols, podzols and stagnosols (Cruickshank 2001; HWSD 2015; Table S1). Wildfires are a component of the island ecology and are present throughout the palynological record (Barrow 1978). Human land-use, mainly livestock rearing and land clearance, has reduced and removed vegetation cover leading to the extensive soil erosion across the islands (Davies 1939; Wilson et al. 1993).

The majority of our revegetation sites were surrounded by grazing-tolerant native species that dominate the islands, namely tussock-forming grass *Cortaderia pilosa* (Whitegrass) and dwarf-shrub species *Empetrum ruburum* (Diddle-dee) and *Baccharis magellanica* (Christmas bush) (Broughton & McAdam 2005). These native species are often intermixed with non-native species introduced to “improve” pastures, notably grasses *Agrostis capillaris* (Bent grasses), *Festuca rubra* (Red fescue) and *Holcus lantanus* (Yorkshire fog) and forb *Rumex acetosella* (Sheep sorrel) (Davis 1939; Broughton & McAdam 2005). Currently the island flora is comprised of 249 non-native taxa compared to 181 native taxa (“non-native” defined as introduced by European settlers since the 1700s; Upson & Lewis 2014).

EXPERIMENTAL DESIGN

Sixteen experimental sites were established across three major exposed soil types (clay, peat and sand) on East Falklands (Fig 1: Table S1). The sites were selected to represent severely degraded habitats with limited natural vegetation recovery since 2010. All sites had little to no vegetation cover and were similar in other characteristics (e.g. geology, climate, slope, aspect and altitude; Table S1). Sites differed in exposed soil type defined by soil texture; eight sites were on clay, six on peat and two on sand (Table S1). All sites had previously been extensively grazed all-year-round at low-stocking densities of Polwarth-Merino sheep (0.5 - 0.9 sheep ha$^{-1}$) and cattle (0.001 - 0.013 cows ha$^{-1}$) apart from at Cape Pembroke that had been fenced for restoration since 2010 and previously grazed by horses (0.6 horses ha$^{-1}$) in the winter between July-September. To encourage vegetation establishment, fences were erected around all sites to exclude grazing by livestock and small herbivores, namely European hares (*Lepus europaeus*); however, it was not possible to prevent grazing by upland geese (*Chloephaga picta leucoptera*).

To revegetate the eroded sites we sowed native seeds in combination with locally sourced treatments. We applied three treatments and their combinations as a full factorial: sheep dung, sheep dags (woolly off-cuts) and geotextile (coir matting). Including sowing native seeds, there were eight treatment combinations: (1) seeds + no treatments, (2) seeds + sheep dung, (3) seeds + sheep dags, (4) seeds + geotextile, (5) seeds + sheep dung and dags, (6) seeds + sheep dung and geotextile, (7) seeds + sheep dags and geotextile, and (8) seeds + sheep dung, dags and geotextile. As part of a split-plot design, these treatments were spread across paired sites of the same soil type on a given farm i.e. all combinations in the full factorial were applied to paired sites. Additionally, there were two control plots at each site: one with no seeds or treatments (herein referred to as ‘control’) and another without seeds but with all treatments (dung, dags and geotextile) (herein referred to as ‘treatment control’). Paired sites on the same soil type were a minimum of 1 km apart. We had two paired sites that deviated from this design and that were grouped into a single site: one on Fitzroy Farm due to an inability to find a paired sand soil type and the other on Cape Pembroke due to issues with landowner permission to establish paired sites (Table S1). At the sand site on Fitzroy Farm there were several tidal storm surges that flooded plots, but no similar natural disturbances occurred at other sites.

As part of the trial we used a mixture of 15 native species collected from wild populations across East Falkland in 2013. Seeds were dried to 15% equivalent relative humidity in drums containing silica gel; cleaned at Millennium Seed Bank, Kew following standard procedures; and, finally stored at -20°C prior to use (see protocols: MSB 2015). The native seed mixture contained: *Acaena magellanica* (forb), *Carex fuscula* (sedge), *Deschampsia flexuosa* (grass), *Elymus magellanicus* (grass), *Festuca contracta* (grass), *Festuca magellanica* (grass), *Gunnera magellanica* (forb), *Hierochloe redolens* (grass), *Juncus scheuchzeriodes* (rush), *Leptinella scariosa* (forb), *Luzula alopercurus* (wood rush), *Poa flabellata* (grass), *Poa alopercurus* (grass; both peat and sand ecotypes) and *Trisetum phleoides* (grass). This mixture was designed to investigate the establishment rates of different species rather than restore a specific wild plant community. Germination of seeds collected from the wild was highly variable (Table S2). Thus, in order to improve germination success quantities of seeds within the mixture were adjusted for empty, infested and immature seeds. For each species 400 'viable' seeds were included in the mixture (200 seeds $m^{-2}$) apart from *E. magellanicus* that was represented by 260 seeds due to limited stock. For germination trials *in situ* we were unable to successfully germinate *G. magellanica* seeds; nevertheless, seeds germinate *ex situ* so this species was retained within the native seed mixture (Table S2).

The majority of treatments were obtained from local sources on the islands. Sheep dung was collected from Fitzroy Farm shearing shed, while the sheep dung and dags and dag treatments were collected from Goosegreen Farm. Both farms are on East Falkland near to restoration sites (Fig 1). Dung treatments had been mulched for one growing season to reduce the number of viable seeds in dung. Dags were not treated to remove adhering seeds, yet visible inspection showed a low number of seeds in the wool. Locally sourced wooden pallets were a successful treatment in the pilot study, but they were deemed impractical for a wider trial due to transportation costs of moving material. Instead, we imported coir geotextile matting, derived from coconut husks (0.9 kg $m^{-1}$ with mesh size of 1 × 1 cm). Although a non-local treatment, geotextile matting is commonly used to restore degraded habitats. Furthermore, if successful, an equivalent local product could be manufactured on the islands using native grass fibers. Geotextile matting was shipped from the UK at a cost of 4.90 USD per $m^2$ (incl. shipping costs), for this study there was no cost for sheep dung and dag treatments.

ESTABLISMENT PROCEDURE

Each trial site was approximately 6 × 12 m in size and contained eight marked out experimental plots, including: four treatment plots (sown seeds, dung, dags, geotextile and combinations), two control plots (control and treatment control) and two additional harvestable plots. Each plot was 2 × 2 m in size and plots were spaced 0.5 m apart to reduce cross contamination of treatments and seeds. Applied treatments were designated randomly using a random number generator. Harvestable plots were sectioned into four 0.5 × 0.5 m subplots that matched the main treatments found within the plot. Separate harvestable plots were created to avoid hindering revegetation of treatment plots. We did not create harvestable plots for the control treatments. All plots were hand raked twice to a depth of 3 cm to decompact the soil surface, first in the direction of the prevailing wind and then perpendicularly to the wind direction. During raking any large rocks (>10 cm) were removed. For seeded plots, the native mixture was sown at a density of 10.32 g seed per plot (or 2.6 g $m^{-1}$), similar to seed densities used for non-native agricultural grassland sowing on the islands (Jo Tanner, Head Dep. Agriculture, Falkland Island Government, pers. comm.). This sowing density was within guidelines of between 1-4 g seed $m^{-1}$ suggested to restore semi-natural grasslands (Stevenson et al. 1995; Wells 1999; Kiehl et al. 2014); yet it is important to note that little is known about the rates of seed production by grasslands on the Falklands. Prior to hand broadcasting, seeds were mixed with 50 g of wet sand to facilitate equal dispersal of the seeds and to reduce seed loss to the strong winds. After sowing seeds, treatments were applied at rates of 4.5 kg $m^{-1}$ dags, 11.5 kg $m^{-1}$ dung and 7.5 kg $m^{-1}$ dung and dags (average fresh weight). These treatment quantities were selected to ensure full coverage of the plot. Weights differed between treatments as dung was heavier and dags lighter. Geotextile was always the final treatment applied to plots with mats being pegged to the soil. All treatments used in the trial had low nitrogen contents with 0.149 kg N $m^{-1}$, 0.077 kg N $m^{-1}$, 0.101 kg N $m^{-1}$ and 0.003 kg N $m^{-1}$ for dag, dung, combined dung and dags and geotextile.

MONITORING

*Vegetation monitoring*

To assess the effectiveness of the revegetation, plots were surveyed prior to applying treatments and a year later between December and January in 2015 and 2016. Within each plot, total plant cover was estimated using a randomly placed 1 × 1 m quadrat. The quadrat was divided into 361 smaller squares (19 × 19 squares, each ca. 5 × 5 cm) and we recorded the total number of squares containing green plant tissue whether from sown or unsown species. Following the same protocol, individual species cover was recorded for all species within a plot. We divided the recorded number of squares by the total number of quadrat squares to generate total plant cover and species-specific cover. For each species within a plot we recorded the presence or absence of flowers, including dead inflorescence as evidence of earlier flowering within the season. Maximum plant height was recorded at three locations within each plot using the drop-down method (Barthram 1986).

Plant biomass per plot was determined from a randomly selected harvestable plot. Before harvesting a plot, total plant cover and each species cover were determined to ensure plant cover for harvestable plots mirrored the larger treatment plots within each site. We found no differences in the statistical analysis for total cover or species cover for treatment plots compared to harvestable plots (below). All plant biomass was clipped within the 1 × 1 m area to 1 cm from the ground surface and separated by species *in situ*. Biomass was oven dried for 48 hours at 70°C and weighed (± 0.001 g; Oertling GC42, Orpington, Kent, UK) and expressed as kg $m^{-2}$.

*Microclimate and sediment movement*

To understand how microclimate potentially influences plant establishment and growth across treatments and soil types we monitored soil temperature, soil moisture and ground surface windspeed at the plot-scale each month. Plot-scale microclimate was monitored by spot measurements between January 2014 and January 2015. We used handheld probes to monitor soil temperature (°C) to a depth of 10 cm (HI 98501 Checktemp, Hanna instruments, Woonsocket, Rhode Island, USA) and soil moisture (%) to a depth of 5.5 cm (ML3, Delta-T, Cambridge, UK) at three random points in a plot every month. Maximum ground surface windspeed on each day of monitoring was taken from a height of 10.5 cm from the center of the plot and expressed as m $s^{-1}$. However, on two months, July and November 2015, we were unable to visit all trial sites due to exceptionally challenging weather conditions (e.g. ice and persistent severe gales) thus these have been omitted from the data analysis. Additionally at the site-scale, cumulative monthly ground surface sediment movement (or 'surface creep') was measured using buried sediment traps (7 × 7 × 7 cm) (see Koyama & Tsuyuzaki 2012). Traps were monitored every two to four weeks throughout the year. Sediment was oven-dried at 105°C for 48 hours, sieved to 2 mm to remove any stones and weighed (± 0.001 g). We calculated both the mean and range in soil temperature and moisture, average wind speed and sediment accumulation per week.

STATISTICAL ANALYSIS

To identify the most effective revegetation approach we investigated difference in sown treatments in terms of total plant cover, total biomass, maximum height and number of species native and non-native species. Only 11 out of 92 plots contained self-seeding native species not found in our species mixture, comprising on average 0.03 % total plant cover. Thus, these species were dropped from the analysis and all non-sown species reported here are non-native. All parameters were analyzed using Analysis of Variance (ANOVA) models with residual maximum likelihood (REML) to account for the slight imbalance of the design of the trial. For the main analysis we compared all treatments with sown native seeds using fixed component structure of dung, dag, geotextile treatments, treatment interactions, soil type, soil type and treatment interactions, region (i.e. farm) and region and treatment interactions. The random component of the model was trial site nested within paired block (i.e. split-plot design). Both total biomass and maximum height were log transformed to comply with model assumptions. The same model structure was used to analyze number of species in flower but following a poisson distribution. The total plant cover model used an offset of 1/361 (reciprocal of the total number quadrat of squares i.e. the smallest possible positive response) as the logit transformation cannot be performed on a zero response. Similar but simpler model structures outlined above were used to contrast plots sown with native seeds without treatments to control plots: both, without seed or treatment and no seeds but all treatments. There were no harvestable plots for control plot treatments so we did not compare native sown and controls in terms of biomass accrual. Separate ANOVA models with REML were also used to determine the effect of treatments on average soil surface wind speed, soil moisture and temperature and annual range in soil moisture and temperature. Models were analyzed using either Genstat version 18.1.0.17005 (VSN International Ltd., Hemel Hempsted, UK) or R version 3.3.1 Mavericks build 7238 (R Foundation for Statistical Computing, 2016).

Reduced models were fitted to the data, based on the statistical significance of factors in the full model. P-values were obtained using the F-distribution comparing variation of the treatment being tested against the appropriate random variation. The reduced model had the same random effects as the full model but only fixed effects with $p<0.05$ in the full model were included. Lower order effects of statistically significant interactions were also kept in the reduced model regardless of their statistical significance. Predicted means from the reduced model were extracted along with appropriate standard errors for any statistically significant treatment, soil type and region. The difference between relevant terms and the significance of the difference along with a 95% CI for the difference were calculated. No adjustments were made for multiple comparisons as a pre-specified subset of possible comparisons were used. P-values generated from the differences within treatment, soil type and region are shown in parathenses.

## RESULTS

### REVEGETATION APPROACHES DUNG, DAGS AND GEOTEXTILES

Sowing native seeds in combination with sheep dung, sheep dags and geotextile and their combinations increased total plant cover, total plant biomass, number of flowering species and maximum height across all eroded soil types (Fig 2; Table S3). Importantly, in the absence of supportive treatments sowing native seeds alone resulted in little revegetation (Fig 2a). Plots with seeds only had on average 1.4% plant cover, which was not significantly different from control plots (no seeds or treatments), which averaged 1.0% cover (p= 0.389).

Dung treatments increased plant cover (sown and non-sown) on average by 55.1%, sheep dags 35.2% and geotextiles 19.5% (ANOVA; $F_{1,47}$=105, p<0.001). Similarly, within a year treatments accrued total plant biomass averaged 1.88 kg $m^{-2}$, 1.40 kg $m^{-2}$ and 0.54 kg $m^{-2}$ for dung, dag and geotextile alone treated plots (Fig 2b, Table S3). The number of species flowering was enhanced by dung ($X^2$ = 50.09, df=1,13, p<0.001) and dags ($X^2$ = 7.20, df=1,13, p=0.007), but not by the addition of geotextiles ($X^2$ = 0.46, df=1,12, p=0.499) (Fig 2c). Swards on dung and dag treated plots were significantly taller than those with seeds only, reaching 19.4 cm and 11.19 cm, respectively (ANOVA; dung $F_{1,46}$=87, p<0.001; dags $F_{1,46}$=39, p<0.001). However, swards underneath geotextile were short, averaging 1.75 cm, and did not significantly differ from seed only plots (Table S3). Nevertheless, the low stature of plants under geotextiles did not impact total plant cover or biomass accrual.

Plant cover, biomass and height were not enhanced by combining treatments, except for the addition of dung in the presence of dags for both total cover from 49.1% to

86.1% (37% increase) and biomass from 4.89 kg $m^{-2}$ to 10.1 kg $m^{-2}$ (106% increase; Table S3). When dung was already present adding dags resulted in only a small increase in plant cover or biomass. The positive impact of dung on revegetation differed across soil types (ANOVA; $F_{2,48}$=4.4, p=0.017): dung increased plant cover on peat by 81.3% (p<0.001) and on clay 73.7% (p<0.001), but only 26.7% cover on sand (p=0.28) in contrast to plots without dung. Likewise, the presence of dung significantly increased plant biomass (ANOVA; $F_{2,41}$=27, p<0.001): on peat (p<0.001) and clay (p<0.001), but not on sand (p=0.059). The impact of geotextiles was also dependent on soil type (ANOVA; $F_{2,41}$=10, p=0.012) and matting significantly increased plant biomass from 0.03 kg $m^{-2}$ without to 5.43 kg $m^{-2}$ with geotextiles (p<0.001) on sand, yet there was no significant additional benefit of geotextiles for total plant biomass on clay (p=0.097) or peat soils (p=0.075). Nevertheless, it is noteworthy that all interactions between treatments and soil type were driven by sand soil type, of which there was only one site.

NATIVE VS. NON-NATIVE SPECIES ACROSS TREATMENTS AND SOIL TYPES

A total of 13 out of 15 sown native species were surveyed across all sites. Three native species grew consistently across all sown treatments and soil types: *E. magellanicus*, *P. flabellata* and *P. alopecurus* occurring in 64.1, 50 and 50% of all sown plots. Moreover, these three species individually accounted for between 10 to 45% of plant cover on average, while other sown native species typically covered less than 5%. *G. magellanica* and *C. fuscula* were not detected across all sites and both of these species had negligible germination rates prior to the trial (Table S2). *Juncus scheuchzerioides* only occurred on peat soil at Cape Pembroke, while the majority of other native species were found across multiple sites and soil types (Fig 3). *Juncus scheuchzerioides* was present in low abundance prior to establishing the trial and is thus likely to have established from rhizomes rather than sown seeds.

Dung treatments supported greater numbers of sown native species averaging 7.0 native species (ANOVA; $F_{1,46}$=73, p<0.001) followed by 4.6 species for dags (ANOVA; $F_{1,46}$=15, p<0.001) but not geotextiles with 2.3 species compared to treatment controls (Table S3). Although the use of geotextile matting facilitated the establishment of total plant cover (both natives and non-natives), geotextiles did not significantly increase the number of native species compared to sowing seeds without treatments (Table S3). Sown native species cover was detected in control plots indicating movement of seeds across plots during hand broadcasting, but sown species cover was low averaging 0.36% in controls and 7.9% in treatment control plots (Fig 2a). Soil-specific establishment of native species was limited: *Festuca magellanica* established slightly better on clay, *Festuca contracta* on peat and *Leptinella scariosa* on sand (Fig 3). Because some regions only had a single soil type and only one region had sand soil, we were unable to differentiate effects of soil type and region in our species analysis. Thus, soil-specific establishment rates could alternatively be region-specific (Fig 3).

Treatment control plots without the native seeds had similar total plant cover, number of flowering species and sward heights to native sown treatments (Fig 2a,c). Treatment control plots had significantly higher plant cover ($p<0.001$; Fig 2a) and plant height ($p<0.001$) than control plots. Yet, treatment control plots were dominated by non-native species rather than native species, non-natives comprising 76.8% of the plant cover. The number of non-native species occurring in treatment controls was significantly higher than control plots without treatments, which comprised an average of 52.8% of the cover ($p=0.002$). Non-native species occurrence in native sown plots was low, averaging 1.1 species on dung and dags and 0.63 species in geotextile plots (Fig 2a; Table S3). In general, the common non-native species had lower rates of occurrence than native species throughout the trial with highest being 33.7% for *Aira praecox*, 27.2% for *Poa annua* and 12.0% for *Holcus lanatus*. In addition, other non-natives species accounted for less than 7% plant cover across all treatments. There was no significant relationship between native species and non-native species cover (linear model: $F_{1,91}=0.442$, $p=0.508$) or biomass (linear model: $F_{1,61}=0.523$, $p=0.4071$) across all plots, suggesting neither a negative or positive relationship between native and non-native species.

Non-native species showed associations both with soil type and region with *Agrostis stolonifera* and *Festuca rubra* occurring primarily on sand at Fitzroy, while *Aira praecox* occurred on peat and *Cerastium fontanum* on clay (Fig 3). Due to confounding effects of soil type and region we were unable to ascertain the source of the non-native species: whether they were derived from treatments themselves (i.e.

weak regional effects) or whether they were colonized by dispersed seeds from nearby vegetation (i.e. strong regional effects) after the treatments were applied. If non-natives were derived from treatments themselves, then organic sources such as dung or dags would likely support greater numbers and cover of non-native species compared to geotextile. While non-native diversity was low on geotextile only treatments, this treatment had the highest non-native cover compared to dung or dags treatments only (Fig 2a). Nevertheless, it is also possible that non-native species germinated from treatments, but were outcompeted by native species, particularly on dung that strongly supported native species (Fig 2a). Moreover, during monitoring non-native seeds were observed covering treatments in the summer months. There were a higher number of flowering non-native species compared to native species suggesting that non-natives were more ruderal in the short-term (Fig 2c).

IMPACT OF TREATMENT AND SOIL TYPE ON MICROCLIMATE AND REVEGETATION

Average soil moisture and temperature significantly differed between treatments but the differences were small, varying on average in soil moisture by 1% and in temperature 0.1°C between dung, dags, and geotextile. Instead, microclimatic differences between soil types were much greater with 11% for moisture and 1.2°C for temperature (Fig 4). On average, peat soils were cooler and wetter with a larger range in the maximum and minimum soil moisture, while sand was warmer with a high variability in temperature and clay warm and dry with a low variability (Fig 4). There was greater treatment-induced variability in soil moisture on peat and temperature on sand (Fig 4). Geotextile matting significantly reduced soil moisture on peat soils but not on sand or clay, yet these did not influence total plant cover, biomass or the ratio of natives to non-natives (Table S4). During the trial soil surface windspeed across all sites averaged 9.5 $ms^{-1}$ (18.5 knots) and the highest recorded windspeeds was 32 $ms^{-1}$ (62.2 knots). Average annual soil movement rates were 60.3 kg $m^{-2}$ on peat, 86.4 kg $m^{-2}$ on clay and 155.2 kg $m^{-2}$ on sand, but annual soil movement was unrelated to site-scale plant cover or biomass accrual. Across our study sites both native and non-native species were able to establish in challenging climatic and soil movement conditions.

**DISCUSSION**

In this study, we demonstrate that sowing native seeds in combination with locally sourced treatments can be an effective approach to revegetating severely eroded habitats on remote islands. Trialing different revegetation approaches on the Falkland Islands, native species were able to establish across multiple soil types and in challenging edaphic and climatic conditions. As part of this trial, we were able to revegetate degraded habitats previously viewed as impossible (e.g. clay) when planting tillers of native species or sowing non-native species (Kerr 1994; Cris et al. 2011). Yet, we stress that revegetating was limited in the absence of effective supportive treatments. For this study, supportive local treatments such as sheep dung and dags were freely available, and local treatments may be preferable to incurring costs by importing treatments for habitat restoration on islands (e.g. geotextile matting) (Holl & Howarth 2000; Smith 2006). All treatments supported native species establishment, although they also facilitated establishment of non-native species. Therefore, this approach may be inappropriate for ungrazed oceanic islands that are managed to mitigate the spread of introduced species (Chapin et al. 2000; FIG 2016; Sax & Gaines 2008; Van der Wal 2015). Nevertheless, within the first year of this trial, plant cover, biomass and the number species was dominated by native rather than non-native species. Thus, in the short-term our approach can provide rapid native plant cover on degraded soil on remote oceanic islands.

From this study the mechanisms underlying how treatments enhance plant establishment remain unclear. Treatments are often applied to ameliorate microclimatic and edaphic conditions altered due to the loss or degradation of organic topsoil (Allen 1995); yet, contrary to our hypothesis, treatment effectiveness seemed unrelated to changes in soil microclimate. Similarly the greatest revegetative effects of the treatments were not observed on the most challenging soils on the island, that is, heavy clays. Instead, soil type dependent treatment effects occurred on peat and sand. On peat, dung had a greater impact than on clay or sand soils. This could have been due to stimulation of the microbial community that has been shown to underpin successful revegetation (Harris 2009; Wubs et al. 2016) and is likely to be more developed in peat than clay or sand. However, Leiber-Sauheitl et al. (2015) found no evidence that the addition of sheep excreta stimulated pristine peat microbial community, although results may be different on degraded peat with differing microbial communities (Anderson et al. 2013; Elliott et al. 2015). On sand, we found that geotextiles enhanced plant biomass compared to other soil types. Our sand site had the greatest rates of soil movement and the success of this treatment could have been due to a stabilizing effect that facilitated plant establishment (Koyama & Tsuyuzaki 2012). Nevertheless, neither soil microbes nor soil movement satisfactorily explains the effectiveness of all treatments across all soil types. Alternatively, perhaps treatments did still operate via amelioration of soil microclimatic and edaphic conditions but within the initial days or weeks after sowing during seedling emergence (Koyama & Tsuyuzaki 2012; Madsen et al. 2016) and this was not detected over our coarser monthly (to annual) measurement intervals. For example, there was significant cover and biomass on dung only plots, yet for most of these plots a significant quantity of dung had dried and been blown away after the first few months.

Prior to this study little was known about the autoecology of many Falkland Island plant species in order to optimize their application. We found that species used in this trial had few specific soil associations or microclimatic requirements and were therefore typically generalist colonizers. Three native species dominated the trial: *Poa flabellata* (tussac), *Elymus magellanicus* (Fuegian couch grass) and *Poa alopecurus* (Bluegrass, sand ecotype). Of these species, *P. flabellata* (Tussac) is the most well studied and similar to our results Smith (1985) on South Georgia found that planted two-leaf *P. flabellata* seedlings established across soil types and under challenging climatic conditions (*sensu* exposure), yet seedling biomass production was significantly increased by nutrient solution addition. On the Falkland Islands, the successful native species in our trial are predominantly coastal and often receive significant nutrient inputs from marine mammal and sea bird colonies and the plant productivity benefits of such allochthonous (marine-derived) nutrient inputs has been observed on other island ecosystems (Bergstrom et al. 2001; Ellis 2005). Furthermore, anecdotal evidence suggests that allochthonously nutrients can enhance planted *P. flabellata* tiller establishment and growth (Kerr 1994; Smith & Karlsson 2017). Thus, a nutrient source, however small in quantity (i.e. sheep dung), may play an important role in ensuring establishment and growth of Falkland Island plant species.

A major drawback with using native seeds for revegetation is collecting and/or generating sufficient quantities of seeds to address the large spatial scales of degraded habitats (Mijnsbrugge et al. 2010; Merrit & Dixon 2011). In order to attain sufficient seeds for this trial required 59 seed collections involving 47 people harvesting seeds over four months and additional hours of seed processing and cleaning. However, the quantity of seeds required to revegetate Falkland grasslands could potentially be significantly reduced. We sowed seeds at densities of 200 seeds per species $m^{-2}$, yet many of the successful species form large tussocks (Broughton & McAdam 2005; Moore 1968). For example, individual *P. flabellata* tussocks can reach sizes of 1.5 $m^2$ area and 3 m tall (Gunn 1976; Smith & Karlsson 2017). Potentially only a handful of seeds would be necessary to revegetate each square meter. Yet, it is not known whether at the seedling stage sown individuals facilitate one another enhancing rates of plant establishment on bare soil. Additionally, little is known about undisturbed native plant community seed production and seed bank activity and such knowledge could be used to better estimate seed densities required for restoring native communities on degraded soil. Further long-term research is required to test the establishment rates of sown large-tussock species at different densities to optimize the use of sowing native seeds. Equally, the longevity of these plants must be monitored, as species may not persist once the original treatment is exhausted or outgrown.

A second challenge to the wider reintroduction of native species for revegetation in the Falkland Islands is livestock grazing. Extensive soil erosion on the islands can be attributed to over grazing (Wilson et al. 1993) with many of the native species used in this trial having been largely 'grazed out' of the archipelago's mainlands (Strange et al. 1988; Brought & McAdam 2005). In our study, in order to revegetate soil we excluded livestock and there is a strong likelihood that without fencing many of our native species would be intensely grazed thereby hindering revegetation. Thus, it is questionable whether farmers and landowners would readily exclude livestock in order to revegetate eroding soil as ceasing grazing and fencing represents a financial and labour cost, and excluding livestock diverges from the cultural and historic norms of free-ranging livestock (Davies 1939). As we did not tailor the seed mixture, a potential avenue for further work may be to investigate the use of a seed mixture that contains both strong native colonizers as well as native species tolerant to livestock grazing such as *Cortaderia pilosa* (White grass) and dwarf-shrub species (McAdam 1986). Sowing our successful native species could be integrated with alternative grazing practices that are increasingly being adopted across the islands. For example, seeds and treatments could be applied within rotational livestock grazing management, during the period of 'rest' when a paddock is ungrazed. Nevertheless, for our approach to be adopted and gain widespread traction across the islands requires better integration of sowing native seeds with livestock grazing.

Many remote island communities have a limited capacity to undertake revegetation of degraded habitats. Here we demonstrate that sowing wild collected native species in combination with local treatments can be an effective approach to revegetating eroded soils. However, the main disadvantage of this approach is that many of the native species have been 'grazed out' of islands. Without temporary cessation of grazing or integration with new grazing regimes sowing native species may be ineffective at revegetating eroded soil. The Falkland Islands Biodiversity Framework aims to find solutions to environmental issues that consider environmental sustainability, economic prosperity and social wellbeing (FIG 2016). In this study, we identify an environmentally sustainable approach using native seeds and local treatments that addresses widespread soil erosion across the islands. Yet, further work is necessary to explore if this approach of sowing native species can be integrated with grazing management; whether by tailoring a seed mixture with grazing tolerant species or sowing seeds as part of rotational livestock grazing practices.

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**FIGURES**

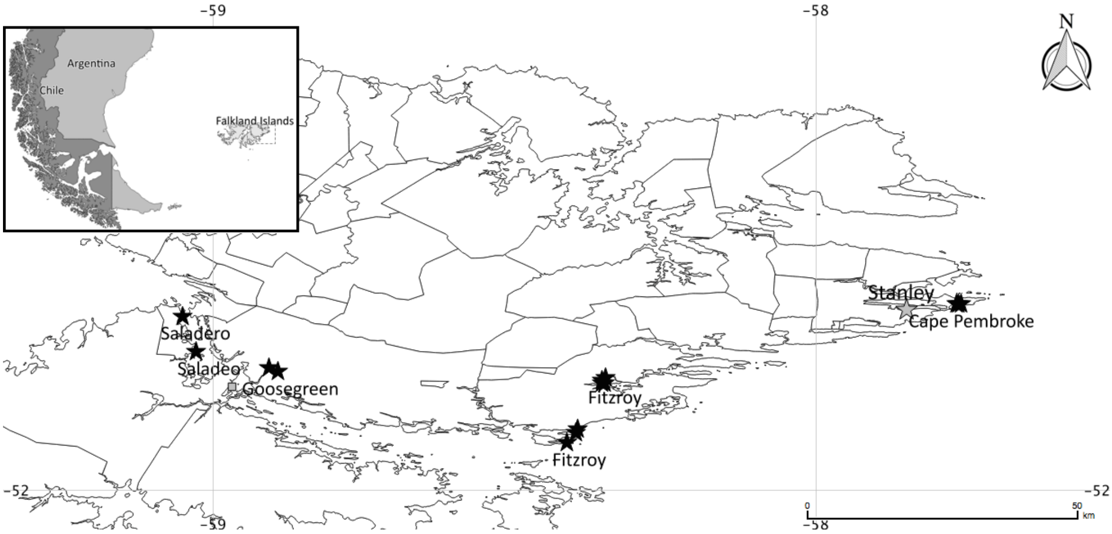


Figure 1. Native seed restoration trial sites on eroded soil established across East Falkland mainland in 2014. A total of 16 sites are shown as black stars, although within farms some are less than 1 km apart. Farms boundaries are shown as well as major settlements, including: the capital Stanley and Goosegreen.

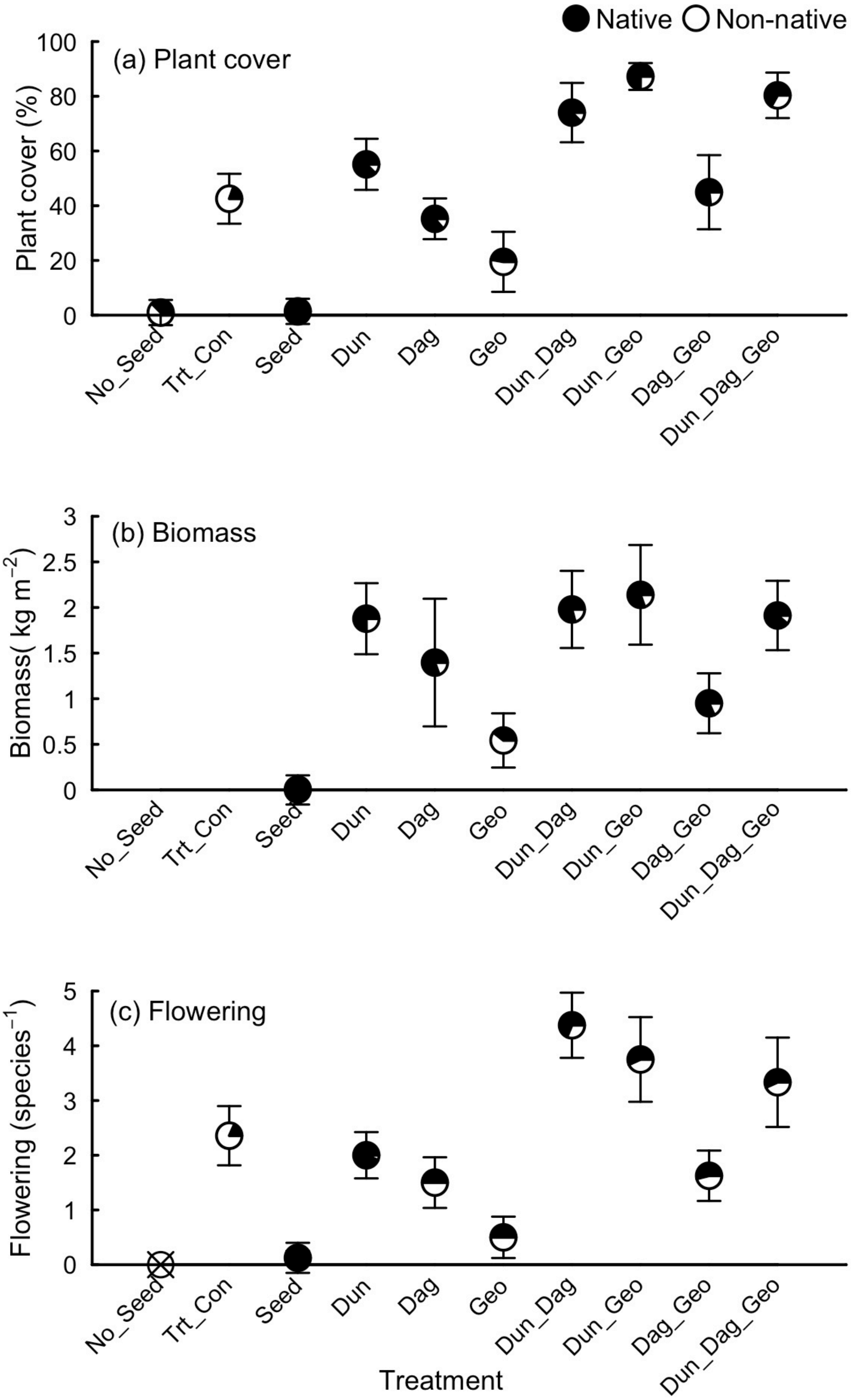


Figure 2. Average (a) plant cover, (b) biomass and (c) flowering for revegetation treatments and their combinations. The proportion of total plant cover, biomass and number of species flowering with native species shown in black and non-native species in white. A crossed symbol represents a zero value. All error bars are ±1 SE.

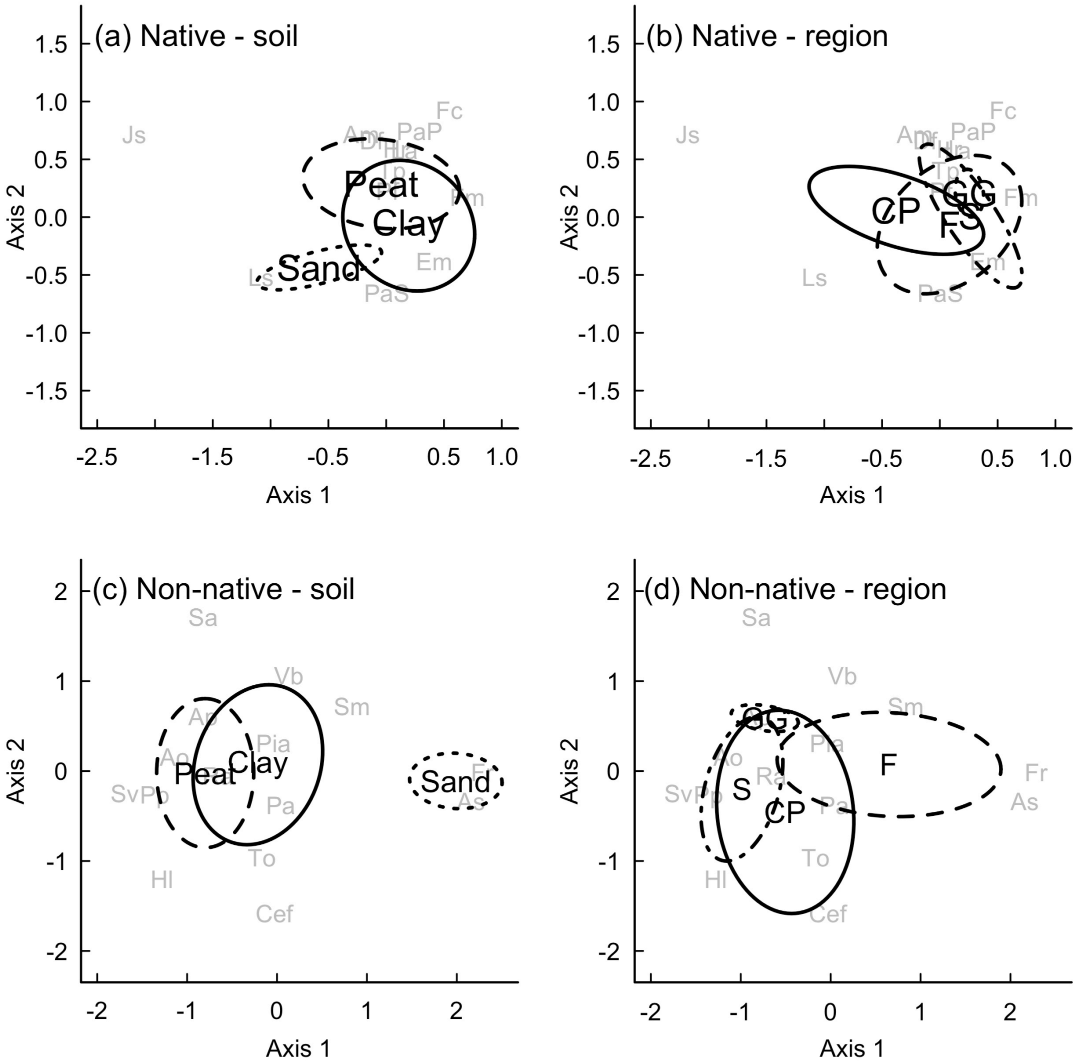


Figure 3. Non-metric dimensional scaling ordination using Bray-Curtis dissimilarity of native species plant cover in relation to (a) soil type and (b) region and non-native species plant cover in relation (c) soil type and (d) region for all revegetation plots. Associations with soil type and region are shown using different line types with 95% confidence intervals. Soil types are labeled as clay, peat and sand, while regions are abbreviated as follows 'CP' is Cape Pembroke, 'F' is Fitzroy Farm, 'GG' is Goosegreen Farm and 'S' is Saladero Farm. Plant species are in light grey and have been abbreviated as follows for native species: Am = *Acaena magellanica,* Cf = *Carex fuscula*, Df = *Deschampsia flexuosa*, Em = *Elymus magellanicus*, Fc = *Festuca contracta*, Fm = *Festuca magellanica*, Gm = *Gunnera magellanica*, Hr = *Hierochloe redolens*, Js = *Juncus scheuchzerioides*, Ls = *Leptinella scariosa*, La = *Luzula alopecurus*, PaP = *Poa alopecurus* Peat, PaS = *Poa alopecurus* Sand, Pf = *Poa flabellata*, Tp = *Trisetum phleoides* and non-native species: As = *Agrostis stolonifera*,

Ac = *Agrostis capillaris*, Ap = *Aira praecox*, Ao = *Anthoxathum odouratum*, Cef = *Cerastium fontanum*, Fr = *Festuca rubra*, H = *Holcus lanatus*, Md = *Matricaria discoidea,* Pia = *Pilosella aurantiaca*, Pa = *Poa annua*, Pp = *Poa pratensis*, Ra = *Rumex acetosella*, Sa = *Spergula arvensis*, Sv = *Senecio vulgaris*, Sm = *Stellaria media,* To = *Taraxacum officinale* and Vb = *Vulpia bromoides*.

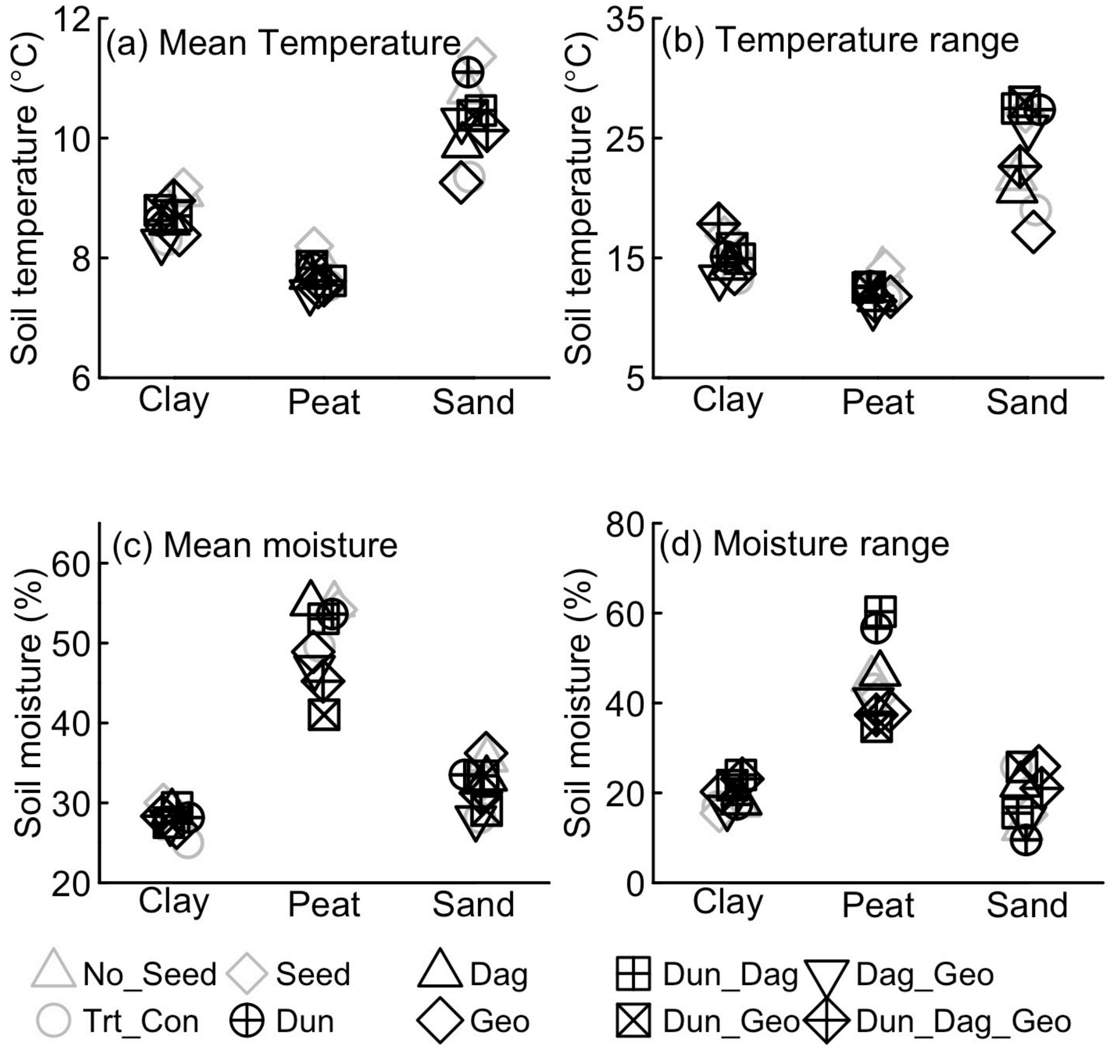


Figure 4. Annual (a) average temperature, (b) temperature range (maximum minus minimum), (c) average moisture and (d) moisture for revegetation treatments and their combinations across three soil types (clay, peat and sand).