Progress in
Physical Geography

Vegetation structure influences the retention of airfall tephra in a sub-Arctic landscape

Journal:	*Progress in Physical Geography*
Manuscript ID	PPG-15-094.R1
Manuscript Type:	Main Article
Keywords:	aeolian sediment, tephrochronology, Iceland, photogrammetric analysis, vegetation structure

Abstract:

Vegetation cover mediates a number of important geomorphological processes. However, the effect of different vegetation types on the retention of fine aeolian sediment is poorly understood. We investigated this phenomenon, using the retention of fine, pyroclastic material (tephra) from the 2011 eruption of the Grímsvötn volcano, Iceland, as a case study. We set out to quantify structural variation in different vegetation types and to relate structural metrics to the thickness of recently deposited volcanic ash layers in the sedimentary section. We utilised a combination of vegetation and soil surveys, along with photogrammetric analysis of vegetation structure. We found that indices of plant community composition were a poor proxy for vegetation structure and were largely unrelated to tephra thickness. However, structural metrics, derived from photogrammetric analysis, were clearly related to variations in tephra layer thickness at a landscape scale and tephra layers under shrub patches were significantly thicker than those outside the shrub canopy. We therefore concluded that a) vegetation cover was a critical factor in the retention of fine aeolian sediment for deposit depths up to few centimetres and b) structural variation in vegetation cover played a major role in determining the configuration of tephra deposits in the sedimentary section. These findings have implications for the analysis of ancient volcanic eruptions and archaeological/palaeoenvironmental reconstructions based on the interpretation of tephra deposits. Furthermore, they present the possibility that the detailed form of tephra layers may be used as a proxy for palaeo vegetation structure.

Abstract

Vegetation cover mediates a number of important geomorphological processes. However, the effect of different vegetation types on the retention of fine aeolian sediment is poorly understood. We investigated this phenomenon, using the retention of fine, pyroclastic material (tephra) from the 2011 eruption of the Grímsvötn volcano, Iceland, as a case study. We set out to quantify structural variation in different vegetation types and to relate structural metrics to the thickness of recently deposited volcanic ash layers in the sedimentary section. We utilised a combination of vegetation and soil surveys, along with photogrammetric analysis of vegetation structure. We found that indices of plant community composition were a poor proxy for vegetation structure and were largely unrelated to tephra thickness. However, structural metrics, derived from photogrammetric analysis, were clearly related to variations in tephra layer thickness at a landscape scale and tephra layers under shrub patches were significantly thicker than those outside the shrub canopy. We therefore concluded that a) vegetation cover was a critical factor in the retention of fine aeolian sediment for deposit depths up to few centimetres and b) structural variation in vegetation cover played a major role in determining the configuration of tephra deposits in the sedimentary section. These findings have implications for the analysis of ancient volcanic eruptions and archaeological/palaeoenvironmental reconstructions based on the interpretation of tephra deposits. Furthermore, they present the possibility that the detailed form of tephra layers may be used as a proxy for palaeo vegetation structure.

Keywords

Aeolian sediment, tephrochronology, Iceland, photogrammetric analysis, vegetation structure

Introduction

Vegetation cover is a key factor in terrestrial geomorphology, as it mediates microclimate, hydrological processes and mass movement (Marston, 2010). Vegetation plays a particularly important role in the entrapment and stabilisation of sediment carried by fluids, whether the fluid is water (e.g. salt marshes) or air (e.g. sand dunes) (see, e.g., Baas, 2002; Langlois et al., 2003). However, the precise impact of different vegetation types on terrestrial sediment cycles is still poorly understood. For example, volcanoes produce considerable quantities of airborne ash and this material is a major component of soils worldwide (Takahashi and Shoji, 2002). However, the processes by which fine, pyroclastic particles (tephra) are trapped and incorporated into soils are not well defined. In contrast to the quasi-continuous aeolian deposition typical of arid or coastal environments, tephra are typically deposited rapidly, ballistically and in discrete events (often separated by many years), so the rules that govern other forms of sediment accumulation may not be strictly applicable. Vegetation cover is likely to play a role in the retention of tephra, but the importance of this factor has not been explored. The overall aim of this research was therefore to investigate how different vegetation types influence the retention of episodically deposited aeolian sediment, using the deposition of volcanic ash as an exemplar.

Previous work has indicated that the capacity of vegetation to trap and retain sediment is dependent upon its structure (the physical configuration of above ground biomass and the intervening voids: Zehm et al., 2003) and the way in which this structure modifies local wind fields (e.g. structural configurations which greatly reduce wind speeds are likely to result in sediment retention). Many different metrics of vegetation structure have been proposed; however, previous studies have demonstrated that the ability of vegetation to trap sediment is captured by relatively straightforward characteristics e.g. vegetation height, density and porosity (i.e. the network of voids defined by stems, leaves, etc. within the vegetation: Moller, 2006). Whilst these aggregate characteristics are conceptually simple, they are difficult to measure reliably in the field. The most promising techniques for investigating vegetation structure have involved photogrammetry i.e. the quantitative analysis of high-resolution photographic images. Surveys utilising this technique have demonstrated that photogrammetric studies of vegetation can be rapid, detailed, reproducible and, under ideal circumstances, non-destructive (Moller, 2006; Neumeier, 2005; Zehm et al., 2003). Consequently, we set out to refine existing photogrammetric techniques in order to capture the essential structural characteristics of low-growing vegetation (mosses, forbs and short graminoids), structural types that have been neglected by previous researchers.

Our study focused on the deposition and retention of airfall tephra. Tephra particles are pyroclastic fragments produced during explosive volcanic eruptions (Lowe, 2011; Thorarinsson, 1944). Coarse tephra grains (lapilli with a diameter > ~4 mm) are rapidly sedimented from the atmosphere and are mostly confined to a region proximal to the volcano. However, fine grains may be transported considerable distances (100s to 1000s km) in the atmosphere before they are deposited as airfall tephra (Stevenson et al., 2015). Once on the ground, they are readily mobilised by wind and water unless something acts to stabilise them (Sarna-Wojcicki et al., 1981). If the tephra deposit is stabilised and of sufficient thickness it can form clearly defined layers in sedimentary sections. These layers cover large parts of Earth's surface. Tephra deposits are of interest for three main reasons. Firstly, they may be used in the reconstruction of the fallout area and erupted volume of past volcanic eruptions (Lowe, 2011). When conducting reconstructions of this type, it is essential to know how faithfully the tephra layer records the characteristics of the initial deposit. This is particularly important in spatially extensive distal locations where the quantity of tephra is greatest (see, e.g., Sarna-Wojcicki et al., 1981), but the deposit is thin, fine-grained and readily transformed. Secondly, tephra layers are frequently used as chronostratigraphic horizons (Lowe, 2011). In this case, all that matters is the identification of the isochron. Thirdly, if a tephra layer is considered to be a pulse of sediment of known age and provenance, it may be used as a tracer to understand a) geomorphological processes that are otherwise impractical to investigate e.g. aeolian erosion and deposition and b) the environmental impacts of an eruption, using palaeoecological techniques.

The interpretation of tephra layers in the soil is premised on the assumption that the thickness of the layer in the soil is directly related to the thickness of the initial deposit. Airfall tephra mantles the landscape, i.e. the thickness of a fresh deposit is likely to be more-or-less the same in locations separated by a few kilometres, unless such locations are near the edge of the plume. However, tephra layers in the sedimentary section are often highly variable over small spatial scales (centimetres – metres) (Streeter and Dugmore, 2013b). If ancient tephra layers are to be correctly interpreted, it is necessary to understand the processes by which a fresh tephra deposit is ultimately transformed into a sedimentary layer. Thick tephra deposits (tens of cm – metres thick) obliterate vegetation cover and geomorphological processes are likely to determine the overall configuration of the final deposit. However, there is evidence that some vegetation can survive moderate (up to a few cms) tephra deposition. Some mosses, for example, are porous to fine tephra particles and can absorb light falls without detrimental effects. Bjarnason (1991) reported that carpets of the moss *Racomitrium lanuginosum* can absorb falls of up to 8cm without incurring significant damage; Zobel & Antos (1997) noted moss recovery from falls < 2cm in forest adjacent to Mount St. Helens and Hotes *et al* (2004) reported the recovery of *Sphagnum* spp. moss from beneath deposits 6cm thick. It is therefore possible that surviving biomass can trap and stabilise tephra, thus influencing the formation of tephra layers (Streeter and Dugmore, 2013a).

A number of studies have investigated the impact of tephra deposition on vegetation cover (see, e.g., Kent et al., 2001; Arnalds, 2013a). However, few have considered the problem in reverse. This project investigated the relationship between vegetation structure and tephra depth on a series of sites in southern Iceland. Tephra-producing volcanic eruptions occur on average every 3 years in Iceland and the tephrochronology of the island is well constrained (Haflidason et al., 2000; Thordarson and Larsen, 2007; Larsen et al., 1999). It is therefore an ideal location for a study of this type. Our specific research aims were to 1) assess the utility of plant community composition as a proxy for vegetation structure; 2) establish whether qualitatively different types of vegetation cover, defined largely on the basis of species composition, could be differentiated using photogrammetric analysis of structure and 3) relate metrics of vegetation structure to the thickness of recently deposited tephra layers in the sedimentary section.

Methods

Sampling locations

The research was conducted on three sites in southern Iceland: Fossdalur, Kalfafell and Blómsturvellir (Fig. 1). The Kalfafell site provided two sampling locations (one dominated by moss and one by grass), giving four sampling locations in total (Table 1). Tephra were deposited on the sites during the 2011 eruption of the Grímsvötn volcano (hereafter referred to as G2011). The G2011 eruption produced ~0.6 – 0.8 km3 of tephra which were subsequently distributed over a large area of southern Iceland (Gudmundsson et al., 2012). All of the study sites were located between 50-55 km from Grímsvötn caldera and within the main axis of fallout from the eruption (Fig. 1e). The initial depth of the tephra deposit was similar on all the sampling locations. By the time the surveys were conducted (June 2014) the G2011 tephra was not visible on the surface, either because the vegetation had grown through tephra and/or the particles had percolated through the vegetation. Rather, the G2011 tephra formed a distinct, dark layer in the upper horizons of the soil. Three years of post-eruption deposition had led to a layer of sediment 0.25 – 1.5 mm thick on top of the tephra, deposition rates in line with measures of accumulation in southern Iceland over the past 100 years (Streeter and Dugmore, 2013a).

The sampling locations were broadly flat or gently sloping and had limited microtopographic variation (Fig. 1). The key characteristic that varied between the sampling locations was vegetation cover, which was categorised qualitatively at the beginning of the study, based on the dominant functional type of vegetation. The major growth forms encountered were mosses, graminoids and dwarf shrubs. With the exception of the Blómsturvellir sampling location (where the moss/graminoid heath was interrupted by small shrub patches) we deliberately chose sampling locations with relatively homogeneous vegetation cover.

Table 1: Site characteristics

Fig. 1: Site photos

Vegetation surveys

The vegetation cover on each of the four sampling locations was recorded using systematic quadrat surveys (Table 1). A 50 x 50 cm quadrat was deployed on a grid; the grid dimensions varied according to the size and shape of each sampling location. We recorded all of the plant species present and estimated the cover of each taxon according to the Domin scale (Kent, 2012). The survey encompassed both mosses and vascular plants. The survey was conducted in June 2014; the 2011 tephra was deposited in March, so the vegetation at the time would have been relatively less developed. However, the relative change in vegetation density between seasons is low in Iceland and we therefore assumed that the vegetation surveys would give us an indication of the relative differences between vegetation types.

The Blómsturvellir site, which was characterised by patches of woolly willow (*Salix lanata*) in a matrix of grass/moss heath, was initially surveyed using a grid of quadrats (the Bg survey). This survey mainly covered the low-growing vegetation (predominantly composed of mosses and graminoids). Ground-layer vegetation under the shrub patches was then surveyed using haphazardly-placed quadrats (the Bh survey, N = 20), to see if the presence of a willow canopy impacted on the graminoid/bryophyte community.

Photogrammetric surveys

The survey technique applied was based on that developed by Zehm et al. (2003) and subsequently refined by others (Moller, 2006; Neumeier, 2005). A side-on, high-resolution digital photograph was taken of a patch of vegetation 35 cm across x 25 cm deep (Fig. 2). A 35 cm wide x 27 cm high white backing board was placed behind the target vegetation. The camera was positioned on a line normal to the centre of the board, at a distance of 80 cm. The vegetation immediately adjacent to the target zone was removed by excavation: this made the ground line visible and permitted high-resolution measurements of the underlying tephra layer. The remaining vegetation between the camera and the target zone was flattened with a board, so that it did not appear in the photograph.

Fig. 2: cartoon of camera set-up

Tephra depth

The G2011 layer exposed in the excavated area was measured at five points at ~12.5 cm intervals (i.e. at both ends of the exposed section and at three points in between). The tephra layer was identified on the basis of colour (black, in contrast to the orange-brown andisol). Measurements of tephra thickness were made to the nearest millimetre.

Photographic image processing

The raw digital images were converted to grayscale and cropped to the boundaries of the backing board, using the programme Adobe Photoshop™. Each image was then processed using a bespoke routine written in MATLAB. First, the grayscale images were converted to black and white images using a threshold parameter that was adjusted according to camera exposure and vegetation type to ensure correspondence between pixel colour and true plant presence/absence. Starting from the base of each image and working upwards, the routine counted the numbers of black pixels (vegetation) in each row of the image, thereby encapsulating the vertical structure of the vegetation. From these data, it was straightforward to calculate the overall density of the vegetation i.e. the proportion of black pixels and the maximum height of the vegetation. However, these simple metrics are likely miss some of the complexity of the vegetation structure e.g., where maximum height is driven by a single, slender leaf that extends above the bulk of the vegetation. Consequently, the programme was designed to return more detailed structural metrics. For example, vegetation density (proportion of black pixels) at any given height may be calculated. It is also possible to derive more nuanced metrics of vertical vegetation structure e.g. the height below which a given proportion of black pixels occur (P_x, where x is proportion of the total number of pixels). If P_x is plotted against height, vegetation cover with different structural configurations would be expected to produce qualitatively different curves (Fig. 3).

Figs 3: Hypothetical analyses of vegetation structure

Analysis

Detrended correspondence analysis (DCA) was applied to the vegetation survey data. DCA is a robust multivariate technique that is capable of dealing with noisy data (ter Braak, 1995). DCA was used to graphically represent the different vegetation communities and to establish whether a) the initial, qualitative assessments of vegetation type were supported by quantitative analysis of community composition and b) how similar the ground layer vegetation under the willow canopy on the Blómsturvellir site was to the surrounding, unshaded vegetation. DCA was also used to calculate the compositional variability of the plant communities, expressed in terms of multivariate inertia, a unitless metric of variability that is analogous to variance. If community composition is a good proxy for vegetation structure and vegetation structure influences tephra depth, then compositional variability should be correlated with variation in the tephra thickness. Shannon diversity was also calculated as a metric of compositional variability.

Photogrammetry was used to describe vegetation structure at each sampling location. The MATLAB routine was used to calculate the cumulative proportion of black pixels (P) with height for each quadrat. The distributions were then modelled for each sampling location by fitting a curve of the form $y = a(1 - e^{-bx})$, which represents a gradual attenuation of vegetation density with height (Fig. 3). This two-parameter function was chosen as it provides sound fits and also contains parameters which are intuitively helpful: a rate (*b*) describing the change in density with height, and an asymptote (*a*) describing the total vegetation density of the image (i.e. the curvature of the fitted line). The significance of the fit was established using Monte Carlo techniques.

Mean tephra thicknesses on each site were analysed using ANOVA and the sites compared using a post hoc test (Tukey's HSD). We also calculated the coefficient of variation (CV) of tephra layer thickness for each sampling location, so this figure could be compared with variability in plant community composition. We assessed the relationship between vegetation structure and tephra thickness using a linear mixed effects model, with mean G2011 thickness in each quadrat as the response variable, vegetation height (derived from the photogrammetric analysis) as the fixed effect and site identity as the random effect. The variables were log-transformed prior to the analysis, which was conducted using the lme4 package in R (Bates et al., 2015). The significance of the model was assessed by comparing it to a null model (i.e. omitting the fixed effect) using ANOVA (Bolker et al., 2009).

We assumed that the extant plant community was a good analogue for vegetation cover at the time of the eruption as a) the initial tephra deposits were thin (previous work has estimated the critical deposit thickness for abrupt vegetation change in Iceland at 20 cm: Arnalds, 2013b) and b) Icelandic vegetation is very resilient and previous observations have shown how thin tephra deposits may percolate through the ground layer without disrupting plant growth (Bjarnason, 1991). The sampling locations were close to cultivated areas, but were not artificially cleared of G2011 tephra. The sites were visited by the authors immediately after the 2011 eruption, and annually thereafter: there was no evidence that vegetation had changed markedly post-G2011.

Results

Vegetation surveys

The distribution of the quadrats in ordination space broadly matched the qualitative assessments of vegetation type. Quadrats on the left hand side of the DCA biplot (Fig. 4a) could be characterised as grass-dominated vegetation (note the position of common grasses *Festuca* sp. and *Agrostis* sp. in relation to the quadrats from Kg and B). Those on the right hand side were moss-dominated: all the dominant moss species (*Racomitrium lanuginosum, R. ericoides, Hylocomium splendens*) were on this side, with the exception of *Rhytidiadelphus squarrosus*, a common moss often found in grass sward. The Fossdalur quadrats spanned both regions.

The DCA also indicated that the sampling locations differed in terms of their compositional variability (Fig. 4a). The F and Km sites were the most variable in terms of community composition, based on the distribution of quadrats in ordination space and multivariate inertia (Table 2). In contrast, the Kg and B sites were tightly clustered and largely overlapping. On the Blómsturvellir site, there appeared to be no substantial difference between the vegetation under the willow canopy and the plant communities between the willow patches (Fig. 4b).

Fig. 4: DCA biplot

Table 2: Metrics of variability

Models of vegetation structure

The exponential curve selected was a good fit for the data (Fig. 5): adjusted R^2 values were all above 0.95, and the model parameters were highly significant in all cases ($p < 0.001$). The initial part of the fitted curve was clearly steeper on the mossy sites (F and Km). On the grassy sites (Kg and B), the curve was flatter (note the lower values of *b*:

Fig. 5). Mean vegetation height, represented in this case by the height below which 70% of vegetation occurred (U0.7) was markedly higher on the grassy sites.

Fig. 5: modelled curves for each sampling location

Vegetation structure and tephra depth

Mean tephra depth varied significantly according to site location (ANOVA: $F_{4,61} = 42.1$, $p < 0.001$), even though the initial deposit depth was similar (Olsson et al., 2013). The tephra layer in the Bh survey (i.e. under the willow canopy) was significantly thicker than the G2011 layers in the other surveys; conversely, the layer on the Km site was significantly thinner (Fig. 6). There was no significant difference in the thickness of the tephra layers on the F, Kg and Bg sites.

U0.7 figures were used to express vegetation height in each quadrat. Maximum vegetation height (U1.0) could have been used, but this figure is sensitive to the presence of isolated stems and may be unrepresentative of overall vegetation structure. At the scale of each sampling location, the relationship between vegetation height and tephra thickness was unclear. However, at a landscape scale, tephra thickness increased with vegetation height in a broadly hyperbolic fashion (Fig. 7). A linear mixed effects model of the log-transformed data indicated a significant positive relationship ($\chi^2(1) = 8.46$, $p = 0.004$).

Fig. 6: Box plots indicating G2011 tephra thickness in each sampling location.

Fig. 7: The relationship between vegetation height (U0.7) and G2011 thickness on the sites.

Discussion

Vegetation composition

The results of the DCA were consistent with the qualitative assessments of vegetation types that were made during site selection. The sampling locations could be broadly divided into 'mossy' locations (Km) and 'grassy' locations (Kg, B), with Fossdalur occupying an intermediate position. The mossy sites were more variable, in terms of species composition and abundance, than the grassy sites. The apparent variability of the Km site was largely driven by the inclusion of a handful of quadrats that encompassed very different surface cover (i.e. two quadrats on totally eroded surfaces and several on boggy ground, located in the upper right quarter of Fig. 4a). When these quadrats were excluded, the Km location was less variable. Even allowing for this site-specific factor, a thick grass sward is likely to exclude colonisation by other plants and the hence suppress botanical diversity, so it was not unsurprising that the grassy sites were less variable.

If plant communities do influence tephra layer thickness, then one could hypothesise that variability in the plant community would be related to variability in the thickness of the G2011 tephra layer. Following from this, we had hoped that plant community composition would be a surrogate for vegetation structure. However, the relationship between community variability (Shannon diversity, multivariate inertia) and variability in the G2011 tephra layer was weak. Whilst plant community composition and vegetation structure are related on a fundamental level, within-species variation in growth form is likely to obscure this relationship. Furthermore, many species present in the plant community will make minimal contributions to the structural factors relevant for tephra stabilisation, whilst other species will dominate. For example, a single shrub species drove major changes in tephra depth on the Blómsturvellir site. It is possible that plant traits related to structural features might be more useful predictors than species identity and this topic could be the focus of a future study. Without this information, the generic structural properties identified by the photogrammetric surveys appear to be much more informative than metrics of plant community composition.

Ultimately, the relationship between plant community composition and tephra thickness will depend on the spatial scale at which the wind responds to variation in vegetation form. For example, the scale of turbulence in the wind is large compared to individual plants, then a relationship between plant community composition and tephra thickness would not necessarily be expected. Put another way, small-scale, plant-to-plant variation might not have any effect on the deposition or stabilisation of tephra. If this model applies, then the most meaningful vegetation data to collect would relate to structural properties averaged over a certain distance. We speculate that the key distance is larger than our quadrat size, but smaller than the quadrat spacing. Further spatial analysis based on transect measurements will be required to establish this.

Differentiating sampling locations on the basis of structural characteristics

The models of vegetation structure derived from the photogrammetry captured qualitative differences between the sampling locations. On the Km site (dominated by a dense layer of the pleurocarpous moss, *R. lanuginosum*), the vegetation was clearly concentrated close to the ground. On sites dominated by graminoids, tall, erect stems meant that the vegetation was more evenly distributed over a range of heights, approximating the straight line plot in Fig. 3 (indicated by the lower values of b on the grassy sites). It was therefore possible to distinguish between the sampling locations in a physically meaningful way without explicitly referring to species identity. This finding has implications for the generalisation of our results to other locations.

Survey methods other than photogrammetry could have been applied. For example, a pin-touch technique could have been used for conducting high-resolution surveys of vegetation height. However, this technique is relatively slow to apply in the field and records just one variable. In contrast, we found the photogrammetric approach to be relatively quick and the resulting data set rich and versatile.

Vegetation structure and tephra thickness

Our study strongly suggested that vegetation structure is a key factor in determining the thickness of the tephra layer preserved in the sedimentary section. This relationship is strongest at a landscape scale, i.e. between sampling locations. The relationship was less clear within sites (10s of m). At a site scale, variability in vegetation structure was limited as we chose sites with relatively homogeneous cover and noise (generated by unmeasured or essentially random processes) most likely obscured clear relationships. Higher resolution sampling of the vegetation may resolve this issue, as there was a mismatch between the scale of the vegetation metric (quadrat scale) and the tephra measurements (sub-quadrat scale).

At a larger scale, where the variation in vegetation structure was greater, a positive correlation suggestive of a deterministic relationship emerged. This was probably because the large scale analyses included vegetation types at different ends of the continuum of vegetation types (moss vs tall grass and, in the case of Bh, dwarf shrubs). The relationship appeared to be non-linear. No G2011 tephra was observed on sites without vegetation cover i.e. the eroded sites within the Km sampling location. Presumably, fresh tephra on these denuded surfaces is readily eroded. When vegetation cover was low, small increases in vegetation height appeared to have a major impact on the thickness of tephra in the soil. In taller vegetation, height increases of the same magnitude have a smaller (but still broadly positive) effect, leading to hyperbolic relationship (Fig. 7). The analysis of tephra thickness on the Blómsturvellir site reinforced the impression that vegetation cover plays a major role in determining tephra depth. The tephra layers in patches of *Salix lanata* were significantly thicker than those under the surrounding, low-growing vegetation (Fig. 6), even though the plants in the ground layer were essentially the same.

This study focussed on aboveground vegetation structure as the major agent mediating tephra layer thickness. However, other factors also likely to be significant. Antecedent moisture levels, for example, are likely to change the ‘stickiness’ of newly deposited tephra. Plant traits that influence the way that moisture is retained on leaves and stems could therefore work alongside the morphological aspects of vegetation cover. Belowground structure might also be significant e.g. the particularly dense root structures associated with tussocky graminoids could influence the incorporation of tephra into the soil (although we did not observe this effect during out study).

Implications of research

Our findings have clear implications for the interpretation of tephra layers. For the purposes of volcanic reconstruction, it is usually assumed that airfall tephra deposits do not undergo modification, unless they are very thick, in which case slope processes may come into play. However, our research shows that vegetation cover is likely to be important, too, particularly on smaller spatial scales and where the initial deposit depth is not so great that plant cover is extirpated. This finding offers the tantalising possibility that, under certain circumstances, variability in tephra layer thickness across a site may be used as a proxy for the vegetation cover extant at the time of the eruption (in terms of structure, if not taxonomy). This finding is especially important for the calculation of past eruptive volumes if vegetation cover may have varied significantly through time. If vegetation was significantly taller at the time of eruption, calculations of eruption volume may be over-estimated. Furthermore, assessing variation in multiple, well-dated tephra layers may give insight into the spatio-temporal dynamics of vegetation cover over long time periods (Streeter and Dugmore, 2013a).

Conclusions

Our research shows that the thickness of a recent tephra layer was correlated with the vegetation structure present at the time of deposition. We found that plant community composition was a poor surrogate for the physical structure of vegetation cover. However, photogrammetric analysis proved to be an effective way of capturing relevant structural characteristics. Analyses using this technique demonstrated that vegetation cover on different sites could be differentiated according to generic structural properties. These findings have implications for the interpretation of tephra layers, whether this work involves the analysis of ancient volcanic eruptions or archaeological/palaeoenvironmental reconstructions. Furthermore, it is possible that small-scale variability in tephra layers, rather than being interpreted as unhelpful ‘noise’, could be used as a proxy for palaeo vegetation structure.

References

Arnalds O. (2013a) The Influence of Volcanic Tephra (Ash) on Ecosystems. In: Sparks DL (ed) *Advances in Agronomy, Vol 121.* 331-380.

Arnalds O. (2013b) The Influence of Volcanic Tephra (Ash) on Ecosystems. In: Sparks DL (ed) *Advances in Agronomy, Vol 121.* 331-380.

Baas ACW. (2002) Chaos, fractals and self-organization in coastal geomorphology: simulating dune landscapes in vegetated environments. *Geomorphology* 48: 309-328.

Bates D, Maechler M, Bolker B, et al. (2015) Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 67: 1-48.

Bjarnason ÁH. (1991) *Vegetation on lava fields in the Hekla area, Iceland,* Uppsala: Acta Phytogeographica Suecica.

Bolker BM, Brooks ME, Clark CJ, et al. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology & Evolution* 24: 127-135.

Gudmundsson MT, Höskuldsson Á, Larsen G, et al. (2012) The May 2011 eruption of Grímsvötn. *EGU General Assembly.* Vienna, Austria: Copernicus.

Haflidason H, Eiriksson J and Van Kreveld S. (2000) The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review. *Journal of Quaternary Science* 15: 3-22.

Hotes S, Poschlod P, Takahashi H, et al. (2004) Effects of tephra deposition on mire vegetation: a field experiment in Hokkaido, Japan. *Journal of Ecology* 92: 624-634.

Kent M. (2012) *Vegetation description and data analysis,* Chichester: Wiley-Blackwell.

Kent M, Owen NW, Dale P, et al. (2001) Studies of vegetation burial: a focus for biogeography and biogeomorphology? *Progress in Physical Geography* 25: 455 - 482.

Langlois E, Bonis A and Bouzille JB. (2003) Sediment and plant dynamics in saltmarshes pioneer zone: Puccinellia maritima as a key species? *Estuarine Coastal and Shelf Science* 56: 239-249.

Larsen G, Dugmore A and Newton A. (1999) Geochemistry of historical-age silicic tephras in Iceland. *Holocene* 9: 463-471.

Lowe DJ. (2011) Tephrochronology and its application: A review. *Quaternary Geochronology* 6: 107-153.

Marston RA. (2010) Geomorphology and vegetation on hillslopes: Interactions, dependencies, and feedback loops. *Geomorphology* 116: 206-217.

Moller I. (2006) Quantifying saltmarsh vegetation and its effect on wave height dissipation: Results from a UK East coast saltmarsh. *Estuarine Coastal and Shelf Science* 69: 337-351.

Neumeier U. (2005) Quantification of vertical density variations of salt-marsh vegetation. *Estuarine Coastal and Shelf Science* 63: 489-496.

Olsson J, Stipp SLS, Dalby KN, et al. (2013) Rapid release of metal salts and nutrients from the 2011 Grímsvötn, Iceland volcanic ash. *Geochimica et Cosmochimica Acta* 123: 134-149.

Sarna-Wojcicki AM, Shipley S, Waitt RB, et al. (1981) Areal Distribution, Thickness, Mass, Volume, and Grain Size of Air-Fall Ash from the Six Major Eruptions of 1980. In: Lipman PW and Mullineaux DR (eds) *The 1980 Eruptions of Mount St. Helens, Washington.* Washington D.C.: USGS, 577-600.

Stevenson JA, Millington SC, Beckett FM, et al. (2015) Big grains go far: understanding the discrepancy between tephrochronology and satellite infrared measurements of volcanic ash. *Atmospheric Measurement Techniques* 8: 2069-2091.

Streeter R and Dugmore AJ. (2013a) Anticipating land surface change. *Proceedings of the National Academy of Sciences of the United States of America* 110: 5779-5784.

Streeter RT and Dugmore AJ. (2013b) Reconstructing late-Holocene environmental change in Iceland using high-resolution tephrochronology. *Holocene* 23: 197-207.

Takahashi T and Shoji S. (2002) Distribution and classification of volcanic ash soils. *Global Environmental Research* 6: 83-98.

ter Braak CJF. (1995) Ordination. In: Jongman RHG, ter Braak CJF and van Tongeren OFR (eds) *Data Analysis in Community and Landscape Ecology.* Cambridge: Cambridge University Press, 91-173.

Thorarinsson S. (1944) Tefrokronologiska studier på Island. *Geografiska Annaler* 26: 1-217.

Thordarson T and Larsen G. (2007) Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *Journal of Geodynamics* 43: 118-152.

Zehm A, Nobis M and Schwabe A. (2003) Multiparameter analysis of vertical vegetation structure based on digital image processing. *Flora* 198: 142-160.

Figure captions

Fig. 1: The sampling locations: a) Fossdalur (F); b) the mossy Kalfafell sampling location (Km); c) the grassy Kalfafell sampling location (Kg) and d) Blómsturvellir (B: the lighter patches in the image are the dwarf willow, *Salix lanata*); e) the survey area.

Fig. 2: Diagram indicating the set up used for the photogrammetric survey.

Fig. 3: Hypothetical analyses of different vegetation types (designated X, Y and Z). The vertical lines in the top three plots are diagrammatic representations of stems, viewed side-on; the height scale is indicative. The graph at the bottom of the image plots the proportion of biomass against height for each vegetation type. Hypothetical vegetation comprising vertical stems of equal height (vegetation type X) produces a straight line on the plot. Structural configurations where the vegetation thins with height (types Y and Z) produce plots of different curvatures.

Fig. 4: DCA biplots, with each coloured circle indicating a quadrat survey. Plot a) is of all the sampling locations where grid surveys were conducted. The quadrats on the left hand side are broadly ‘grassy’ in terms of dominant growth form; those on the left are ‘mossy’. Plot b) illustrates the plant community on the Blómsturvellir site in more detail, comparing the grid survey (solid circles) with the haphazard survey of ground vegetation under willows (open circles). Key to common species: Agr_sp = *Agrostis* species; Car_sp = *Carex* sp.; Equ_pal = *Equisetum palustre*; Fes_sp = *Festuca* species; Hyl_spl – *Hylocomium splendens*; Rac_eri = *Racomitrium ericoides*; Rac_lan = *Racomitrium lanuginosum*; Rhy_squ = *Rhytidiadelphus squarrosus*.

Fig 5: Vertical vegetation structure for each sampling location. The points have been fitted with a curve of the form $y = a(1 - e^{-bx})$. In this case, the value of *a* (the asymptote) has been fixed at 1. The top two graphs (F, Km) have moss-dominated vegetation; those on the bottom have predominantly grassy vegetation cover. The mean height below which 70% of vegetation structure occurs (U0.7) is indicated on each plot.

Fig. 6: Box plots showing mean tephra thickness in each sampling location. The thickness from the Bh survey (beneath willow canopy) is included for comparison.

Fig. 7: The relationship between vegetation height (expressed here as U0.7, or the height below which 70% of vegetation occurs) and the mean thickness of the G2011 tephra layer in each quadrat. Mean values ±1 SE are indicated for each site. Key to sites: Km = Kalfafell (moss-dominated); F = Fossdalur (moss/grass heath); Kg = Kalfafell (grass-dominated); Bg = Blomsturvellir (grass/shrub).

1

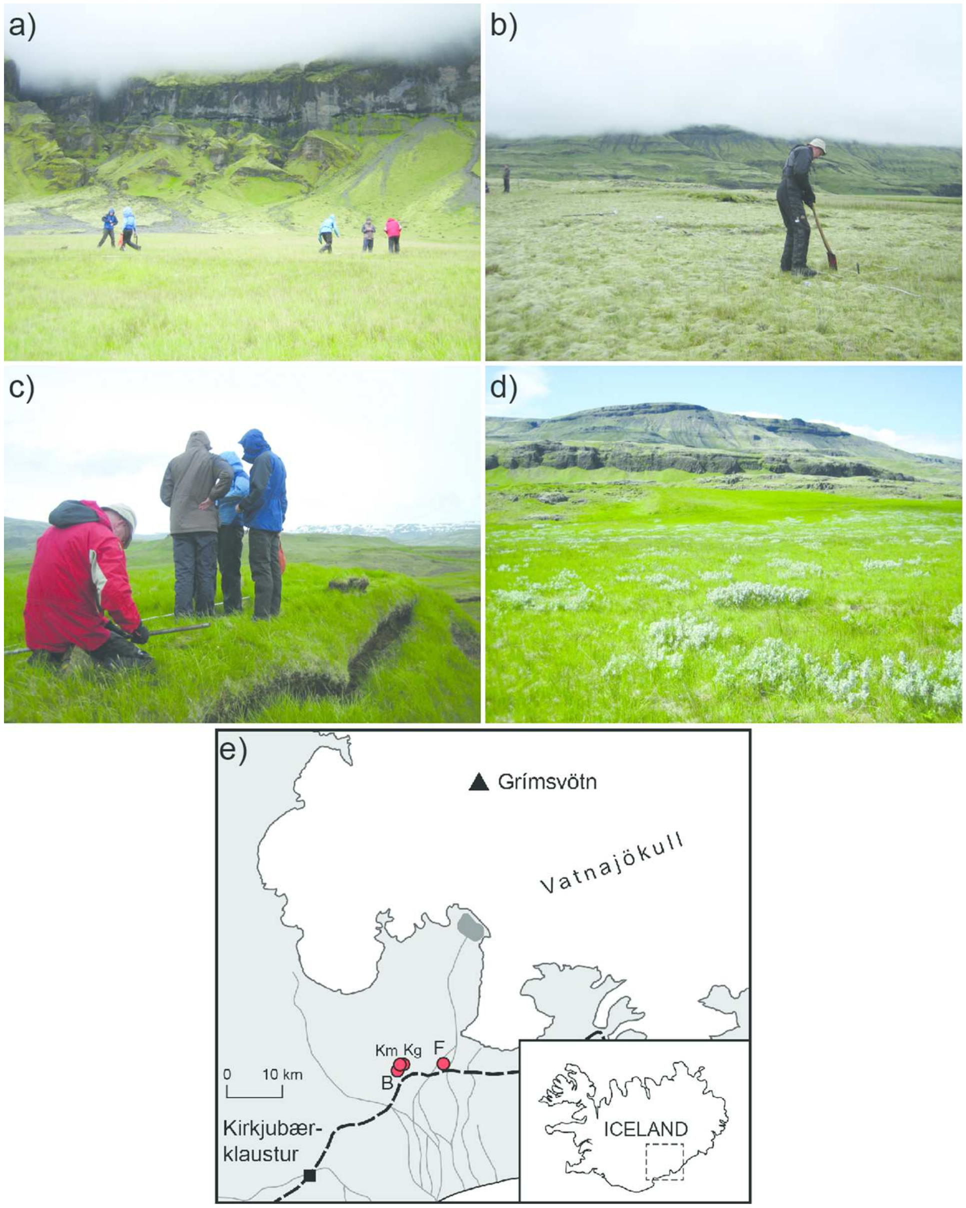
Site	Location	Survey area	No. quadrats	Vegetation cover
Fossdalur (F)	63.97° N 17.49° W, 75 m asl	30 x 30 m	36 at 6 m intervals	Moss heath dominated by *Racomitrium* spp. & *Hylocomium splendens*; sparse graminoid cover (mainly *Agrostis* sp., *Kobresia myosuroides*).
Kalfafell (moss) (Km)	63.97° N 17.65° W, 185 m asl	35 x 20 m	40 at 5 m intervals	Mainly low-diversity *Racomitrium lanuginosum* moss heath, but encompassing small, denuded areas and boggy patches.
Kalfafell (grass) (Kg)	63.96° N 17.66° W, 136 m asl	35 x 10 m	24 at 5 m intervals	Dense grass sward dominated by *Agrostis* sp.
Blómsturvellir (B)	63.97° N 17.65° W, 96 m asl	30 x 18 m	24 at 6 m intervals	Boggy ground characterised by mixture of grass (primarily *Festuca* sp., *Carex* spp.) and moss (*Hylocomium splendens*, *Rhytidiadelphus squarrosus*) heath with patches of *Salix lanata*.

2

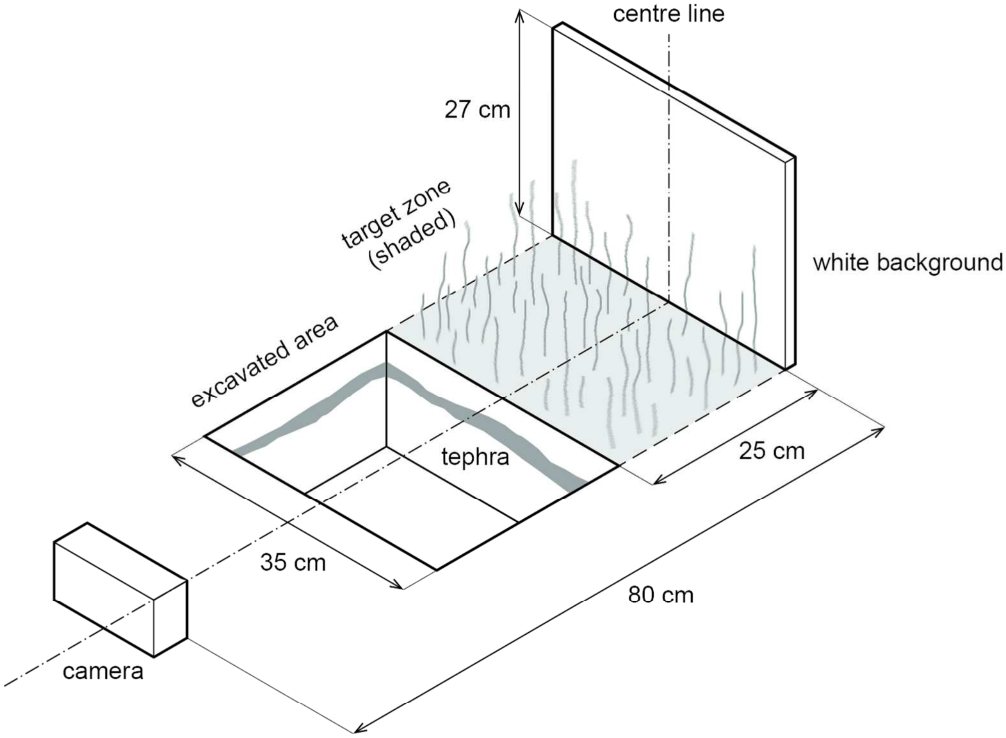
3 Table 1: Details of sampling locations.

Site	Shannon diversity, H	Multivariate inertia	CV of G2011
Fossdalur	1.23 ± 0.46	2.37	0.22
Kalfafell (moss)	0.64 ± 0.44	2.08	0.37
Kalfafell (grass)	1.44 ± 0.21	0.52	0.19
Blómsturvellir (grid)	1.59 ± 0.27	1.70	0.25

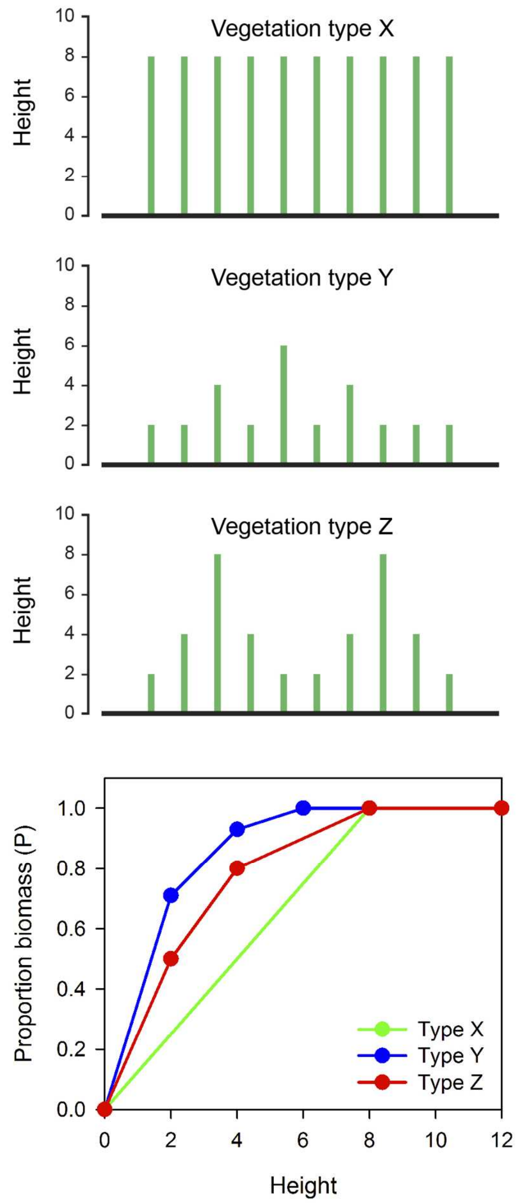
Table 2: Metrics of plant community diversity and variability in tephra layer depth (CV = coefficient of variation). Refer to Fig. 6 for mean tephra depths on each site.



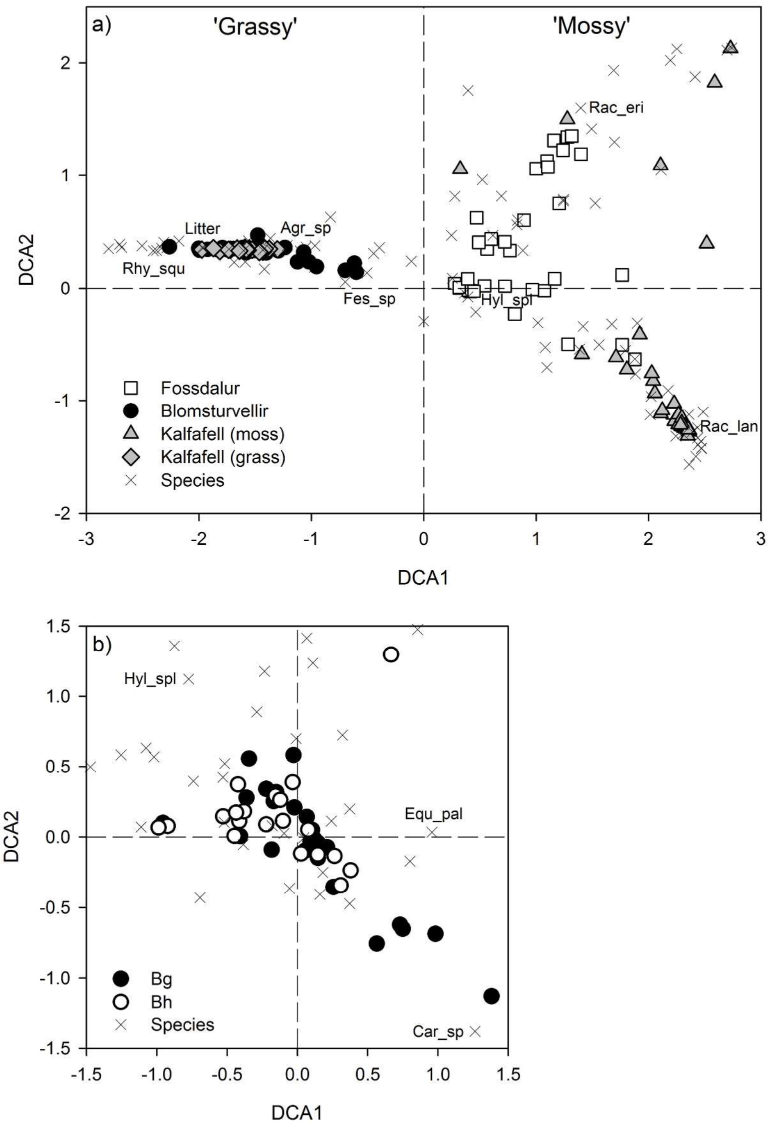
107x134mm (300 x 300 DPI)



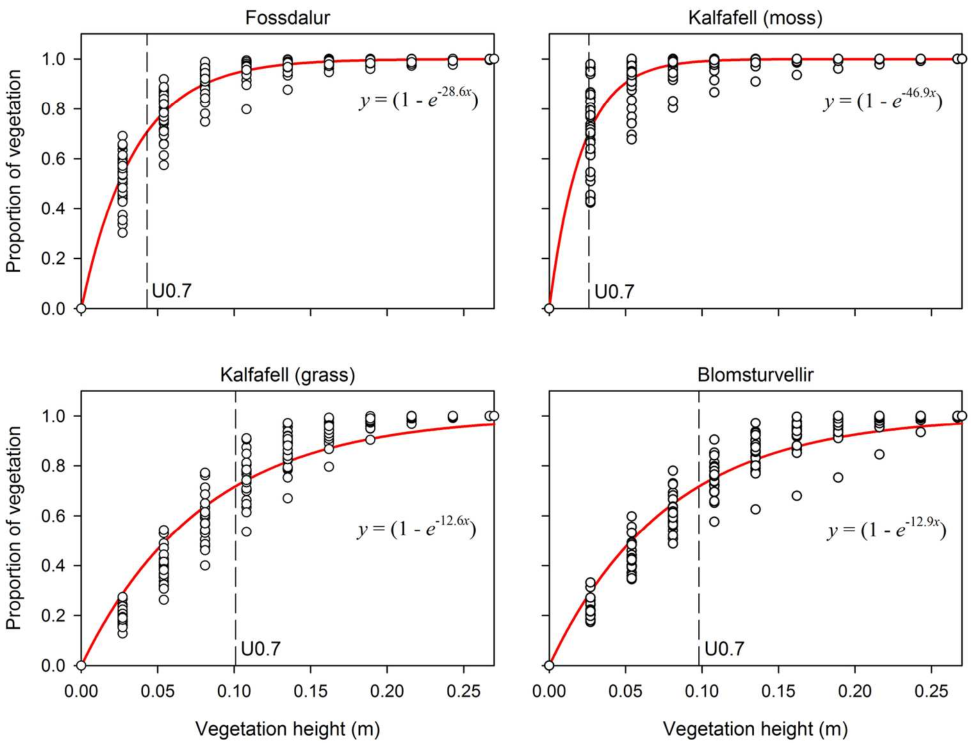
130x106mm (300 x 300 DPI)



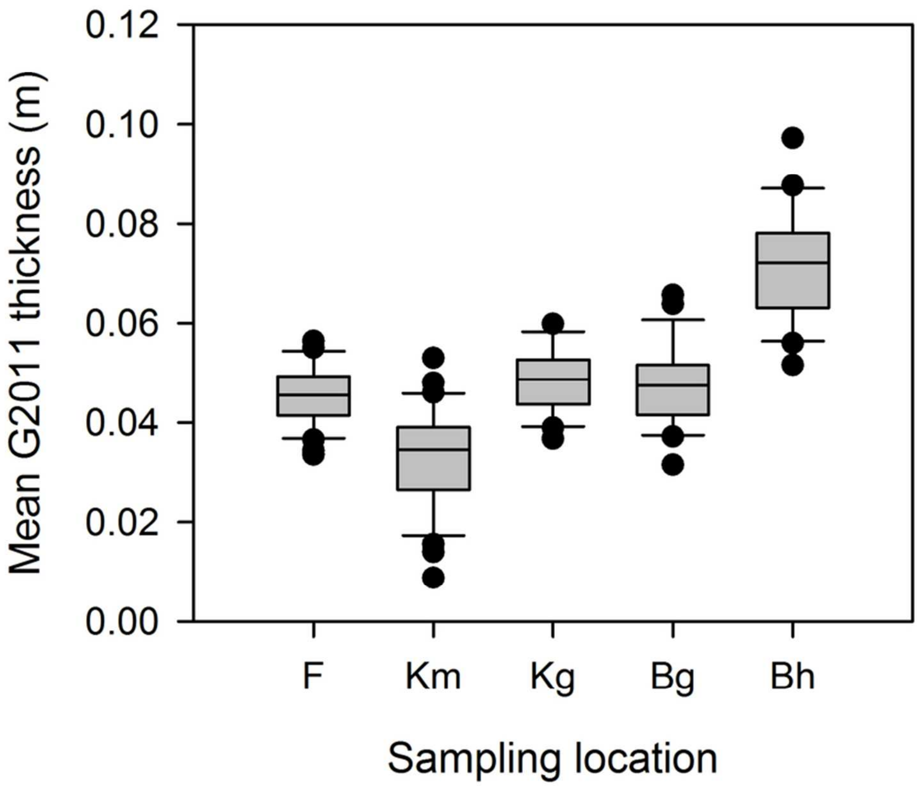
82x180mm (300 x 300 DPI)



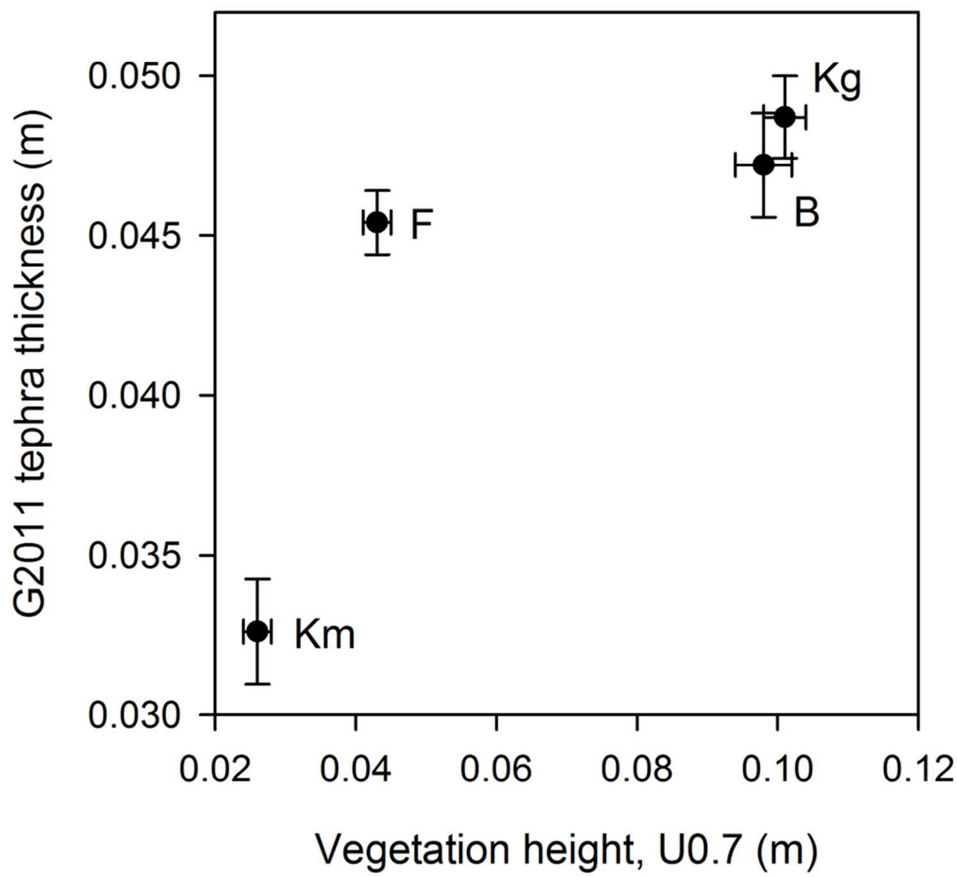
212x315mm (300 x 300 DPI)



135x101mm (300 x 300 DPI)



76x70mm (300 x 300 DPI)



86x88mm (300 x 300 DPI)