Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP)

ERAMMP Technical Annex-105TA1S9: Wales National Trends and Glastir Evaluation Supplement-9: Soil Erosion

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Abbreviations Used in this Report

APGB	Aerial Photography for Great Britain
BGS	British Geological Society
EO	Earth Observation
GIS	Geographical Information System
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
NFS	National Field Survey
OS	Ordnance Survey
RMSE	Root Mean Square Error
SDR	Sediment Delivery Ratio
SED	Soil Erosion and Disturbances
UKCEH	UK Centre for Ecology & Hydrology
UKRI	UK Research and Innovation
USEPA	United States Environmental Protection Agency
USLE	Universal Soil Loss Equation

Contents

1 OVERVIEW & APPROACH

1.1 Soil Erosion and Disturbance (SED) & Objectives

Soil Erosion and Disturbance (SED) through compaction represent major forms of land degradation worldwide. Soil compaction may arise from animals, termed poaching, or by repeated traffic by vehicles or machinery, particularly on wet soils. This leads to structural degradation of the soil, reduction of porosity and a heightened susceptibility to soil erosion. Additionally, compacted bare soil can be a potential source of N_2O emissions (Tye & Robinson, 2020). Erosion may strip agricultural areas of fertile topsoil, while surface runoff that is laden with eroded soils and excess nutrients contaminate receiving water bodies, posing risks to freshwater ecology and pushing up costs for water treatment. Three soil threats are interlinked, loss of soil organic matter, compaction and erosion. Porosity in soils is linked to SOM (Robinson, et al., 2022; Thomas, et al., 2024), compaction reduces infiltration, enhances runoff resulting in erosion of soil by water. Thus, soil erosion is often a manifestation of other soil health issues and is important for environmental policy, including in Wales where it is a compliance issue as outlined in Good Agriculture and Environmental Conditions 5 (Welsh Government, 2022).

National scale assessment can help address soil erosion by identifying locations, extent and links to land use practice. As part of ERAMMP, SED feature mapping has been undertaken in survey squares across Wales. An Earth Observation (EO) based approach was carried out in 2020, using high resolution (25 cm) aerial images from May 2018 to map SED features across 261 out of 300 ERAMMP survey squares. This was followed up with a field survey (NFS) in 2021, focussed on a 200-metre radius around X-plots within each survey square to ground-truth this EO assessment and identify other features that may not have been detected from aerial images. Full details of the EO and NFS datasets can be found in ERAMMP Report-70 (Tye, et al., 2023).

Separately, national scale maps of soil erosion risk have been generated for Great Britain using a version of the Revised Universal Soil Loss Equation from InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) as part of the UKRI-funded AgLand project[1] (Hooftman, et al., 2023). This soil erosion rate modelling reflects conditions for the period 2016-2020, which closely aligns with both the ERAMMP EO and field survey assessments of SED. Furthermore, the modelling has been shown to possess good overall agreement with observed suspended sediment flux data from river catchments across the country; thus, it should present a robust picture of erosion risk across Wales.

This work provides an overview of the current state of soil erosion and disturbance in Wales. The aim of this analysis is to complement existing observational data (both the EO and NFS ERAMMP datasets) with modelling to enhance the extent of information on soil erosion that can be gleaned from SED features. This is split into 4 core objectives:

- Summarise the predominant types and magnitudes of SED feature coverages at 1 km^2 survey square level across Wales.
- Determine the dominant controls on SED feature areal extent per square kilometre across Wales.
- Assess the distributions of SED feature areal coverage per square kilometre by different SED categories & dominant controls on SED.
- Determine the correlation between SED feature extent & modelled gross erosion rates by water.

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[1] www.gtr.ukri.org/projects?ref=NE%2FT000244%2F1

1.2 SED Feature Collection

Soil erosion can be quantified in a number of ways, including field or plot experiments, walk-over surveys, Earth Observation (EO) and modelling. Common issues with various SED quantification approaches include:

- Incomplete process representation (especially in the case of catchment studies and simple spatial models like the Universal Soil Loss Equation (USLE) and its variants).
- Enormous time requirements and limited spatial application (especially in the case of field or plot experiments and more complex landscape evolution models, with more complete process representation, such as CAESAR-Lisflood).

An alternative approach, based on identifying and classifying erosion features, offers a spatially extensive and relatively low time-consuming approach, allowing a national scale assessment of soil erosion that is repeatable over time to be undertaken. ERAMMP Report-70 presents a hybrid approach that combines mapping of erosion features from above using aerial imagery, with ground-truthing and identification of additional features that have been obscured (e.g. by dense tree cover or cloudy aerial images) by field survey (Tye, et al., 2023).

Full details of the methods involved are presented in ERAMMP Report-70, with the key information summarised below.

1.2.1 Earth Observation (EO) Survey Using Aerial Imagery

The first step in the national-scale assessment of SED was a desk-based EO survey, undertaken in 2020 (Tye & Robinson, 2020). For this desk-based collection, 261 squares (note: 252 contained mappable features) were selected and high resolution (0.25 m) aerial photographs were cut to these squares in a desktop geographical information system (GIS). The aerial images used were the Aerial Photography for Great Britain (APGB) high resolution aerial imagery licensed to BGS from BlueSky International Limited. These images were supplemented by other spatial datasets, including OS maps, landscape characteristics derived from a digital terrain model and Google Earth imagery, to help interpret potential areas of erosion. Features were identified by a trained expert, which is important as the analyst's knowledge of landscape features and land-use practices is an important factor in accurately identifying a 'true' erosion feature.

Features were digitised as polygons (see examples in Figure 1-1) at a 1:1,250 scale in a GIS, which was identified as the optimum zoom level to see features without images becoming a pixelated blur. This process typically required 2-2.5 hours per five 1 km survey squares. However, in some areas that were dominated by lowland dairy farming, individual squares often required more than 40 minutes to map because of the large number of compaction-related features from livestock and machinery. Features were classified into one of several categories (see sub-section 1.3.1 in this supplement).

The specific dates of the aerial images were not easily identified, though they mainly represent Spring 2018. For the purposes of this assessment, the time period of the photos was not considered to have a major impact as large-scale changes in spatial land use and agricultural practices are not expected to occur. It should also be acknowledged that not all SED features (e.g. rills, erosion under dense tree cover) can be identified from aerial images. Repeat mapping of features over time has not yet been undertaken, so rates of erosion for instance cannot be considered here.

Figure 1-1 Examples of suspected SED features visible in aerial images with polygons digitised at a 1:1250 scale in desktop GIS software: a) gateway soil disturbance from machinery and livestock and poaching around a feeder; b) poaching in fields where livestock access to farmyards is required; c) gateway soil disturbance; d) area of soil erosion on very steep slope; e) terracettes lining slopes into a localised depression in the landscape. Taken from ERAMMP Report-70 (Tye, et al., 2023).

1.2.2 National Field Survey (NFS)

The second phase of the national-scale SED assessment was the field survey. Over 2021-23, field surveyors visited 199 survey squares that contained EO-mapped SED features. These surveyors verified the existence of the EO-mapped features and identified additional features that may have been too small or too obscured to identify from the air.

Each survey square consists of five “X-plots”, locations where soils are sampled and vegetation is assessed. Circles of 200 m radius were drawn around the X-plots and SED features marked within these zones were checked by the field surveyors. SED features digitised from the EO surveyor were loaded into tablets carried by each field surveyor, allowing them to see what had been previously identified from aerial images (Figure 1-2). This generated a subset of SED features that were located, presence confirmed or rejected, new features mapped, categorised and photographed. SED features were only verified and identified in land with access permitted to the field surveyors.

First-order estimates of the area of a SED feature were made by marking the feature on the tablet. New features were classified as per the scheme presented in Table 1-1 (see sub-section 1.3.1 in this supplement). SED feature guidance to field surveyors is given in more detail in ERAMMP Report-71 (Robinson, et al., 2021).

Figure 1-2 An example of the style of map that the field surveyors used to record SED features and validate the presence of EO-mapped features. Features were recorded within a 200 m radius of each X-plot in the survey square. Shapes with dashed shading indicate EO-mapped features, which when clicked, provide information of the expected SED feature (in this example, peat erosion). Taken from ERAMMP Report-70 (Tye, et al., 2023).

1.3 Analysis Methods

1.3.1 SED Feature Typology & Distribution

SED features are categorised into 16 different sub-groups, each belonging to 1 of 4 major categories (Table 1-1). Peat & organo-mineral erosion features reflect bare exposures of peat and erosion of these soils including along drainage ditches and as hags. Soil disturbance represents SED arising from traffic, be that from heavy machinery, livestock or humans. These types of features are common around feeders, along footpaths or other popular walking routes, and near points of egress such as gateways, stiles and gaps in fences. Scar or slip features typically occur on sloping land, including landslides and scree in mainly upland areas, and terracettes from repeated foot traffic on sloping grassland (e.g. from grazing sheep or cattle). Mineral soil erosion features arise from soil erosion via water, including from river flow and wave action in the case of riverbank and coastal erosion, respectively, and from rainfall-runoff for all other sub-groups in this SED category.

It is important to acknowledge that several identifiable SED features could belong to multiple categories, and in some cases, could represent compound features (e.g. poaching at riverbanks could easily be recorded as soil disturbance and mineral soil erosion). However, for both the EO and NFS surveys, each uniquely identified feature was recorded only once and assigned to the category that the surveyor felt was the most appropriate.

SED features were tallied at the 2 category levels: major categories (n = 4) and sub-groups (n = 16). For each survey square, the "dominant" SED feature type was determined at the major category and the sub-group levels by calculating the mode. For each survey square, the total area (in hectares) was calculated and distributions were plotted based on the dominant SED major category as box and whisker plots. All analyses were performed in R 4.4.0 (R Core Team, 2024).

Table 1-1 The four major categories of SED and their sub-groupings derived from the EO and NFS surveys.

Peat & Organo-mineral erosion	Soil disturbance	Scar or slip	Mineral soil erosion
Peat drainage ditch erosion	Footpath erosion	Landslides or other mass movements	Coastal
Peat erosion or hags	Gateway disturbance	Scree	Drainage ditch
	Machinery disturbance	Soil creep / terracettes	Gully
	Poaching or compaction	Soil scar or slip	Riverbank erosion
			Sheet erosion
			Soil erosion general

1.3.2 Landscape Drivers of SED Feature Occurrence

Key environmental variables similar to those used in ERAMMP Report-70 (Tye, et al., 2023) were spatially extracted and summarised for each 1km survey square in R (Table 1-2). Tallies of ERAMMP survey squares and their dominant (most common) SED feature classes were summarised for each soil type, habitat and for ranges (similar to those used in ERAMMP Report-70) of altitude, relief and mean annual rainfall (see section 2.1 in this supplement). This differs from ERAMMP Report-70's analysis in that we can determine the numbers of survey squares that are dominated by key environmental characteristics. For instance, ERAMMP Report-70 showed that most SED features were associated with either Improved Grassland or Acid Grassland, while in the current report's analysis, we show that most ERAMMP squares are predominantly covered with these 2 land cover types; thus, it's quite possible that the high frequency of SED features associated with Improved or Acid Grassland can simply be explained by how common these habitats are across Wales. These environmental variables were also used as co-variates, or potential predictors of SED feature occurrence, in our statistical modelling using regression trees.

Regression tree modelling offers a powerful way of considering the interactions among multiple potential predictor variables to estimate a dependent variable – in this case, using factors such as land cover class, soil type, topography and rainfall to estimate the areal extent of SED features. Crucially, this type of model constructs a decision tree in which branches represent different combinations of predictor variables, and leaves represent (usually) mean predicted values for the dependent variable of interest.

We applied the rpart package in R (Therneau & Atkinson, 2023) to implement our regression tree modelling. A training dataset was created by extracting a random sample of 80 % of the EO-mapped SED dataset (the NFS dataset is much smaller and wasn't used here); the remaining 20 % was kept as testing data. An important weakness to regression tree models is their sensitivity to parameter settings and to the input dataset used to train the models. To mitigate these weaknesses, first, tree depth was controlled by optimising the complexity parameter value via 10-fold cross-validation with the "caret" package in R (Kuhn, 2008), automating the usual step of "pruning" decision tree sub-nodes to reduce model over-fitting; second, an ensemble of 1,000 regression trees were constructed, each based on a unique combination of training and testing dataset. Regression tree accuracy was assessed by applying the model fitted to the training dataset to the testing dataset and calculating the root mean square error (RMSE), with the model corresponding to the lowest RMSE being selected. The nodes, or leaves, of this final decision tree represent what we describe as the SED driver groups: combinations of environmental factors that best predict different extents of SED.

Once a final regression tree model was constructed, spatial data layers representing the relevant environmental predictors were summarised at a 1km grid resolution using the Ordnance Survey (OS) 1km squares within Wales. This allowed the predicted SED driver groups to be mapped at national scale to illustrate the spatial distribution of different environmental controls on SED feature extents.

Table 1-2 Environmental attributes extracted from spatial datasets and summarised for each ERAMMP survey square.

Spatial dataset	Environmental variable (units)	Calculated summary per ERAMMP survey square
UKCEH Land cover map 2021 (25m raster)	UKCEH land cover classes converted to broad habitat categories	Mode class per 1km square
UKCEH CHESS rainfall (1km raster)	Long-term mean annual rainfall (mm yr^{-1}) for 1961-2017	Mean value per 1km square
NATMAP vector (1:250,000)	NATMAP soil series converted to the 12-class DEFRA soil type system (Feeney, et al., 2023)	Mode class per 1km square
Intermap DTM (25m raster)	Mean elevation (m)	Mean value within 1km square
	Local relief (m)	Maximum minus minimum value per 1km square

1.3.3 Relationships Between SED Features & Modelled Soil Loss

A key limitation of the approach to SED assessment in ERAMMP is the lack of quantitative information on process rates, namely, soil loss and export of sediments to river networks. This leaves us with an uncertain picture in terms of the scale of the problem with SED across Wales and its wider significance for ‘off site’ areas – i.e. the water quality impacts on rivers within affected catchments.

Recently, a spatial modelling assessment of soil erosion was undertaken for Great Britain at a high spatial resolution (50 m) as part of the UKRI-funded AgLand project (Hooftman, et al., 2023). Specifically, the Sediment Delivery Ratio (SDR) model from the InVEST ecosystem services modelling platform was applied to simulate soil erosion from rainfall-runoff. This modelling, which couples a USLE-based model with an SDR formula based on a sediment connectivity index to estimate sediment export to waterways, generated spatially continuous estimates of long-term annual soil loss for all land nationwide, and covers the time period 2016-2020, which overlaps with the EO survey of SED features. The authors of the study also found a good overall level of agreement between their predictions and long-term observations of riverine suspended sediment loads. This modelling dataset is thus ideal for testing whether the areal extent of SED features is linked to soil loss rates. If a link is found to exist, this would give the SED feature surveying added value. However, a negative result would also highlight that popular spatial erosion models based on the USLE model and its variants fail to capture important details on SED – which is also important to know.

Here, we clipped the soil erosion rate estimates for Great Britain to the extent of Wales (Figure 1-3). For each survey square, the median soil erosion rate from all intersecting grid cells was calculated, and compared against the total surface area of all SED features recorded in the survey square. The comparison was visualised on a scatterplot with Spearman's rank correlation calculated to assess the strength of the relationship between observed SED feature areal coverage and predicted soil loss rates across Wales.

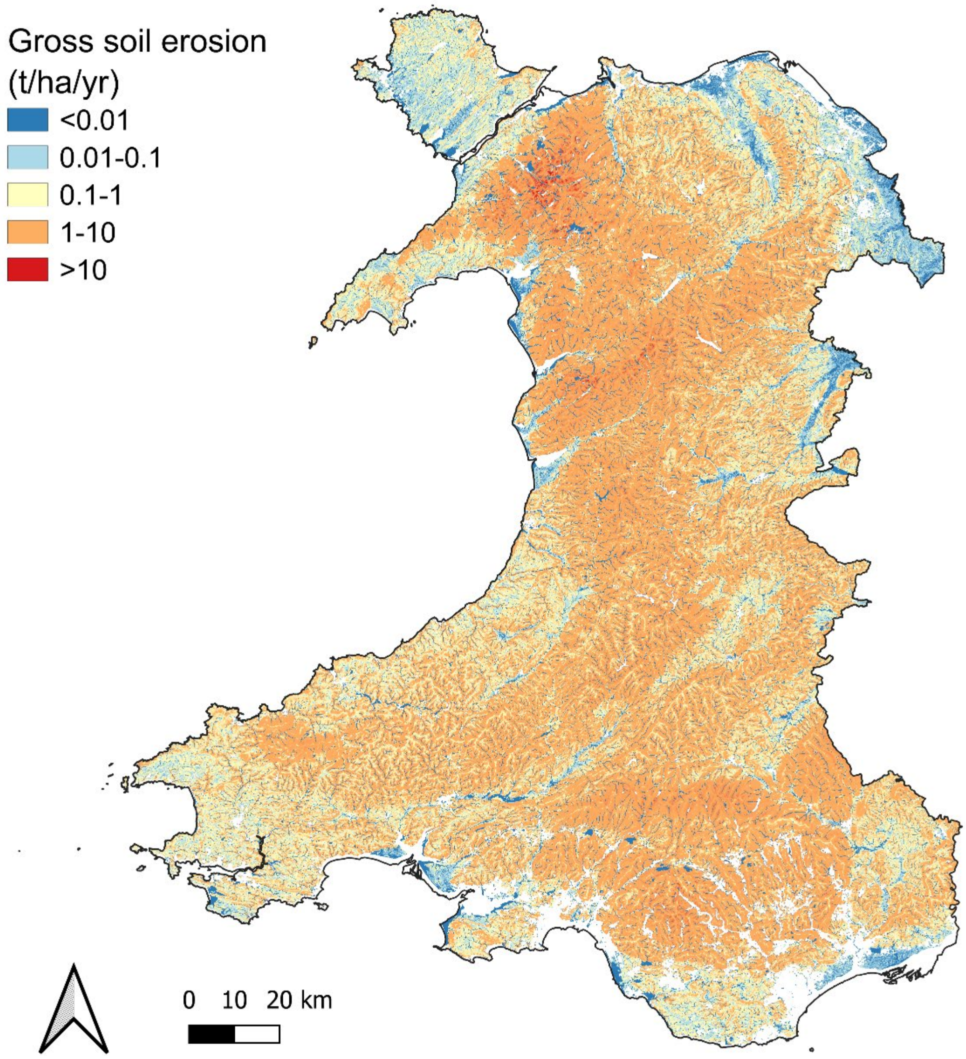

Figure 1-3 Gross soil erosion rates (t ha^{-1} yr^{-1}) across Wales, predicted for all 50 metre grid pixels using the InVEST Sediment Delivery Ratio model. Adapted from Hooftman et al. (2023).

2 NATIONAL TRENDS

2.1 SED Feature Distributions

Soil disturbance features represent the most common SED types by far, representing 78% of all individual features surveyed by EO, and being the most common category in 146 (58%) and 85 (43%) of all 252 EO and 199 NFS surveyed squares, respectively. The majority of SED features are shown in the main report to occur in survey squares dominated by either Improved Grassland or Acid Grassland. Additionally, we note the following trends here in the supplement:

Most survey squares occur in areas with rainfall in the 1000-1500 mm yr^{-1} range followed by those in the 1500-2000 mm yr^{-1} range (Figure 2-1). In the former group, soil disturbance is the most common feature type, reflecting the high prevalence of agricultural land-use here. In the latter group, SED features are more evenly spread across all 4 SED categories, perhaps reflecting a greater proportion of semi-natural habitats and upland landscapes with steeper slopes and areas of blanket peat.

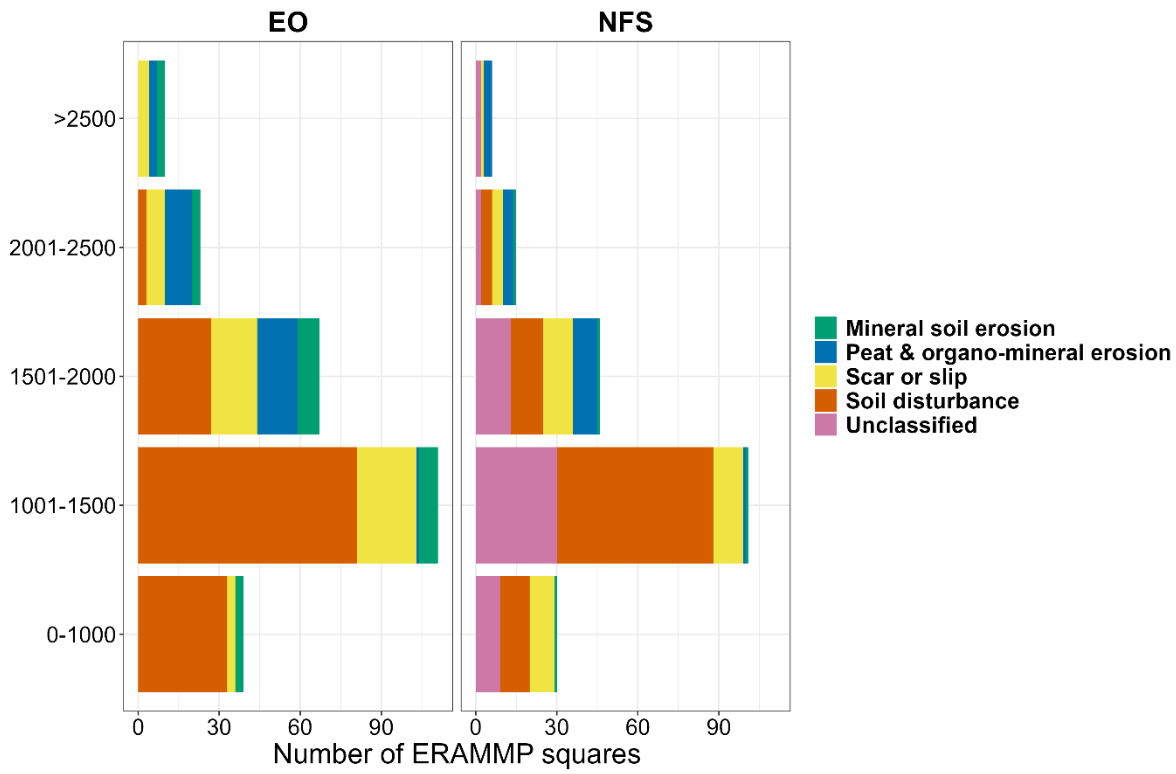

Figure 2-1 Most common SED feature category in ERAMMP survey squares by mean annual rainfall (mm yr^{-1}).

Most survey squares occur in areas with elevation below 200 m and are dominated by soil disturbance features in these instances (Figure 2-2). Above 400 m, SED is characterised mainly as either “scar or slip” or as “peat & organo-mineral erosion”. These patterns may reflect a transition from predominantly agricultural to predominantly semi-natural land-use and steeper slopes.

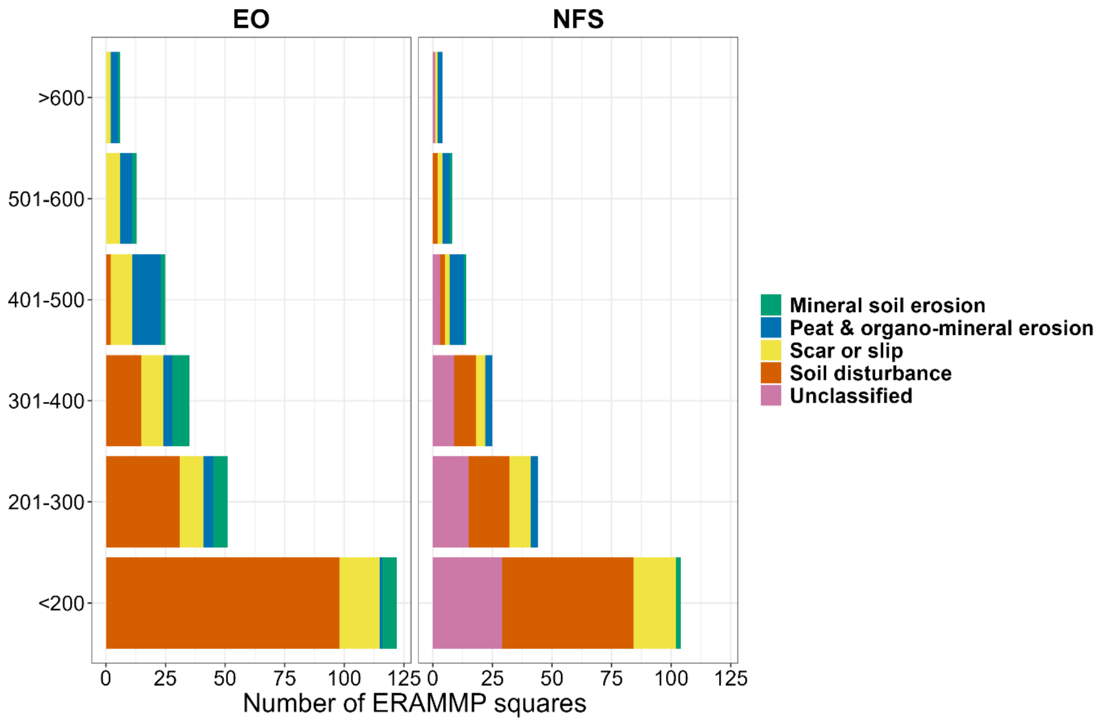

Figure 2-2 Most common SED feature category in ERAMMP survey squares by elevation above mean sea level (m).

The majority of ERAMMP survey squares are characterised with a relief of >30 m. Soil disturbance overwhelmingly characterise SED features in the 31-90 m and to a lesser degree, the 91-150 m relief ranges; for areas with >150 m relief, other types of SED – especially soil scar or slip features – characterise much of the observed SED across Wales (Figure 2-3).

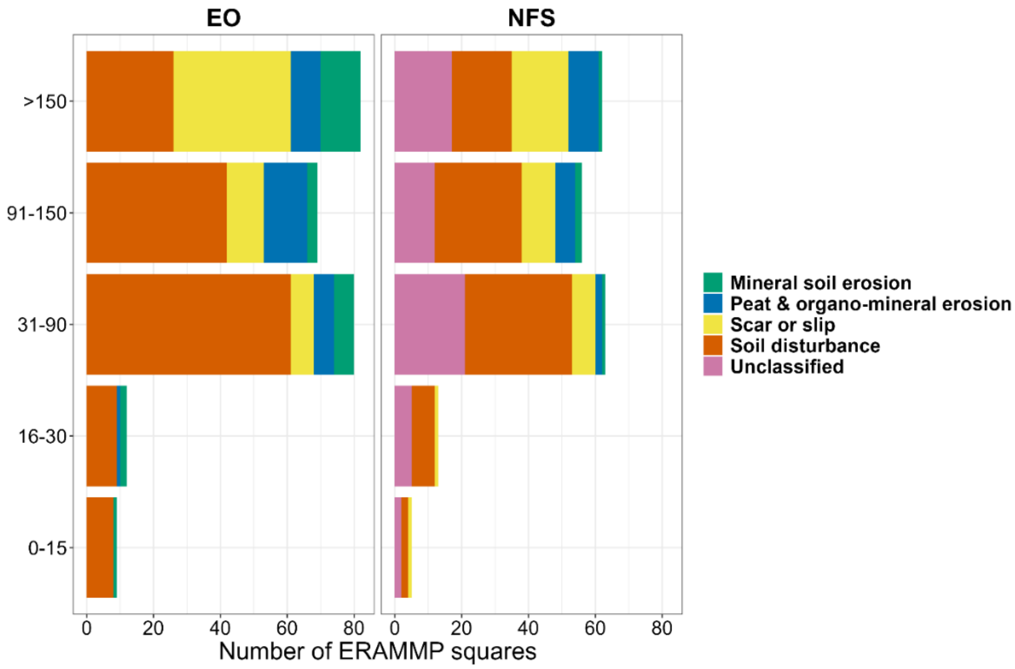

Figure 2-3 Most common SED feature category in ERAMMP survey squares by relief(m), defined here as the difference between the maximum and minimum elevation in a given ERAMMP survey square and applied here as a proxy for slope.

Most survey squares consist of predominantly medium loamy soils with free drainage, while several other squares are dominated by medium loamy soils with poor drainage, organic wet soils with poor drainage, deep peat, and light sandy soils with free drainage (Figure 2-4). Soil disturbance is the most typical form of SED across most soil types, however, organic soils consist of a more even mix of all SED categories, and unsurprisingly, deep peat soils are dominated by peat & organo-mineral erosion features.

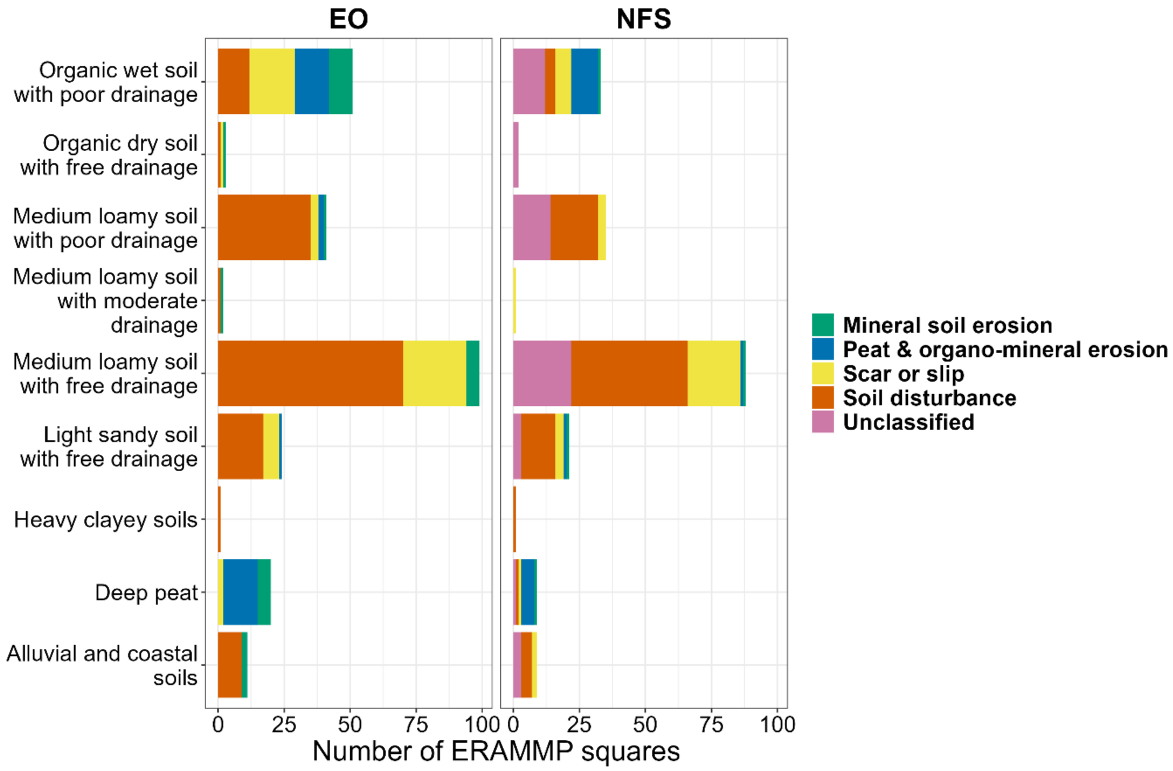

Figure 2-4 Most common SED feature category in ERAMMP survey squares by soil type.

The median areal coverages per 1km survey square are 0.5 ha (NFS) to 0.7 ha (EO) for SED features overall (Figure 2-5). Peat & organo-mineral features typically occupy the largest areas, whereas mineral soil erosion and soil disturbance features typically represent the smallest areal coverages. This indicates that although the number of survey squares that are dominated by soil disturbance features is highest, other forms of SED (especially peat & organo-mineral erosion) are typically much more extensive in size.

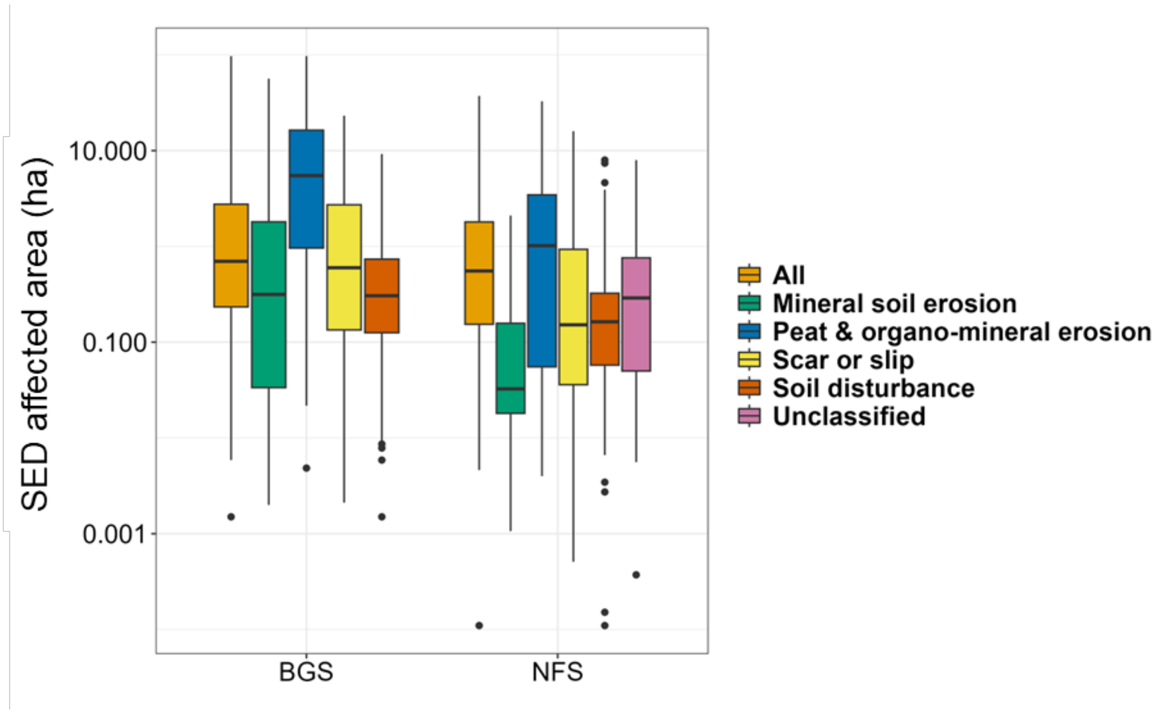

Figure 2-5 Distributions of SED affected area per square by survey (EO and NFS). Note the logarithmic y-axis on each plot which is used here as individual feature areas range over multiple orders of magnitude in size.

2.2 Drivers of SED Across Wales

Elevation, habitat type and mean annual rainfall were revealed to be the strongest predictors of SED feature areal coverages, with 5 distinct combinations of these factors controlling SED feature presence across Wales Table 2-1. These 5 groups of SED driving factors are mapped in Figure 2-6.

Table 2-1 Characteristics of each SED driver group classified from modelling of environmental controls on SED feature extents.

SED driver group	General group description	Elevation (m)	Habitats	Rainfall (mm yr^{-1})	Predicted mean SED area (ha)	Fraction of ERAMMP squares (%)	Fraction of land in Wales (%)
1	Agriculturally dominated	< 455	Any except Acid grassland or Bog	Any	1.22	63	74
2	Dry lowland bog & acid grassland	< 455	Acid grassland; Bog	< 1779	1.9	13	13
3	Wet lowland bog & acid grassland	< 455	Acid grassland; Bog	≥ 1779	6.14	9	6
4	Dry uplands	≥ 455	Any	< 1948	10.1	5.5	3
5	Wet uplands	≥ 455	Any	≥ 1948	27.44	9.5	4

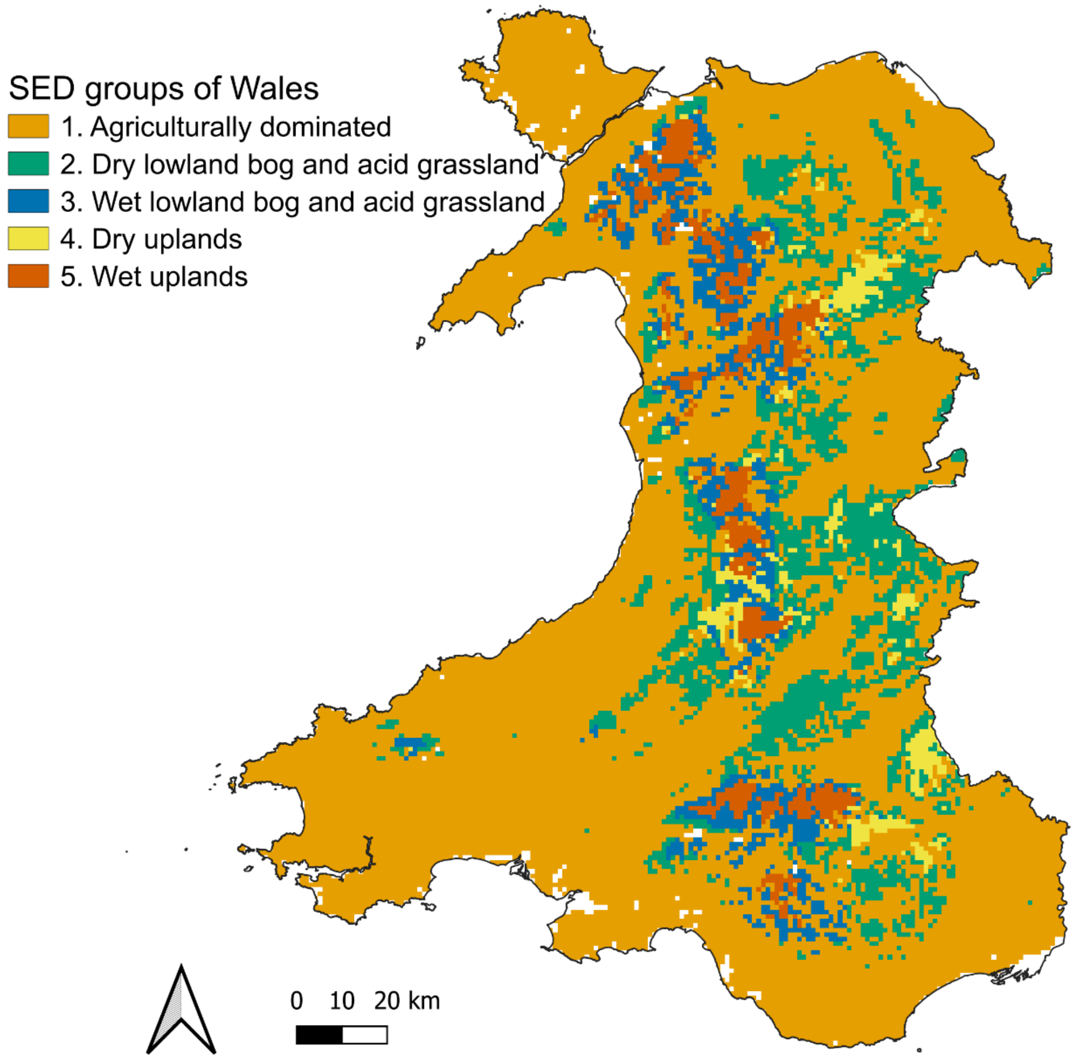

Figure 2-6 The 5 groups of driving factors of SED occurrence across Wales, predicted from regression tree modelling of EO-surveyed ERAMMP squares.

Analysing SED feature types by SED driver groups reveals a split between predominantly agriculturally driven soil disturbance in groups 1 and 2 versus wetter semi-natural systems in groups 3-5. Understanding the boundary between these 2 types of areas may help with future more targeted monitoring and mitigation of SED across Wales.

SED features in group 5 (wet uplands), particularly scar or slip and peat & organo-mineral erosion features are typically 10 times larger than those found in any of the other SED driver groups Figure 2-7. This suggests that while wet uplands represents one of the rarest environments (<1 % of Wales), it may be contributing a disproportionately high amount of SED nationally.

Soil disturbance is the most common SED feature type in SED driver groups 1 (agriculturally dominated) and 2 (dry lowland bog and acid grassland) (Figure 2-8), with poaching / compaction and gateway disturbance representing the bulk of these features (Figure 2-8). SED driver groups 3 (wet lowland bog and acid grassland), 4 (dry uplands) and 5 (wet uplands) are represented mainly by scar or slip and peat & organo-mineral erosion SED features (Figure 2.8). In these areas, soil creep / terracettes, soil scar / slip, and peat erosion / hags are the main sub-groups that typify SED (Figure 2-9).

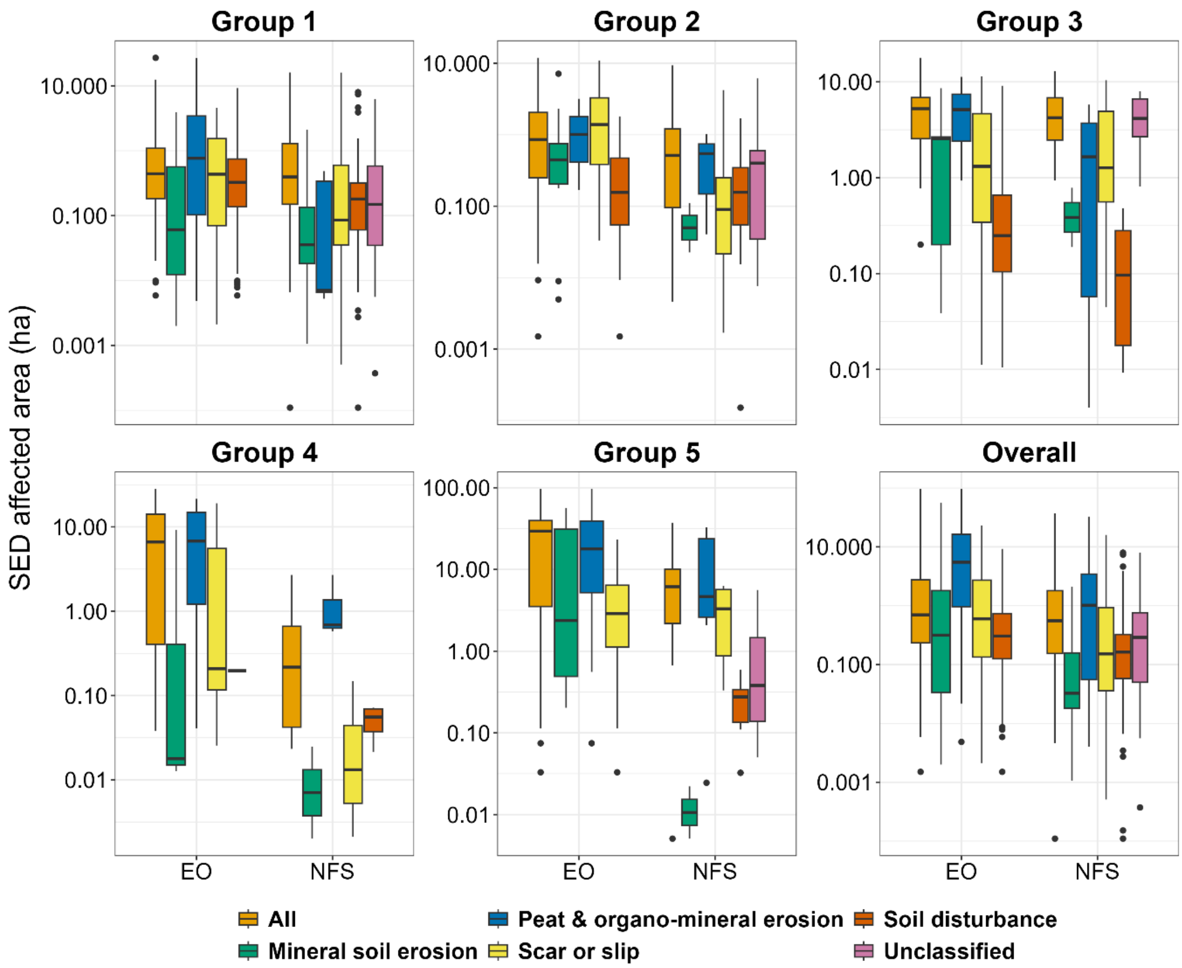

Figure 2-7 Distributions of SED affected area per square by the 5 groups of environmental drivers of SED and overall. Note the logarithmic y-axis on each plot which is used here as individual feature areas range over multiple orders of magnitude in size. The plot from Figure 2-4 is given in the "Overall" panel for comparison purposes.

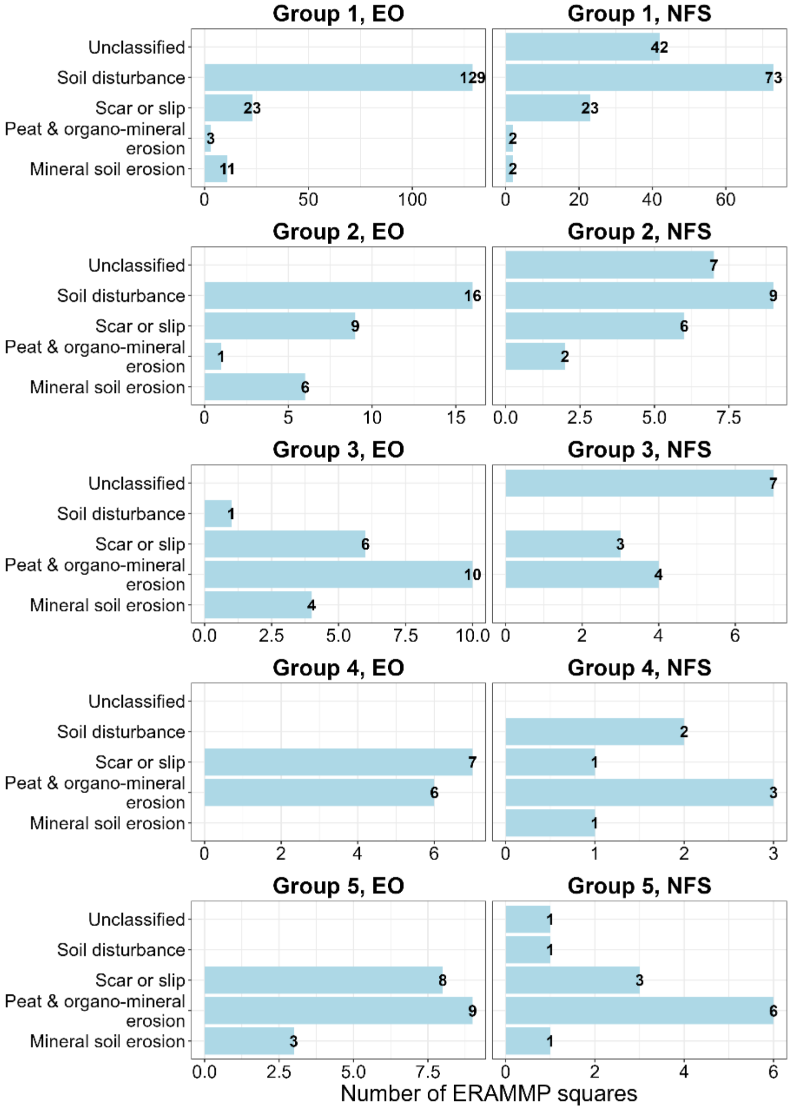

Figure 2-8 Most common SED feature category in ERAMMP survey squares by SED driver group (1. Agricultural dominated; 2. Dry lowland bog and acid grassland; 3. Wet lowland bog and acid grassland; 4. Dry uplands; 5. Wet uplands).

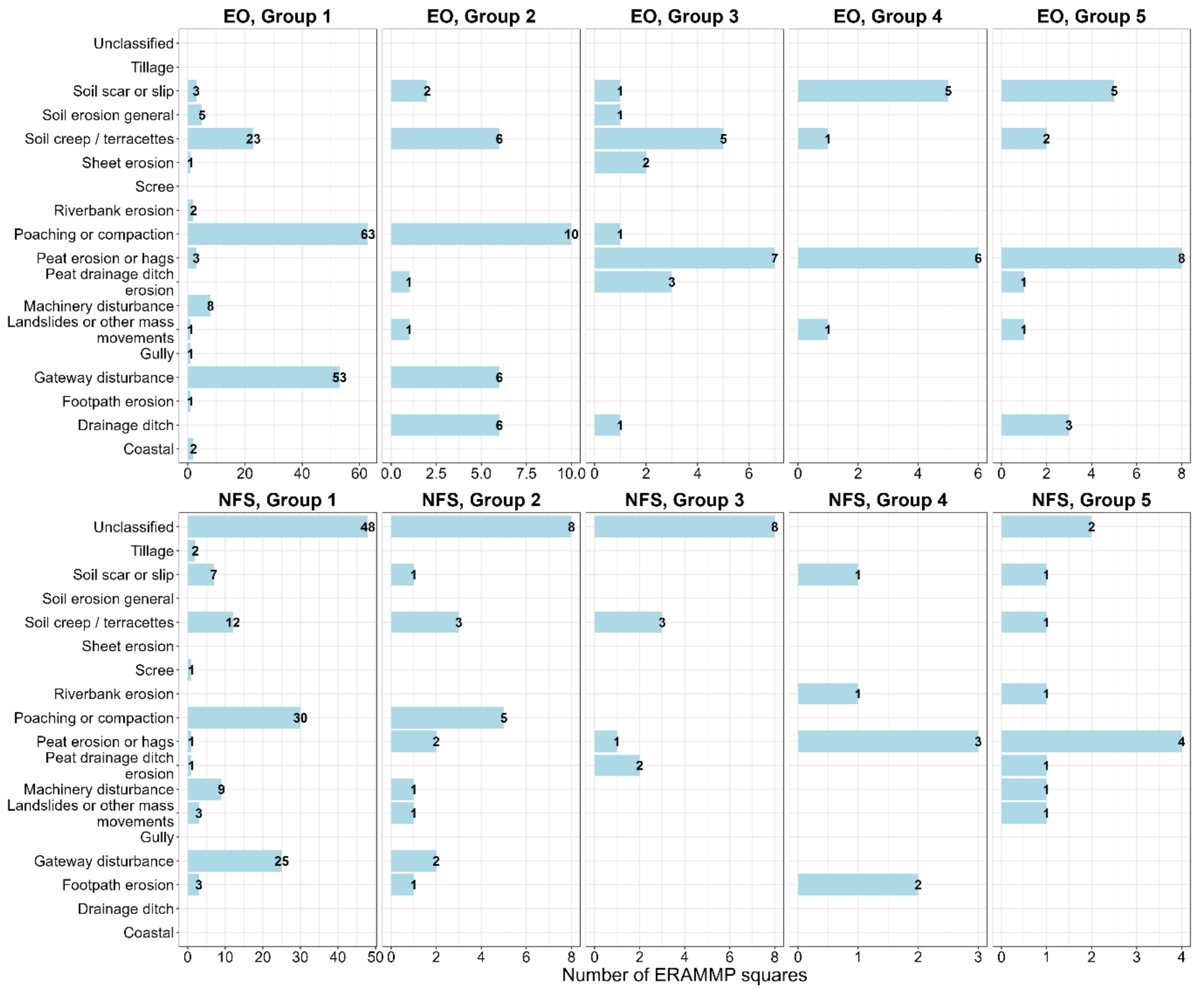

Figure 2-9 Most common SED feature sub-group in ERAMMP survey squares by SED driver group (1. Agricultural dominated; 2. Dry lowland bog and acid grassland; 3. Wet lowland bog and acid grassland; 4. Dry uplands; 5. Wet uplands).

2.3 SED Feature Areas vs Modelled Soil Loss Rates

The areal extent of SED features shows a statistically significant correlation with modelled soil erosion rates overall for both the EO and NFS SED features (Table 2-2). However, plotting these relationships shows a very noisy picture overall and the correlation coefficients are weak (Figure 2-10). For the most part, SED feature presence is not closely connected to rates of soil loss and delivery to stream networks. This does not invalidate the modelling, but simply highlights the degree to which observable SED is under-represented in or otherwise disconnected from current spatial soil erosion models.

Stronger positive correlations are visible for mineral soil erosion SED features for the EO dataset and peat & organo-mineral soil erosion features for the NFS dataset (Figure 2-10). These types of SED features are more closely associated with the factors used to model soil erosion rates and delivery to stream networks, so the stronger correlation in these cases is to be expected. The strong correlation for “Mineral soil erosion” features in the EO but not the NFS dataset may indicate that these types of features may be easier to identify from the air than in the field, whereas for “Peat and organo-mineral erosion” features, ground survey may be more accurate.

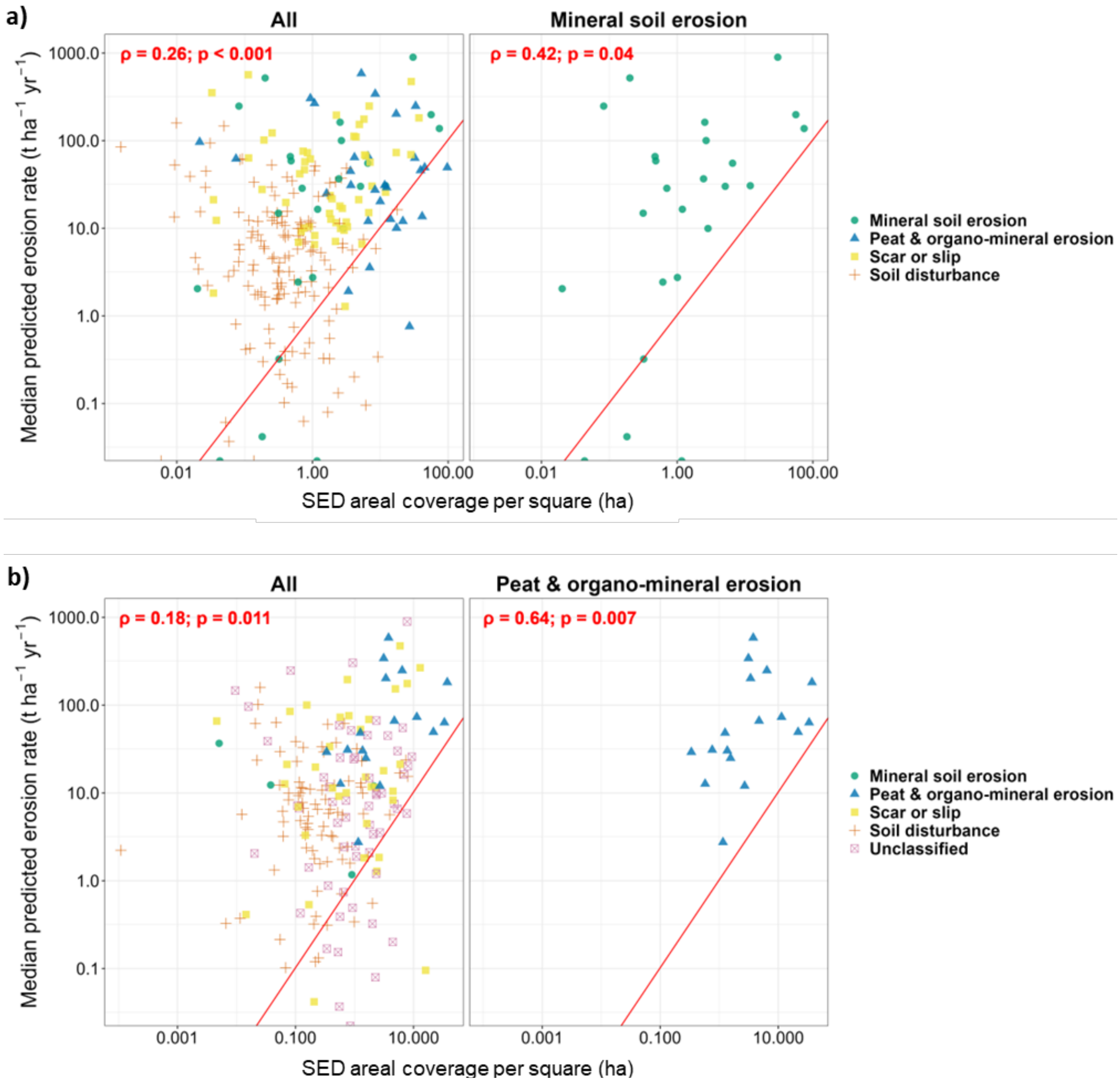

Figure 2-10 a) Bivariate plots of SED areal coverage from EO vs median predicted soil erosion rates from InVEST; b) Bivariate plots of SED areal coverage from NFS vs median predicted soil erosion rates from InVEST. Axes are on logarithmic scales due to ranges of modelled erosion rates and SED feature areas each spanning multiple orders of magnitude. The 1:1 line is shown in red.

Table 2-2 Correlation coefficients for SED feature areal extents vs modelled soil loss rates. Comparisons were made for EO and NFS separately, including for all features, and broken down by feature types. Statistically significant correlations are highlighted in yellow.

Survey	Category	Spearman's ρ	P value (α = 0.05)
BGS	Overall	0.25822	0.00003
BGS	Mineral soil erosion	0.42227	0.03983
BGS	Peat & organo-mineral erosion	-0.21182	0.26876
BGS	Scar or slip	0.17828	0.20095
BGS	Soil disturbance	-0.11622	0.16243
NFS	Overall	0.17969	0.01119
NFS	Mineral soil erosion	-0.80000	0.33333
NFS	Peat & organo-mineral erosion	0.63971	0.00692
NFS	Scar or slip	0.14955	0.38256
NFS	Soil disturbance	-0.01345	0.90266

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