

An analysis of landslides in Great Britain using soil texture,
rainfall, and topography reveals contrasting failure conditions
between organic and mineral soils

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March 4, 2026

NOTICE: PREPRINT (SUBMITTED VERSION)

The manuscript has been submitted to and subsequently accepted for publication in
Earth Surface Processes and Landforms (ESPL)
This manuscript is the original submitted version of the article and **does not reflect
changes undergone during the peer review processes.**

This preprint is shared in accordance with the publisher's preprint policy. The final
version will be available via the journal website upon publication and the DOI
provided here.

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Abstract

Rainfall-induced landslides cause millions of pounds in damage to infrastructure in Great Britain (GB) annually and occasionally result in human fatalities. However, there are limited guidelines or policies aimed at reducing landslide risk in GB and few studies have broadly characterized landslide incidence across the region. Furthermore, peat landslides, which are a phenomenon that occur almost exclusively in the British Isles, have recently made headlines for their destructive impacts and degradation of a non-renewable terrestrial carbon store. Given the environmental significance of peat, we explore the knowledge gaps surrounding the mechanical conditions that induce peat failures. We start by empirically characterizing landslide incidence in GB considering landslide events recorded in the British Geological Survey (BGS) database. Soil texture, topographic, and antecedent rainfall data were acquired for the considered landslides. Key distinctions in spatial, temporal, and triggering conditions between organic and mineral soil landslides were identified using a heuristic analysis, statistical testing, and dimension reduction techniques. Organic landslides had significantly steeper slopes and higher antecedent rainfall sums than mineral landslides and occurred most frequently in late summer and early autumn months. Using a K-means clustering analysis, landslide groups exhibiting similar slope, soil, and rainfall characteristics were identified revealing unique intra-cluster spatial and temporal patterns. The spatial distribution and temporal patterns of organic landslides are interpreted to suggest that antecedent rainfall, and by proxy soil moisture content, play key roles in rainwater infiltration and organic soil landslide susceptibility in GB. Seasonal drops in peat moisture content may facilitate rainwater infiltration via desiccation cracks and increase peat landslide susceptibility in late summer months. Our results highlight contrasting mechanisms for peat landslides, which can be used to guide more accurate landslide risk management considering region and preconditioning factors which is pertinent for recent peatland restoration activities in GB.

1 Introduction

Landslides are a natural process in the geologic cycle whereby rock, soil, or organic material moves down a slope under the force of gravity [1]. Despite being a natural phenomenon, landslides can pose serious risks to the built environment and human safety. Globally each year, landslides cause an estimated \$20 billion in economic costs [2], and between 2004 and 2016, about 56,000 human deaths were caused by rainfall-induced landslides [3]. Landslides can also impose damage to natural environments. Landslides in organic soils (peat) can deposit large volumes of organic matter into waterways altering water chemistry and killing fish populations in rivers and lakes [4, 5]. Additionally, peat landslides can mobilize thousands of cubic meters of peat, causing loss of particulate carbon stored in intact peatlands [6].

Various geographical conditions can predispose a region to landslides (e.g., topography and geology) but there is usually one triggering mechanism, such as heavy rainfall, that acts to alter soil mechanical conditions and apply external loads that initiate a landslide [7, 8]. Rainfall-induced landslides typically occur when rainwater increases matric potentials in the soil until the forces of gravity overcome the resisting soil shear strength, which is a function of soil moisture and texture [9]. Globally, most landslides are triggered by rainfall [10] and as precipitation patterns are expected to alter under climate change [11, 12] more frequent, heavy rainfall events may increase landslide susceptibility in certain parts of the world [13, 14]. Understanding how predisposition factors (e.g., topography or soil properties) interact with landslide triggers (e.g., rainfall), is essential for determining landslide susceptibility, managing landslide risk, and adapting to climate change.

Great Britain (GB) has a relatively mild landslide setting compared to more rugged regions of the world [15, 16, 7]. Despite this, landslides in GB still cause considerable damage to infrastructure, the natural environment, and occasionally result in human fatalities. Between April 2022 and March 2023, Network Rail, the owner of most railways in GB, spent £38.6 million repairing landslide damages along its rail network [17]. Since 2000, recurring landslides on the ‘Rest and Be Thankful’ pass in Scotland have caused £60 million in economic losses and substantial disruption to the region [18]. In that same time period, landslides in GB have claimed 13 lives [19].

Furthermore, the British Isles are unique as the only places in the world where landslides occur in peatlands [20, 21, 22]. It is estimated that 80% of global peat landslides occur within the British Isles despite the region making up less than 1% of the global peat inventory [23, 24, 25]. In GB, peat is defined as having at least 50% organic matter and a minimum thickness of 30 cm [26, 23, 27]. Due to its high organic matter content, the physical and engineering properties of peat are wholly different from mineral soils [28].

For example, peat soils are often found to have moisture contents between 600 and 1800% [29, 30] compared to about 5 to 40% for typical mineral soils [31].

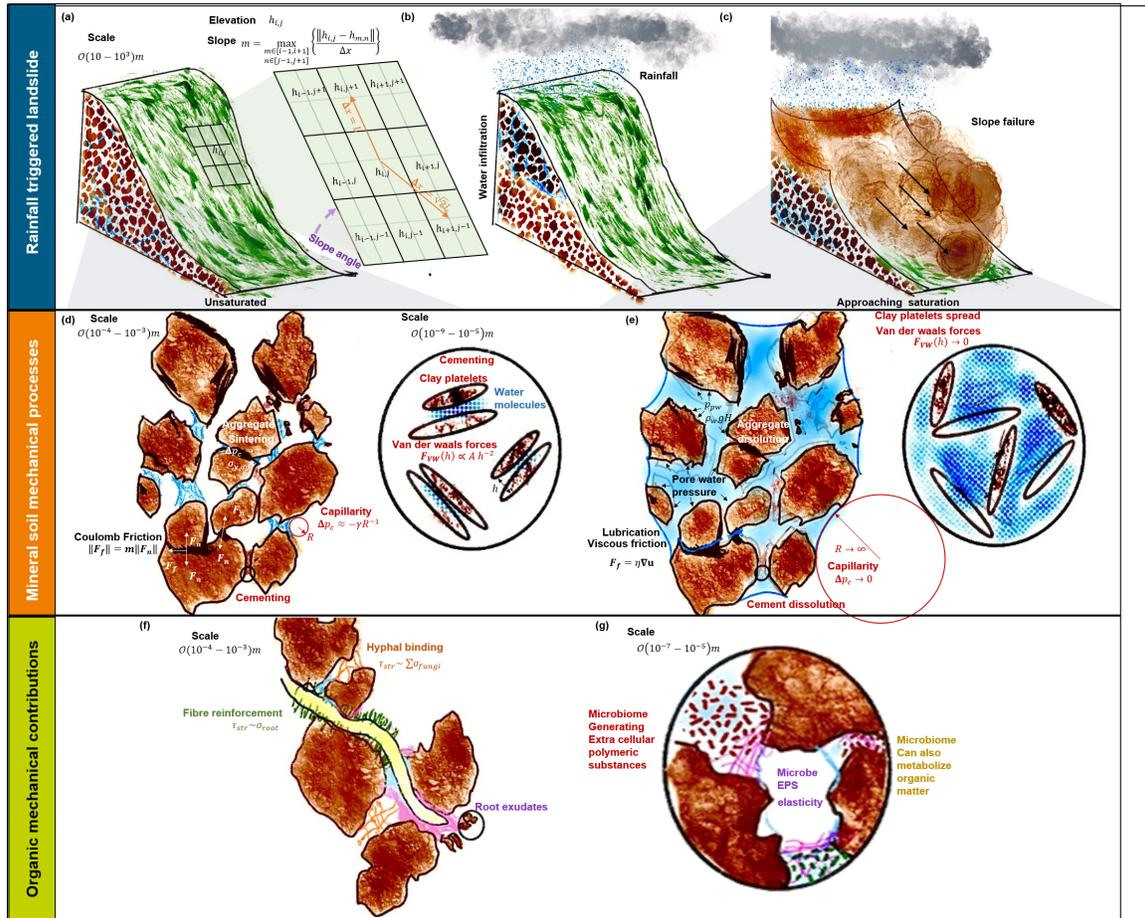


Figure 1: Rainfall induced landslide events and their failure mechanisms. (a) illustrates an unsaturated hill slope. For any given latitude and longitude position, we compute the slope based on the 8 adjacent grid points. (b) The hillslope undergoes wetting via rainfall until (c) catastrophic failure. For mineral soils (d-e), soil shear strength results from friction, capillarity, and clay cementation. As mineral soils approach saturation (e), capillarity transitions into hydrostatic pressures, clay cementing dissolves, and Coulomb friction transitions to viscous sliding. For organic soils (f-g), organo-constituents act to bind soil solids together. For example, (f) roots will reinforce soil, hyphae bridges will form between particles, and (g) extra cellular polymeric substances (EPS) generated by plants and microbes will create connections between particles. We note that microbes can also act to metabolize and break down EPS structures. Figure was inspired/adapted from [32].

Mineral soils (Figure 1d-e) are largely comprised of sand, silt, and clay particles [33]. Under unsaturated conditions (i.e., typical soil conditions), soils are not under pressure, but are bound together by capillarity and chemical binding agents. At the bulk scale, soil shear strength is considered a function of Coulomb friction between soil particles and an effective cohesion factor, which are often empirically linked by soil moisture or matric potential [34]. More fundamentally, soil aggregate structures form through particles being pulled together due to capillary action, thus tightly binding together under dry conditions [35]. Fine scaled clay particles act as cementing agents between sand and aggregate particles, and clay platelets also become tightly bound during drying [33]. This ensemble of features manifests as soil shear strength, which can change drastically due to changes in moisture conditions. Many of these bonding mechanisms rapidly deteriorate under water saturated conditions.

By contrast, soils with high organic content (1 (f-g)) are likely to have a separate set of mechanisms that govern their shear strength. Traditional soil mechanics is based on inter-particle forces which is not applicable to fibrous and amorphous peat bodies. While we do not have immediate literature regarding mechanisms associated with peat soil shear strength, we can make inferences from other organo-constituents. For example, fine plant roots and fungi entangle within soil aggregates, creating fibril reinforcement [32] that can persist even under saturated soil conditions (i.e., positive pore water pressures). Furthermore, habitats ranging from the scale of microbial communities to plant roots modify soil mechanical properties by exuding extra-cellular polymeric substances (EPS) [36], which act to absorb large quantities of water and act as strong adhesive agents under drying. There is evidence to suggest that these analogues are fitting for describing peat soils.

Historically, there has been complacency and a lack of research surrounding peat landslides, because they are rare events that typically occur in remote regions of GB with minimal impacts on society [21]. However, the inclusion of degraded peat emissions into the UK greenhouse gas inventory [37] added roughly 3.5% (23 MtCO₂eq) to total UK greenhouse gas emissions [38] and has triggered a government funded campaign of peat restoration [39], that largely focuses on altering the hydrology of peat. Therefore, understanding a) how the incidence of peat failures affects the stability of the stored carbon and thus contributes to emissions, and b) how restoration activities of both the use of heavy machinery and altering the hydrological properties of peat may affect the incidence of peatland failures is now a pressing issue. Additionally, in 2003, several destructive peat landslides occurred in Ireland [40, 41] and Scotland [21], bringing greater public and academic awareness to peat landslides. The Scotland slides occurred in Shetland after heavy precipitation triggered over 20 peat landslides, each between 1,000 and 60,000 m³, causing an estimated £2 million in uninsured damages to public and private property [21].

Topography and soil texture play important roles in landslide susceptibility [42, 43, 44] particularly as it relates rainfall infiltration and soil pore pressure/matric potential effects in landslide initiation [45]. As an inactive seismic region, rainfall is the dominant landslide trigger in GB [46, 7]. Rainfall intensities and periods of prolonged rainfall are projected to increase in the region over the next 100 years [47] which could increase landslide susceptibility and occurrence [48]. As such, antecedent rainfall is a commonly used parameter in empirical landslide analysis and in establishing landslide rainfall thresholds [10] useful for landslide forecasting and risk reduction.

Furthermore, summers in GB are generally predicted to be warmer and drier [49], which would increase evapotranspiration rates and decrease soil moisture contents altering the suction and pore pressures at play in slope dynamics [50]. Yet, there has been limited research on rainfall thresholds and characterization of landslide incidence broadly in GB. Most GB landslide studies evaluate singular landslide events [51, 18] or regions [46, 52] without taking into account preconditioning factors such as soil texture or topography. Additionally, no studies to date have evaluated antecedent rainfall or preconditioning factors for peat landslides.

This study aims to improve the characterization and indexing of rainfall-induced landslides in GB with the prospect of contributing to landslide susceptibility mapping and policy for landslide risk reduction in GB. Using a landslide inventory managed by the British Geological Survey (BGS), soil texture, topographic, and antecedent rainfall data were acquired for over 900 past landslide events. Landslides were grouped into mineral soil groups (sand, silt, and clay), and organic soil groups (peaty and peat, comprised of over 20% and 100% organic matter, respectively). We examine possible differences in antecedent rainfall between mineral and organic landslides, while accounting for slope angle using a data driven approach. Lastly, clustering methods were used to group landslides with ‘similar’ failure triggers which identified broad groups of landslides that occurred in distinct regions of GB and periods of the year.

2 Methods

2.1 Study Region

The region used in this study was defined by the BGS National landslide Database (NLD) which includes landslides in England, Scotland, Wales and their isles [53]. For simplicity, the study region is referred to as Great Britain (GB). The geologic setting of GB is highly varied encompassing pre-Cambrian metamorphic rocks in the Scottish Highlands [54] and Upper Cretaceous sedimentary formations, such as The Chalk Group, in southern England [55, 56]. Millennia of orogeny, tectonics, and glaciation have resulted in diverse

landforms and soil types throughout GB [57, 58]. Loamy soils are the predominant soil type in GB, covering about 58% of the region (Figure 2) [59, 60]. Peaty and peat soils are pervasive throughout Scotland and western GB and cover about 5 and 20% of the region, respectively. Clay and sand soils comprise about 11 and 3% of GB and are most common in inland southern England and coastal regions, respectively. GB is generally considered a low-risk landslide region [15] due to its fairly gentle and eroded topography [7]. However, destructive landslides still occur causing millions of pounds in economic damages annually [18], and occasional fatalities [17, 19].

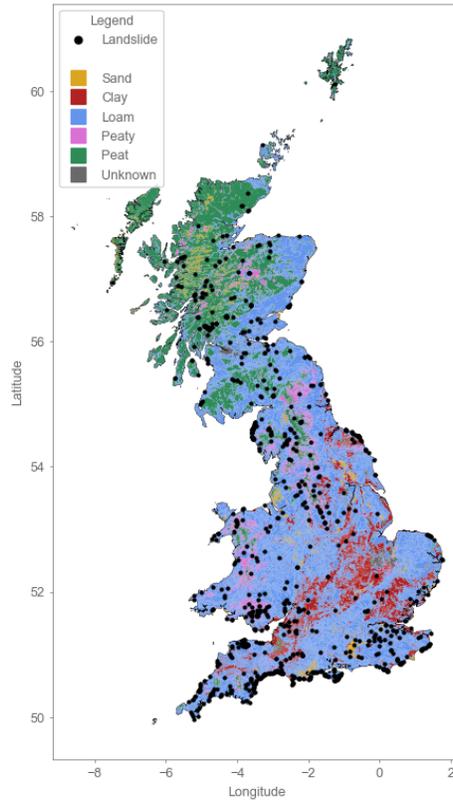


Figure 2: Soil texture map of Great Britain (GB) with filtered National Landslide Database landslide points.

2.2 National Landslide Database

The BGS National Landslide Database (NLD) contains locations and dates for over 18,000 landslides that have occurred in GB between 1664 and present day [53, 16, 61]. Each landslide in the database contains landslide location coordinates, and if known, the date and time of the event. The NLD was the base dataset onto which supplemental data unique to each landslide (e.g., soil texture) were acquired. The NLD was filtered to landslides with dates and locations verified by BGS for spatial and temporal accuracy in acquiring supplemental data. Data with temporal accuracies of day or hour were retained so that the time of each landslide is known within one day. The dataset was further filtered to landslides that had occurred after 1941; the earliest date that historical daily rainfall records were available for. The filtered dataset used for analysis contained 903 landslides. For certain spatial and temporal analyses, 49 particular landslides that occurred in Exmoor, England on 15 August 1952, were excluded. These 49 landslides are associated with a large storm event, and the spatial and temporal density of these events can introduce bias in the analysis. Figure 3 presents the data structure and the following sections describe how the additional data were acquired, filtered, and amalgamated with the NLD for analysis. Spatial data were converted to the World Geodetic System 84 (WGS84) coordinate reference system for analysis. Data curation, amalgamation, filtering, and analyses were performed using Python [62] scripts in conjunction with the GeoPandas [63] library.

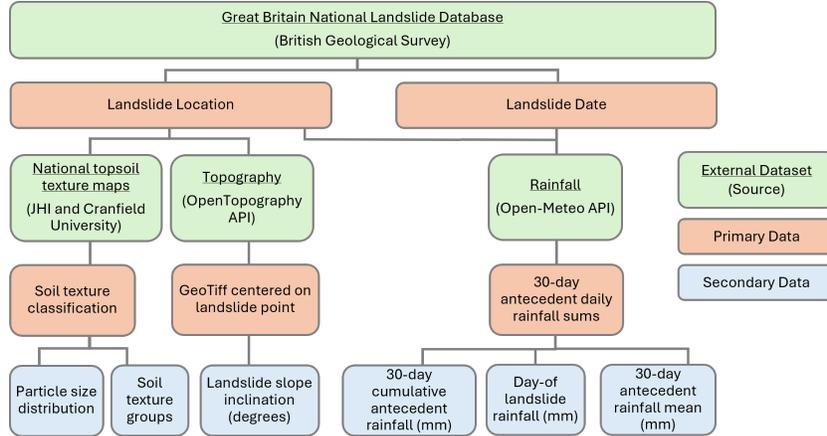


Figure 3: Data structure used in analysis: external datasets (green), primary data provided by dataset (orange), and secondary data determined/calculated for analysis (blue).

2.3 Antecedent Rainfall

Daily rainfall sums were acquired from OpenMeteo’s historical rainfall Application Programming Interface (API) [64] via Python. OpenMeteo’s historical rainfall data is based on the ERA5 European Centre for Medium-Range Weather Forecasts with a spatial resolution of 25km [65]. Using the coordinates and date of each landslide, 30-day antecedent daily rainfall sums (i.e., daily rainfall sums for the 30 days preceding a landslide event) were acquired for each landslide location. An antecedent duration of 30 days was selected based on other studies in GB which had shown this duration to be a meaningful threshold parameter for describing landslide incidence [46, 66]. A 30-day cumulative antecedent rainfall sum (30-DCAR) was calculated from the daily rainfall values. 30-DCAR, 30-day mean rainfall, the day-of-landslide rainfall (DOLR) were the rainfall parameters used in the analysis.

2.4 Soil Texture

Topsoil textures were used to ensure that the effects of rainfall on soil texture were captured in the analysis. Scotland soil texture data were acquired from the James Hutton Institute (JHI) 1:250,000 topsoil texture map [60]. Soil texture data for England and Wales were acquired from the National Soil Inventory 1:250,000 topsoil texture acquired under license from Cranfield University [59]. British Standards Institute texture classes [26] were used in both datasets. Particle size distributions were not included the mineral soil texture data and the British Standards soil texture triangle was used to obtain average particle size distributions for each soil texture class. Figure 4 presents the texture groupings with respect to the British Standards texture classes. For organic soils, peat was defined as having 100% organic matter in the absence of information on a mineral soil component. Peaty soils were defined as soils with between 20 and 50% organic matter [26], and the respective mineral soil component was calculated as the remaining proportion. Each soil texture class was reduced to a general ‘soil texture group’ based on the dominant textural class (i.e., ‘sandy silt loam’ became ‘loam’) to facilitate analysis between soil groups [67] and to account for low observation points in certain texture classes. By retaining the average particle size distributions for each texture class, textural groupings did not limit the analysis of texture effects on landslide incidence.

2.5 Topography

Slope inclination for each landslide was acquired from the OpenTopography API digital terrain model (DTM) of Europe [68] via Python. The DTM data was generated from GEDI and Icesat2 satellite data collected between 2000 and 2018 with a raster resolution of 30m. Using the landslide coordinates as the center points, a Geotiff request extending 100m to the north, south, east, and west from each landslide point was made. Slope inclinations were calculated on each Geotiff in 8 radial directions from the landslide center point and the

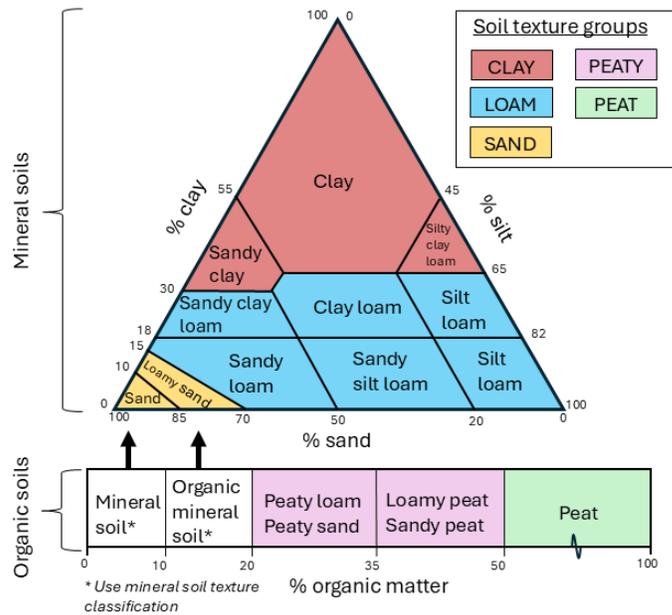


Figure 4: Soil texture classification and groupings used for analysis. Adapted from Natural England Technical Note TIN037.

maximum slope value retained as the slope inclination for the landslide (Figure 1 a). The NLD coordinates reference the maximum elevation point of each landslide if known, therefore this approach should accurately capture the inclination of the failed slope, however it does assume that the landslide occurred on the steepest section of slope, which is not necessarily the case. However, considering that this estimate is conducted on a projected area of 0.04 km², we expect any error associated with this assumption to be minimal.

2.6 Data Analysis

2.6.1 Heuristic Spatial and Temporal Analysis

As a first step in characterizing landslide incidence in GB, a heuristic data analysis approach was employed using Python Geopandas. This approach focused on examining the spatial and temporal (monthly) frequency trends of landslides by soil texture group, as well as making general comparisons of landslide-associated rainfall and slope parameters between texture groups. Landslide spatial frequency was evaluated by calculating the total area of each texture group in GB. Landslide counts for each texture group were then normalized to the overall area of their respective texture in GB. The temporal frequency of landslides among different soil textures was assessed by organizing landslides according to soil texture and the month of occurrence. Monthly landslide counts for each soil texture group were subsequently plotted to facilitate the visualization of their general temporal incidence. Each texture group was then normalized to the total monthly landslide count (e.g., clay landslides in March were divided by the total number of landslides in March) to understand if certain texture groups exhibited unique prevalence in any particular month. To further highlight monthly landslide trends by texture, each texture group was normalized to the total landslide count of each texture group (e.g., peaty landslides in October were divided by the total number of peaty landslides in all months) and plotted by month. This step minimized the effect that different group sizes had on interpreting monthly landslide patterns. The Exmoor 1952 landslides were omitted from the spatial and temporal analyses due to potential bias in temporal and spatial frequencies given the high density of landslides within a small region on a single day. Finally, the distributions of slope and rainfall variables were normalized for each soil texture

group and plotted as histograms to facilitate comparative analysis. The 30-day mean rainfall values were also calculated and included in this step to understand how DOLR values compared to 30-day mean rainfall values.

2.6.2 Statistical Tests

To check for significant differences in 30-DCAR and slope inclinations between soil texture groups, parametric and nonparametric equivalent statistical tests were performed with a significance level of $p < 0.05$. The raw data sets for 30-DCAR and slope inclinations did not meet normality or equal variance assumptions for the analysis of variance (ANOVA) tests, so both datasets were transformed with a box-cox transformation ($\lambda = 0.36$ and 0.37 , respectively). A one-way ANOVA and post-hoc Tukey test was performed on the slope inclination dataset to compare landslide slopes between soil groups. The 30-DCAR dataset did not have equal variances between groups after transformation, so a non-parametric equivalent ANOVA test and post-hoc Games-Howell test was performed. The DOLR values could not be transformed to a normal distribution for statistical analysis and therefore was not statistically tested. All statistical tests were performed in Minitab Version 21.4.3 [69].

2.6.3 Dimension Reduction Analyses

To explore variable relationships and spatial patterns of landslide incidence across GB, K-means clustering analysis was performed. K-means analyses were performed independently for the mineral soil (loam, clay, and sand) and organic soil (peaty and peat) landslide groups. Soil texture was excluded to observe spatial patterns independent of soil texture distribution biases. Slope inclination (x), DOLR (y), and 30-DCAR (z) were the variables used in the analyses, such that $\mathbf{x} = (x, y, z) \in \mathbb{R}^3$. Prior to performing the analysis, the variables were standardized to a mean of 0 and standard deviation of 1. The number of clusters ($k = 3$) was manually selected using the ‘elbow method’ [70] which plots a range of k values against the within-cluster sum of squares (WCSS) to optimize the variance using the least number of clusters.

We randomly set k number of initial ‘mean values’ $m_1^{(0)}, m_2^{(0)}, m_3^{(0)}$ such that $m_i^{(0)} \in \mathbb{R}^3$. Through an iterative process, we define a cluster for the given iteration n as:

$$C_i^n = \{\mathbf{x}_p \in \mathbb{R}^3 : \|\mathbf{x}_p - m_i^{(n)}\|_2 < \|\mathbf{x}_p - m_j^{(n)}\|_2, \forall j \in [1, k] \setminus \{i\}\}, \quad (1)$$

where $\|\cdot\|_2$ denotes the L2 norm (Euclidean distance, i and j indicate the indices of separate clusters and n designates the number of iterations after a given initialization. Once the clusters are established, we establish a new set of updated mean values for each cluster:

$$m_i^{(n+1)} = \frac{1}{\tilde{n}(C_i^n)} \sum_{\mathbf{x}_p \in C_i^n} \mathbf{x}_p, \quad (2)$$

where $\tilde{n}(C_i^n)$ denotes the cardinality operator, which counts the number of elements of a given set C_i^n . This process is repeated for reinitialized $m_i^{(0)}$ values until clusters are determined to minimize the variance within clusters. K-means analyses were performed in Python using the Sklearn module [71]. The resulting landslide data were color coded with their associated clusters and plotted onto their spatial map location. Three groups ($k = 3$), labeled 1o, 2o and 3o for organic soils and 1m, 2m and 3m for mineral soils, were selected as the optimal number of clusters for both mineral and organic soil landslide groups (SI Figure SI 1).

3 Results

3.1 Spatial, Temporal, and statistical overview

Most landslides in the NLD have occurred in loamy soils ($n=690$) and the least in sandy soils ($n=18$) (Figure 5), which reflects the distribution of soil texture classes within GB (Figure 2). Figure 5b presents the landslide counts normalized to the overall area of each soil texture group in GB, excluding the Exmoor 1952 events. Loam landslides were the most spatially frequent (0.49 landslides/ 100 km^2) and peat landslides the least (0.16 landslides/ 100 km^2).

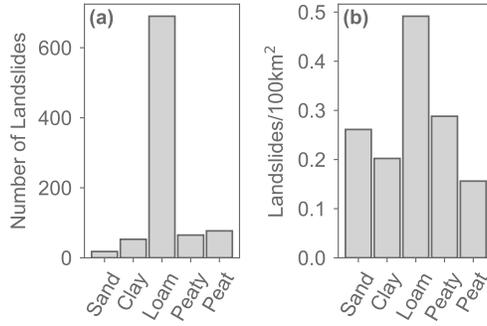


Figure 5: Spatial landslide incidence, excluding August 1952 Exmoor events (a) raw landslide counts in National Landslide Database by soil texture group; and (b) number of landslides by soil texture group normalized to respective soil texture area within GB.

Mineral soil landslides peaked during the winter months (January, February, and December) and decreased in frequency during the remaining months (Figure 6a). By contrast, peat and peaty landslides increased in frequency during the late summer and early autumn months and peaked in August ($n=22$, $n=5$, respectively). When normalized to the total landslides each month, peat and peaty landslides comprised between 15% and 39% of the monthly landslides that occurred in GB between June and October (Figure 6b). In all other months, peat and peaty landslides comprised between 5% and 9% of the monthly landslide total. When normalized to the landslide total within each soil texture group (Figure 6c), the trend of increased peat landslides in August is more pronounced showing that about 30% of peat landslides occur in August, the highest value of all textures in any given month.

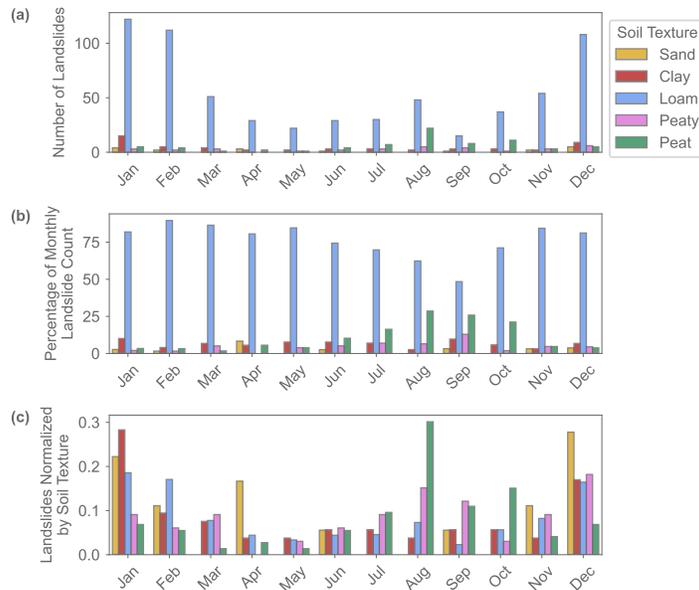


Figure 6: Monthly landslide incidence, excluding August 1952 Exmoor events, grouped by soil texture (a) raw monthly counts, (b) counts normalized within each month, and (c) normalized by total landslides within each soil texture group.

Histograms of the slope and rainfall parameters within each soil texture group are presented in Figure 7. Most landslides in sand and clay soils (67% and 56%, respectively), were within the shallowest slope values (<10 degrees) (Figure 7a). For the category of slopes with <10 degrees, loam, peaty, and peat soil

landslides had more evenly distributed slope values with 39%, 39%, and 18%, respectively. Of all groups, peat landslides had the highest proportion (19%) of landslides in the steepest slope values (>31 degrees). Nearly all sand, clay, loam, and peaty landslides (94%, 100%, 88%, and 91%, respectively) had 30-DCAR values between 0 and 200 mm (Figure 7b). By contrast, peat landslides had 58% of points in the same 30-DCAR range and had the highest proportion (13%) of landslides with 30-DCAR greater than 301 mm. The DOLR values (Figure 7c) for all landslides tended to be lower than their respective 30-day daily mean rainfall values (Figure 7d). This trend was especially apparent for mineral soil landslides as sand, clay, and loam landslides had the majority (73%, 87%, and 64%, respectively) of rainfall values in the lower (≤ 10 mm) DOLR values. By contrast, 16% and 26% of peaty and peat landslides fell under the same DOLR category (≤ 10 mm), respectively. Peaty soils had the largest portion of landslides laying in the 11-15 mm DOLR bin. Of all soil groups, peat had the highest proportion (15%) of landslides in with DOLR values exceeding >31 mm (the final two bins), with its mode DOLR bin occurring between 16-30 mm.

Figure 8 presents averages and variation of slope inclination, 30-DCAR, and DOLR for each soil texture group (Table SI 1. Peat landslides have occurred on significantly steeper slopes $p < 0.05$ ($F4 = 13.43$) (Figure 8c) and with a significantly higher 30-DCAR rainfall $p < 0.05$ ($F4 = 8.55$) (Figure 8d) than landslides in other soil texture groups in GB. Additionally, clay landslides have occurred with significantly lower 30-DCAR values than loam landslides.

3.2 K-Means Analysis

K-means clustering was applied to mineral and organic soil landslides independently considering slope inclination (x), DOLR (y) and 30-DCAR (z) as variables (i.e., $\mathbf{x} = (x, y, z)$). Importantly, soil texture was not considered as a variable to observe groupings independent of the soil texture maps.

Table 1 presents the summary statistics of the rainfall and slope variables within the mineral soil (1m, 2m, 3m) and organic soil (1o, 2o, 3o) clusters. Table 2 presents a simplified summary of the slope and rainfall characteristics of each cluster. The descriptors ‘low’, ‘moderate’, and ‘high’ were assigned as relative terms within the range of values for each variable (see Table 1). Cluster 1m was characterized by low/shallow slope inclinations (M=7.91, SD=4.12 degrees) low to moderate rainfall values (30-DCAR, M=112.13, SD=46.42 mm; DOLR M=6.52, SD=6.94 mm) with a high count (n=192) of DOLR values between 0 and 3 mm. Cluster 2m was characterized by shallow to moderate slope inclinations (M=14.44, SD=7.95 degrees) and moderate to high rainfall parameters (30-DCAR, M=254.24, SD=86.82 mm; DOLR M=31.42, SD=13.57 mm). Cluster 3m was characterized by moderate to high/steep slope inclinations (M=22.45, SD=6.46 degrees) and low to moderate rainfall parameter values (30-DCAR, M=108.40, SD=54.29 mm; DOLR M=4.21, SD=5.45 mm). Cluster 1o was characterized by shallow to moderate slope inclinations (M=10.23, SD=4.69 degrees) and low to moderate rainfall amounts (30-DCAR M=108.54, SD=42.57 mm; DOLR M=12.25, SD=7.47 mm) with 13 points with DOLR values between 0 and 3 mm. Cluster 2o was characterized by moderate to steep slope inclinations (M=22.80, SD=8.77 degrees) and moderate to high rainfall amounts (30-DCAR M=309.40 mm, SD=102.63; DOLR M=38.00 SD=13.00 mm). Cluster 3o was characterized by moderate to steep slope inclinations (M=27.71, SD=5.59 degrees) and low to moderate rainfall amounts (30-DCAR M=176.36, SD=77.26 mm; DOLR M=15.60, SD=8.47 mm).

Cluster ID	n	Slope (degrees)			30-DCAR (mm)			DOLR (mm)		
		Mean	Mdn	SD	Mean	Mdn	SD	Mean	Mdn	SD
1m	426	7.91	8.05	4.12	112.13	112.70	46.42	6.52	3.90	6.94
2m	98	14.44	14.22	7.95	254.24	236.85	86.82	31.42	28.70	13.57
3m	237	22.45	20.30	6.46	108.40	106.10	54.29	4.21	1.60	5.45
1o	74	10.23	9.90	4.69	108.54	121.00	42.57	12.25	14.10	7.47
2o	48	22.80	23.67	8.77	309.40	289.00	102.63	38.00	36.60	13.00
3o	20	27.71	27.59	5.59	176.36	165.80	77.26	15.60	14.40	8.47

Table 1: Summary statistics of slope (degrees), 30-day cumulative antecedent rainfall (30-DCAR) (mm), and day-of landslide rainfall (DOLR) (mm) within K-means mineral soil clusters (1m through 3m) and organic soil clusters (1o through 3o).

Cluster ID	Slope	30-DCAR	DOLR
1m	Low	Low to moderate	Low to moderate
2m	Low to moderate	Moderate to high	Moderate to high
3m	Moderate to high	Low to moderate	Low
1o	Low to moderate	Low	Low to moderate
2o	Moderate to high	Moderate to high	Moderate to high
3o	Moderate to high	Low to moderate	Low to moderate

Table 2: Relative variable values within K-means clusters. Slope mineral clusters ‘low’ 0 to 15, ‘moderate’ 16 to 30, ‘high’ > 31 degrees. Slope organic clusters ‘low’ 0 to 15, ‘moderate’ 16 to 30, ‘high’ > 31 degrees. 30-day cumulative antecedent rainfall (30-DCAR) mineral clusters ‘low’ 0 to 100, ‘moderate’ 101 to 200, ‘high’ > 201 mm. 30-DCAR organic clusters ‘low’ 0 to 150, ‘moderate’ 150 to 300, ‘high’ > 301 mm. Day-of-landslide rainfall (DOLR) mineral clusters ‘low’ 0 to 15, ‘moderate’ 16 to 30, ‘high’ > 31 mm. DOLR organic clusters ‘low’ 0 to 15, ‘moderate’ 16 to 30, ‘high’ > 31 mm. See Table 1 and Figures SI 2 and SI 3 for range and distributions of each variable for all clusters.

Figure 9 presents the clusters plotted spatially. Cluster 2m, the moderate to high rainfall cluster, was predominantly found in the western half and the northernmost areas of GB. Cluster 3m, the steep-sloped cluster, was generally found along coastlines and the upland regions of GB. While a distinct spatial pattern was less apparent for Cluster 1m, the shallow and lower rainfall cluster, it did exhibit a notable concentration of points in southern GB and near major urban centers. Similar to Cluster 2m, Clusters 2o and 3o the organic moderate rainfall clusters, were found in the western half of GB. A spatial pattern was not as obvious with Cluster 1o, the low to moderate rainfall and shallow slope group, though it was the only organic cluster to plot in the northeast of GB and on northern isles.

To understand if the K-means clusters exhibited patterns with soil textures (not included in clustering), particle size and organic matter content statistics were calculated for each cluster and the results presented in Table 3 for mineral soils and Table 4 for organic soils. Cluster 2m was characterized by relatively low clay and higher sand content. Clusters 1m and 3m had similar distributions with relatively moderate sand and lower clay content. Clusters 2o and 3o were characterized by higher organic matter content and thus was represented by more pure peat than peaty landslides. Cluster 1o (Table 4) was characterized by lower organic matter content than the other clusters and thus included more peaty than peat landslides. It is worth noting that all particle size distributions had high standard deviation values and large differences in the mean and median values, indicating a variability in particle size within each cluster due to the prescriptive method used to derive the particle size distributions. Unsurprisingly, mineral soil clusters all had their highest number of landslide events in winter months (Table 3), consistent with monthly patterns of mineral soil landslides (Figure 6). However, the most frequent months were split between summer and winter in organic clusters: Landslides in 1o and 3o occurred most frequently in August, while 2o had most landslides in December (Table 4).

Cluster ID	n	% Sand			% Clay			Month
		Mean	Mdn	SD	Mean	Mdn	SD	Mode (n)
1m	426	41.40	35.00	19.88	22.47	26.50	14.58	Feb (83)
2m	98	53.14	65.00	16.12	15.34	9.00	9.42	Dec (32)
3m	237	44.36	35.00	17.32	19.89	26.50	12.92	Jan (49)

Table 3: Mineral clusters associated texture data and most frequent month of landslide.

Cluster ID	n	Mean	% OM		Month
			Mdn	SD	Mode (n)
1o	74	60.51	42.50	34.21	Aug (39)
2o	20	84.08	100.00	28.57	Dec (5)
3o	48	76.08	100.00	32.94	Aug (21)

Table 4: Organic clusters associated organic matter content and most frequent month of landslide.

4 Discussion

4.1 Temporal Landslide Incidence

Total monthly landslide trends showed increased landslide occurrence in the winter months (January, February, and December) and a relative decline in the remaining months with a spike in August (Figure 6a). The winter landslide peak coincides with rainfall patterns in GB, which receives the highest amounts of precipitation in December and January [72]. With regards to the spike in August, a possible explanation for the increased landslide incidence is that tension cracks and fissures form after the drier summer months resulting in rainfall infiltration via preferential pathways. This ultimately saturates deeper soil strata, increasing the pore water pressures at depth that lead to unstable subsurface layers that result in hill slope failures [73, 74]. We note that this process is expected to be more common in soils with finer textured material (*i.e.*, clay, loam) [74]. In the case of peat and peaty landslides, it is well documented that they occur more frequently in August and September in the British Isles [40, 75, 76, 77]. Similar to the processes described for fine textured soils, desiccation cracks forming in the summer and subsequent rainfall infiltrating the peat mass was also concluded to be partially causal in several peat landslide case studies (*e.g.*, [76, 75, 77]). Peat landslides are the least spatially frequent of all textures in GB (Figure 5b) yet comprise the second highest landslide raw count from June to October (Figure 6a), indicating a temporal trend driving organic soil landslides in summer and early autumn in GB. This may suggest that there are auxiliary mechanisms that uniquely contribute to the summer failure of organic soils.

Metabolic activity of micro-biota is accelerated with increased temperatures, thus biodegradation and breakdown of organic constituents would likely be amplified. While mineral soils may not be as sensitive to these processes, organic soils that might rely more heavily on incorporated organo-constituents for its mechanical shear strength may be profoundly impacted by this enhanced biological activity [78]. Furthermore, organic soils may be rich with high concentrations of EPS. Certain types of EPS (*e.g.*, root mucilage) are surfactants, thus they can become hydrophobic under drying [79]. For the case of preferential water flow, the organic soil is less likely to absorb and redistribute infiltrated water due to the dried EPS blocking pore structures. Therefore, there is an increased likelihood that infiltrated water will accumulate at depth and incur large pore water pressures, leading to failure.

Peat landslides were characterized by significantly steeper ($p < 0.05$) slopes than all other texture groups in the NLD (Figure 8c). This result contradicts much of the existing literature, in that peat landslides typically occur on shallow slopes (<15 degree) [75, 77, 80, 20], less than the mean peat landslide slope in this dataset ($M=20.82$, $SD=10.53$). Peat landslides would be expected to inherently have shallower slopes than mineral soil landslides by the nature of typical peat formation processes, which are facilitated by the accumulation of organic matter, typically in flat or gentle topography [29, 23]. Several interpretations can explain the ANOVA slope result. One is that relative to overburden weights (*i.e.*, shear stresses), the organic matter fibers in peat provide greater tensile strength and reinforcement relative to the cohesion and friction in mineral soils, thus do not flow as readily as the mineral soils do at lower slope angles. Conversely, the result could be due to the distribution of peat slopes; there are not many steep peat slopes, but where they do exist, they are more prone to landslides. Given that most peat landslide case studies do not support this, a preferred interpretation is that some of the steep peat landslides represent a different failure mechanism, such as rockfalls or debris flows with a thin peat veneer. It would be expected that thinner peat layers are present on slopes given peat forming principles. This interpretation was not verifiable with the topsoil texture maps used in this analysis.

It should be considered that the ANOVA result may be a reflection of limitations in the slope dataset.

Slope angles were calculated under the assumption that the landslides occurred on the steepest section of slope, which may artificially skew slope gradients to steeper values. Furthermore, inclinations were calculated as average values at a relatively coarse resolution, meaning local topographic variability was not captured, which can play a role in peat landslide susceptibility [22]. However, these limitations apply to all landslides in this study, not just organic landslides, so broad or relative comparisons between groups would still be appropriate.

The ANOVA analysis on rainfall values revealed that peat landslides have occurred with significantly higher ($p < 0.05$) 30-DCAR than other soil groups. This result is consistent with existing case studies that reported high antecedent rainfall quantities linked with peat landslides [75, 77]. However, unlike mineral soil landslides, antecedent rainfall thresholds for organic soil landslides have not been studied for comparison with this result, and most studies reference the DOLR value or rainfall intensities. Although not statistically tested, the DOLR distributions showed that peat and peaty landslides had the greatest proportions of landslides in the highest DOLR values (>16 mm) (Figure 7c). Alternatively, mineral soil landslides had greater proportions of landslides with low <5 mm DOLR values. During periods of heavy rainfall, blanket bogs have been shown to efficiently facilitate run-off, with estimates of about 99% of flow occurring at the surface and the upper 5 cm of the peat mass [81]. [82] concluded that because peat is inherently water logged, only small increases in pore pressures may be needed to induce failure in a peat mass. Our data analysis suggests this is not necessarily the case; relative to mineral soils, greater DOLR and 30-DCAR amounts are observed for organic landslides. While our analysis does not explicitly consider pore-water pressure, we assume that higher rainfall is associated with increased pore-water pressure.

The results of the statistical tests and heuristic analysis show promising distinctions between organic and mineral failures. These comparisons enabled relative quantification of DOLR, 30-DCAR, and slope angle. However, the results do not always agree with interpretations from the literature due to the large spatial extent considered, highlighting that a more robust analysis was needed to understand if differences exist between texture groups.

4.2 Spatial Analysis

The K-means results further refined the slope and rainfall interactions and provided important spatial context to the results. Clusters 2m (shallow to moderate slope with moderate to high rainfall) and Cluster 3m (moderate to steep slopes with low to moderate rainfall) exhibited inverse rainfall and slope relationships, as expected with general slope stability principles. Cluster 2m plotted exclusively in the western and northern regions of GB (Figure 9a), consistent with the highest rainfall regions in GB [83]. Cluster 3m plotted along coastlines and in northern GB and thus may be represented by steep coastal and upland landslides (Figure 9a). Cluster 1m was alternatively characterized by shallow to moderate slopes and low rainfall values. Given the cluster's spatial density in southern GB and near major urban centers (Figure 9a), it may be represented by landslides associated with anthropogenic actions. Cluster 1m had a high count ($n=192$) of DOLR values between 0 and 3 mm, a condition unique to this cluster. This result suggests that rainfall may not be the only trigger in initiating Cluster 1m landslides. It is also possible these are in fact engineered slopes over short distances and the actual steepness is not accurately captured by our approach due to the relatively coarse resolution of the digital elevation map used (30m). Cluster 1m also had the highest proportion of clay landslides ($n=39$) compared to Clusters 2m ($n=1$) and 3m ($n=13$). Cluster 1m may thus be represented by lithologies more prone to landslides with lower slope and rainfall thresholds, such as the London Clay, an over-consolidated fissured clay which has been documented failing on slopes as shallow as 8 degrees [84]. The clay landslides evaluated in this study are concentrated in the southeast and London basin where the London Clay outcrops [56]. Furthermore, the moisture content and plasticity index of certain clays can be causal in landslide incidence on shallow slopes [85], which was not evaluated in this research.

Cluster 1o (shallow slopes and low to moderate rainfall) was the only organic cluster in the northeast of GB and on the Isles (Figure 9b). Cluster 1o landslides are consistent with slope, spatial, and temporal conditions of past peat landslides in GB and Ireland such as the 2003 peat slides and flows in Shetland [75]. Unfortunately, the 2003 Shetland landslide locations were not verified by the BGS and thus were removed from the database during the data filtration process so this direct comparison could not be validated. The mean 30-DCAR of Cluster 1o ($M=108.54$ mm) was less than or roughly equal to the mean 30-DCAR values of each mineral soil texture group (Table SI 1) and the lower rainfall mineral soil Clusters 1m and 3m

(Table 1). By comparison, the other organic clusters had higher mean 30-DCAR values, 309.40 mm (Cluster 2o) and 176.36 mm (Cluster 3o). Of the organic clusters, Cluster 1o had the highest incidence in August (n=39) (Table 4 which may point to a temporal explanation for the lower rainfall values in this cluster. As previously discussed, under normal water-logged conditions, blanket bogs efficiently facilitate surficial runoff during heavy rainfall periods [81]. If peat and vegetation dry out during summer months and desiccation cracks form, rainfall may infiltrate the peat into deeper horizons via preferential pathways, thus lowering the antecedent rainfall threshold needed to raise pore pressures at depths to initiate a failure. Acceleration of metabolic processes can also play a role in the degradation of organic matter, thus leading to a reduction in bulk shear strength. Conversely, if peat does not seasonally dry out due to higher overall annual rainfall volumes and groundwater levels, it may be less susceptible to failure given its ability to promote rainfall runoff. This interpretation implies that changes in peat soil moisture content play a key role in peat pore pressures and landslide susceptibility and initiation. This interpretation can be applied to Clusters 2o and 3o (moderate to steep slopes and moderate to high rainfall) which plot on the western side of GB. This region receives around 2,000 mm more annual rainfall than the northeast [83], where Cluster 1o primarily plots. From this we conclude peat on the western side of GB is less prone to drying out to critical values, and only under the most extreme cases of steep slopes and high rainfall (*i.e.*, Clusters 2o and 3o) do peat landslides occur in western GB. This can be interpreted to mean that the western regions of GB are relatively stable from an organic soil landslide perspective.

Furthermore, because Clusters 2o and 3o are characterized by moderate to steep slopes, the peat is likely shallow due to peat forming processes previously described, thus the underlying mineral soil or bedrock may be controlling the failure mechanics. These failures would then fall under the ‘peaty-debris slide’ classification in which shear failure occurs exclusively in the mineral substrate with the peat cover playing a minor role in the failure mechanics [86]. Peaty-debris failures have been documented failing on slopes up to 32 degrees [86], which more closely aligns with the slope conditions of Clusters 2o and 3o (M=22.80 and 27.71 degrees, respectively) than other types of organic landslides (*e.g.*, bogflows) or Cluster 1o (M=10.23 degrees). Considering this interpretation that Clusters 2o and 3o are failures initiating in the mineral substrate, this could indicate that peat acts as a stabilizing force on these slopes given that they are characterized by both steep slopes and high rainfall sums. This is further supported when compared to the mineral soil landslides with similar slopes in the same region of western GB (Cluster 3m) which were characterized by lower 30-DCAR (M=108.40 mm) than Clusters 2o and 3o (M=309.40 mm and 176.36 mm, respectively). This can be interpreted to mean that with a peat cover, even if shallow, higher antecedent rainfall values are needed to induce failure than on similar mineral slopes. Peat cover, therefore may act as a stabilizing factor on slopes, regardless of where the failure plane is. Moisture content may play a role in this relationship and given that Clusters 2o and 3o plot in higher-rainfall regions of GB [83], the peat cover may maintain adequate moisture contents (alternative to Cluster 1o) throughout the year to promote runoff, hence Clusters 2o and 3o are not as frequent in late summer as Cluster 1o. Thus, shallower peat slopes (more similar to Cluster 1o) are not as common in western GB because the region may be more stable from an organic soil landslide perspective. Furthermore, given that peat is the least spatially frequent landslide type in GB (Figure 5), this speaks more broadly to peat landslides in GB, and that peat is less susceptible to landslides than other soil types, further supporting that peat cover may act as a stabilizing force on slopes.

The NLD provides additional information on landslides for certain entries in the database such as measured slope and failure type. Since the ambition of this project was to work towards susceptibility mapping for landslides in the UK, we purposefully did not include this data in the analysis. Having the analysis dependent on bespoke measurements of failed slopes, the resulting predictive models would only be applicable to where these measurements have been taken (*i.e.*, where a landslide has already happened) or as preemptive risk analysis. With our approach of using data which is available across the whole of GB (30m-slope, soil texture, organic matter content, rainfall) the resulting analysis could potentially be used to predict future landslides on all slopes. Incorporation of additional data such as rainfall intensity values, vegetation cover, and failure mechanism, should be considered for further refinement of this work.

The present framework enables us to distinguish landslide triggering conditions (*i.e.*, slope, 30-DCAR, DOLR) between mineral and organic soils and identify risks associated with mineral and organic soils for given regions and seasons. In principle, this could be used to generate rapid prescreening tools for predicting landslide risks. For example, given the texture, organic matter, slope, and geographic location, a site can be associated with a given cluster (1m-3m or 1o-3o). Those clusters can be used to gauge months of highest

likelihood of failure. 30-DCAR can be monitored and associated with the texture histograms in Figure 7b) to give a rainfall threshold for the specific texture on day by day basis.

While this is a promising first step, future improvements can make this tool more robust. Precipitation was used as an indicator of soil moisture and pore-water pressure soil moisture possibly leading to inaccuracies. Monitoring 30-DCAR is not necessarily the most suitable time window to approximate soil moisture. Furthermore, soil moisture is highly texture dependent, thus it remains a challenge to consider this variable directly. Consideration of more detailed soil texture can aid in refining our categorization of soil types. This could enable the applicability of broader statistical techniques (e.g., PCA). Lastly, future investigations should explore fundamental mechanisms associated with peat landslides and peat mechanics in general. Experimental lab or field scale tests need to be carried out to better assess shear strength, failure mechanisms (both moisture and temperature dependent) and conditions that can lead to catastrophic failure events.

5 Conclusions

This study was the first to characterize landslide incidence broadly across GB using antecedent rainfall and preconditioning factors, slope inclination and soil texture. We show that organic soil landslides in GB are characterized by significantly higher antecedent rainfall amounts and slope angles than mineral soil landslides suggesting key differences in rainfall thresholds, initiation mechanics, and the role of soil moisture between groups. Consistent with current literature, we conclude that peat landslides are most common in late summer and early autumn months, while mineral soil landslides are most common in high-rainfall winter months. Soil moisture and the unique hydrological properties of peat, likely play a considerable role in driving the observed differences.

K-means clustering successfully identified clusters of organic and mineral soil landslides with similar preconditioning and rainfall characteristics and importantly, intra-cluster spatial and temporal similarities were observed. A cluster of mineral soil landslides characterized by shallow slopes and lower rainfall values (Cluster 1m) was identified in southern GB and near urban centers. Further work is needed to understand what is driving this trend, but it is interpreted that rainfall is not the only trigger given the cluster's low DOLR values. We postulate that anthropogenic actions or a more susceptible lithology may be causal in initiating Cluster 1m landslides. Mineral soil landslides characterized by shallow slopes and high rainfall values (Cluster 2m) were found on the west side of GB, consistent with regional rainfall patterns. Lower-rainfall and steep sloped-landslides (Cluster 3m) were generally found along coastlines and upland regions and may represent bedrock landslides and coastal cliff failures.

Organic landslides in the northeastern regions and isles (Cluster 1o) occur more frequently in August and are characterized by lower organic matter, shallower slopes, and lower rainfall values than the other organic clusters. The slope, spatial, and temporal characteristics of Cluster 1o are consistent with many peat landslide case studies performed in Scotland and Ireland [87, 75, 77]. We conclude that the high incidence of Cluster 1o landslides in August may be driven by lower peat moisture contents in summer months, which facilitates the formation of desiccation cracks, inhibits rainfall overflow, and thus lowers the amount of rainfall needed to raise pore pressures to failure.

Organic landslides in the western half of GB (Clusters 2o and 3o) were characterized by steep slopes and high antecedent rainfall values. We postulate that these clusters represent peaty-debris slides in which the failure plane initiates in the underlying mineral substrate, rather than in the peat mass. Similar mineral soil landslides in the same region (Cluster 3m) were characterized by lower antecedent rainfall sums. We conclude that in western GB, slopes with peat cover, have higher rainfall thresholds than those without peat. Peat moisture content likely plays a role in this dynamic, and in this region of GB, higher annual rainfall amounts allow peat to maintain moisture contents and vegetation cover that promote runoff rather than infiltration, making peat-covered slopes less susceptible to landslides in this region. More research is needed to understand how long-term climate patterns (e.g., dry periods followed by heavy rainfall) relate to organic soil landslide initiation.

Climate projections are forecasting more frequent high-intensity rainfall events in GB [47] and potential for increased drought periods [49]. These effects along with continued anthropogenic development, may increase landslide susceptibility or hazard exposure in GB. Importantly, this study highlights that landslide

policy and mitigation strategies should be developed separately for mineral and organic landslides and for specific regions. Work should continue to further characterize landslides in GB with the goal of developing resources for landslide mitigation strategies such as high-resolution susceptibility maps for use by the public, land developers, and local governments.

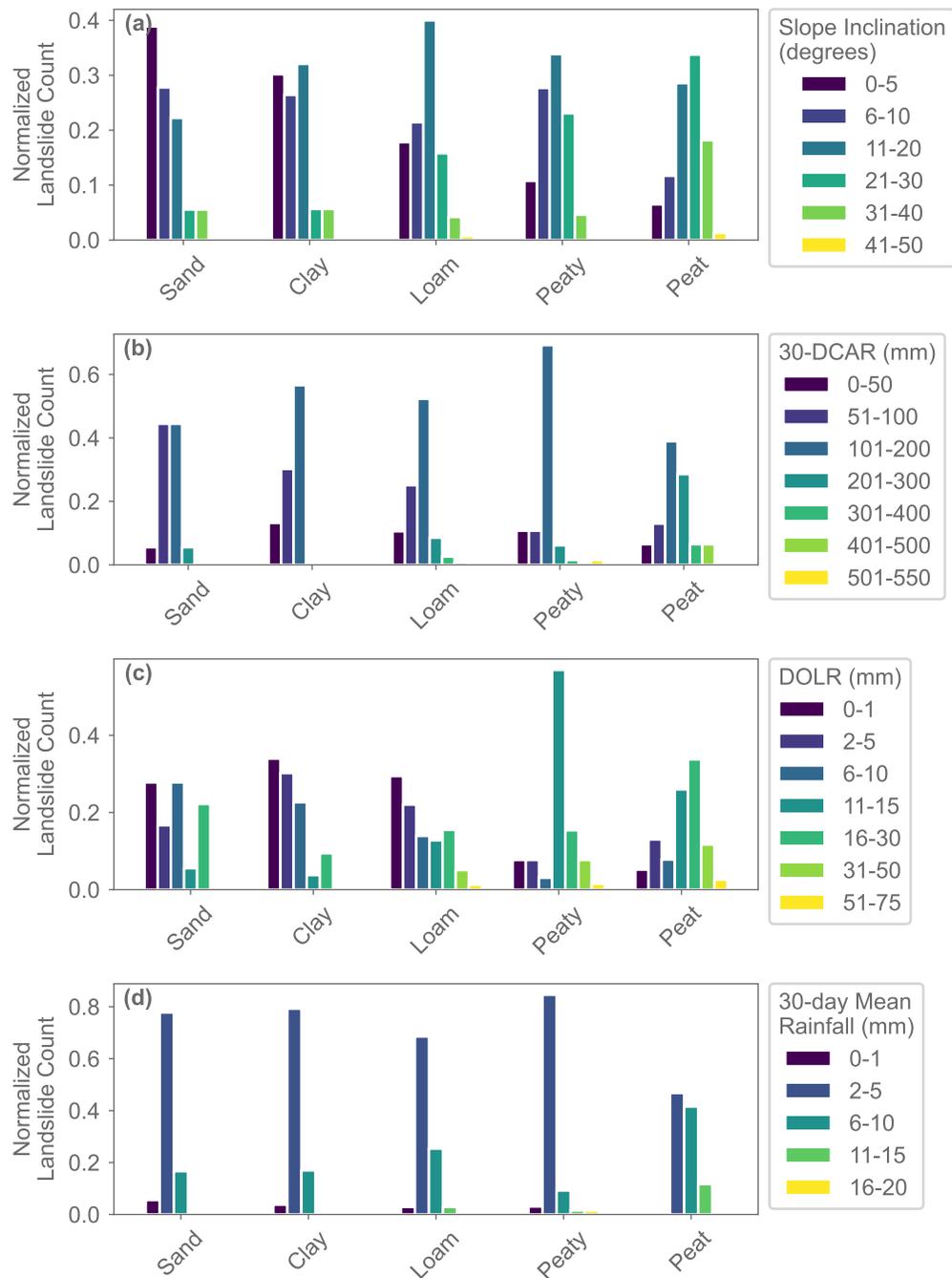


Figure 7: Distribution of rainfall and slope variables normalized within each soil texture group: (a) slope inclination (degrees), (b) 30-day cumulative antecedent rainfall (30-DCAR) (mm), (c) day-of landslide rainfall (DOLR) (mm), and (d) 30-day mean rainfall (mm).

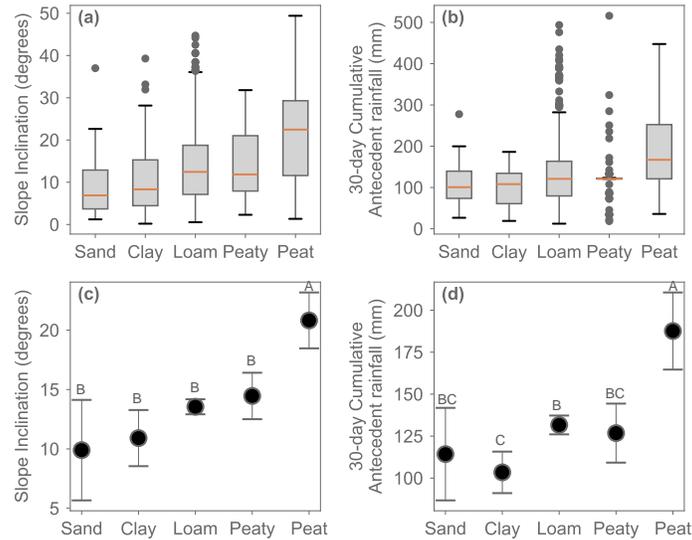


Figure 8: Box plots showing median (orange) and inter-quartile ranges of (a) slope inclination (degrees), and (b) 30-day cumulative antecedent rainfall (30-DCAR)(mm). Mean values with 95% confidence intervals of (c) slope inclination (degrees), and (d) 30-DCAR (mm). Letters represent statistically significant differences between groups, as determined by ANOVA followed by Tukey (slope) and Games-Howell (30-DCAR) post-hoc tests. Groups not sharing a common letter are significantly different at $p < 0.05$. Peaty 30-DCAR distribution in plot b) obscured by high count ($n=32$) of landslides with the same or similar 30-DCAR amounts associated with the 1952 Exmoor landslides. Note different y scales between plots (a) and (c) and between plots (b) and (d).

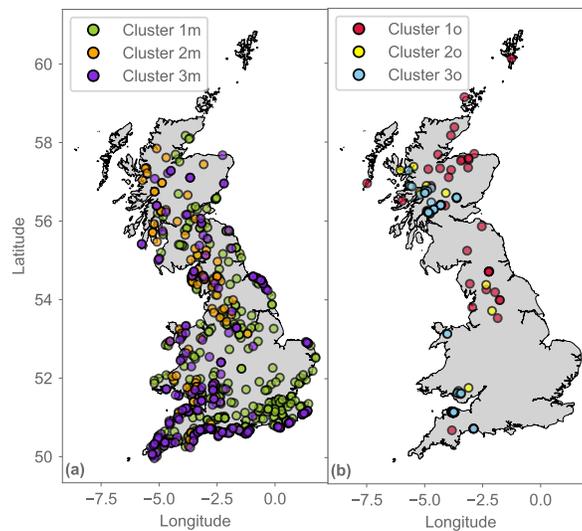


Figure 9: K-means clusters spatial plots (a) mineral soil landslides and (b) organic soil landslides.

Author contributions

JE and DMF developed the study and all of the codes used in this study. JE conducted all of the analysis and statistical tests. JE DMF and SR provided result interpretation. JE wrote the initial draft. All authors contributed to writing the submitted manuscript.

Acknowledgments

This paper developed from dissertation from the Soils and Sustainability MSc at the University of Edinburgh. This work was supported by the Rural and Environment Science and Analytical Services Division (SRUC-C5-1). This work was supported by the Rural and Environment Science and Analytical Services Division (SRUC-C3-2). SR is funded by BBSRC Discovery Fellowship BB/X010147/1 and Royal Society University Research Fellowship URF\R1\231622 for

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Supporting Information

Supporting Information.1 Figures

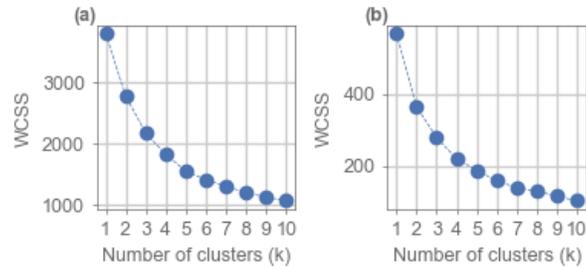


Figure SI 1: Results of elbow method within-cluster sum of squares (WCSS) against number of clusters for (a) mineral soil landslides, and (b) organic soil landslides.

Supporting Information.2 Tables

Soil Texture	n	Slope (degrees)			30-DCAR (mm)			DOLR (mm)		
		Mean	Mdn	SD	Mean	Mdn	SD	Mean	Mdn	SD
Sand	18	9.90	6.89	9.16	114.28	100.80	59.65	7.21	5.35	7.10
Clay	53	10.91	8.31	8.78	103.41	108.20	45.92	4.85	2.10	6.27
Loam	690	13.55	12.45	8.48	131.65	121.00	75.12	9.37	4.50	11.97
Peaty	65	14.46	11.85	8.04	126.78	121.00	72.30	15.96	14.10	10.57
Peat	77	20.82	22.46	10.53	187.59	167.10	102.81	17.90	14.40	13.56

Table SI 1: Summary statistics of slope (degrees), 30-day cumulative antecedent rainfall (30-DCAR) (mm), and day-of landslide rainfall (DOLR) (mm) by soil texture group.

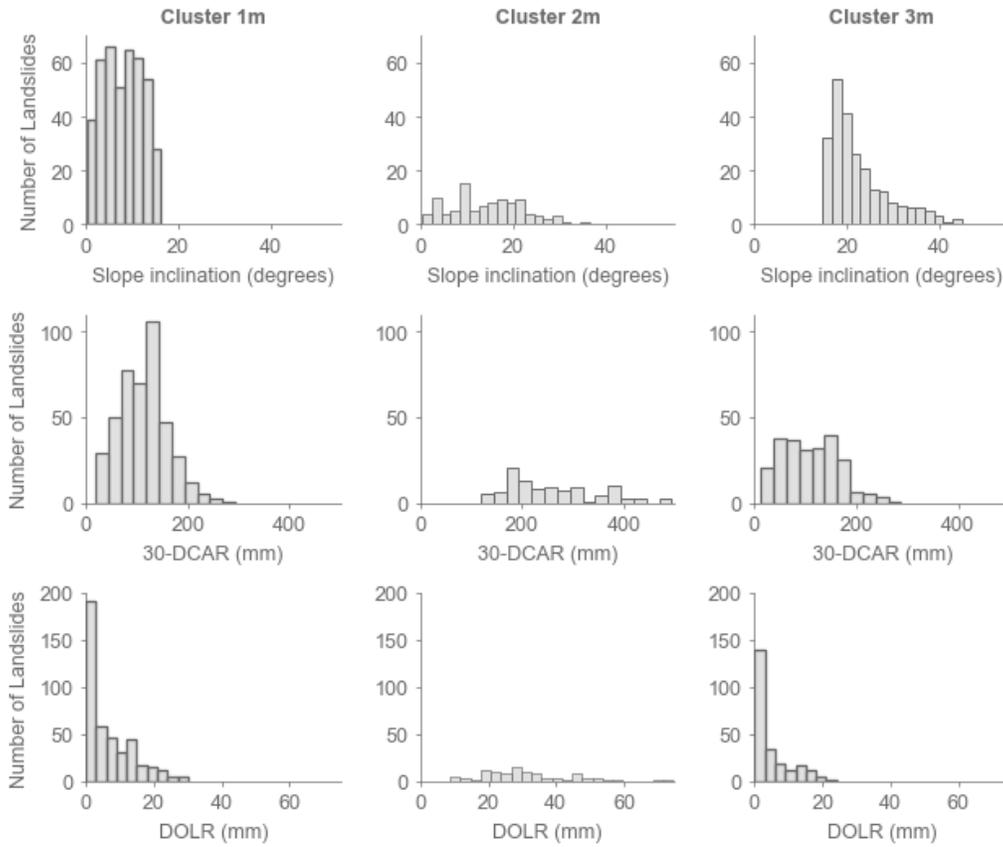


Figure SI 2: Distribution of slope and rainfall variables within each mineral soil K-means cluster (columns). Top row: slope inclination (degrees); middle row: 30-day cumulative antecedent rainfall (30-DCAR) (mm); and bottom row: day-of landslide rainfall (DOLR) (mm).

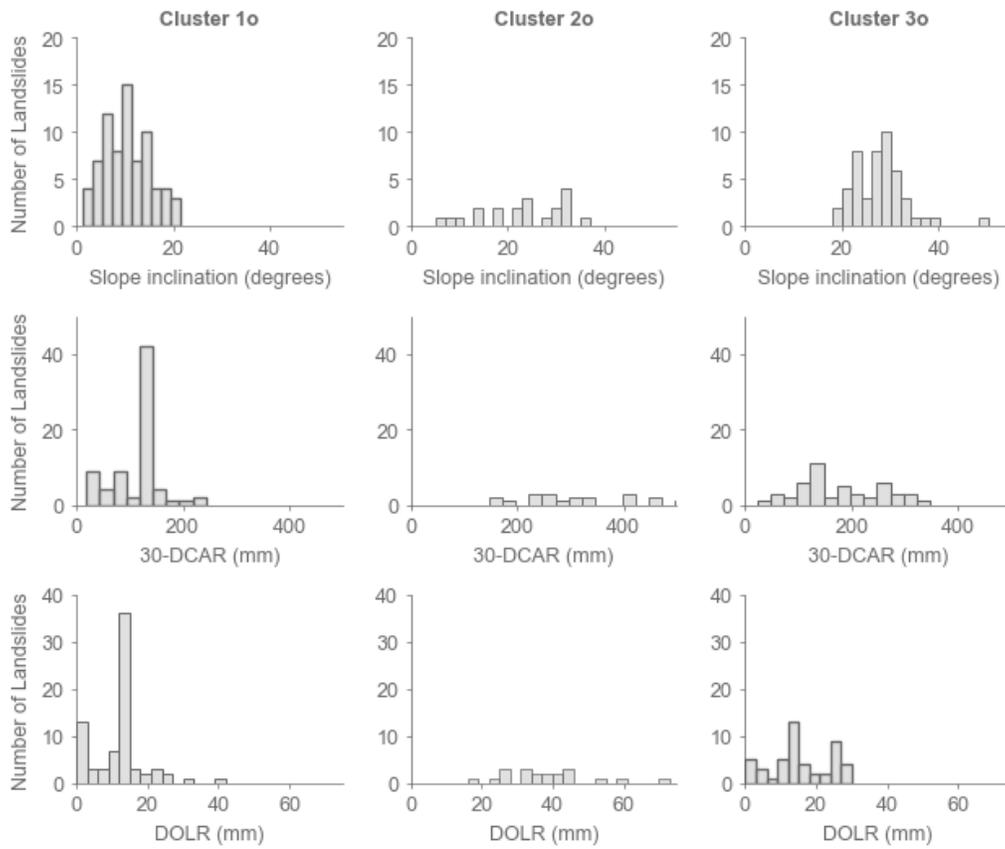


Figure SI 3: Distribution of slope and rainfall variables within each organic soil K-means cluster (columns). Top row: slope inclination (degrees); middle row: 30-day cumulative antecedent rainfall (30-DCAR) (mm); and bottom row: day-of landslide rainfall (DOLR) (mm).