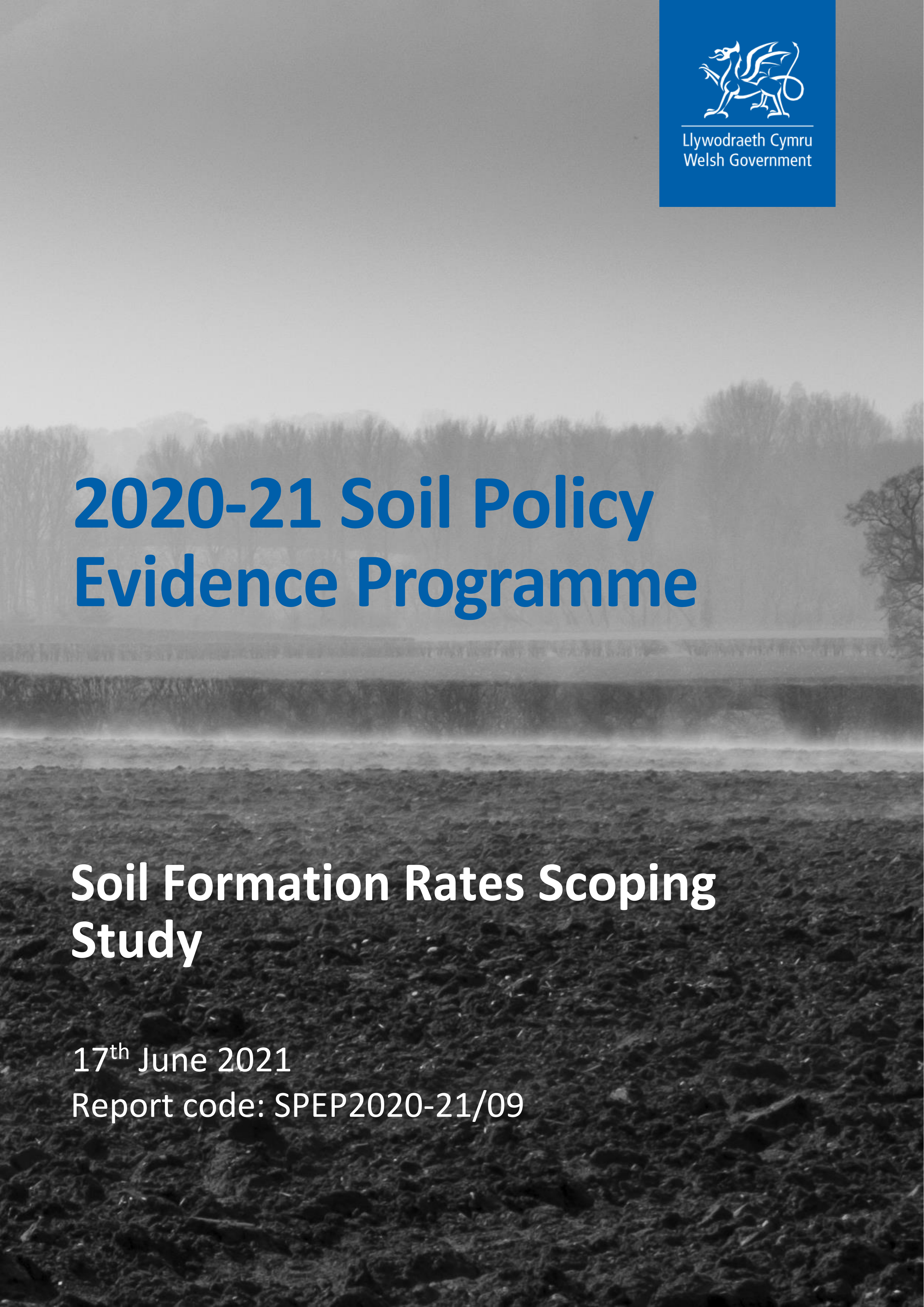

Llywodraeth Cymru
Welsh Government

2020-21 Soil Policy Evidence Programme

Soil Formation Rates Scoping Study

17th June 2021

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General Notes

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Glossary

Blanket Bog
Peatland formed by paludification, where peat soils have formed a blanket over the landscape. Generally found in upland landscapes in Wales. These are oligotrophic with nutrient and water inputs from rainfall.

Brown earth
These are soils in which pedogenic processes have produced dominantly brownish or reddish subsurface horizons with no prominent mottling or greyish colours (gleying) above 40 cm depth. They are widespread, mainly on permeable materials and at elevations <300m and are typically used in agriculture.

Consolidated rocks
For the purposes of this review, these include SPM formed from sedimentary, igneous and metamorphic rocks. These SPM make up the soil parent material of soils directly weathered from rock and account for ~50% of soils in Wales.

Elluviation
Removal of dissolved or suspended material from a layer or layers of the soil by the movement of water when rainfall exceeds evaporation.

Fen
Peatlands where water inputs are from rainfall and groundwater. Comparatively nutrient and mineral rich peatlands (minerotrophic).

Gley soils
Gley soils come in two major types, surface water gleys (saturated from top) and groundwater gleys (saturated from bottom). Surface water Gleys usually are formed from slowly permeable SPM types whilst groundwater gleys argillic, often form in permeable SPM but are flooded by a fluctuating water table. Gleying is identified by red / grey mottling, the result of chemical oxidation-reduction reactions due to the exclusion of oxygen.

Horizonation
Soils develop horizons (Brady and Weil, 2010) due to the combined process of (1) organic matter deposition and decomposition and (2) illuviation of clays, oxides and other mobile compounds downward with the wetting front and (3) a change in soil structure (e.g. Bw horizon).

Iluviation
The accumulation of dissolved or suspended soil materials in one area or layer as a result of leaching (percolation) from another. Usually clay, iron, or humus wash out and form a line with a different consistency and colour.

Lessivage
Lessivage is the transport of clay particles in suspension down a soil profile

Mire
Peat forming system. Also defined under the EU habitat's directive as "active bog" – a system which support a significant area of peat forming vegetation (Lindsay et al 2014)

Organo-mineral soil
A generic definition of organo-mineral soils is that they have a surface horizon or top soil which is relatively rich in organic matter or peat but which is < 40 cm thick. They include rankers, rendzinas,

podzolic and gleyed soils. These are further defined to three types of organo-mineral soils: (1) Humose topsoil greater than 15 cm thick; (2) Peaty loam or peaty sand topsoil greater than 15 cm thick; or (3) Peat less than 40cm thick starting at or near the surface, or less than 30 cm thick where the peat lies directly on bedrock.

Peat
These are predominantly organic soils derived from partially decomposed plant remains that accumulate under waterlogged conditions. In England and Wales peat soils are defined as those greater than 40 cm depth (or 30 cm if directly overlying rock) and greater than 20% organic matter by dry weight.

Peaty top soil
A term used by Claydon and Hollis 1984 (P.13) and referring to a position on the reference diagram for Peat soils. A peaty top soil is a peaty horizon, 7.5-40 cm thick, overlying mineral soil or rock. May be known as 'Rankers'.

Podzol soils
Soils with a black, dark brown or ochreous subsurface horizon resulting from the pedogenic accumulation of a combination of iron, aluminium or organic matter. They form under acid weathering conditions and under natural or semi natural vegetation have an unincorporated acid organic layer at the surface. In Wales podzol soils can form on a range of SPM including sandstones, shales and igneous/metamorphic rocks.

Raised Bog
Generally lowland bog formed as an end point of terrestrialisation. Oligotrophic as isolated from ground water so mineral and water input from rainfall.

Soil Association
The Soil Survey England and Wales 250k map classification of soils is based on Association codes (Avery, 1980). Each association has a code which relates to the predominant major soil group, group and subgroup. For example:

> Association 654a is the Hafren association
> The Hafren association is dominated by soils of the Hiraethog series which belongs to subgroup 6.5.1 which are 'ironpan Stagonopodzols'
> Subgroup 6.5.1 is a subdivision of soil group 6.5 which are 'Stagnopodzols'
> Soil group 6.5 is part of the major group 6 which are 'Podzolic Soils'

Soil Formation
The process by which soil is formed as a result of interactions over time between parent material (rock), climate, topography, and organisms. Also known as pedogenesis and includes both soil production, horizonation and upbuilding.

Soil Parent Material (SPM)
Soil parent material is the geological material from which soils form from or into and is often known as the 'C' horizon or 'R' horizon denoting hard or very hard bedrock. It is the principal source of weatherable material

Soil Production
Soil production is the process by which bedrock weathers into soil. The soil production function shows how the rate of bedrock-to-soil conversion is affected by the thickness of soil overlying the bedrock. Soil production can also take place at the same time as soil upbuilding (see below), thus allowing the soil to thicken from the bottom and top.

Soil Profile
A vertical column of soil as exposed in a pit, normally consisting of layers called horizons, roughly parallel to the ground surface. It passes down to relatively unaltered material known as the bedrock

Solum
The solum is defined as the surface and subsoil layers of a soil profile that have undergone the same soil forming conditions. The base of the solum is the relatively unweathered parent material

Unconsolidated deposits
These include superficial deposits which sit on top of consolidated rocks and have been formed through processes of erosion and deposition. These may include water eroded SPM (alluvium), wind or aeolian deposits and those SPM produced by glacial erosion and deposition

Upbuilding
Whilst soil production and formation are often viewed as a top down process, formation can also occur via upbuilding. Upbuilding can take place at the same time as soil production meaning the soils can be thickening in two directions. This can be through the deposition of sediment (e.g. through erosion and deposition processes) or through the thickening of the soil profile though the build-up of organic matter due to climatic influences and poor drainage.

Executive summary

Soil is a finite resource and to ensure its sustainability knowledge of the processes and rates involved in its formation need to be considered. Increasingly, the concept of soil lifespans is being used to address the issues relating to the balance of soil loss and formation. This scoping study aims to assess soil formation across Wales, identifying information from the global base, regarding rates of ‘production’ (formation of soil from bedrock) to the formation and development of soil profiles. This information is placed within a Welsh context.

Soil formation and development follows the concepts contained within the equation of Jenny (1941):

$$\text{Soil} = f(Cl,O,R,P)t$$

Where soils are a function (f) of climate (Cl), Organisms (O), Relief (R); Parent material (P) subject to Time (t). This scoping study assesses Welsh soil formation within this context. The assessment of soil formation in this scoping study has largely been based on soil parent material (geology), where many of the properties involved with soil formation and development (e.g. texture, mineralogy) are derived. Three major soil groups dominate the Welsh landscape, these being Brown soils (30.2 %), Surface water gleys (24.4 %) and podzols (32.3 %). Podzols are generally formed direct from parent materials such as sandstone and mudstone. Brown soils and groundwater gleys are largely formed in thick drift deposits (glacial till). Along with parent material, relief and climate (precipitation in particular) are also fundamental to the development of Welsh soils, where it is clear that soil types exist in key parts of the landscape, where drainage properties and relief control the dynamics of moisture within the soil system which is fundamental to formation processes. Relief and climate also influence vegetation types which contribute to the formation of the organo-mineral (~20% of area) and peat (~3.3 % of area) soils of Wales, so important as organic carbon stores.

Central to understanding soil production and formation is being able to date the length of time it has taken for the soil profile to be produced or for horizonation to occur. This allows production or formation rates to be established. A review of methods available for dating soils revealed that no one method can be used, and methods used would need to be appropriate for soil type and parent material. These may include the use of cosmo-genic radio nuclides for soils where significant quartz is present, to the dating of organic carbon or sand horizons covered by accreting sediment. For many soil types in Wales appropriate methods may not exist and a first-order approximation of time could be used. For Wales, covered in ice during the last glacial period, it is considered that all soils started to develop ~10000 years ago after the ice retreated.

When assessing soil production and formation rates the scoping study categorised soil parent materials in three main groups, these being Consolidated rocks (hard rocks), Unconsolidated rocks (erosion driven soil parent materials such as glacial till, alluvium, colluvium) and Organic soils (organo-mineral soils, peat). Soils formed from consolidated rocks cover ~54 % of Wales whilst soils from unconsolidated rock cover ~37%, whilst peat covers ~3.3%. Soils formed from unconsolidated rock have largest continuous areas in the north of the country, whilst climatic peats and organo-mineral soils are generally found above c.300-400m and where soil moisture is at field capacity > 300 days per year. No specific soil 'production' rates were available for Wales for consolidated rocks. Global inventories were analysed to identify those rates that may be applicable based on rock types or climate. Data for a granite soil in south west England showed soil production rates to be between 0.01 and 0.02 mm yr^{-1} and for soft sandstones in the midlands of England, productions rates of up to 0.2 mm yr^{-1} had been recorded. These are reasonable end members of geological hardness. These rates fitted a range of international rates obtained from the Köppen climate classification system for the CfB (Oceanic climate) category of between 0.004 – 0.193 mm yr^{-1}, depending on whether the parent material is hard or soft rock. These are an appropriate range for Wales based on the current information available. The principal way to assess soil formation in unconsolidated rocks is by establishing the time taken for horizonation to develop. Again, no data specific to Wales was available. Data from the Baltic region for Podzol development provided the best likeness for the Welsh climate. Based on this data, it may take in the order of ~100 yrs. for soil horizons to be seen in development, and low 1000's of years for soil profile maturity. These formation ranges, represent ball park figures for soil profile development around the world, and can be applied to Wales.

The selected soil production rates for Wales were considered in the context of erosion rates for Wales, particularly those of grassland which is the primary agricultural practice. Overall soil erosion could be considered within the same general bands as production. However, it must be remembered that erosion can be highly local and can be intensive, and this is where erosion rates are likely to outstrip production rates. Suggestions are made for how the concepts of soil formation rates could be applied spatially to the Welsh soil resource as the concept of soil lifespans is a desired aim. Key points discussed include how the granularity of knowledge can be increased using with respect to spatial mapping and through the use of soil maps. A key factor for increasing resolution is to improve the datasets currently pertaining to soil formation and production, globally and more specifically to Wales. In addition, increased erosion data specific to Wales is needed.

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INTRODUCTION

Soils are fundamental to society, providing food and clean water, regulating climate, a medium to recycle waste and supporting about a quarter of global biodiversity. Accounting for the rates of soil formation and loss is an important ambition to underpin the sustainable management of this resource into the future. The importance of soils to Welsh society, is recognised by, '*concentration of carbon and organic matter in soil*' being identified as number 13 of 46 national indicators in section 10(1) of the Well-being of Future Generations (Wales) Act 2015.

Key policy drivers in Wales

In Wales, the Environment (Wales) Act (2016) ensures that the goals laid out in, 'The Wellbeing of Future Generations Act' (2015) are achieved. Together they promote the sustainable management of natural resources in Wales. The 'State of the Natural Resources Reporting (SoNaRR)' procedure, published on a 5 year cycle, captures information regarding the state and change of natural resources. It uses a five-step method that incorporates the Driver-Pressure-State-Impact-Response (DPSIR) framework and four measures of sustainable management of natural resources, including:

1. Natural resources are safeguarded and enhanced
2. Ecosystems are resilient to expected and unforeseen change
3. Wales has healthy places for people, protected from environmental risks
4. Contributions to a circular economy with more efficient use of natural resources

Soils are one of the natural resources that must be reported on, with SoNaRR identifying gaps in knowledge and evidence requirements. One of these evidence gaps concerns the balance between **Rates of soil formation and loss rates.** Soil formation rates along with rates of soil loss are not well understood in Wales. Some work is being undertaken or proposed by a range of organisations on soil loss through modelling, earth observation and field measurements (e.g. Tye & Robinson, 2020). Further understanding of soil formation rates is necessary to understand the sustainability of soil use across a range of land use activities, soil types and climatic ranges. This project is the first step in understanding what research has been done in this area; it's relevance to Wales; and, what a Welsh study may look like. Understanding this balance in Wales will assist decision making into the future, as soil underpins food production and ecosystem services. Headlines such as 'only 100 or 60 harvests left' can be misleading (Wong, 2019). The report will also contribute to other areas including:

- **Understanding of tipping points in Wales**
- **Condition information on non-statutory geodiversity sites (RIGS)**
- **Current state and trends of soils in Wales and their vulnerability and resilience to land use, land management and changing weather patterns and climate.**

The report uses the five-step SoNaRR reporting approach as its structure.

SoNaRR step 1: Introduction to the ecosystem or theme

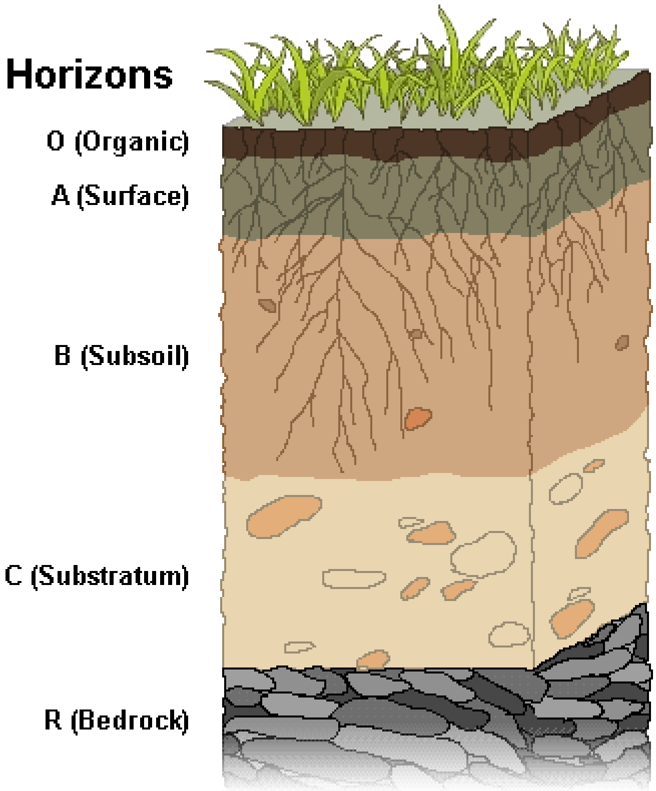
Soil formation/production definitions – establishing terms going forward

Soil is defined as, "*The layer(s) of generally loose mineral and/or organic material that are affected by physical, chemical, and/or biological processes at or near the planetary surface and which usually hold liquids, gases, and biota and support plants*" (Van Es, 2017). Soils organic component and life is how it is distinct from sediment. It is the physical, chemical and biological processes which combine in '**pedogenesis**', which results in the formation of soil. The definition of soil formation in its simplest form is, 'the transformation of parent material into soil' which Jenny's (1994) functional equation describes:

$$\text{Soil} = f(Cl, O, R, P)t$$

Where soils are a function (f) of climate (Cl), Organisms (O), Relief (R); Parent material (P) subject to Time (t). **Parent material** and the **soil solum** are important concepts in soil science. A 'soil parent material' is defined as a geological deposit over, and within which, a soil develops', whereas the solum is the topsoil and subsoil horizons that have undergone alteration, distinguishing them from the parent material. The solum will form in consolidated rocks, unconsolidated deposits and organic materials that develop into peat. Soil development results in layers, termed horizons (Figure 1). Horizons are used to classify soils and are given letters, O, A, E, B, C and R. O horizons are composed of organic material, A horizons are near the surface with organic matter incorporated, E horizons show evidence of removal of organic material, iron or clay, while B shows evidence of accumulation of these materials and is altered from the parent material C which shows little pedogenic alteration. Soils may form directly over hard rock which is termed R.

Figure 1: A representation of a soil profile



(Source: https://en.wikipedia.org/wiki/Soil_horizon. Wikipedia Commons)

In this report we consider soil formation in the context of these three soil parent material subdivisions, consolidated, unconsolidated and organic, which is consistent with soil survey practices in England and Wales (Clayden and Hollis, 1984) with each material denoted by a letter A-F.

- Organic soil formation: These are soils with 40 cm or more organic material with three parent material classes; i) peat over litho-skeletal material, peat with mineral layers and peat. Peat is divided into ***peat substrates*** (A) of different characteristics. Active peatlands have a two-layer structure – the upper layer, or acrotelm, comprised of growing vegetation is a few cm deep, while the catotelm, or lower layer, is waterlogged decaying vegetation matter that forms the bulk of the peat substrate. Peatlands modified by human activity such as agriculture or forestry will have lost this structure.

- Consolidated soil formation: These are soils formed from the weathering of hard rocks such as acid (granite) and basic (gabbro) igneous rocks, metamorphic or sedimentary rocks such as limestone, chalk, sandstone and shale. They are termed as having a ***litho-skeletal substrate*** *(B)*. **Soil production** is the term used to describe the rate of bedrock weathering and its transformation into soil.
- Unconsolidated soil formation: The soil survey of England and Wales recognises four subdivisions for unconsolidated materials, *gravelly soils (C)*, *soils over gravel* (D), *soils in thick drift (E) and soils with a soft pre-quaternary substrate (F).* The term drift (now superseded in BGS lexicon as superficial deposits) in the UK encompasses recent **alluvial** and **colluvial** materials of Quaternary age.

Soil classification: Pedogenic processes lead to soil formation and the development of horizons (Figure 1). These horizons are used as a basis for classification with soil seen as a natural body emergent from the soil forming factors. In England and Wales, a systematic classification was conducted by the soil survey and described in Avery (1973; 1990). Soil profiles are classified to a depth of 1.5m. Classes are differentiated by intrinsic soil properties that are easily identifiable in the field and relatively permanent (Avery, 1990 p46). Four levels are defined, *major soil group, soil group, soil subgroup* and *soil series*. The classification uses differentiating criteria to determine these. The first three divisions are largely based on the framework of diagnostic horizons, similar to the USDA, FAO and WRB classifications. The concept of soil series is based on '*lithological characteristics not used for differentiating classes in higher categories* (Clayden and Hollis, 1984), which traces its origins to the geological classification of soils used prior to the systematic classification in the 1970's and 80's. The main map is the 1:250,000 scale map, now referred to as NATMAP part of the LandIS (Hallett et al, 2017), plots **soil associations**. Plotting individual soils is impractical in mapping at this scale, so soils are grouped into associations of similar characteristics, usually named after the dominant series. However, soil series were the primary mapping unit on which NATMAP was largely based (mainly

1:63360 and 1:25000 published mapping), as well as unpublished reconnaissance maps covering about 50 % of Wales. Given that this general classification is widely used in land use planning and policy it is important to consider soil formation in this context.

The changing model of soil: The approach to soil classification and the view of soil formation that has developed, stems largely from the development of soil science from geological and geomorphological origins. However, the ideas of an Anthropocene where man plays a dominant role in altering the environment requires us to reconsider the model of soil (Richter and Yaalon, 2012). The geologic view of soil led to ideas that soils were largely monogenetic, i.e. that consistent soil types would emerge from the dominant soil forming processes. This view still largely underpins soil classification. However, this view is increasingly challenged due to human activities and classifications such as WRB recognise the increasing importance of polygenetic or buried soils (WRB, 2001). Polygenetic soils recognised that, '*a different soil has evolved prior to the present one (often under different environmental conditions) and both soils can be classified'*. While buried soils are those that have a mantel of new material covering 50 cm or more. Many of these processes that now alter soils are due to human activity, drainage, tillage, earth moving for infrastructure development and this cannot be ignored. In Wales for example, drainage is an important management factor affecting soil, which may lead to changes in wetness class. In addition, in Wales (a) the impact of built development is low compared to much of England and (b) it must be remembered that the SSEW taxonomy was developed arguably *after* most of the England and Wales main agricultural intensification / land use changes had been made. The SSEW taxonomy does allow for man-made, disturbed soils (category 9) and buried horizons.

Humans as drivers of soil alteration: Geoscientists now estimate that humans move more than an order of magnitude more sediment (including soil) around the globe annually than natural processes. About 30% is attributed to construction with the balance being due to agriculture, largely tillage. Hooke (2000) estimated that the ancient Egyptians moved ~625 kg of soil per capita per year.

Estimates for the current globe as of 2000, were ~6000 kg per capita per year. Moreover, in developed countries such as the USA this might be as high as 31,000 kg/capita/yr. Graves et al. (2015) estimated that soil degradation in England and Wales, based on an ecosystem services framework to assess how degradation affects the capacity of soils to support a range of final goods, was between £0.9 and £1.4 bn. This was mainly linked to loss of soil organic carbon (47% of cost), compaction (39%) and erosion (12%). Thus, the impact that humans have on the soil resource should not be underestimated and should be considered along with other environmental factors. In addition, humans manipulate soils through land use change, altering habitats, and through management activities such as, tillage, drainage, irrigation, manuring, fertilizing and liming. A major soil intervention in Wales has been the drainage systems implemented in Welsh soils since Roman times. Prior to 1939, Wales had drainage coverage exceeding 25 % of land area (Robinson, 1986). This was before the peak drainage installation period in England and Wales of over 100 000 ha per annum in the 1970's. However, much of Wales still relies on drains installed prior to 1939 (DEFRA, 2002). The importance of land drainage is reflected in NATMAP where a drained and undrained Soil Wetness Class is provided for each Association.

Soil change: the natural body approach to soils and their classification was critiqued by Dudal et al (2002). They opined that, '*soil classifications have not systematically catered for soils which have been modified by human activities*.' Humans are an increasingly important soil forming factor. The soil survey of England and Wales includes man made soils, but the classification is not designed to capture changes in transient properties such as pH and nutrient status which will impact formation. Moreover, the premise of developing general soil classifications was to select criteria that are significantly correlated with others that can aid prediction and are generally 'static' in time. As Avery (1980, p 28) noted, 'in British agricultural soils, properties such as pH, exchangeable cations and organic matter status often correlate hardly at all with other, less easily altered properties'. These are considered the more 'dynamic' aspects of soil related to soil change (Richter and Markewitz, 2001). Anthropogenic modification of the erosion, C, P, N and water cycles and soil management has increased greatly over the last century impacting largely the ‘dynamic’ properties of soils. Thus, alongside mapping and classification, focusing on long term (mainly physical) ‘static ‘properties, soil monitoring focuses on changes in ‘dynamic or variable’ soil properties, now largely considered under the concepts of soil health or soil quality (Bünemann et al. 2019). Both static and dynamic properties are important in terms of potential soil behaviour and the impact of land use relating to services. Previous work by the Welsh Government and RDS (now Natural England) showed reasonably close links between Soil Association and Agriculture Land Classification (ALC) Grade (hence land capability potential) (ADAS, 2020a; MAFF, 1988). This link is modified by climate and gradient influences. ALC does not factor in chemical properties unless severely limiting / toxic. An assumption is that ALC assumes a ‘moderate not exceptional’ standard of management. This was also the basis for the 2007 EC Areas of Natural Constraint work and the Predictive ALC. Consequently, whilst the static properties may not correlate to dynamic ones, they do affect soil behaviour in terms of workability, porosity, drought, wetness etc. and hence agricultural potential. This is complicated as different Associations (mostly in the same major soil groups) can behave very similarly agriculturally due to sometimes quite subtle differences between them. Likewise, the same association can behave very differently in different climate areas but these relationships are well understood. For non-agricultural soils (e.g. semi-natural habitats and designated habitats and forestry) the same concept applies in that the static and dynamic processes do not correlate. Again, the dynamic properties come from the vegetation, influenced by climate and relief, whilst the static properties act as the framework.

Soil genoform vs. soil phenoform: Recognising the importance of both ‘static’ and ‘dynamic’ components of soils for formation and classification, Droogers and Bouma (1997) sought to reconcile survey and monitoring approaches by introducing the concept of the soil genoform vs. soil phenoform. The genoform is the classification according to soil genesis or the natural body approach. Whereas, phenoforms are where a soil might have the same genesis but different managed characteristics, such as pH, soil carbon or drainage. An example of the production of phenoforms in Wales is where land drainage has taken place which may shift the Soil Wetness Class and the number of days a soil is workable (Rudeforth et al. 1984). This may represent an intermediate development stage where certain characteristics of the soil have changed, but sufficient genetic characteristics remain so as not to reclassify the soil. The soil survey of England and Wales provides soil wetness classes for a soil association in a drained and undrained soil state, indicating phenoform characteristics.

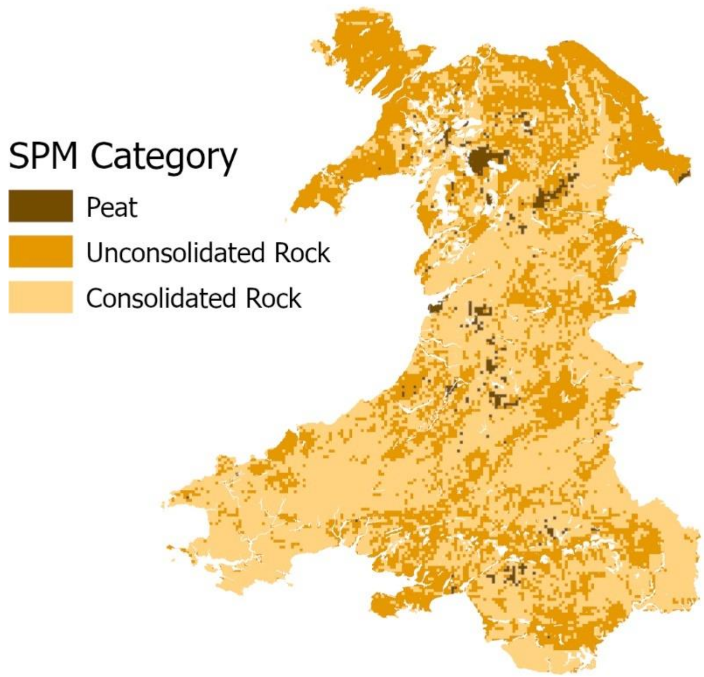
SOIL FORMATION FACTORS IN THE WELSH CONTEXT

Wales covers a land area of 20,735 km^2 and an overview of soil formation characteristics is provided.

Parent material: The geology is dominated by Paleozoic and Pre-Cambrian mudstones, slates and sandstones. Unlike England there is very little carbonate parent material, limestone or chalk. Large areas are covered by drift deposited from the receding Devensian glaciation, which covered Wales almost entirely. The cool wet climate is conducive to the development of peat (climatic peats and organo-mineral soils are generally found above c.300-400m (DEFRA, 2007) and have > 300 field capacity days). This means that all parent materials (consolidated rock, unconsolidated rock and organic substrates) are found. Figure 2 shows the distribution of consolidated, unconsolidated and organic substrate (peat) based soil parent materials found in Wales.

Relief: Wales is characterised by mountains of from 600 - 1000m and substantial coastline and coastal plains. The mountains form a spine from Snowdonia in the north to the Brecon Beacons in the south. The topography means that much of the land is sloping and subject to geomorphic processes associated with mass movement.

Figure 2: Distribution of soil parent materials in Wales based on consolidated and unconsolidated rock geology and organic substrates (peat). The blank areas are where the soils present do not fall into the three SPM categories used in this work. These would include lithomorphic 'peaty top soils' of the Revidge and Bangor Associations, marine alluvium soils and raw terrestrial soils (sand dunes). See Figure 3.



Climate: 'The climate is classified as maritime, characterised by weather that is often cloudy, wet and windy but mild. The mean annual temperature at low altitudes in Wales varies from ~9.5 °C to 11 °C, with the higher values occurring around or near to the coasts. The mean annual temperature decreases by approximately 0.5 °C for each 100 metre increase in height. Rainfall in Wales varies widely, with the highest average annual totals being recorded in the central upland spine from Snowdonia to the Brecon Beacons. Snowdonia is the wettest area with average annual totals exceeding 3000 mm. In contrast, locations along the coast and, particularly, close to the border with England, are drier, receiving less than 1000 mm a year' (Met Office, 2016). High annual precipitation results in high levels of leaching that interact with vegetation, leading to organic acids and Podzolization; and standing water leading to Gleying depending on SPM type. The combination of relief and climate is a key influence on (i) annual precipitation, (ii) temperature and (iii) evaporation, all of which affect vegetation. The number of days in the year where the soils are at field capacity generally increases as altitude increases. Increasing precipitation and decreasing temperature and evaporation leads to lower organic matter decomposition and its accumulation.

Vegetation: Grasslands of different types are dominant in Wales, improved (41%); neutral (11%) and acid (14%). Arable and horticulture cover an area of (9%), while broadleaf (6%) and conifer (7%) forests cover (13%) together. Dwarf shrub heath accounts for (5%) and Bogs (2%) based on land cover map 2007 statistics (Morton et al., 2011). The large extent of improved grassland and the low coverage of woodland is a good indication of the impact of management on Wales, pollen analysis in peats for example points to evidence for woodlands post-glaciation (Chambers, 1982). This has likely had substantial impact on the soil-scapes we see today, especially peats and organo-mineral soils which have probably formed as a result.

Time: The ending of the last glaciation is a significant time point as the retreating ice left glacial drift and scoured bare rock surface behind. Hence, soils in Wales are relatively young in a geological context (~10,000 years). Glaciation will have reincorporated old soils into Till and other glacially derived parent material. In a recent study, Parry et al. (2015) ^{14}C dated humin samples from two soil profiles in England (Dartmoor) and Scotland (Glen Dye). The maximum soil ages were 15,600 and 4400 years for the Dartmoor (out with the UK-LGM) and Glen Dye (within the UK-LGM) soil profiles, respectively. It is likely that soils in Wales would lie between these two points dependent on glacial retreat and climate. Alluvial and colluvial soils, are still building and represent younger soils, along with those developing from marine alluvium (sea level change) and sand dune systems.

Peat development appears to be strongly related to anthropogenic activity and potentially human deforestation during periods in its history (Chambers, 1982). While wars in the last century and population expansion have increased the need to produce food and timber. This has transformed the landscape to overcome soil constraints to production. In a major global assessment of soil constraints (Bot et al. 2000), the UK is ranked second in the world, after the Falkland Islands for poor soil drainage (55%). Poor drainage and low pH are common across Wales and management has attempted to address these, and is likely to have resulted in changes to soil formation. The combination of geomorphological processes, land use change and management designed to overcome constraints to production means that we might expect many soils across Wales to be polygenetic. Thus, decades, centuries and millennia are likely to mark significant time points in the development and classification of soils across Wales.

Soil survey and monitoring in Wales

Wales has been active over the last decade in developing both legislation such as the Environment (Wales) Act (2016) and the, 'The Wellbeing of Future Generations Act' (2015). A program of work has produced the predictive ALC maps for Wales (ALC, 2017; Gov.Wales, 2020), principally based on NATMAP **and** preceding SSEW detailed and reconnaissance surveys occupying about 50 % of Wales. In addition, new surveys were commissioned in geographic areas of known problem areas or where data gaps existed (mainly for Associations with limited previous surveys) for a new Soils of Wales series map (Gov.Wales, 2020b). Monitoring of 'dynamic' soil properties is undertaken by the ERAMMP monitoring program (Emmet et al. 2019). The national soil Association map, used in the current work, published in 1983 (NATMAP), covers Wales at a scale of 1:250,000. Rudeforth et al (1984) describes 91 soil associations found in Wales including unclassified land (28 in extensive, 63 extensive). The predictive ALC (2017) updated this approach and comes closest to combining the concepts of genoform and phenoform previously discussed. Based on soil series, it also includes criteria such as drought, wetness and climate (gov.wales, 2020). Moreover, Wales also has a range of data sources associated with soil forming factors which are described more fully and compared and contrasted in the next section.

SoNaRR Step 2: A framework to assess soil state

State and trends of natural resources and current management

This section focuses on soil parent material, soil classification and ecosystem units as a framework for reporting on the state of soil in the context of formation. Factors identified in **SoNaRR** step 1 are used with a number of data-sets to assess the extent of different soil forming factors to gain an insight into the relative importance of different soil forming factors in Wales. The data sets used are:

Soils NATMAP (Climate, Organisms, Relief, Parent Material, Time)

The national soil map (NATMAP) for England and Wales is produced at 1:50k base (NATMAP vector). It displays mapped soil associations at a scale of 1:250k, of which 91 are found in Wales. As soil series are differentiated based on parent material we are able to undertake a matching exercise using Clayden and Hollis (1984) to determine the dominant parent material for each soil association. These can be grouped and compared with the recent soil parent material model produced by BGS.

Soil parent material model (SPMM) (Parent Material)

A 'parent material' is a geological deposit over, and within which, a soil develops. Here we use the free 1km version of the SPMM derived from the 1:50k version (Lawley, 2014). It classifies parent material according to the European Soil Bureau (ESB) definition of Parent Material type. It is an important data set as Avery (1980) opined, "The major soil groups [in the UK]… are distinguished by broad differences in the composition or origin of the soil material".

ITE land class (Climate, Relief, Parent Material)

While designed to aid ecological sampling, the ITE land class system embodies three of the main soil forming factors to divide the landscape. The original classification used multivariate analysis of 75 environmental indicators to identify 32 land classes. The data used in the analysis included climate, relief and parent material (Bunce et al. (1996), and is an early version of what might now be considered a pedometric landscape model.

Ecosystems derived from land cover map (2007) (Organisms)

SoNaRR reports on 8 ecosystems types, here we approximate these based on land cover map broad habitats. They embody the impact of organisms on the landscape, including human activity at a low resolution. A broad habitat might be considered the ecological equivalent of a soil association.

CLASSIFYING AND MAPPING PEDOGENESIS IN WALES

In the following tables data is extracted from the different map products to identify the principal factors and spatial extent of soil forming factors across Wales, allowing high-level patterns and relationships to be identified. Table 1 shows the extent of soils classified as NATMAP (250k) across Wales where soils are dominated by three major soil groups; The brown soils, the podzolic soils and the surface water gleys. Table 2 shows the spatial extent of the ESB parent material types across Wales. Approximately 50 % of the area of Wales is formed from bedrock whilst unconsolidated sediments (particularly glacial Till) account for about 35 %.

Table 1: Percentage of land coverage that major soil groups cover in Wales, along with their key descriptors

	ClORPT		
Code	**Major Soil groups NATMAP (NSRI) 1:250,000 (Thompson, 2007)**	**Extent (%)**	**Key descriptors**
1	Terrestrial raw	<0.1	Recently formed
2	Raw gley soils	0.21	Waterlogged
3	Lithomorphic	2.21	Shallow
4	Pelosols	0.1	Clayey, slowly permeable
5	Brown soils	30.24	Brown, no gleying
6	Podzolic	32.3	Acidic, subsurface accumulation of sesquioxide or organics
7	Surface water gley	24.64	Waterlogged
8	Ground water gley	3.41	Waterlogged
9	Man made	0.43	Spoil
10	Peat	3.39	Organic
	Unclassified land	2.97	

Table 2: Percentage of land area associated with each ESB parent material class. ESB classes 100,200, 300 and 400 represent the 'Consolidated' grouping used later in this review. Classes 500 and 600 form the 'Unconsolidated' grouping used in this review and organic materials represents the 'Peat' grouping.

ESB Class	**Parent Material Major class**	Extent (%)
100	Consolidated clastic sedimentary rocks	48
200	Sedimentary rocks (chemically precipitated, evaporated, or of organo-genic or biogenic origin)	2.4
300	Igneous rocks	1.7
400	Metamorphic rocks	0.2
500	Unconsolidated deposits (alluvium, weathering residuum and slope deposits)	3.5
600	Unconsolidated glacial deposits / glacial drift	31.7
700	Aeolian deposits	0.1
800	Organic materials	1.1
900	Anthropogenic deposits	0

INTERACTIONS OF SOIL PARENT MATERIAL AND SOIL ASSOCIATIONS

The major soil groups as defined by the Soil Survey of England and Wales are shown in Figure 3, whilst the distribution of Soil Parent Materials based on the European Soil Bureau of soils classification is shown in Figure 4. The extent of major soil groups in relation to parent materials are presented in Table 3 according to both the ESB classification and the soil survey parent material classification (Clayden and Hollis, 1984). The major soil groups with high percentage coverage associated with parent materials are shaded in grey. This data helps us to narrow down which parent material types we need to focus on to understand soil formation. Table 3 clearly shows that soils over litho-skeletal parent material (consolidated or hard rock) and soils over thick drift (unconsolidated soft rock) are dominant, with peat soils covering a minor area. Table 4 shows the major soil groups in relation to the ESB soil parent material code across Wales.

Figure 3 The distribution in Wales of the major Soil Groups as defined by the Soil Survey of England and Wales

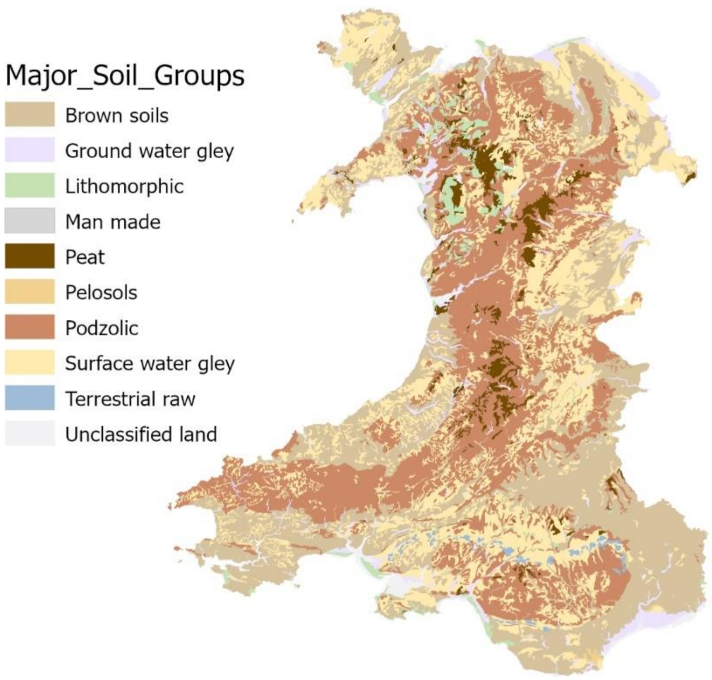


Figure 4: The distribution in Wales of Soil Parent Materials based on the classification by the European Bureau of Soils. See Table 4 for definitions.

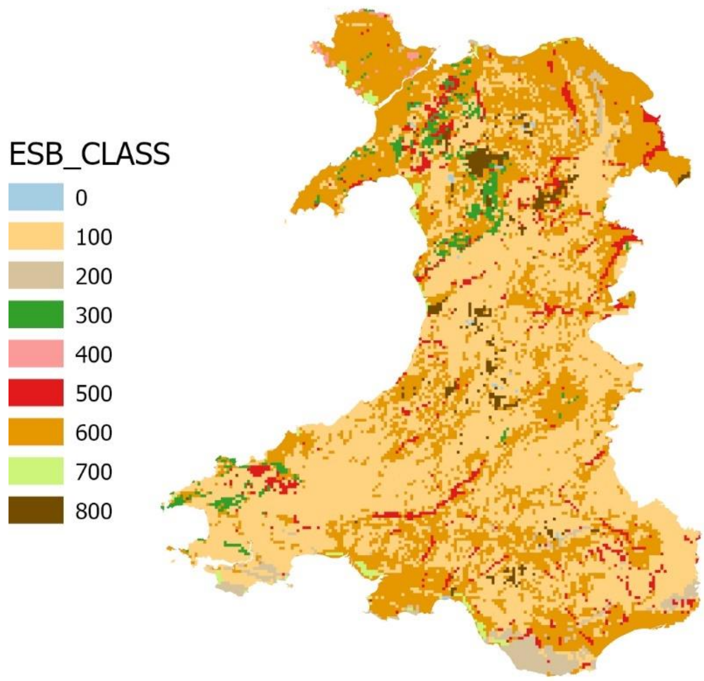


Table 3: % major soil groups are associated with parent materials according to the Soil Survey of England and Wales (SSEW). Corresponding European Soil Bureau (ESB) parent material codes are provided along the top. Some soil associations occupy substantial extents, e.g. Manod 18.04% (Podzolic); Hafren 6.36% (Podzolic); Cegin 7.19% (Surface water gley); Denbigh 9.73% (Brown soils); Milford 5.13% (Brown soils).

ESB	100-400	500	500	500	600	800	900	
		500-520	530	530				Other
Major Soil Groups, SSEW	Litho-skeletal	Soils with a soft pre-quaternary substrate	Soils over gravel	Gravelly soils	Soils in thick drift	Soils in peat	MM	
Terrestrial raw soil								
Raw gley soil		0.21						
Lithomorphic	1.62				0.59			
Pelosols		0.10						
Brown soils	**19.54**	0.94	0.54	0.01	**9.21**			
Podzolic	**32.25**			0.05				
SWG		0.33			**24.31**			
GWG	0.14				**3.27**			
MM							0.43	
Peat						**3.39**		
Urban								2.97
Total	**53.55**	**1.58**	**0.54**	**0.06**	**37.38**	**3.39**	**0.43**	**2.97**

Table 4: The area of each of the major soil groups associated with the ESB Soil Parent Material classification (km²)

	Parent material Major class	Extent (%)	**Brown**	**Podzolic**	**Surface Water Gley**	**Peat**
100	Consolidated clastic sedimentary rocks	48.9	**3346**	**4985**	**1748**	**284**
200	Sedimentary rocks (chemically precipitated, evaporated, or of organogenic or biogenic origin)	2.4	**418**	**24**	**69**	**0**
300	Igneous rocks	1.8	**40**	**273**	**43**	**25**
400	Metamorphic rocks	0.2	**35**	**3**	**9**	**0**
500	Unconsolidated deposits (alluvium, weathering residuum and slope deposits)	3.6	**376**	**224**	**143**	**24**
600	Unconsolidated glacial deposits / glacial drift	32.1	**2291**	**1192**	**3198**	**132**
700	Aeolian deposits	0.1	**13**	**5**	**2**	**1**
800	Organic materials	1.8	**7**	**99**	**55**	**230**
900	Anthropogenic deposits	0.0	-	-	-	-

In Table 5 the subdivision of the litho-skeletal and thick drift categories is further explored and shows that five soil parent material types are dominant. The important litho-skeletal substrates are sandstones and mudstones (e.g. shale). There is only a small area of soils over basic crystalline rocks. Soils in drift with siliceous stones dominate the Welsh landscape with regard to drift. Clearly there are soil types associated with these parent materials. Podzolic soils form over coarse and fine grained litho-skeletal parent material. Gleys form over the drift and brown soils can be found in drift as well as coarse and fine grained litho-skeletal material. Thin soils tend to form over litho-skeletal parent materials, often less than 80 cm (Rudeforth et al., 1984). This means that soils on these parent materials have a greater vulnerability if thinning occurs due to erosive processes. This primarily may be driven by a combination of landscape position (slope) or agricultural practice (tillage, overgrazing).

The data indicates that podzolic soils based on sandstone, mudstone or slate are the most vulnerable along with those brown soils formed on litho-skeletal parent materials.

Table 5: The relationship between area (%) of major soil groups and sub-categories of the ESB codes that correspond to SSEW parent material classifications.

ESB Code	120	130	300-400	600	800
	Litho-skeletal sandstone	Litho-skeletal mudstone and sandstone or slate	Litho-skeletal basic crystalline rock	soils in drift with siliceous stones	Soils in peat
Brown	3.30	9.73		7.46	
Podzolic	5.37	25.07	1.81		
Surface water gley				23.91	
Peat					3.39

Tables 6 and 7 show the area of the major soil types related to ITE land class and land cover. Table 6 indicates that brown soils and surface water gleys are dominant in the low landscape positions. Whereas podzolic soils dominate in the upland locations. This is consistent with catenary sequences and soil forming factors illustrated in Figure 5. Peats are split between those that form in the lowlands and uplands. While parent material is used as a key differentiating-criteria for soils, Table 6 clearly shows that position in the landscape is an important factor such that catenary sequences are to be expected in the Welsh landscape.

Table 6: The relationships between the ITE Land class coverage and the NATMAP major soil groups in Wales (km²)

	Land class	Podzolic	Brown	Surface water gley	Peat
5W (18.1 %)	Shallow slopes/flood plains	458	2271	1082	32
6W (12.1%)	Complex valley systems/table lands	714	1102	738	9
7W (3.1%)	Sea cliffs/hard coast	104	430	110	5
15W (11.1%)	Flat river valleys/lower hill slopes	575	993	779	7
17W1 (8.5%)	Low mountain ridges/valley slopes, N. Wales	974	97	485	254
17W2 (22.7%)	Rounded mountains/scarps/upper valleys, mid/S Wales	2182	1005	1322	307
17W3 (9.3%)	Variable landforms of hills/low mountain, Wales	1265	284	391	33
18W (5.2%)	Upland valley sides/low mountains, Wales	523	213	306	50

Land cover is dominated by grassland, either enclosed or semi-natural (Table 7) and that brown soils are nearly all farmed as these are the most productive, least limited soils. Surface water gleys are also used extensively for farming, but will often be drained.

Table 7: The spatial relationship between ecosystem type (Organisms, plants and management) with SSEW major soil groups found in Wales (km^2)

	Habitats	Brown	Podzolic	Surface water gley	Peat
Enclosed farmland (45.57 %)	Arable, improved grassland	**4413**	**2346**	**2882**	**24**
(Semi-natural grassland (12.99 %)	Neutral, calcareous and acid grassland bracken	**271**	**1738**	**635**	**110**
Woodland (12.03 %)	Broadleaf and conifer	**650**	**1238**	**561**	**102**
Mountains moorlands and heaths (16.21 %)	Bog, dwarf shrub heath, fen marsh swamp, inland rock	**718**	**1350**	**916**	**455**
Other		**473**	**138**	**273**	**9**

Note: for SoNaRR reporting Wales is divided into 8 ecosystems, (marine, coastal margins, freshwater, semi-natural grasslands, mountains moorlands and heaths, woodlands, enclosed farmland, urban) the dominant one is enclosed farmland that covers approximately half the area of Wales (~1 M ha). The extents in this table are taken from Land cover map and are only an approximation of the extents in SoNaRR (2020).

These tables show that the soils of Wales are dominated by three of the SSEW major soil groups, these being the Brown soils, Podzolic soils and Surface Water Gleys (Table 1). These soil groups are found across all the ESB soil parent material types (Table 2, 3, 4 and 5), and for the purpose of this review the major groupings of consolidated and unconsolidated parent materials (Table 2). In addition, the major soil groups are also found across all landscape types (Table 6) and ecosystem types (Table 7). The result of this extensive coverage of major soil groups across different parent materials, relief, climates and vegetation types, demonstrate how Jenny's state variables are the basis of soil formation and are reflected in how the soils of Wales are classified and mapped into the Series and Associations of the SSEW. The dominant positions in the landscapes where these major soil groups are formed, particularly in relation to climate and relief, in Wales are discussed in Section 3.4.

MODELS OF SOIL FORMATION IN WALES: JENNY'S STATE VARIABLES, LOCATION AND LANDSCAPE

The information in Section 2.2 (Jenny's variable's) and in Section 3 outlining the links between parent material, soil type and landcover, form a basis for models describing, where the major soil types are likely to exist within the Welsh landscape (Rudeforth et al. 1984). Figure 5 provides a summary of the interactions between soils, relief, climate and the accumulation of organic matter and where the major soil types are likely to be found. These relationships are fundamental to how and why soils develop in Wales. Key points include; (i) the brown earths (e.g. Denbigh and Milford associations which are extensive and can be good for agriculture, especially grassland but climate and slope angle can be limiting for cereals and horticulture), are generally found on well drained slopes, typically with siltstone, mudstone, shale, sandstone and slate as their parent materials (Table 5), (ii) at higher elevations and increasing precipitation, a transition occurs to brown podzolic soils (e.g. Manod Association) and then stagnopodzolic (e.g. Hafren, and Gelligaer Associations) soils, with peat in the wettest and highest environments. At the bottom of slopes, where drainage accumulates, stagnogley (e,g. Cegin and Brickfield Associations) and stagnohumic gley (e.g. Wilcocks 1 & 2 Associations) soils are typically found, along with peat in basins. Further conceptual soil development models, based on precipitation and slope drainage, have been produced for Wales (Rudeforth et al. 1984), and are an essential driver in producing catenary sequences, particularly determining where podzolization and gleying will occur, depending on drainage and run off. The nature of the permeability of the parent material is a key determinant on soil development.

Figure 5: Relationship of soils, climate and relief in Wales. Source: Redrawn from Rudeforth et al. 1984

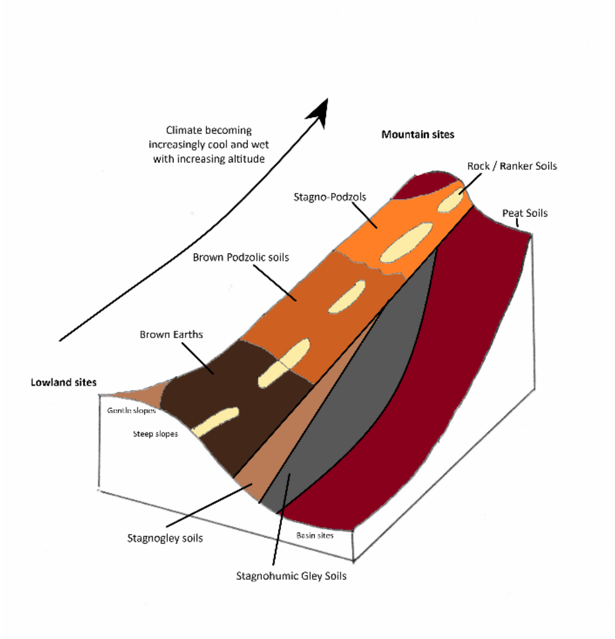
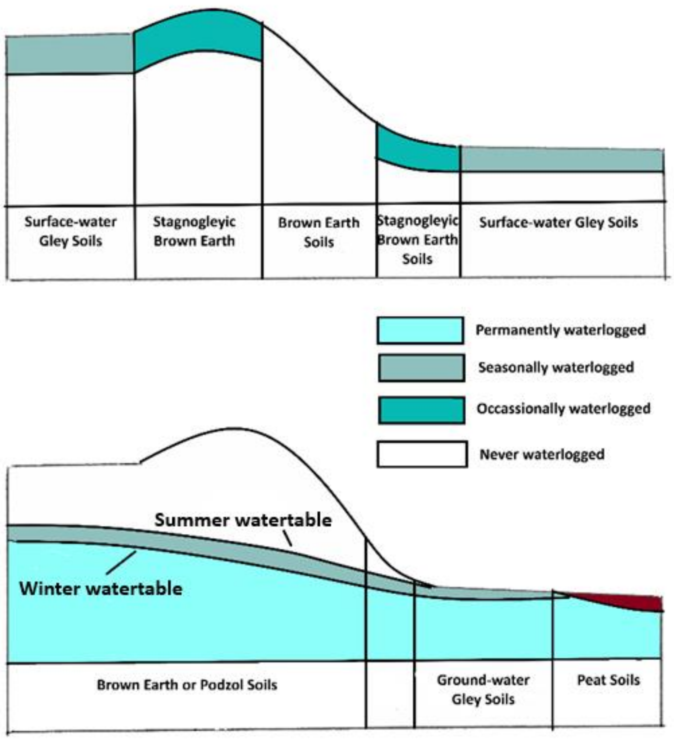


Figure 6: The relationships of relief, hydrology and soil formation in Wales. Source: Redrawn from Rudeforth et al. 1984



Interactions between Jenny's state variables and pedogenesis in Welsh soils

Whilst 3.4 shows where different soil types are likely to develop within the Welsh landscape, there are further interactions that drive pedological development that result from the interactions of Jenny's state variables, that need discussing.

Soil parent material and structure

Soil parent material is recognised as providing soils a broad range of physical characteristics, for example its texture, density, porosity and mineralogy (e.g. 2:1 expanding clays). These are important variables and help determine the way soil parent material weathers and how soil structure develops. Soil structure is important as it controls soil moisture dynamics, a primary driver in determining soil depth and horizonation development. Soil structure and moisture dynamics (see Figure 6) are essential in determining land-use and ecosystem service functions. In Wales, the brown earths (e.g. Denbigh) which develop from consolidated rocks (siltstones, mudstones sandstones, slate) often have very stony lower profiles and a blocky structure allowing drainage to be rapid. Podzolic soils also often have a stony subsoil for this reason. For example, the Hafren series soils, ferric stagnopodzolic soils, typically have a moderately stony sandy loam or large subangular block subsoil. The soil profiles are also shallow (~60cm) these being typical properties of soil developed from hard rock (sandstone and siltstone) parent materials. The cambic stagnohumic gley soils of the Wilcocks Associations (1 and 2) have moderately stony clay loam subsoil with weak medium blocky or prismatic structure and high packing structure, and a weaker structure and evidence of gleying in the 'B' and 'C' horizons indicating that drainage is not as free as in the brown earths. The cambic stagnogleys (e.g. Cegin and Brickfield Associations), derived from unconsolidated parent materials show a more massive and weak structure which impedes drainage and demonstrates gleying. Whilst structure helps determine drainage, landscape position is also important and these are key mechanisms in the developments in soil horizonation and development in Wales. For example, the brown earths are often found on slopes (Figure 5) which both contribute towards drainage and prevents gleying.

Considerations of soil biology

Soil formation relies on the role of biology. Initially parent material characteristics such as pH, particle size and structure, combined with climate and relief will provide a physico-chemical environment for the initial colonization of parent material with plant, microbial, meso and macro-fauna populations, and then to develop community structure. With respect to vegetation, major soil types in Wales are associated with landcover and ecosystem types (Table 7). Through growth, physical (e.g. root penetration) and chemical (e.g. production of organic acids) weathering processes will occur, organic matter will be deposited and distributed through the profile by faunal and floral processes such as pedoturbation and root deposition, and biogeochemical cycling of nutrients will be initiated. The result of this; firstly, the soil biology will help drive the development of diverse soil types (e.g. podzolization), and secondly, each soil type will develop its own soil biodiversity as pedological development occurs. Seaton et al. (2020) demonstrated that soil textural heterogeneity (a property derived from parent material) positively influenced bacterial diversity but had little impact on fungal diversity. Land-use change or intensification of use is expected to further impact soil biodiversity. Recent research using Glastir monitoring (Emmet et al. 2017) demonstrates the link between soil properties, land-use and soil biology. George et al. (2019) demonstrated that animal and microbial (bacteria, archaea, fungi, and protists) richness across 7 temperate ecosystems showed divergent trends, whilst β-diversity (community structure) did not. The richness of microbial communities was strongly influenced by both land-use and soil properties such as pH, C:N ratio, elevation, organic matter and annual precipitation. For animal richness no significant associations were found for environmental variables but richness was negatively impacted by higher intensity land-use. Thus soil biology has a number of feedbacks and tipping points in the development of soils. Biodiversity is a fundamental soil ecosystem service, and relies on the preservation of natural soil development to maintain a full range.

SoNaRR step 3: Resilience - Methods for determining trends based on rates of formation

Combating soil degradation and maintaining sustainability is an important goal, captured in the concept of soil resilience. It is defined as, 'the capacity of a soil to recover its structural and functional integrity after a disturbance' (Seybold et al., 1999). Thus 'resilience' requires understanding rates of soil formation in the context of production and horizon development and ability to recover from land use and climate events. Firstly, methods used in assessing soil formation are reviewed, secondly published rates are assessed and thirdly, rates are assigned to soil production and formation in the Welsh context.

Methods for consolidated rocks

This section of the review considers methods of measuring soil formation on consolidated parent materials, which comprise ESB categories 100 Consolidated clastic rocks), 200 (sedimentary rocks chemically precipitated, evaporated or of organogenic origin) 300 (igneous rocks), and 400 (metamorphic rocks) and litho-skeletal parent material in the soil survey of England and Wales (see Tables 2, 3, 4 and 5). Consolidated parent materials include clastic (e.g., sandstone, shale) and non-clastic (e.g., limestone) sedimentary rocks, igneous rocks (e.g., granite), and metamorphic rocks (gneiss). From our analysis in Table 4 we know these parent materials account for 48 % of Welsh soils and that the dominant parent materials are mudstones, sandstones and shales.

Cosmogenic radionuclide analysis

The ultimate aim of this technique is to ascertain the rate at which the bedrock below the soil profile is weathering into soil. In order to do this, the rate of bedrock weathering is assumed to be equal to the rate at which the soil-bedrock interface is lowering down the profile. This, in turn, is equal to the rate at which soil thickens above this interface. Since the method measures bedrock weathering over millennial timescales, it is unable to detect soil upbuilding; that is, soils increasing in thickness at the surface of the profile (e.g., through addition of organic matter). Incidentally, this is also the reason why the method cannot be used to assess the effects of land use on rates of bedrock weathering, since any changes in land use and management represent only a very small proportion of the timescales over which cosmogenic radionuclide analysis operates. In addition, this technique assumes that the soil profile has been derived from the weathering of the underlying bedrock, rather than allochthonous parent material such as the drift deposits that cover large areas of Wales. To determine the rate of bedrock lowering and soil thickening, it is necessary to determine the current thickness of the soil profile. This is often measured on-site and does not account for a soil's bulk density since the technique is considered not to be sensitive to such properties. The other variable to measure is the duration over which this soil profile has formed; that is to say, the time which has elapsed since the bedrock was at the surface of the profile. Terrestrial cosmogenic radionuclide analysis can be used to ascertain this duration. Cosmogenic radionuclide analysis has been used to determine the rates of a wide array of geomorphic processes (Lal, 1991) including the measurement of soil formation from consolidated deposits (Heimsath *et al*, 1997).

During the death of a star, cosmogenic rays are discharged from the supernova, which bombard the Earth, interacting with minerals in the uppermost metres of the Earth's surface, where a chemical reaction occurs, and cosmogenic radionuclides are produced. These include Beryllium-10 (^{10}Be), Aluminium-26 (^{26}Al), and Chlorine-36 (^{36}Cl); the particular radionuclide produced is dependent on the mineral in the Earth's surface. For example, quartz minerals give rise to Beryllium-10, while carbonate minerals form Chlorine-36. As a result, the effectiveness of the technique is dependent on the availability and abundance of the selected mineral in the bedrock. Since the concentration of a radionuclide is associated with the duration that a mineral has been exposed to cosmic rays, measuring the total concentration of a particular radionuclide can be used to estimate the time since the beginning of such exposure.

Here, the aim is to determine the duration since cosmogenic radionuclides were first generated within the bedrock at a time when the bedrock was positioned at what is now the soil surface (i.e. the position of the bedrock prior to soil formation). However, determining the concentration of cosmogenic radionuclides from a sample extracted at the soil surface is not advised, since soils (particularly topsoils) are prone to translocation, disturbance, and mixing. Instead, a sample should be obtained from a point down the soil profile that has not been subject to vertical or lateral mixing, such as the saprolite or even the underlying, unweathered bedrock. Given that cosmic rays attenuate as they migrate down the soil profile, a smaller concentration of the radionuclide is produced at depth than that which is produced at the soil surface. It is thus important to account for such attenuation. This is often achieved using a model conceived by Lal (1991). In addition, a recent sensitivity analysis by Evans *et al*. (2021) demonstrated the impact that the bulk density of the overlying soil has on attenuating cosmic rays. Other additional considerations are required, including the need to normalize the production rate of the radionuclide in accordance with the elevation, longitude, and latitude of the sampling location. Any above-ground obstructions that may shield the ground surface from the cosmic ray flux (i.e., topography or vegetation) also need to be accounted for (Dunne *et al*., 1999; Stone *et al*., 2000; Balco *et al*., 2008; Stockmann *et al*., 2014).

Since the cosmogenic radionuclide is produced inside a mineral grain *in situ*, it is necessary to isolate and extract the radionuclide prior to measuring its concentration. This entails a sequence of thorough and complex laboratory work. For example, in the case of isolating ^{10}Be in quartz, this procedure includes two major steps. In the first, the quartz is isolated by removing metals and carbonates using hydrochloric and nitric acids, separating quartz from non-quartz material using magnetic separation, and floating off other minerals using froth flotation. Once quartz is isolated, a second step is initiated to separate Beryllium from other elements within the quartz (e.g. Iron, Titanium, Aluminium, etc). Once Beryllium fraction has been extracted, it is converted to Beryllium Oxide and pressed into a cathode.

The cathodes are subjected to Accelerator Mass Spectrometry (AMS) which can measure the concentration of a radionuclide. This measured concentration can then be used to back-calculate the concentration at the surface where the bedrock began forming soil. Knowing the annual production rate of the radionuclide, and this back-calculated concentration, the age of the soil can be estimated; that is, the time since the bedrock was at the Earth's surface. Using this age, and the current thickness of the soil profile, the rate of bedrock lowering can be calculated.

U-series isotopes:

Studying the changes in the composition of Uranium series (U-series) isotopes through soil and bedrock profiles can be used to ascertain the downward lowering of the soil-bedrock interface, and thus allow soil formation rates to be calculated. The abundance of U-series isotopes in soil profiles varies with time, and is dependent on their inherent radioactive decay, their loss through dissolution, and their gain through deposition. When a U-series isotope is weathered into the soil profile, it enters the profile at the soil-bedrock interface. Over time, as the bedrock weathers, the soil-bedrock interface migrates down the profile, thus increasing its distance from this U-series isotope (Dosseto *et al*., 2006; Dosseto *et al*., 2011). Uranium is more mobile and soluble than Thorium. During chemical weathering, ^{238}U (one particular isotope of Uranium) is lost through dissolution, which leads to the relative enrichment of ^{230}Th. A sample of the dissolved phase would thus be expected to contain more ^{238}U than ^{230}Th. Over time, ^{238}U begins to decay, and ^{234}U accumulates. At this point, a sample of the dissolved phase would be expected to contain more ^{234}U than ^{238}U. Measuring the ratios of $^{238}U/^{230}Th$ and $^{234}U/^{238}U$ in the dissolved phase down the soil profile and into the bedrock can help to inform the duration since the initial weathering and release of nuclides from the bedrock into the soil profile. From this, the rate at which the soil-bedrock interface migrates down the profile can be calculated.

Limitations

The efficacy of each technique is constrained by a number of logistical and analytical limitations and experimental assumptions, which are summarised in Table 8. The main limitations with these techniques are that often they require specific mineralogy (e.g. quartz for cosmogenic radionuclides) which limits their use to the rocks investigated, the boundary between rock surface and soil needs to be reached and relatively undisturbed sites are required where soil hasn't been mixed. Sampling design needs to be able to account for geomorphological influences (e.g. slopes).

Table 8: Summary of logistical and analytical limitations, and experimental assumptions

Method	Spatial limitations	Temporal limitations	Monetary costs[a]	Analysis duration[a]	Sensitivity limitations (ClORPT factors)	Main assumptions
Cosmogenic Radionuclide Analysis	Access to saprolite/bedrock required for sample extraction. Constrained by abundance and size of minerals in the sampling horizon where radionuclides form.	1-100 kyr timescales.	~£1,580 per sample	~1 week for sampling; ~8 months for sample preparation and analysis	Technique is sensitive to relief and parent material. Partially sensitive to climate, although there is currently an evidence gap with regards to how sensitive the technique is to local meso-climate variations. Technique is not sensitive to organisms or short-term land management practices.	Assumes that short-term land management operations have a negligible effect on bedrock weathering. Assumes that soil formation only occurs at the soil-bedrock interface.
U-series isotopes	Access to saprolite/bedrock required for sample extraction.	~500 kyr	~£700 per sample	Months	Technique is sensitive to relief and parent material. Climate- and organism-induced effect on chemical weathering rates can be detected. Effect of land management can be detected through changes to chemical weathering rates.	Assumes that soil formation only occurs at the soil-bedrock interface. Assumes that release of U-series isotopes from bedrock is constant. Assumes that U-series isotopes have not been incorporated into, or have leached from, the soil being sampled.

[a]Estimates based on the measurement of soil formation down a single hillslope.

4.2 METHODS FOR DETERMINING SOIL FORMATION IN UNCONSOLIDATED ROCKS

This part of the review assesses those methods suitable for assessing soil formation in the ESB SPM categories 500 (unconsolidated deposits, alluvium, weathering residuum, slope deposits), 600 (unconsolidated glacial deposits, glacial drift) and 700 (aeolian deposits). They are formed through the redistribution of sediment with three principal erosive and depositional drivers; glaciation, water, and wind (aeolian). Sediment redistribution is recognised as a key process in several soil development models such as catena classification (Sommer & Schlichting, 1997), Butler's K cycle concept (Butler, 1959) or the soil-landscape chronograms (Vreeken, 1984). From Table 4, these parent materials account for about 39% of Welsh soils with the greatest proportion occurring in drift (Table 2).

Whilst water, wind and slope erosion processes continue to contribute to soil formation, many of the unconsolidated SPM result from processes linked to long-term climate and geomorphological change. Cold (glacial) climates during the Quaternary generated many slope and alluvial SPM deposits through processes such as solifluction and river terrace building, when vegetation coverage was low and excess material was available due to glacial processes. Glacial retreat led to the deposition of till and other glacial deposits, whilst Glacial Isostatic Adjustment and sea level rises continue to drive re-adjustment in slope angles, affecting slope erosion processes over the longer-term. Holocene erosion processes are dominated by colluvium and alluvium production. Table 9 briefly reviews unconsolidated SPM source.

Table 9: Major unconsolidated SPM deposits found in Wales

Unconsolidated sediment source	Deposit Type	Source	References
Glacial Deposits	Till, Hummocky terrain, morainic material	Glacial retreat and re-advance	McMillan et al. (2011)
Slope Deposits	Head	Periglacial solifluction, and gelifluction. Largely formed during warming from glacial conditions. Very widespread deposit in UK.	Harrison *et al*. (2010)
	Valley infill deposits	These are older deposits that collect in valley bottoms due to glacial conditions and land-use change such as deforestation. Often cyclical in nature with more than one episode of SPM building. Over geological time slope readjustment responds to Glacial Isostatic adjustment and sea level rise.	Preece & Bridgland, 1999; Chiverrell et al. 2007).
	Modern Colluvium	Soil erosion normally associated with land-use change and agriculture. Widespread erosion started with land use change at Mesolithic-Neolithic transition. Climate variation during the Holocene has also produced periods of increased erosion.	Evans, 1990
Alluvial Deposits	Glacial fluvial River terraces	These often exist as a single or a series of terraces often formed from a mixture of sand and gravel. Formation is through the balance between Glacial Isostatic adjustment and sea level rise. Formed in high energy environments when ice melts and plentiful supply of material available	Bridgland, 2000
	Holocene flood plain deposits	These overlay river terraces and reflect Holocene soil erosion. Whilst a continual process, 16 'flooding events' have been identified in the UK during the Holocene where increased erosion and deposition occurred as a result of climatically 'wetter' periods on centennial scales	Benito et al. 2015

Soil formation in these deposits develops in two ways. The extent of soil formation in those glacial related deposits (e.g. till, river terraces) can be assessed by the biological, physical and chemical changes that occur as the solum (e.g. the O-B horizons) develops. This normally coincides with the process of horizonation. The second way in which soils form is via upbuilding, particularly of alluvium and colluvium deposits. Particular interest relates to the rate at which sediment is deposited and later horizonation occurs. The following methodologies provides information as to how we may measure the age of soil formation in unconsolidated SPM.

A range of methods can be used to assess the age of soils in unconsolidated rocks by interpreting the landscape and/or by dating a landscape component that has existed in position since the soil parent material has been laid down. These methods may include (i) geological and geomorphological interpretation and (ii) surface age-profile thickness techniques. More complex measurements can be undertaken on individual soil profiles where dating is undertaken by analysing the amount of an isotope that exists within the profile (e.g.^{10}Be dating). However, the most common dating techniques in unconsolidated sediments are those that date a pedogenic process or a buried soil matrix component such as a buried sand or organic carbon layer at a known depth in the profile. The assumption then is that the soil is younger above this point, thus providing an indication of the age of the soil or process above that dated depth. These techniques include (i) ^{14}C dating, (ii) OSL or TL dating. The third set of techniques use isotope accumulations to determine the rate at which alluvial or eroded soils upbuild. These include the use of (i) ^{137}Cs and (ii) ^{210}Pb. These methods are explored in the following sections.

Geological and geomorphological Interpretation

This technique provides approximate ages of landscape as a proxy for soil age based on knowledge of geological stratigraphy and geomorphology process.

Surface age-profile thickness (SAST) technique:

One of the simplest methods of calculating soil formation rates is by determining the thickness of the soil profile, and relating this to the age of a dated surface, such as a glacial deposit (Egli *et al*., 2014). This is dependent on the dated surface being deposited through the same overall process (e.g. glacial) at approximately the same time as the soil profiles. When the surface is dated, it is an estimate of the time the soil became subaerially and geomorphologically stable (Schaetzl and Thompson, 2005, p. 555). Methods for dating may include ^{10}Be on rocks on moraine systems or lichens. This simple procedure has three key limitations. First, it assumes that rates of soil formation are constant over time. A second assumption is that the method does not account for so-called 'regressive' processes that remove soil material from the surface, including soil erosion, mass wasting, leaching, and harvesting (Phillips *et al*., 2005; Egli *et al*., 2014). As a result, this method can only be deployed on long-term stable landscape positions, or on soils where there is a sufficient vegetation cover to prevent surface soil loss, although this clearly doesn't account for all regressive processes cited above. Third, there are a number of processes that can thicken soils which can include bioturbation, sediment accretion, and organic matter accumulation which may contribute to pedogenesis. These techniques are often best suited to remote locations (e.g. glacial retreat areas) where landscapes haven't been disturbed. In Wales, they may have limited use due to landscapes being heavily managed over a long period of time.

Soil residence time using Meteoric ^{10}Be

Unlike for cosmogenic radio-nuclides where ^{10}Be is captured within quartz particles, meteoric ^{10}Be is produced via interactions of high-energy cosmic radiation with target nuclei in the atmosphere, leaving rainfall to scavenge it from the atmosphere. Once on earth, it accumulates in surface deposits over time. Using this technique, a variety of soil residence times from ~8 Ky to 136 Ky have been dated. The inventory of meteoric ^{10}Be in a soil can be directly related to the soil age (Maejima et al., 2005; Tsai et al., 2008) if its abundance in a soil profile is assumed to have been overwhelming adsorbed to the fine earth fraction. The method relies on the effective recovery of all the ^{10}Be deposited in the profile. It was tested at the Plynlimon Observatory in Wales (Dere, 2014) where conditions were not conducive for successful use (e.g. full recovery of meteoric of ^{10}Be was not achieved). This was considered a function of the acidic nature of the soil environment at Plynlimon which leached the ^{10}Be from sorption sites on clay minerals and oxides. Ideally, soil pH solution values would be >pH 7 as below this value Be retention on mineral surfaces changes markedly (You et al. 1989). In addition, Boschi and Willenberg (2016) demonstrated 97 % Be desorption as pH was reduced from 6 to 4 from clay minerals. This desorption at low soil pH would suggest that this technique's use in the organic rich soils of Wales may induce an error leading to under-estimation of age. It would also be important to select non-eroding profiles as this would again underestimate the quantity of ^{10}Be.

Dating Materials within a soil profile

This is a common technique often used in geomorphological and archaeological studies where buried organic materials can be dated using ^{14}C, quartz particles or paleosols can be dated using OSL or TL and the half-lives of radio-nuclides can be used as spikes.

^{14}C

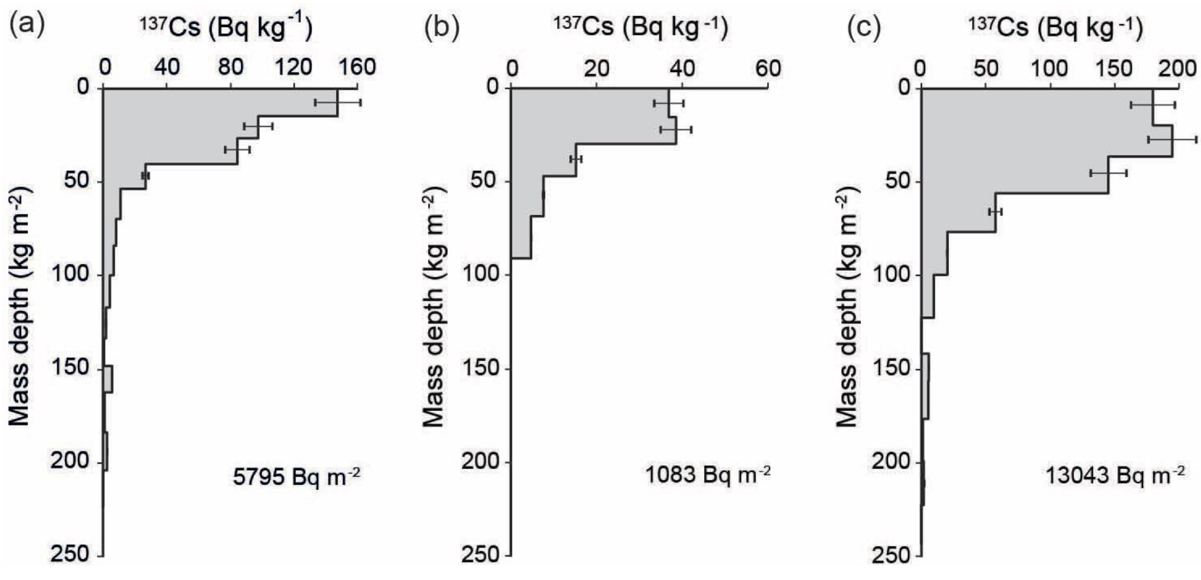
^{14}C is perhaps the most common dating method in unconsolidated sediments (Ramsey, 2008). Radio-carbon is produced in the upper atmosphere and forms $^{14}CO_2$ – a gas – which is then taken up by plants during photosynthesis. As a result, $^{14}CO_2$ is integrated into a plant's biomass. When the plant dies, photosynthesis stops, and the concentration of residual $^{14}CO_2$ can be measured using Accelerator Mass Spectrometry (AMS). The concentration of ^{14}C is used to determine the age of the radiocarbon, indicating the minimum age of the soil. The method has inherent limitations, such that a soil horizon may store organic matter from a range of decomposition stages, with ages spanning millennia. Addressing this issue, some researchers use a 'mean residence time' (e.g. the extraction of humin; Parry et al. 2015). Care needs to be taken to ensure carbon found within a soil horizon hasn't originated at another location, and been transported. Dating using ^{14}C in old organic matter (e.g. sticks), charcoal or other archaeological artefacts, found within colluvial or alluvial deposits is often used for dating.

^{137}Cs and ^{210}Pb

For colluvial and alluvial soils, the use of radioisotopes (e.g. ^{137}Cs and ^{210}Pb) have been used to estimate both the age of deposit and the rate of deposition. In its simplest form the isotope can be used as an estimate of age where its absence or presence indicates the approximate time in which the soil above the sampled sediment has accumulated, and then assessing this with respect to the isotope's half-life. For ^{137}Cs this is approximately 80 years (4 half-lives) and for ^{210}Pb ~130 years (6 half-lives). For ^{137}Cs, which is a product of nuclear bomb testing in the 1950's and after release from the Chernobyl accident (1986), it is nearing the end of its usefulness.

To assess soil formation rates, the essential variable to ascertain is the speed by which these colluvial horizons thicken. For example, given that ^{137}Cs falls out onto the soil surface, the distribution is largely concentrated in the uppermost part of a soil profile. Therefore, with increasing depth down the soil profile, the ^{137}Cs activity by unit of volume decreases (Figure 7). A reference soil profile, that has not been subject to erosion or deposition, will bear a reference ^{137}Cs profile, which can be used as a baseline to compare with other profiles. For a profile which is upbuilding, a greater proportion of the topsoil will have a greater ^{137}Cs activity. Based on the fallout rates, and the rates of radioactive decay, the increase in ^{137}Cs in an aggrading profile can be used to determine the rate of soil upbuilding. This can also be achieved using other isotopes, such as ^{210}Pb, which has a longer half-life.

Figure 7: The ^{137}Cs distribution of a reference site (a), an eroding site (b), a depositional site (c). Note that at the deposition site the concentration of ^{137}Cs is greater than the inventory. Source: Porto et al. (2013)



Optical (OSL) and Thermal (TL) luminescence

Both of these methods use quartz particles to date the time since their burial, making them useful for dating layers within profiles or paleosols. Optical Stimulated Luminescence (OSL) is a technique used to date the last time a quartz sediment was exposed to light. As quartz particles (K-feldspar grains can also be used) are transported on the surface, exposure to sunlight zeros their previous luminescence signal. Once buried, they are exposed to low level radiation in the surrounding sediment, thus accumulating a luminescence signal as ionising radiation excites electrons within parent nuclei in the crystal lattice. A proportion of freed electrons become trapped in defects or holes in the crystal lattice of the quartz sand grain known as luminescent centres and accumulate over time (Atkin, 1998). In the lab these particles are exposed to external blue-green light and the electrons are released, emitting a photon of light upon recombination at a similar site. In order to calibrate to age, the dose equivalent (De) is first calculated for the sample by measuring the natural luminescence of the sample. Then the sample is bleached and is given known laboratory doses of radiation to form a calibration curve. A calibration curve is generated for each sample. The age is then calculated by dividing the equivalent dose (De) by the dose rate of the environment surrounding the sample:

$$\text{Age (kyr)} = \text{Equivalent dose (Gy)} / \text{Dose rate (Gy/kyr)}$$

Thermoluminescence is used to date buried objects that have undergone heating (e.g. pottery) as exposure to heat resets the thermoluminescent signature of the material and is less often used in soil studies.

Methods which date pedological processes

Soil age may be estimated is through dating products of pedological processes such as iron and manganese oxide formation from parts of the soil profile. The methods (U-series, (U-Th)/He, $^{4}He/^{3}He$, ^{40}Ar-^{39}Ar) have largely been developed for the dating of geological materials and have been suggested for use in soils (Cornu et al. 2009). However, they are complicated to use within soils compared to rocks and uptake in by the soil community has been minimal, because of the complexities of soil mineral evolution. Potentially these techniques are more suited to tropical environments where mineral formation (e.g. oxides) often has greater crystallinity.

Table 10: Review of methods used in dating of unconsolidated sediment profiles

Method	Spatial limitations	Temporal limitations	Monetary costs[a]	Analysis duration[a]	Sensitivity limitations (ClORPT factors)	Main assumptions
Geological and Geomorphological Interpretation	Wide spatial		Surveyor time	N/A		
SAST (Surface Age-Profile Thickness)	Constrained by availability and proximity of dated surface. Access to saprolite/bedrock required.	Constrained by ability to date surface.	Low-cost (except for technique used to date surface)	~1 week to measure soil profile thickness; ~1 day for calculations.	Technique can only assess how soil thickens over time.	Assumes soil formation is constant over time. Assumes no removal of soil material from surface. Assumes that soil formation is the only process that thickens soils.
Chemical Depletion Fractions ***(often used in tandem with Cosmogenic Radionuclide Analysis)***	Access to saprolite/bedrock required for sample extraction. See limitations for Cosmogenic Radionuclide Analysis.	1-100 kyr timescales.	~£120 per sample for prep and elemental analysis ; ~£1,580 per sample for cosmogenic radionuclide analysis	~1 week for sampling; ~2 weeks for elemental analysis (?) ~8 months for cosmogenic radionuclide analysis	Technique is sensitive to relief and parent material. Climate- and organism-induced effect on chemical weathering rates can be detected. Effect of land management can be detected through changes to chemical weathering rates.	Assumes that soil formation only occurs at the soil-bedrock interface. Assumes that the physical erosion of soil at the surface can be determined. Assumes no aerial/lateral deposition of studied immobile element into the sampling zone. Assumes stability of immobile element during weathering.
^{14}C	Useful for buried soils and palaesols or extracated humin	Up to 60000 yrs	£300 approx. Depends on number of samples (University of Oxford)	Months		
OSL / TL	Useful for buried soils and paleosols		£550 per sample (Stratabugs)	Months	Sediment needs to have been buried and not seen air	
^{210}Pb / ^{137}Cs	Useful for colluvial and alluvial soils		A 10 sample core would be ~£1500	Months		

A range of methods have been described which have been used to date unconsolidated sediments, some which are more applicable to Wales than others. Perhaps the most attractive are those methods that can date a layer within a soil profile such as ^{14}C or OSL, these also being relatively cheap and extensively used. Other techniques such as those dating pedological processes are very difficult and the cost is high, and the selection of the mineral upon which analysis is undertaken is critical. Those dating Fe oxides are more appropriate for tropical areas where a greater crystallinity is found in oxide minerals. For recent upbuilding soil dating, such as alluvium and erosion deposits, the ^{137}Cs and ^{210}Pb techniques are recognised, along with their much-discussed potential sources of errors. As with consolidated rocks site selection within the landscape is all important.

Methods for determining Peat formation

Peat accumulation methods

The main tool used to determine peat formation rates is radio carbon dating using ^{14}C described in section 4.3.1 (Piotrowska et al. 2011). For example, early work on Denmark (Aaby & Tauber, 1975) used 59 calibrated C-14 dates, to estimate accumulation rates of 0.16 to 0.80 mm/yr over the last 6500 years for 2.5m of peat. C-14 at the time was calibrated against tree ring records, especially those of the American Bristlecone pines. Pollen analysis is often undertaken at the same time as it provides insight into the dominant vegetation types. It is through similar work in Wales on peats for example that we know about periods of peat development and erosion, especially linked to climate (Chambers, 1982; Ellis & Tallis, 2001).

Methods used to assess soil profile horizonation

Horizonation is the ultimate destination of soil formation and evolution processes. Its presence (or lack of it) is the driver behind the classification and mapping of soil types throughout the world, and is central in models of soil development such as that of Jenny (1941). The contribution of each of the soil forming factors are the drivers that explain the variation in soil series development from the same parent material. Alexandrovskiy (2007) examining the rates of horizon development in eastern and western Europe podzols identified annual precipitation as possibly being the most important driver in soil development. When soil moisture is low, the formation processes will occur at a slower rate. Soil moisture acts in the following ways as a transport medium for weathering products and clays, cause erosion and soil thinning and can cause reducing conditions when it excludes O_2.

The different thicknesses of horizons, the processes and rates at which they are created will determine a soil's natural capital stocks (e.g. fertility, moisture storage) and intrinsic functions (e.g. drainage). A number of processes are involved in horizonation, including eluviation, illuviation, upbuilding, podzolisation and gleying. These refer to the transport of materials (physically and in dissolved form) between different depths of the soil profile, the addition of material particularly organic matter and the exclusion of air.

Horizonation in the Welsh context

From Section 3 the major soil types in Wales are identified as (i) Brown soils, (ii) podzols and (iii) surface water gleys. Podzols and Gley soils are those that form the organo-mineral soils that are common in Wales (In Wales, podzols form almost exclusively on litho-skeletal substrates, both sandstones and shales). Gleys typically form on glacial till, whilst brown earths form on litho-skeletal substrates and glacial till. Figure 8 demonstrates examples of each showing what horiozonation may look like.

Figure 8: Images of (a) podzol, (ii) gley and (iii) Brown earth soil profiles showing horizonation

Methodologies for assessing horizonation change and rates

A key requirement to assess soil formation and horizonation rates is being able to date the age of the profile, or to be able date a pedological process using methods previously described (Section 4.1- 4.4). Depending on parent material, soil horizon development brings several disciplines of soil and earth sciences together, these being soil production, weathering and soil erosion and deposition. In addition, a number of processes that thicken or upbuild soils contribute to pedogenesis and these include bioturbation, sediment accretion, and organic matter accumulation.

Methods to assess Pedogenesis - Weathering and soil horizon development

There are a range of indices that are often used to assess the transformation of parent materials into soils and to delineate processes that occur during horizonation, and where the interface of the solum and 'C' horizon occurs. These are usually measured at intervals down profiles or for individual soil horizons in the profile. Typically these include those properties described in the SSEW technical monographs (Clayden & Hollis, 1984) and include the following loss or gain of total elements and carbonates, pH, particle size distribution, and dithionite extractable Fe, Al, and Mn which provide an indication of mineral weathering.

Weathering indices are used to estimate the extent of chemical weathering based on mass balance calculations or a ratio between the geochemistry of the un-weathered parent material and that of the regolith and soil. Methodologies include the following:

Chemical Depletion Factors (CDF)

Riebe et al. (2003) produced a simple quantification of the extent of a weathered product (e.g. soil) relative to its parent material using refractory elements (e.g. Zr) and called this a Chemical Depletion Factor:

$$CDF = 1-[Zr_{Parent}]/[Zr_{Product}]$$

If a soil production rate is available for the profile than the soil chemical weathering rate can be calculated as the product of the CDF and soil production (Dixon and von Blanckenburg, 2012)

Mass balance equations

Mass balance equations describing pedologic processes were developed by Brimhall & Dietrich (1987) and have been used by many (e.g. White, 2005). Mass balance equations and the calculation of time-averaged weathering rates of soil profiles or soil horizons are usually made with the following equations which include volumetric changes through the adoption of the classical definition of strain (ε) (Brimhall & Dietrich, 1987).

$$\tau = \frac{C_{m,s}/C_{i,s}}{C_{m,p}/C_{i,p}} - 1$$

where *c* is the concentration of a mobile (m) or immobile (i) element in the soil (s) or parent material (p). The total mass gain or loss for an entire soil (to some chosen depth or for the entire depth of weathering) is the integration of all layers to a chosen depth, or to the parent material. To calculate volumetric change, the following expression is commonly used:

$$\varepsilon = \frac{\rho_p C_{i,p}}{\rho_s C_{i,s}}$$

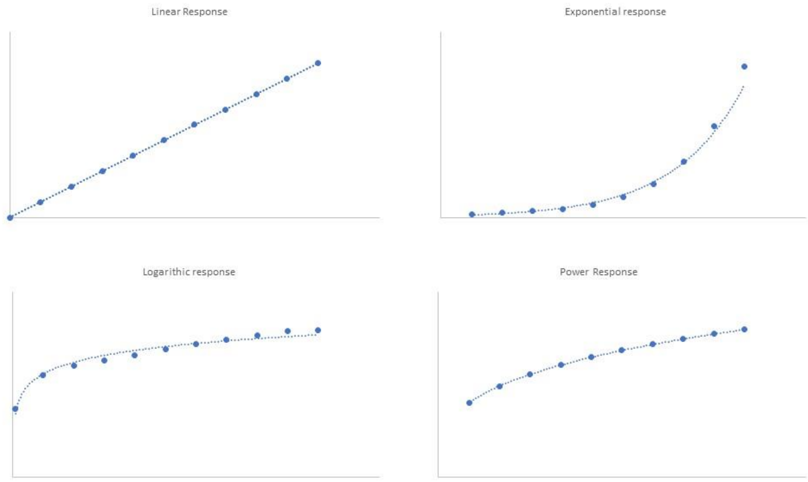
where ε is the fraction volume change of a horizon (or a whole soil if volume change for all horizons is summed over the distance of interest) and ρ is the bulk density (g cm^{-3}) of the soil or parent material.

The use of 'Soil Sequences' to assess horizonation formation and development

Whilst the methods previously described relate to processes involved in the formation of soil horizons, dating is required so that process rates can be applied. Frequently, the rate of horizonation is undertaken using dated soil sequences. Jenny (1941, 1980) defined any dependent soil property as a function of a number of independent properties or state factors. Thus if a soil sequence is to be classified, one state factor can be varied if the other remaining factors or state variables remain relatively constant. Thus lithosequences (differences in parent material mineralogy), climosequences (precipitation or temperature), toposequeneces (slope and relief) and biosequences have been examined.

The most commonly used soil sequence is that of chronosequences, where the time for soil formation and development is allowed to vary. Dating of the different profiles in the chronosequence is most often carried out using ^{14}C or OSL buried layers or paleosols, archaeological artefacts, charcoal or buried organic materials are often dated. A series of typical curves, indicating the potential rates which processes may take place, are often used to describe soil evolution within chronosequences with time depending on property (Figure 9). Where the function is linear it would suggest that the soil system evolves at a constant rate through time, whereas logarithmic models imply that the soil system is in steady state or will reach a steady state eventually sometime in the future. Nonlinear sigmoidal chronofunctions propose that the soil system evolved along periods of rapid pedogenesis followed by decreasing rates (Schaetzel et al., 1994).

Figure 9: Typical curves describing the rate at which soil forming takes place.



Situations where chronosequences provide opportunities include glacial retreat, alluvial terraces, loess and volcanic /lava flows. Typically, when soil sequences are used to assess soil development and horizonation, parameters assessed may include the chemical loss or gain of elements indicating mineral weathering, changes in clay and other soil mineralogical properties, soil organic carbon increases and decreases and pH change. Physical properties include particle size distribution, volumetric change and soil bulk density.

There are requirements for successful use of soil sequences (White, 2005). The first concerns the composition of the bedrock or parent material. Errors can result from the local heterogeneity of the rock. This is more likely when the parent materials are unconsolidated sediments such as alluvial terraces or loess deposits. Secondly, when using elemental changes, they need to be considered in relation to an inert component in the soil matrix such as Zr or Ti. However, in certain circumstances these may also weather slightly leading to possible errors. It is also important to use soil series that have been under similar bioclimatic conditions. Thus, the use of very long chronosequences, that include glacial and non-glacial climate phases will result in an underestimation of the rate of change. Alexandrovskly (2007) suggested that the use of soil sequences be confined to Holocene profiles.

SOIL FORMATION RATES – A REVIEW OF GLOBAL LITERATURE

Consolidated Rocks

Several reviews have been published inventorying soil formation rates from consolidated rock (Portenga and Bierman, 2011; Stockmann *et al*., 2014), although some of these include rates of bedrock weathering in catchments of bare rock terrain (i.e., where the soil mantle is absent). It has been demonstrated that rates of weathering for bare bedrock surfaces are not representative of the weathering rates of rock under soil. Therefore, for the purpose of this review of soil formation only weathering rates for consolidated rock overlain by a soil mantle are presented. Studies of soil formation from consolidated rock using cosmogenic radionuclide analysis were amassed from the published literature (Heimsath *et al*., 1997, 1999, 2000, 2001a, 2001b, 2005, 2006, 2012; Small *et al*., 1999; Wilkinson *et al*., 2005; Dixon *et al*., 2009; Owen *et al*., 2011; Riggins *et al*., 2011; Evans *et al*., 2019; Evans *et al*., in review). These represent three major rock types, including igneous, sedimentary, and metamorphic lithologies, and six major Köppen climate types: Tropical savanna (Aw), Cold semi-arid (Bsk), Cold desert (Bwk), Humid subtropical (Cfa), Oceanic climate (Cfb) and Warm-summer Mediterranean (Csb). Oceanic climate (Cfb) is the most relevant in the context of Wales.

Figure 10 shows the relationship between cosmogenically-derived rates of soil production and the depth down the soil profile from which samples were taken. Rates of soil production span four orders of magnitude, ranging from 0.0001 mm y^{-1} to 0.594 mm y^{-1}, with a median rate of 0.026 mm y^{-1} (*n*=266). The wide distribution is likely due to the diversity in rock types and climate regimes represented in the dataset. Given the overview of the extent of parent material in Wales, the data for Cfb climates (in the top figure) and sedimentary rocks (Figure 11) are likely to be most relevant in this report. Table 12 reports a more specific analysis for different rock types and climate regimes which could be more useful when predicting or estimating soil production rates.

Figure 10: Global inventory of cosmogenically-derived soil production rates for six major Köppen climate types (top) and lithologies (below). Aw=Tropical savanna; Bsk=Cold semi-arid; Bwk=Cold desert; Cfa=Humid subtropical; Cfb=Oceanic climate; Csb=Warm-summer Mediterranean.

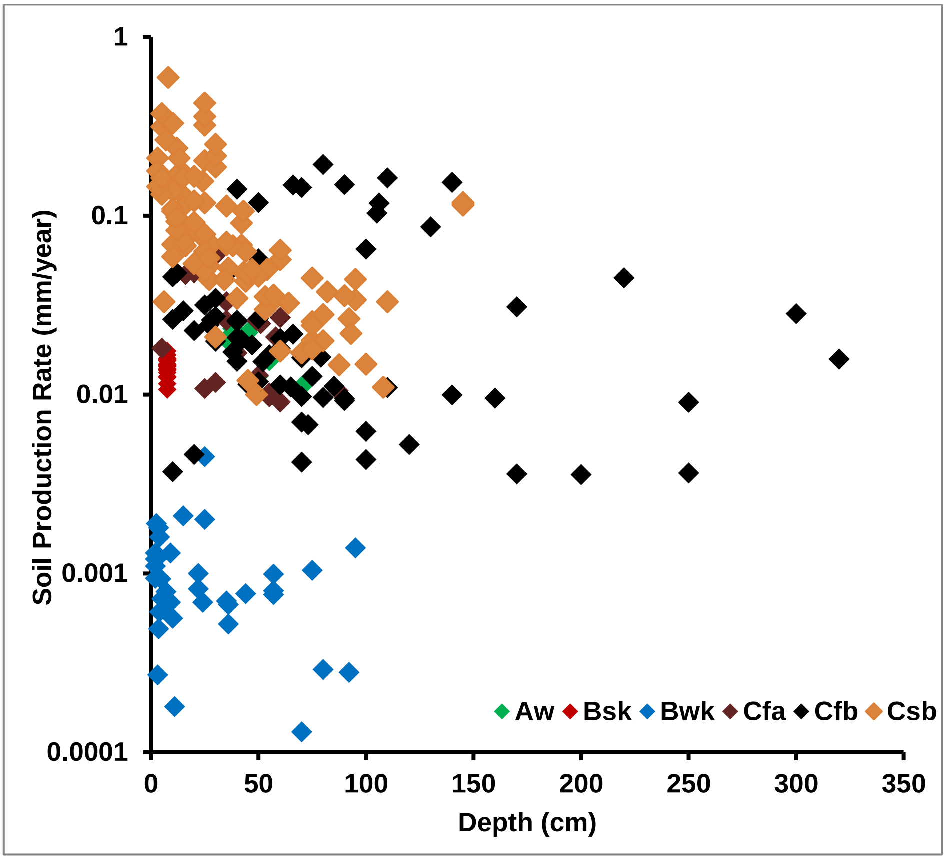


Figure 11: Global cosmogenically-derived soil formation rates for three major lithologies

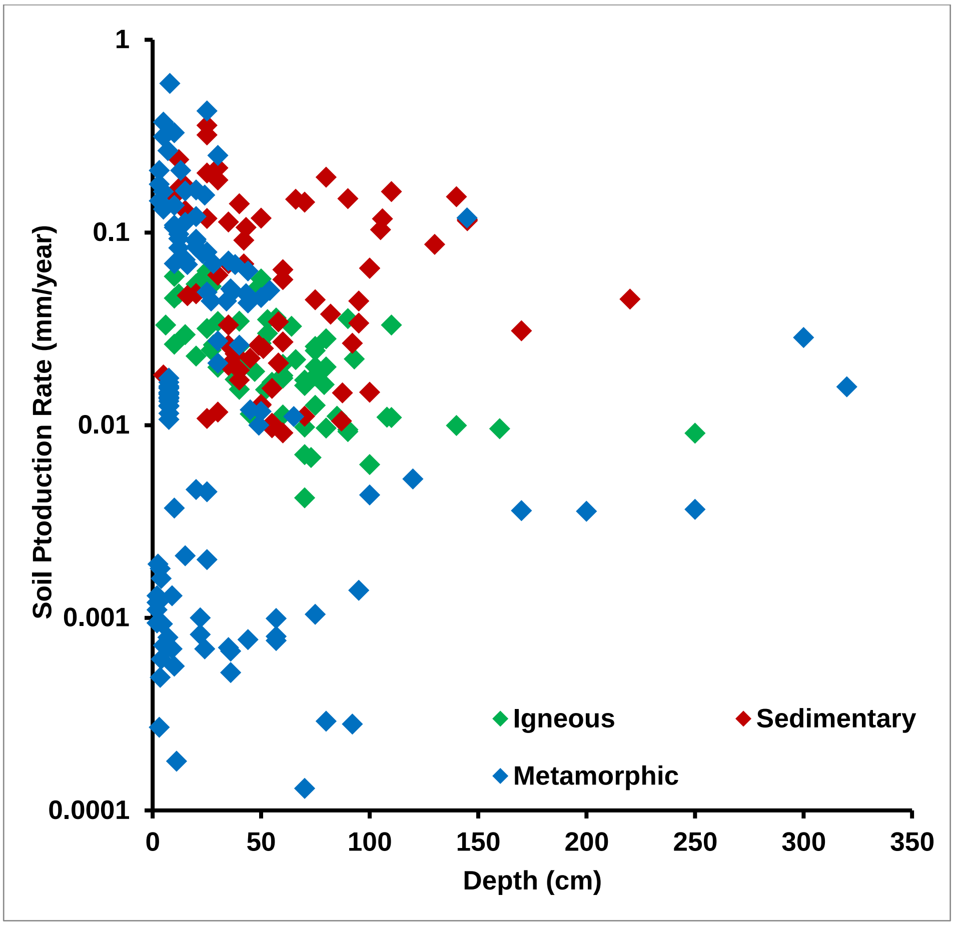


Table 11: Summary statistics of global cosmogenically-derived soil production rates for six major Koppen climate types. The shaded Cfb climate row is the one most appropriate to the Welsh climate (Oceanic Climate)

		Soil production rates (mm yr^{-1})				Soil thickness (cm)			
	N	Median	Mean	Min	Max	Median	Mean	Min	Max
Aw	7	0.019	0.018	0.011	0.023	45	47.571	35	70
Bsk	20	0.014	0.014	0.011	0.018	7.5	7.500	7.5	7.5
Bwk	37	0.001	0.001	0.000	0.005	11	25.959	2	95
Cfa	27	0.026	0.027	0.009	0.060	40	41.296	5	87
Cfb	72	0.020	0.039	0.004	0.193	66	81.944	10	320
Csb	103	0.069	0.106	0.010	0.594	30	40.597	3	145

Aw=Tropical savanna; Bsk=Cold semi-arid; Bwk=Cold desert; Cfa=Humid subtropical; Cfb=Oceanic climate; Csb=Warm-summer Mediterranean.

In Table 12, soil thickness here refers to the depth down the soil profile at which samples were extracted for cosmogenic radionuclide analysis. In nearly all cases, this marks the interface between bedrock and soil.

Table 12: Summary statistics of global cosmogenically-derived soil production rates for three major lithologies

		Soil formation rates (mm yr^{-1})				Soil thickness (cm)			
	N	**Median**	**Mean**	**Min**	**Max**	**Median**	**Mean**	**Min**	**Max**
Ign.	68	0.021	0.026	0.004	0.063	56	59.941	6	250
Sed.	79	0.047	0.077	0.009	0.359	50	59.753	5	220
Met.	119	0.015	0.060	0.000	0.594	15	32.298	2	320

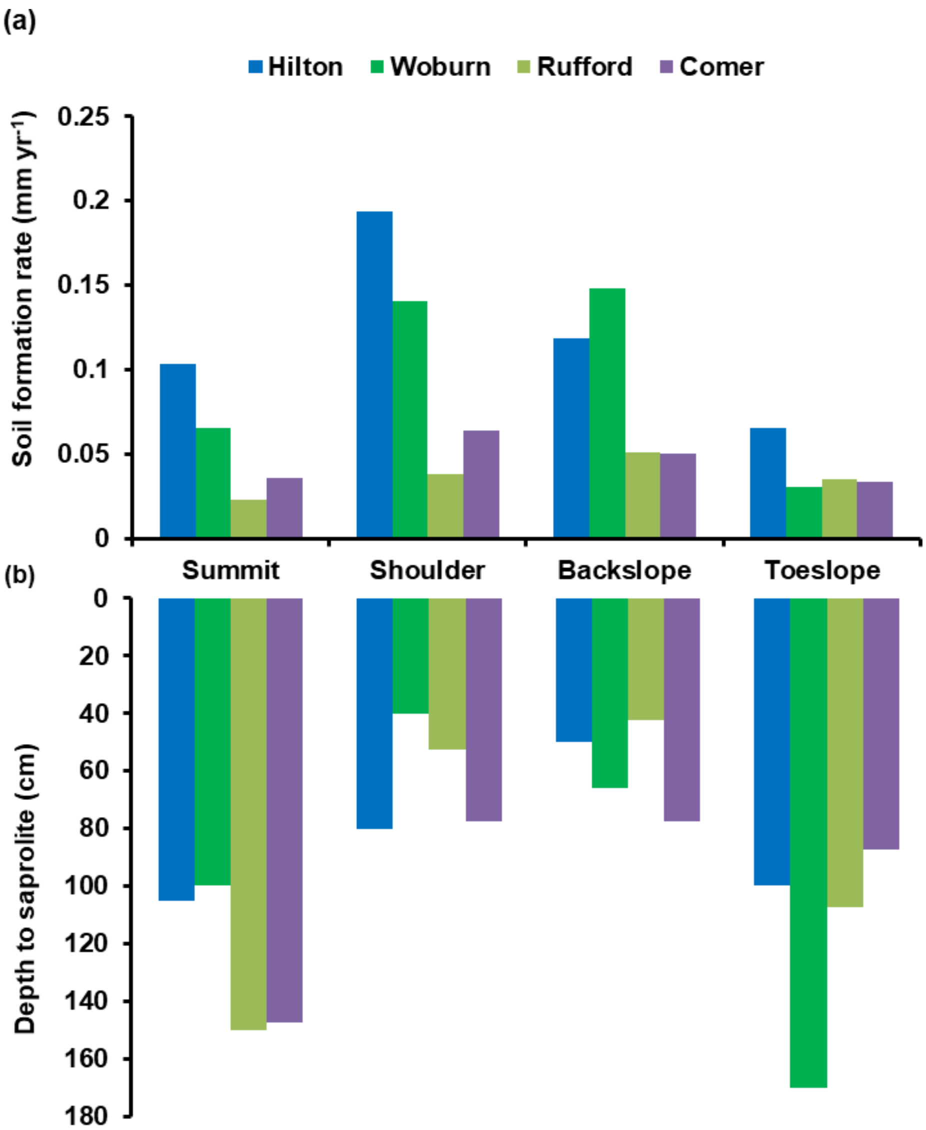
Ign=Igneous; Sed=Sedimentary; Met=Metamorphic.

Figure 11 demonstrates the classic association between soil production and soil thickness. As soil thickness increases, soil production rates tends to decrease. However, there is still a debate as to the specific nature of this relationship when soils are shallow and whether the relationship is exponential or humped. The data here present evidence for both mechanisms, which suggests that the sensitivity of soil formation to soil thickness may differ between sites. As a result, it is important to calculate rates of soil formation for zero soil thickness using the soil production function. This procedure is outlined in further detail in Evans *et al*. (2019; in review).

Effects of topography and slope

The relationship between soil thickness and soil production rates is further demonstrated when assessing how production rates vary in accordance with slope position. Recent work by Evans *et al*. (2019, in review) has studied the association between soil formation rates on consolidated rocks and slope position. Figure 12 consolidates this work by showing soil formation rates for the summit, shoulder, backslope, and toe-slope of four sites in the UK on sedimentary sandstones. Although there are clear differences in the rates between sites, it demonstrates some general trends with regards to slope position. In accordance with geomorphological theory, soil profiles are deeper at the summit (due to the relative absence of erosion processes on these flatter plateaus) and the toe-slope (due to the deposition of soil that has been eroded upslope). At these slope positions, soil formation rates tend to be slower than the rates typically observed at more erosive (and thus, shallower) points such as the shoulder and backslope.

Figure 12: Soil production rates with position on slopes at four sites across England where sandstone was the bedrock and soil parent material (Evans 2020).



4.6.2 **Unconsolidated Rocks – a review of global literature**

'First-order' indications of the rate of soil formation in unconsolidated parent materials can be made by assessing the depth of solum (O, A and B horizons) development with an estimate of age. We can use national soil databases to provide this information, and an estimate of the time of soil development (e.g. Holocene if an area was mostly glaciated). There are also a range of techniques to estimate the rate at which colluvial and alluvial soils form***.***

Database assessment of solum thickness in Wales

Table 13 shows an assessment of solum (O-B horizons) depths verses parent material taken from the NATMAP dataset for common and major soil associations in Wales and the soil series within these associations, in addition to their parent material. An assumption here is due to the Devensian glaciation, most of the soils will be of a similar age, reflecting the time that the ice withdrew. The shallower depths are where the Cr region is described and the parent material is hard rock. The table demonstrates the general relationship where soils formed from consolidated rocks, normally hard in nature, are shallower than those soils developed in unconsolidated deposits. Thus, shallow soils are those which are more vulnerable if subjected to thinning processes.

Table 13: Solum depths for dominant soil series and their Associations in Wales (after Rudeforth et al. 1984)

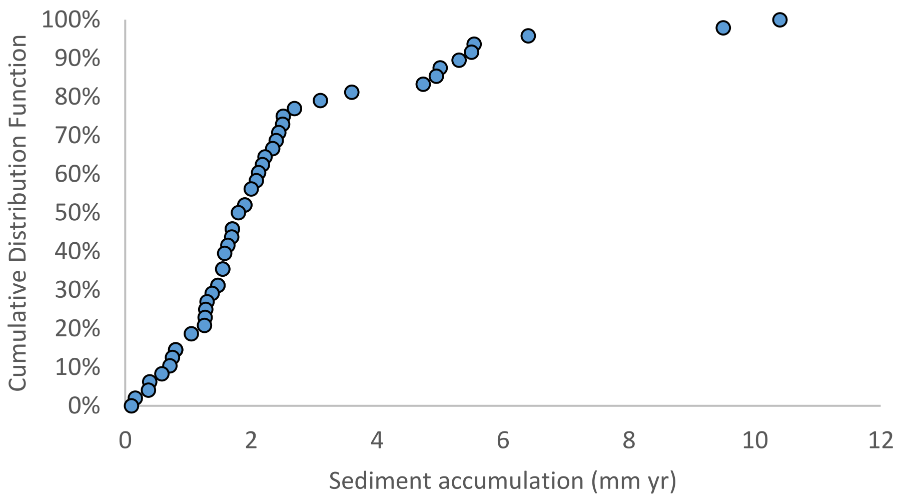
Soil Association	Soil series	Parent Material	Depth of BC or 'C' horizon
Denbigh 1 (541j)	Denbigh	Palaeozoic slaty mudstone and siltstone	BCu – 100cm
	Barton	Siltstone	Cr – 70 cm
Manod (611c)	Manod	Palaeozoic slaty mudstone and siltstone	R or Cu 60cm
	Denbigh	Palaeozoic slaty mudstone and siltstone	BCu 60-100cm
Hafren (654a)	Hafren	Silty shale	Cr 60cm
	Wilcocks	Loamy stony drift	Bcg 50-100cm
Cegin (713d)	Greyland and Brickfield	Palaeozoic slaty mudstone and siltstone	BCg 50 -100cm
	Sannan	Palaeozoic slaty mudstone and siltstone	C >100cm
	Denbigh	Palaeozoic slaty mudstone and siltstone	BCu – 100cm
Wilcocks 1 (721c)	Kielder	Drift from Palaezoic sandstone, mudstone and shale	>100 cm
	Fordham	Drift from Palaezoic sandstone, mudstone and shale	Cg 50-100cm
Wilcocks 2 (721d)	Crowdy	Drift from Palaezoic sandstone, mudstone and shale	Peat >100cm
	Winter Hill	Drift from Palaezoic sandstone, mudstone and shale	Peat >100cm
	Hafren	Drift from Palaezoic sandstone, mudstone and shale	Cr 60cm
Revidge (311a)	Revidge	Humified peat on hard sandstone	0-20 cm
	Crowdy	Palaezoic gritstone and sandstone	Peat >100cm
	Winter Hill	Palaezoic gritstone and sandstone	Peat > 100cm

Alluvial soils

Alluvial soils are an example of soils being upbuilt by the addition of new material. On a first order basis the rate of upbuild of alluvial soils during the Holocene can be described as the depth where differentiation in colour, between low OM sand and gravels from pre-Holocene low NPP times, and higher OM soils have built up in the higher NPP Holocene. In the last 40 or so years the use of ^{137}Cs has enabled estimates of accumulation of soils at specific points on floodplains, often in transects across floodplains in England and Wales. These provide an indication of sediment deposition with distance away from the river. Figure 13 shows the range of sedimentation rates measured on floodplains in England and Wales as determined by the use of ^{137}Cs redistributions (Walling et al. 1999; Owens et al 1999; Du & Walling, 2012; Owens & Walling, 2002). A median value of accumulation of 1.8 mm yr^{-1} is reported. Alluvial soils in Wales include those of the Conway association (1.42% of area of

Wales) and smaller areas of the Enbone, Hollington, Compton and Fladbury 1 and 3 associations. These are typically ~1m deep and consist of fine silt and clay.

Figure 13: Cumulative Distribution Function of estimates of floodplain alluvial soil accumulation as measured by ^{137}Cs and ^{210}Pb redistribution in England and Wales



Colluvial soils

Colluvial soils are those that typically form at the base of slopes, and thicken due to the erosion of soil. Thus it is the major deposit formed from soil erosion and deposition that has occurred since the Mesolithic-Neolithic transition. Deposits often sit on top of other valley infill deposits. Although part of classical slope geomorphology very few examples of their depth and the rate of deposition is known. The thickening of soil profiles and their role in differentiating soil development is probably dependent on soil texture and the grading of particles as they move downslope, steepness and slope length and the frequency of erosion events. Brown Earth soils (e.g. Denbigh association) and brown podzolic soils (Manod associations) in Wales are most at risk as they are used in cultivations and are often on slopes. Water erosion rates across arable transects in England and Wales are shown in Table 14 with data from Evans (2002) which was recompiled in DEFRA report SP1303 (2011). The table shows both the mean erosion rate and a mean loge transformed rate, which takes account of the positive skewness often found in erosion datasets.

Table 14: A review of water driven soil erosion rates in arable agriculture across England and Wales based on soil texture.

<table>
<tr><th>Texture class
(n sites)</th><th>Mean Erosion rate
(M^3 ha^{-1})</th><th>Converted to mm yr^{-1}
(assuming Bulk density of 1g cm^3)</th><th>Log_e Transformed average</th><th>Converted to mm yr^{-1}
(assuming Bulk density of 1g cm^3)</th></tr>
<tr><td>Coarse (704)</td><td>2.9</td><td>0.29</td><td rowspan="2">-0.16</td><td rowspan="2">0.05</td></tr>
<tr><td>Medium (150)</td><td>2.9</td><td>0.29</td></tr>
<tr><td>Medium-fine (633)</td><td>2.2</td><td>0.22</td><td>-0.37</td><td>0.07</td></tr>
<tr><td>Fine (189)</td><td>1.4</td><td>0.14</td><td rowspan="2">-0.68</td><td rowspan="2">0.04</td></tr>
<tr><td>Very Fine (1)</td><td>0.5</td><td>0.05</td></tr>
<tr><td>All soils</td><td></td><td></td><td>-0.31</td><td>0.02</td></tr>
</table>

Grassland covers much of Wales (65%), and is on heavier clay/clay loam soils. Although vegetated, erosion does occur on grassland and may be linked to the establishment of new leys, or primarily enhanced by animal traffic and stocking rates. Estimates of erosion through conventional assessment (not ^{137}Cs) of soil erosion on England and Wales by Evans et al. (2017) suggest erosion in grassland may be of the order of 0.02-0.03 mm yr^{-1} (assuming BD=1).

Organo-mineral Soils

Avery (1980) provides a generic definition of organo-mineral soils as, 'those soils that have a surface horizon (otherwise referred to as topsoil) relatively rich in organic matter but with less than 40 cm of peaty surface layer, and include rankers and rendzinas in the lithomorphic major soil group and some of the soils in the podzolic and surface water gley major soil groups. These are further defined as three types: (1) Humose topsoil greater than 15 cm thick; (2) Peaty loam or peaty sand topsoil greater than 15 cm thick; or (3) Peat less than 40 cm thick starting at or near the surface, or less than 30 cm thick where the peat lies directly on bedrock.' In Wales podzolic (32%) and surface water gley (24%) soils are the dominant major soil groups and both can form organo-mineral soils (Table 2). Organo-mineral soils are an example of a soils that upbuild by accumulating organic carbon. They are hugely important as a shallow store of soil carbon (C), in Wales containing 25.5% of the 159 Tg of topsoil C (Bol et al, 2011).

While most policy attention is focused on avoiding carbon loss from peats, it should be remembered that a Welsh peaty podzol or peaty gley soil also contains substantial amounts of topsoil organic matter. Bradley et al. (2005) suggested that in Wales, to a depth of 1m, organic soils had a stock of carbon of 67 Tg whilst organo-mineral soils had a stock of 59 Tg. Topsoil measurements at Plynlimon for the upper 20 cm of a peat contained SOC levels of about 0.04 g cm^{-3}, whereas an unimproved peaty gley contained about 0.12 g cm^{-3} (3 times more). Assuming no change in bulk density with depth in the peat, this means that the top 20 cm in the peaty gley contains the same amount of carbon as 60 cm of peat (Smith et al. 2007). Obviously, the peat contains a greater stock overall because it is much deeper, as shown by Bradley (2005). However, the greater mass of SOC in the topsoil of organo-mineral soils, and their smaller overall water holding capacity, makes them perhaps more vulnerable than peats to loss of SOC by drought or management. High bulk densities and levels of SOC resulting in large topsoil carbon stocks is evident in organo-mineral soils (Sowerby et al., 2008; Reynolds et al., 2013). Global research indicates that podzols are second only to peats in their ability to store carbon (Cagnarini et al. 2019), due to their capacity to lock carbon up in the subsoil as part of the podsolization process. In this section we focus on podzolic soils with gley soils covered in the mineral soil section.

Major soil associations: Podzols form where the decay of vegetation leads to intense chemical weathering by humic acids, hence their formation and change is intimately linked to habitat. Two major soil associations account for the majority of podzolic soils in Wales (Rudeforth et al., 1984). These are the Manod (Brown Podzolic, 18%) and the Hafren (Ferric stagnopodzols, 6%) associations. Based on the high-level analysis in Table 3, all podzols form over litho-skeletal mudstone, shale, sandstone or slates. Moreover, the soils tend to be thin not extending below 80cm deep.

Historical formation: Podzols, like other soils in Wales are relatively young as they have formed in the last 10,000 years following the retreat of the ice from the last glaciation. The formation of podzols can be linked to long term land use history which provides evidence of the rate of formation

(Robinson et al. 1936. Adams and Raza, 1978; Robinson et al. 2016), who initially suggested that the soils of North Wales were immature (Robinson 1930), but this view was revised to eluviation and erosion being the dominant processes leading to the modern presentation of podzols (Robinson, 1930). He proposed that cycles of forest growth, followed by episodes of 'catastrophic' deforestation e.g. Neolithic (starting ~6000 yrs BP), Roman and mediaeval times led to the formation of truncated podzols; native forestry to ~1700 feet caused mild podsolization with its clearance migrating soils toward brown soil formation, followed by the removal of base cations and abandonment leading to podsolization by acid grassland and heath. He further refined his view that normal erosion was sufficient to account for the truncated soils in a paper in Nature (1936). Crompton (1960) rejected the truncation hypothesis by cycles of erosion and proposed that podzol formation and the enrichment of sesquioxides occurred due to rapid desilication. When Adams and Raza (1978) revisited the issue they took a more holistic landscape view arguing that formation was a function of slope, creep erosion and crack/slip sequences linked to the soil hydrology of the system. They also dismissed the idea of 'catastrophic' deforestation and erosion events forming the soils. Therefore, the prevailing view of formation is one of landscape process dependent on slope, habitat and the hydrology and lateral movement. It is important to note that soils of the Hafren series are often found in association with the peats of the Crowdy series. Clearly, elevation, temperature, rainfall and slope (drainage) play an important part in the formation of these associated soils (Rudeforth et al. 1984).

Recent studies and environmental impacts: Two modern study sites shed further light on soil formation in Wales, the Plynlimon observatory (50 yrs) in mid Wales (Hafren on shale) and the Clocaenog climate change manipulation study site (Hafren on shale) in North Wales (20 yrs). A range of monitoring and experiments are conducted at these sites. Most relevant was the inclusion of Plynlimon in the international critical zone observatories and the soil formation rate studies of Dere (2014).

At the Clocaenog site long-term impacts of climate change, warming and drought have been studied as part of an international group that studying ecosystem carbon stability and cycling in response to climate change (Beier et al. 2004). The formation of podzols is intimately linked to vegetation and climate, with the plant productivity a key driver of the humification process through the development of humic acids. Plant productivity values for shrubs are typically about 0.382 kg C m^{-2} yr^{-1} (SD=199) (Tipping et al. 2019). Plant productivity at the site indicates an inter-annual variability but with an above ground biomass that was found to be relatively resilient to warming and drought treatments (Dominguez et al. 2015). In warming treatments root production increased, which may account for increased respiration compared to control. This was not observed for drought indicating the potential for soil carbon losses. This work identified an important potential link to soil structure with cracking of the subsurface in response to drought, with the peaty top of the Hafren series soil being exceptionally vulnerable to changes in management and climate. The peaty top lacks the depth of a peat (>40 cm) and dries out in the summer months unlike peats which are permanently wet which makes peats more resilient to drought. Robinson (2016) in a concurrent study was the first to demonstrate a shift to an alternative soil moisture state induced by drought. The mechanism proposed suggests that drought cracks the subsurface soil allowing the perched water table in the peaty topsoil to drain. This reduction in moisture is linked to carbon loss from the peaty surface horizon compared to control (Dominguez et al. 2015).

This experimental finding of the soil not rewetting in winter was also identified by soil moisture monitoring at Plynlimon on podzolic Hafren series soils and peat following the 1976 drought (Hudson, 1988). Moisture shifts occurred in the podzol, but not in the wettest peat soil that recovered in the following winter. Initial recovery on podzolic soils took 3-4 years, but moisture levels were still lower 7 years after the drought event. The peat soils showed mixed results, grassland recovering faster than woodland, but at one site the peat never fully recovered. Robinson et al. (2016) hypothesised that periodic draining and rewetting could be part of the soil formation cycle as proposed by Adams and Raza (1976), with frequent cracking observed at sites like Plynlimon

(Hudson, 1988; Bell, 2005) on the soils formed on shale substrate. The monitoring observations of Hudson (1988) also indicate that land use plays an important role in the cycle, with recovery fastest in the sequence grass, heath, trees. This is intuitive, as the larger vegetation such as trees will deplete the soil of water faster than grasses or heath. Given the interest in planting more trees on large areas of Wales, due consideration should be given regarding the trade-off between storing carbon in trees and potentially losing it from soils (ADASb, 2020).

Peat, organo-mineral soils and peaty top soils

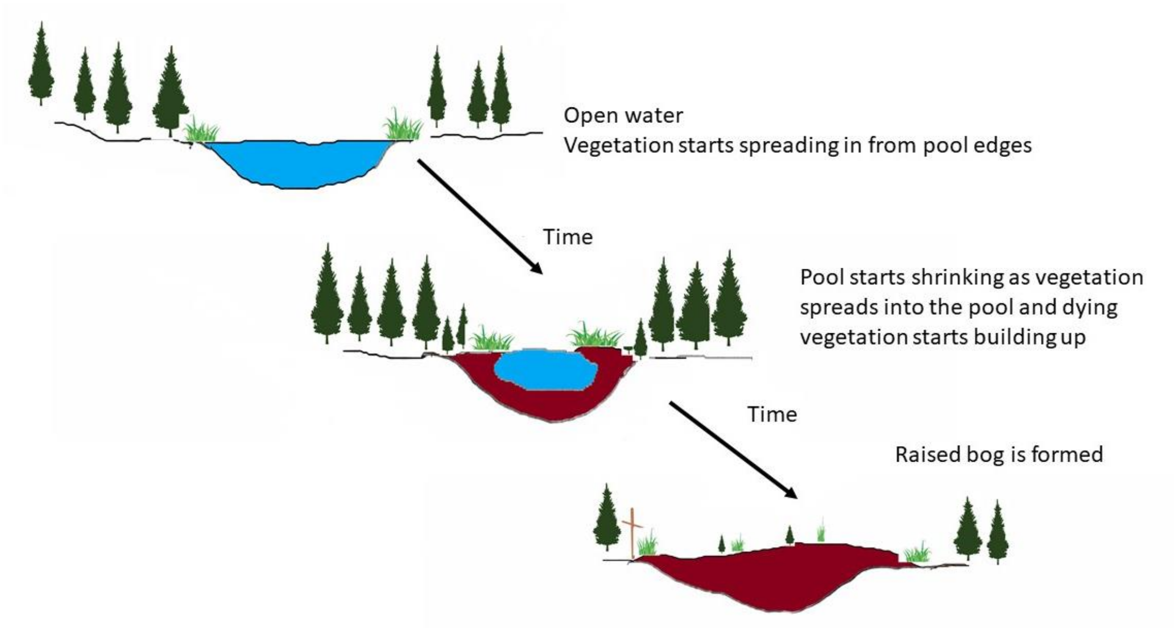
In the Soil Survey of England and Wales (Avery, 1990) mires are categorised as three principle types, raised bog, fen and blanket bog. In this section, accumulation rates for soils with a peaty top such as Hafren series are also considered as they are likely to be similar to accumulation rates in the associated Crowdy peat series. In Wales, blanket bog is dominant (Crowdy associations) with some fen peat (Adventurers association) and a number of small, but nationally important, raised bog sites. Climate is highly influential and most (not all) blanket bogs occur at high altitude (high rainfall and lower temperatures creating a long duration of wetness). Jones and Thomasson (1985) suggest that areas of blanket bog correlate closely to the 300 Field Capacity day isopleth. For example, the Crowdy 1 association (1013a) is generally found above 350m where precipitation may exceed 2000m yr^{-1} (Rudeforth, 1984) whilst blanket peat in the Crowdy 2 association also similar annual precipitations and may occur up to 600m.

Evans et al (2015) reported that there are nearly 91,000 ha of peat soil in Wales, of which approximately 50,000 ha is currently overlain with potentially peat forming vegetation according to the 1990 Phase 1 habitat mapping of Wales (although not all of this will be actively peat forming, and many areas have been subject to drainage and grazing). The remainder has been subject to a number of anthropogenic pressures including conifer plantation, conversion to grassland, management for grouse and small areas of arable land on peat. Peatland mapping is currently been reviewed as part of the National Peatland Action programme.

The two primary formation processes that result in the development of peat soils are terrestrialisation, or the infilling of shallow lakes (fens and raised bogs), and paludification (blanket bogs), whereby terrestrial systems are covered by the growth of peat forming vegetation (Mitsch and Gosselink 2000). Peatlands in the UK are less than 10,000 years old, having formed since the last ice age (FAO). Tree remains can still be found in Welsh peat sites (Chambers, 1982) indicating that at one time they were wooded. Blanket peat formation in the UK is considered to have begun 5-6000 yrs BP (Lindsay et al 2014).

Terrestrialisation is the classic process of peatland succession, where plant cover that is either partially rooted in the lake sediment or free-floating develops out over the lake surface. Fens form under the influence of ground water and contain species such as reeds and sedges. The vegetation mat may go on to be colonised by peat forming Sphagnum species, and later by other typical bog plants. Over time, the partially decomposed plant remains build up as peat, and once this has occurred to such an extent that the peat surface is isolated from the water table nutrient inputs are much reduced (Figure 14). This results in the formation of an ombrotrophic raised bog, with Welsh examples including Cors Caron and Cors Fochno in Ceredigion, and Cors Goch near Trawsfynydd in Gwynedd. There are seven raised bog sites in Wales designated as Special Areas of Conservation (SACs), and these represent over 10% of the designated raised bog area in the UK (Natural Resources Wales, 2021).

Figure 14: Peatland succession. The process (terrestrialization or hydrarch succession) where a pond fills in over time and forms a peatland.



Paludification, the more common process in Wales, occurs when peat spreads out over existing inorganic substrate, without the presence of an open water stage. This can occur when the hydrological balance of the area is positive, i.e. rainfall is greater than evapotranspiration and runoff, and can be influenced by changing climate, the underlying geology and topography. Jones and Thomasson (1985) opined that, 'areas of blanket bog correlate closely to the 300 field capacity day isopleth', indicating that low evaporation and high rainfall resulting in soil wetness in the uplands is conducive to peat formation. Blanket bog peat often occurs overlying a clay mineral layer, as the compressed clay is relatively impermeable to water loss. Blanket peat formed via paludification is generally shallower than peat formed through terrestrialisation, with depths of 0.5 – 3 m occurring in the former and typical of Wales, while depths of up to 10 m are possible in the latter. This is partially because paludification processes generally started more recently (5-6000 yrs BP in the UK Lindsay et al. 2014) and because the generally sloping nature of the ground increases water and nutrient throughput (Lindsay et al 2014). Generally areas of blanket peat will not form deep deposits on slope angles greater than 18-20 degrees (Mitsch and Gosselink 2000).

Peat formation rates are dependent on the productivity of the overlying vegetation, and the rate of decomposition (Thormann et al 1999), which is linked to climate and drainage (Stivrins et al 2017, Mires and Peat). Although fens have higher rates of vegetation production than bogs, rates of decomposition in fens can also be higher leading to a theoretical peat accumulation rate that is similar to or lower than that of bogs depending on litter inputs (Thormann et al 1999). In Wales, lowland fen peats are associated with the Adventurers 1 association covering about 17 km^2 with notable occurrence on Anglesey. Forrest and Smith (1975) suggest productivity figures for British bogs, dominated by *Calluna, Eriophorum* and *Sphagnum*, range from 0.3-0.8 kg m^{-2} yr^{-1}. Recent reports for Scottish peats agree, with Anderson (2002) reporting a mean long-term apparent rate of C accumulation for three bogs as 0.213 kg C m^{-2} yr^{-1} over the past eight to nine thousand years. This results in a general figure for the growth of temperate peat bogs of 0.5 – 1.0 mm per year (Lindsay et al 2014, Charman 2002, Belyea and Clymo 2001). In Wales, the dominant associations with upland peat are the Crowdy associations covering about 680 km^2 with blanket bog. The association contains the Crowdy series (peat), but grades into the Hafren series discussed in the organo-mineral section where peaty topsoils are typical, or they occur as an associated series in a mosaic. We therefore consider that the accumulation rates for peat are likely to be similar for the organo-mineral soils with a peaty top. Similar accumulation rates, 0.16 to 0.8 mm yr^{-1}, have been documented for raised bog peat development in Denmark (Aaby and Tauber, 1974). However, a raised bog complex in Latvia showed 2.8 – 3.5 mm per year of peat accumulation (Stivrins et al. 2017), but higher growth rates in raised bogs are often associated with slower humification.

It should be noted that not all peat soils are overlain by peat forming vegetation, and many are in a degraded condition whereby the soil is losing peat through decomposition, erosion and compaction. This loss rate can be an order of magnitude or more, greater than the peat accumulation rate in temperate regions (Evans et al 2019), although peat loss has historically been little studied in the UK. The most famous example in a UK context is the Holme Fen post, which has shown a surface level drop of approximately 4 m since drainage began in the 1840s (Great Fen, 2021).

Moisture is key to maintaining peat and so drying processes, whether management induced drainage or drought will degrade peat. The evidence from Plynlimon discussed in the organo-mineral section shows that tree planting on both peaty podzol soils and peat makes them more vulnerable to drying and resulting in soil carbon loss, particularly where ground preparation for planting included drainage (e.g. Sloan et al 2018). Grassy mires bounced back the following winter after drought but peat and podzols didn't, taking longer to rewet, if at all. Conditions that contribute to peat formation include the presence of peat forming species, continued elevated water table (Wetness class VI) meaning that the peat catotelm remains anaerobic; peaty top podzols similarly.

Rates of soil profile Horizonation obtained from chronosequences – a global review

In this section we review the literature regarding the rate of horizon development, largely through chronosequence studies (see Section 4.5.5). Chronosequences are the most commonly examined soil sequence, where time is the variable that changes out of the five state variables of Jenny (1941). The examples provide an overview and an indication of the rates at which soil horizons or key soil properties (e.g. organic carbon) develop (see Figure 9), across a range of climates and whether we can draw general patterns of response.

Podzols

Podzols and podzol formation has been the subject of distinct study (Sauer et al. 2007; Lündström et al. 2000), however, most of the formation described in the literature is relevant to lowland podzols that often form over sandy materials, while most podzols in Wales are upland podzols where high rainfall and lack of drainage can be an important soil forming factor. Lowland podzols to form on sandy materials in cool moist climates. Vegetation plays an important role with conifers and ericaceous heath vegetation playing an important role in generating the organic acids that drive podsolization which is true also in the uplands. With regard to rates of formation, Alexandrovskiy (2007) examined lowland sandy podzols across the Baltic (Table 15). Three models were examined including a (i) top-down model of soil development, (ii) a pedo-turbational model and (iii) a model where periodical sediment deposition was taking place. Table 15 shows results from the top-down model. It can be seen that pedogenic processes exponentially decrease and become very small after 2000-3000 yrs. Comparing across Baltic regions, podzol development was found to be different between the north and south region. In northern regions, podzols are shallow with the eluvial layer being typically < 10 cm whilst in southern regions the thickness of the eluvial layer is 15 - 30cm. In humid and tropical regions the process of podzolisation continues after 2000 yrs and the thickness of the eluvial and illuvial horizons can be 45 and 65 cm respectively. The Baltic climate is considered to be Dfb on the Köppen scale. Summers will be warmer (but below an average temperature of 22°C) than Wales and winters much colder (below -3°C on average) with generally <1000 mm. In some respects, this climate is reasonably similar to that of parts of Wales, and it would be expected that soil formation processes may be of a similar order of magnitude.

Table 15: Rates of increase in the thickness of humus horizons* of sandy podzols in the Baltic region during different stages of soil development (cm / 100 yrs) based on the top-down model

Horizons	Time (yrs)			
	First Hundreds	Hundreds	First thousands	Thousands (mature stage)
Elluvial part of the profile(A+E)	1 (0-4)	0.5 (0-1.5)	0.2 (0-0.8)	0
Full solum (A1+E+B)	10 (0-25)	2 (0-5)	0.5 (0-1.5)	0.1 (0-0.4)

*In podzols humus is progressively transported and covers both the A horizon and stains the E horizon where iron is being leached out.

Mokma et al. (2004) examined podzol development in pedons in Finland, similar to Wales. Table 16 shows how the horizons develop in thickness over time. Whilst the O and A horizons developed rapidly, the thickness of the E horizon was found to thicken over time, whilst the B horizon with sesquioxides also thickened.

Table 16: Thickness of horizonation development over 1800 yrs of podzols in Finland. The horizons include all differentiation of horizons (e.g. Bs will include Bs, Bhs, Bc) for simplification of presentation of results

	0	230	340	450	560	670	900	1800	8300	9100	10700	11300
O		0-2	0-2	0-5	0-3	0-2	0-4	0-11		0-25	0-8	
A		2-10	2-9	5-9	3-10	2-8	4-7	11-14	0-32 (Ap)			0-14
E		10-23	9-20	9-13	10-20	8-18	7-14	14-32	32-45	25-36	8-36	14-18
Bs*			23-46	20-57	13-61	20-63	18-67	32-107	45-75	36-115	36-101	18-111
C	0-15		46-72	57-75	61-80	63-80	67-84	107-117	75-90	115-170	101-153	111-150

The general consensus seems to be that formation rates start at about 100-500 years for a podzol to form in moist cool climate and increasingly longer, up to 1000 years, in drier climates (Lundström et al. 2000; Sauer et al. 2007), with full maturity being reached in 1000-6000 years (Sauer et al. 2007). Very rapid podzol initiation has been observed to occur in decades (Lundström et al. 2000; Stützer, 1988). Land use change may have a considerable impact on podzolisation. Willis et al., 1997 proposed that vegetation change from conifer to deciduous woodland in Hungary had led to a change from podzolization to the formation of brown earths. They proposed that climate change was largely responsible with drier conditions leading to more wild fires, the oxidation of the O horizon and the transition to brown soil formation. They estimate that the transition from conifer to deciduous woodland occurred over about 100 years, whereas the soil change took closer to 1000 years.

Brown soils

Brown soils in Wales such as the Denbigh and Milford Associations (Table 3 are formed from litho-skeletal (19.54%) and thick drift (9.21%). Typically, they have a darker brown Ap or Ah horizon from the mixing or build-up of organic matter. The ‘B’ horizons are often slightly lighter in colour and will extend to about 1m in thickness. They typically drain well, and have a subangular blocky structure.

Alexandrovskiy (2007) examined the top down model on Brown earths (Luvisols) in the Carparthian region. Results show that early stages of horizon development takes 0-15 years for a O-C or AO-C horizons with a thickness of several cm to form, whilst 30-50 years for a O-AO-A1-A1C-BW-C horizons with a thickness of 15cm to form. In the period 70-140 years further differentiation of the profile continues with the solum reaching a thickness of 150 cm. Later development properties are shown in

Table 17, with maturation of horizons taking several thousand years. In particular it can be seen that the rate of humus accumulation is relatively constant after 500 years compared to the initial period. This likely reflects the abundance of free mineral surfaces to store organic carbon at the start of soil development, which will decrease with time as they are used (an example of a logarithmic relationship – Figure 9).

Table 17: Rates of increase of horizonation and soil characteristics over time in Luvisols (cm/100 years). Figures in parenthesis represent the mass of material accumulated or removed.

Age (years	10	35	100	500	1000	2000	3000	10000
Profile thickness A + B (cm)			5-10	50-70	85	>100	150	>160
Thickness of eluvial horizon (cm)			5	16-20	20	30-35	30-35	30-40
Bulk density in B horizon (g cm3)			0.9-1		1.1-1.3	1.35-1.55	1.35-1.55	
Lessivage (g m^2 yr^{-1})		40 (1.2)		200-300 (0.5)	500-1000 (0.5-1)	1000-2400 (0.5-1)	1000-2400 (0.5-1)	2000-2500 (0.25)
Humus accumulation (g m^2 yr^{-1})	7 (0.7)		70 (0.7)	90-100 (0.02-0.06)		100 (0)	100 (0)	2000-2500 (0.25)

Comparison between soil types

Alexandrovskiy (2007) reviewed soil formation through the top down model for a range of soil types in western and Eastern Europe along with Alaska (Table 18). The formation rates are relatively rapid compared to those found in drier climates.

Table 18: Characteristic times of soil development from Alexandrovskiy (2007)

Soil	Characteristic time stages (years)		
	Development Profile A-C	Appearance of Diagnostic Horizons	Mature Profile
Tundra Gleysols A-G	10	10-20	200
Sandy Podzols E-Bs	20	50-100	1500
Loamy Sod-Podzolic E-Bt	10	100-500	2500-3000
Gray Forest A1E-Bt	5-10	300-700	3000
Chernozems A1-Bk	5	100-200	2500-3000
Kastanozems A-Bk-Bz	10	100-200	1500-2000
Solonetz El-Bt-Bk-Bz	10	100-200	1000-2000

Sauer et al. 2015 compared soil chronosequences from different climates and lithologies. Various relationships were found for the development of soil thickness (A + B 0.5*thickness of transitional Ac/CA/BC/BC horizons) over 16 K yrs, with indications that most of the soil thickness had developed within 6000 years. The difference in development of soil thickness was climate influenced between humid temperate climate of southern Norway and semi-arid desert of Patagonia.

Patagonia Beach ridges: Soil Thickness (cm) = 14.33 Lnsoil age (Ka) + 3.39; R2 = 0.76

Norway beach Soil: Soil Thickness (cm) = 30.27 Lnsoil age (Ka) + 14.32; R2 = 0.78

Norway Loam: Soil Thickness (cm) = 22.39 Lnsoil age (Ka) + 85.39; R2 = 0.47

OTHER SOIL-SEQUENCE STUDIES RELATING TO CHANGE IN SOIL PROPERTIES

Climosequence and mineral weathering

Dere et al. (2016) investigated mineral weathering across a climosequence where the soil parent material consisted of largely organic matter-poor, iron-rich Silurian-aged shale. The sites were selected from Plynlimon in Wales, with other sites in Pennsylvania, Virginia, Tennessee, Alabama, and Puerto Rico. They showed the effect of mean annual rainfall (range: 100- 250 cm) and mean annual temperature (range: 7 to 24°C), two main drivers of mineral weathering, on transformations of minerals from soil surface to bedrock. Variations across the across the climosequence were found in soil depth (35cm in Wales to 632cm in Puerto Rico), morphology, particle-size distribution, geochemistry, and bulk and clay mineralogy. As temperature and precipitation increased there were overall increases in horizonation, depth, clay content, and element depletion, which are trends expected with soil development and weathering processes in warmer and wetter locations. Secondary minerals were present at higher concentrations at the warmest sites of the climosequence; kaolinite, the end point of clay weathering was <5% in the northern most sites in Wales and Pennsylvania, whilst in the wettest site in Peurto Rico was ~30%. Of the mineralogy examined, plagioclase feldspar was found to have altered at the deepest depth, followed by the transformation of chlorite and illite to vermiculite and hydroxy-interlayered vermiculite, suggesting that the plagioclase feldspar was the first mineral to be altered during the transformation from bedrock to regolith.

Chronosequence and mineralogy

Egli et al. (2001) examined the changes in mineralogy and organic carbon in soils forming from granitic glacial deposits in a Swiss alpine region. The greatest change in mineralogy was found in the first 3000-4000 years of soil development. After, the weathering rates decreased rapidly, and the overall depletion of elements nearly reached an asymptote. In addition, the ratio $[Al_{Total}Fe_{Dithionite}]/[Al_{Dithionite}Fe_{Total}]$ in the fine earth fraction was closely linked to the duration of soil development and asymptotic values arrived after ~3000 yrs. A close relationship was also found between the mass of organic C or N in the whole profile and the soil age, whilst the relationship between % OC in horizons and age was variable.

Bain et al. (1993) examined chemical and mineralogical weathering in a chronosequence of 6 soils developed in river terraces in the Caingorms, Scotland. The soils ages were in the range 80-13000 years BP. One of the key findings was the decrease in base saturation, which fell from ~25 to 5% in 4000 years and remained relatively constant. The loss of base saturation from the A horizon took the form:

$$\% \text{ Base saturation} = 3.372 + 2.612 \exp^{(-0.0007365 * \text{Time})}$$

Chronosequence and OC dynamics

Turk et al. (2008) examined soil morphology of a debris flow chronosequence, in a coniferous forest in southern California, taking samples over the range of 20 to 244 years. Results showed that humus form changed from Mormodors (20 years) to Hemimors (26-101 yrs) and finally Lignomors (163 years and Resimors (184-244 years). Humus depth increased from 0 to 36 cm over this time period. After 20 years it was ~5cm, after 50 years 15 cm, after 100 yrs 20 cm and 200 yrs ~25cm. It was found that development started quickly before slowing down towards 100 years, but accelerating again after 200 yrs. The rate of change being best described by the polynominal equation:

$$\text{Humus form thickness (cm)} = 7.36*10^{-6}x^3-2.91*10^{-3}x^2+0.415x+0.191;\ R^2\ 0.96,\ P<0.001$$

A second study examined soil development after windthrow events in three pristine forest ecosystems in southeast Alaska, using a 350 yr chronosequence (Bormann et al. 1995). Accumulation of C formed a linear relationship between stands and averaged 21 g m^{-2} yr^{-1}. About 37% of the OC accumulated in the O horizon (8 g m^{-2} yr^{-1}), 31% in the Bh horizon and the remainder in the other mineral horizons). The results did not however imply equilibrium had been reached.

Darmody et al. (2005) examined soil organic C accumulation across the Storbreen glacial foreland sites in Norway over a period of 10000 years. Soil C went from 0 to ~160 g m^{-2} between 0 and 2000 years and only increased to 180 g cm^{-2} after 9000 yrs, again demonstrating the initial phase of C building as being rapid due to the abundance of mineral surfaces initially allowing storage. In the first 250 yrs a relationship at all sites gave the equation:

Soil Organic C (g cm^{-2}) = 38.28Ln(Soil age yrs) -170.31; R^2 = 0.98

THE ROLE OF LAND-USE CHANGE ON HORIZONATION DEVELOPMENT AND SOIL FORMATION

Richter and Yalon (2012) revisited the model of soil formation in the context of the intensification of land use in the 21st century. Three specific changes were noted: (i) that soil is being transformed globally from a natural to human-natural body, (ii) that the lower boundary of soil is much deeper than the solum historically confined to the O to B horizons, and (iii) that most soils are a kind of pedogenic paleosol, archival products of soil-forming processes that have ranged over the life of most soils. They suggest that 'human forcing' represents a global wave of soil polygenesis altering fluxes of matter and energy and transforming the thermodynamics of soils to potentially very deep systems'.

Some examples of soil formation alterations produced by land use change are provided below:

- The loss of natural horizonation through the formation of Ap horizons through cultivation.
- Use of soil in urban areas and the loss of natural horizonation. Herrmann et al. (2018) reviewed how urbanization in 11 cities representing 10 of the 12 soil orders and demonstrated that urban soils have ~50% fewer soil horizons than pre-urban soils.
- Drainage of soils can cause horizonation to occur. Labaz & Kabala (2016) examined the formation of mollic and umbric horizons in farmed drained swampy alluvial soils in Poland since the 17th century

- Further effects of under-field drainage have been identified. Montagne et al. (2008) identified the main effects of subsurface drainage on an Albeluvisol as (i) increasing precipitation of Mn oxides and Mn-rich ferrihydrite with decreasing distance to the drain as a result of the change in redox conditions and (ii) increasing loss of clay-sized oxides and smectites due to the enhanced eluviation in the vicinity of the drain.

- Land use change can reverse soil forming processes. Barrett & Schaetzl (1998) examined de-podozolisation after the removal of forest and reversion to prairie. They found that podsolization was more active in the forested pedons than the prairie. De-podzolisation in the prairie pedons was associated with organic C changes and the requirement for organo-metallic complexes.

- Landuse change may affect carbon sequestration and change its distribution and properties throughout the profile (Kurganova et al. 2019).

- Reversion to woodland will change soil moisture and water table dynamics

- Soil erosion, depending on the extent and rate will have the capacity to thin the soil profile causing changes in horizon thicknesses.

- Compaction will change soil gaseous exchange leading to new redox zones

Because of the time it takes for horizonation to occur monitoring these changes is often complex and requires very specific land-use changes to be monitored over lengthy time periods, which seldom occurs. In addition, some land use or land management changes may not produce significant changes in horizon depths, but may cause changes in properties within the horizon, leading to changes in Natural Capital Stock. In particular this revolves around OC and nutrients. The use of long-term experiments (e.g. Rothamsted) in relation to changing land use, and management practice (e.g. tillage type) may provide some indication as to the effects.

Section 4.6.7 described the importance of environmental change (drought, land-use) on organo-mineral soils which supply important ecosystem services (e.g. sequestering carbon, filtration and regulation of water flows). The landscape position and potential to improve organo-mineral soils makes them vulnerable to land use change, especially for agriculture and forestry. These activities often include disturbance, mixing and liming that may change the function of organo-mineral podzols. A more thorough analysis of the impact of land use and management on OM soils in England and Wales is provided in Bol et al. (2011). A synthesis of some of their findings, for which they acknowledged evidence is poor is summarised below. Cropped OM soils in Wales are rare, but the consensus is that it promotes the loss of carbon. Best practices for grassland carbon retention include rewetting, whilst reducing stocking density also has substantial impact. The report indicated that the impact of converting OM soils from grassland to forestry was not well understood. The report suggested a marginal increase in carbon storage associated with forestry on OM soils. Research in Scotland suggests impact on soils include an increase in topsoil carbon but losses at depth (Razauskaite et al. 2020); losing what is considered to be deep stable carbon is not desirable. It should be noted that this research was on sandy soils not the finer textured soils often found in Wales, which may potentially lose more carbon; the Scottish soils containing about 4% SOM in their B horizons in comparison to over 30 % for example in the Clocaenog Hafren series B horizon (Robinson et al. 2016). Best management practices proposed were to increase the length of forest rotation to reduce soil disturbance and to conduct good site management which may include continuous cover forestry and minimal soil disturbance.

EFFECTS OF CHANGES IN JENNY'S STATE FACTORS – CLIMATE

Similar to the effects of land-use and management change, climate change needs to be considered in the context of Jenny's equation. Warmer wetter winters and drier summers are currently predicted as a consequence of atmospheric CO_2 increases. Again, it is likely that a change in horizonation may occur gradually over time. However, it is likely that within horizons some natural capital changes may occur.

- Based on Q_{10} theory, rising temperatures may increase microbial respiration leading to decreases in SOC
- This may be balanced against increased plant growth due to higher CO_2 which may increase deposition of C via roots.
- Increased precipitation may increase mineral weathering (e.g. K-Feldspar) that may reduce natural capital of minerals, whilst increasing the products of weathering.
- The biogeochemical cycles of N and P may well be impacted worth nutrient loss and greater GHG emissions, due to soil moisture changes.

AN ASSESSMENT OF SOIL FORMATION IN WALES AT NATIONAL SCALE

Tables 19 and 20 provide estimates, based on our literature review of suggested soil production and formation rates. The rates are provided for SPM and soil types. These values have been identified from those values obtained from literature reviews in Section 4.6, discussed by the authors as an indication of rates based on information, and considering the climate of Wales. In organo-mineral soils there will likely be soil production occurring as well as upbuilding of the organic layer, meaning that the soil depth is potentially expanding from the top and bottom of the profile. Thus, we would select a soil production rate from Table 19 and an organic layer development rate from Table 20.

Table 19: Suggested 'first order' soil production rates for different SPM in Wales from consolidated rocks

ESB Code	Parent material Major class	Parent material Area (%)	Production Rates (mm yr^{-1})	Notes
100	Consolidated clastic sedimentary rocks	23.88	0.03-0.2	Based on data for Cfb climate and sedimentary rocks; Evans et al. 2019
200	Sedimentary rocks (chemically precipitated, evaporated, or of organogenic or biogenic origin)	N/A	N/A	No production rates available for Limestone / chalk
300	Igneous rocks	2.35	0.01 -0.02	Based on data for Cfb climate and igneous rocks; Riggins et al. 2011
400	Metamorphic rocks	0.24	0.004-0.05	Cfb climate (Heimsath et al 2001
500	Unconsolidated deposits (alluvium, weathering residuum and slope deposits)	4.57	N/A	
600	Unconsolidated glacial deposits / glacial drift	36.43	N/A	
700	Aeolian deposits	0.72	N/A	
800	Organic materials	1.95	0.5 -1	Based on Uk peat formation rates
900	Anthropogenic deposits	0	N/A	

Table 20: First-order estimates of time required for Horizon development and maturity. This includes the rate (3) at which organic matter in peat builds which is assumed also as the rate of upbuilding of organic layers in organo-mineral soils.

	Major Soil groups NATMAP (NSRI) 1:250,000 (Thompson, 2007)	Land coverage (%)	Horizonation initiation	Maturity of Horizonation	Notes
1	Terrestrial raw	<0.1			
2	Raw gley soils	0.2			
3	Lithomorphic Sandy Organic	2.2	<50 yrs 0.5-1mm yr	50yrs-350yrs	Based on sand dune rates in Newborough Warren, Anglesey (Jones et al., 2008) Based on UK peat accumulation rates. Lithomorpohic soils represent those soils where shallow OC rich horizon is upbuilding on rock
4	Pelosols	0.1			
5	Brown soils	30.2		1000-2000 yrs	Based on luvisol rate
6	Podzolic	32.3	<50 yrs	>1000 yrs	Based on reported Podzol rates
7	Surface water gley	24.7	<50 yrs	1000-2000 yrs	
8	Ground water gley	3.4	<50 yrs	1000-2000 yrs	
9	Man made	0.4	N/A		
10	Peat	3.4	0.5-1mm yr	N/A	Based on UK peat accumulation rates.

SoNaRR step 4: Ecosystem services

This section presents a rationale demonstrating why an assessment of soil formation rates is important in the context of natural capital and ecosystem services. Soils provide vital functions for society (Blum, 2006). They sustain our terrestrial ecosystems; grow our food, feed, fibre, and wood; filter water; regulate the atmosphere; recycle waste; preserve our heritage; act as an aesthetic and cultural resource; and provide a vital gene pool and biological resource. Despite this, soils are often overlooked within the ecosystem services framework, largely because they are considered to provide supporting services (MEA, 2005). As natural capital accounting frameworks have developed, especially the UN SEEA (2014a), the acknowledgement of the importance of soils in their own right has been recognised, but their contribution to the general framework lacks development (Obst, 2015). Within the SEEA (2012), which is the overarching framework used by the UK in the development of Natural Capital Accounting, soils are recognised as one of 7 major assets for satellite accounting. Within the SEEA, soil is dealt with in two main areas, as a "physical asset," and in the "physical supply and use tables" (UN, 2014a). As a physical asset, assessment is based on area and volume; hence, soil formation and loss underpin this part of SEEA. The criteria for reporting soils in SEEA and in the UK natural capital accounts is yet to be developed. However, a proposal based on changes to the soil asset was proposed in Robinson et al., (2017) based on soil cycles:

Extent and volume/mass accounts for soil cycles:

- Soil production and erosion
- Soil carbon gain and loss
- Soil nutrient release and loss
- Soil water and energy balance

Within this framework soil formation and erosion are considered together to determine whether soils are degrading, increasing or simply maintaining the balance. The work argued that the overall reporting unit should be by landcover, subdivided by soil type or property of interest, as land is managed by habitats at the highest level. Furthermore, the framework stresses the importance of change, especially within the exploratory ecosystem service accounting framework (UN, 2014b). The Office for National Statistics (ONS) has made some attempt to include soils in their accounting to date with soils information contained in the cross-cutting carbon accounts (ONS, 2016) and the change in soil properties in some of the habitat accounts (ONS, 2017). Wales is in a strong position to develop and report natural capital accounts for soils as SoNaRR reporting is consistent with the ONS approach. Furthermore, ONS largely used Countryside Survey (CS) data for reporting and Wales has undertaken the Glastir monitoring (2013-16; now ERAMMP), which is consistent with the CS approach. A soil formation and erosion assessment has not been undertaken anywhere in the world to our knowledge and Wales would be in a strong position to undertake such an analysis given the data available from both the National Soil Inventory and ERAMMP monitoring program.

SoNaRR step 5: Options for more sustainable management

Here we summarise the findings in the Welsh context and identify key knowledge gaps resulting from the review. In the final sections of the report we identify centres of excellence for research on soil formation, and options for assessing soil formation rates at a national scale.

Key knowledge Gaps

For mineral soils

- For consolidated rocks, evidence to support soil production rate data in Wales are very limited, particularly on the major soil parent materials of sandstones and mudstones/shale. The global database and particularly those soil production measurements taken in England (Evans et al. 2019; Riggins et al. 2011) provide a good indication of rates for end members of hard (e.g. granite) rock and soft (e.g. sedimentary sandstone) geology in reasonably similar climates (Midlands of England and Dartmoor). Thus, for a granite soil in south west England soil production rates were found to be between 0.01 and 0.02 mm yr^{-1} and for soft sandstones in the English midlands up to 0.2 mm yr^{-1}. International rates obtained from the CfB (Oceanic climate) category (Table 11), in which Wales fits climatically are in the range is 0.004 – 0.193 mm yr^{-1}. These would appear to represent reasonably realistic upper and lower limits for Wales, based on those studies in England. However, further field validation in Wales would be useful as the strength and mineralogy of the bedrock is a key factor. For example, it has been shown that soil production rates for sandstones vary according to whether they are categorised as hard or soft (which is dependent on the nature of the sedimentary environment the sediment was laid down in, and the subsequent lithification and diagenetic processes the sediment undergoes), the type and nature of the cements (e.g. silica overgrowths, iron oxides) that hold the particles together and the degree to which the rock has been weathered. The high precipitation gradient across Wales and its interaction with relief would be a key influence to test, to assess the degree of variation on production rates. Three soil types are dominant in Wales, (brown soils, podzols and surface water gleys). Therefore, focusing on those would appear to be a good starting point. Further constraints on the rates at which soil production occurs, along with erosion rates for Wales (particularly grassland) would be important to achieve, as potentially erosion and production rates, in many instances could be very similar.

- To the best of our knowledge no 'time series' analysis of soil horizonation rates have been undertaken in Wales in either consolidated or unconsolidated rocks. This may reflect the absence of suitable soil sequence sites. Identification of potential sites (if any exist) would be useful, especially as Wales has high annual precipitation to drive soil formation processes. Again, analysis on an east to west basis and with altitude and relief would provide considerable insights. Data from the Baltic region (Tables 15 and 16) largely on podzols provide an indication of the rates of formations in climatic regions closest to that of Wales. Soil horizonation is evident within a hundred years with maturity of profiles taking at least 1000 yrs. These time frames of hundreds of years for development to be recognised and thousands of years for profile maturity can be seen for other soil types (Tables 17 and 18) and would represent a good approximation for Wales.

- With the assignment of values collected from the global analysis of soil production and horizonation to the soils of Wales, it is apparent that understanding of soil formation currently exists at low resolution. A particular emphasis on the variation of soil production and formation on slopes is important as slopes (particularly on arable soils) as these are where soil thinning is likely to take place and the key question is 'Does formation equal erosion?'.

- Data on the development of horizons in Gley soils, that make up ~30% of Welsh soils, is very limited within the reviewed data (both Wales and internationally). One suggestion of 200 yrs for a gley profile maturity in Tundra ecosystems was reported (Table 18). This is obviously an area that requires more research particularly as its related to drainage issues and land use change. However, a rule of thumb of hundreds of years for horizon recognition to start developing and thousands of years for maturity would be sensible for Wales.

- Chronosequence data also show that different soil horizons properties develop at different speeds (see concept in Figure 9). Reviewed data suggests that organic carbon horizons start developing and can be identified on a period of tens to hundreds of years. This would be expected in Wales which has high rainfall and climates, especially over 300m where organic matter is likely to accumulate.

- An important missing factor in ascribing soil production rates in Wales is greater knowledge of soil depth. Broad brush knowledge such as the BGS 'Depth to Rockhead' map or soil profile information from NatMap exist, but greater spatial resolution would be useful. Firstly, in consolidated parent materials it is a key determinant on formation rates (i.e. how much water reaches the rock-soil interface for chemical and physical processes to occur). Secondly, for unconsolidated SPM it represents the depth of material into which soils can develop. If the unconsolidated sediment is lost, further soil production would then reflect that of the underlying consolidated geology. Thirdly, soil depth in a glacially arranged landscape, especially in upland areas is likely to be highly variable due to geological debris underneath, and more knowledge would help derive the range of soil production and formation rates. Soil depth is important for storage of water, nutrients and is required for rooting depth, and erosion may decrease the potential for delivering these services, particularly where soils are already thin. The ratio of topsoil depth to total profile depth would be useful, particularly in upbuilding soils where organic carbon is being stored.

- Further understanding is required for the rates of soil upbuilding are also important to understand further. Depending on the depth of profile and parent material, two rates of development will be occurring, both bottom-down as parent material is weathered from rock to soil and upwards as accumulation of organic matter accumulates. This is particularly important in organo-mineral soils. Thus, soil production rates would be expected to be of the order suggested for Welsh bedrocks and a suggested upbuilding rate of 0.5 to 1 mm yr^{-1} has been identified for peats and organic rich horizons for Wales. Elevation, annual temperature and rainfall have all been cited as controls on the upbuilding of peat. Modelling of Countryside Survey data (Reynolds et al., 2013) using machine learning for GB indicates that the threshold for bog formation, excluding lowland systems is at an elevation of 208m, an annual average temperature of < 8°C, and with precipitation that is greater than 3.942e-05 kg m^{-2} s^{-1} (~1150 mm yr^{-1}). The data supporting this are for GB, and a more refined analysis for Wales could be undertaken. Below this threshold soils will be dominated by mineral constituents, but may still contain considerable amounts of carbon, especially if they are saturated for long periods. However, no UK studies have examined the controls on organic matter build up in mineral soils at lower altitudes, along precipitation gradients for example.

- Land-use is a key determinant on organic carbon storage and soil upbuilding, with arable land reportedly experiencing the greatest decreases in OC within the UK (Reynolds et al., 2017). With the majority of agricultural land being grassland in Wales, losses of OC associated with arable land cultivation, particularly prevalent in lowland England, is potentially less important on a national scale, than across lowland England, but is likely to continue on the Welsh arable soils.

- Upbuilding rates for alluvial soils in England and Wales are reasonably well constrained with a median value of ~1.8mm yr^{-1}. The upbuilding rates of toe slope deposits are rarely known, not just in Wales but internationally. Both alluvial and colluvial upbuilding rates are linked to catchment or hill slope erosion, demonstrating how useful further information would be for this major geomorphological process. Both alluvial and colluvial soils are important with respect to hydrology and carbon storage within catchments.

- The upbuilding of soil through sediment accretion is linked to soil erosion. With respect to understanding the balance of soil formation to soil erosion, and thus the concept of soil life spans, greater understanding of erosion rates within Wales are required. Currently data are skewed towards peat and, in soil erosion surveys in England and Wales surveys towards arable land-use. Greater focus is required on erosion on Welsh grasslands which are dominant in Welsh agriculture.

- Measuring change in soil thickness is challenging. However, satellite interferometry data, especially using the free EU sentinel satellites could prove useful for at least determining changes in surface movement that might link to erosion and help identify vulnerable locations.

For organo-mineral and Peat soils

Some understanding of general formation rates of organo-mineral soils and peat is known through reported studies. Rates specific to Wales are less well known, but organic matter accumulation for peat, organo-mineral soils and peaty top soils is suggested as being in the range of 0.5 -1 mm yr^{-1}, the same as that measured in Scotland (see Section 4.6.8).

- The rate at which upbuilding of organo-mineral soils may be altered by management and climate change is not fully understood in Wales. With respect to maintaining soil formation processes, best practice in retaining carbon in semi-natural environments may include the reduction of stocking density and grazing. In managed systems, water table management and stocking density are important (Bol et al. 2011) so oxidation of organic carbon is not increased.

- The big management change in Wales may be the conversion of organo-mineral grassland to forestry, particularly as part of environmental stewardship schemes. This may change water table levels leading to loss of carbon through oxidation. A recent study by Williamson et al. (2021) suggests that planting of forestry on organic soils in Scotland has led to an increase in DOC export from catchments, which may affect drinking water quality. Increasingly dry summers may lead to increases in soil hydrophobicity which may increase erosion.

- Peat depth is poorly constrained at high resolution and is key to its management.

- The mapping of peatland drainage is incomplete at a national scale, impairing restoration and management prioritisation.

MANAGEMENT

- Water is clearly an important factor in Welsh soil formation, where high precipitation and poor drainage leads to the development of organo-mineral soils, peaty top soils and peat formation, along with being a driver for erosion and soil thinning. The impact of drainage or lack of drainage on soil formation is not well documented for Wales or within the wider global literature. However, drainage is undertaken for soil improvement and is highly likely to affect horizon formation, by changing the hydrological status. The history of drainage in Wales would suggest that these changes are likely to have occurred since the Roman period. Key properties of soil horizonation affected would be the amount of and degree to which gleying soil horizons would undergo (including mineralogical change through change in redox status), podzol formation and organic carbon accumulation. Opportunities now exist to track changes in moisture status using satellite data.

- How extensive tree planting will affect certain soil types is not well understood, but they are likely to have an important impact on the soil water balance. Evidence from the uplands suggests that clearing trees allowed peat to develop post glaciation, essentially causing a soil formation state shift. Conversely, if trees are planted *en masse*, will it lead to a change in the water balance and the drying of soils, which in the case of podzols might inhibit podzolization or lead to the oxidation of peaty top soils? These are key questions.

- One possible way to understand the effects of long-term management and associated soil change is to consider what a soil might be like if it were to exist in its natural state without any human interference, along with the time frame since first human impact. An analysis based on this approach would be an interesting exercise and would contribute much to understanding how management has changed Welsh soils over time. It would also be instructive in assessing future change.

Environmental change

- Organo-mineral and peat soils make up ~25 % of the soils in Wales. Organic carbon contents in these soils, as well as the other ~75% of the Welsh soil resource, are vulnerable to change due to changes in climate. The balance between expected greater precipitation and warmer temperatures is not currently well understood. Potential tipping points in these relationships and dynamics need to be understood to protect carbon stocks, but also will impact the future direction of soil formation and horizonation. Limited evidence suggests droughts could lead to the drying and release of carbon from organic soils and change soil hydrology in Welsh podzols (Section 4.6.7).

- Land-use change is key to how soils in Wales have developed over time and increasingly into the future. A key knowledge gap is whether soil function has been impaired or changed permanently and the rate at which future changes may occur. This particularly links to soil structure, carbon storage and water storage. What impact will interventions such as rewilding, tree planting and floodplain water storage have on soil formation.

Data

- There are many national datasets (held by e.g. BGS, UKCEH, Cranfield University, Met Office) available which may help inform knowledge on soil formation and production (e.g. Soil Parent Material, Natmap, Climate, Lidar, Welsh Soils Map). Improved data on soil depth would be a useful addition to soil management so potential areas or soil types, with naturally thin soils or prone to slope erosion, can be identified and conservation measures introduced. Soil depth is also a key knowledge requirement for assessing soil lifespans when soil production and formation are linked to potential erosion rates

A key question is whether it is possible to increase spatial mapping granularity or resolution by using existing data mapped at a 1:50K or higher resolution. This could be through the use of soil associations and soil series (e.g. new Welsh Soils Map; Gov-Wales 2020b). For soils forming on 'consolidated' geology through bedrock weathering this may be possible, but would need to link soil series to bedrock type. For soil formation and horizonation rates on 'unconsolidated' geology linking to soil association/series would be possible, as Jenny's state variables would be key drivers. However, the basis would still be the soil parent material as this provides the properties that soil formation will change. There is potential for assessing similar soil types on different parent materials. For both though, the development of improved databases, covering a greater range of bedrocks and horizonation /soil formation processes rates would be the key to developing greater spatial granularity, along with improved estimations of rates.

SUMMARY AND KEY CONSIDERATIONS FOR WALES

- **Are soil formation rates greater than soil erosion rates in Wales (or vice-versa)?**

The scoping study has reviewed global soil production rates. As with many field studies, the collected data are often taken where conditions are most suitable for experiments to be carried out to answer the specific questions asked. However, the datasets are reasonably consistent with respect to orders of magnitude, in relation to climate and rock type. These have been analysed and suggestions made for Welsh soils with a 0.004 – 0.193 mm yr^{-1} for a range of soft to hard rocks being considered appropriate. Localised rates may be expected to differ slightly as a result of variations in Jenny's state variables. Considering, the bulk of soil production rates are likely to be considerably less than the upper figure in this range, there is potential for water erosion rates identified in England and Wales (Table 14) to exceed production rates. This is partially borne out by values in Table 14 where the mean values for erosion in the dataset are an order of magnitude higher. However, when $\log_e$ transformed the back converted mean values are closer to those of formation, demonstrating the possible influence of more localised higher erosion rates. On land more susceptible to erosion (sandy, silty texture) and because of land-use (e.g. where bare soils exist on slopes for periods or where erosion is aided by tillage) it is the general consensus within the soil science community that erosion may often be an order of magnitude greater than soil production. However, this combination of land-use and soil texture is rare in Wales as arable agriculture accounts for only ~6 % by area in Wales. The greatest area of arable agriculture is in Eastern Wales, where it does occur on slopes, making these susceptible to erosion rates exceeding formation rates. Importantly, grassland covers much of Wales (65%), particularly on the heavier clay/clay loam soils. Estimates of erosion by Evans et al. (2017) in England and Wales suggest erosion in grassland may be of the order of 0.02-0.03 mm yr^{-1} (assuming BD=1) which falls within the range of soil production. However, it must be remembered that when erosion does occur it may take the form of a low frequency, high magnitude event. In addition, some areas within fields will be more susceptible to erosion (e.g. mid-slopes). Thus, the potential for erosion to exceed formation by an order of magnitude or more remains a possibility, but may be local rather than widespread.

A different set of issues exist for peatland and organo-mineral soils in upland areas. Peat erosion can be quick and extensive, when initiated by the drying of upland areas. The loss of organic carbon will be dependent on the magnitude of climate change and extent of changing land-use. These drivers may, and are likely to, affect the hydrological balance and will have a knock-on effect in determining carbon storage and soil thickness, the spatial extent of these soil types and may change the long-term direction of soil formation and soil type.

- **What are the main drivers, considerations and issues for discussion?**

This review has demonstrated how the soil diversity in Wales reflects Jenny's state variables, with particular key drivers affecting soil production and formation being the parent material, climate and relief (see Figures 5 and 6). Time is a relative constant across these soil production and formation processes as it is linked to the Devensian glacial retreat, whilst vegetation and biological contributions to soil formation are dominated by climate and relief. A key knowledge gap is the role soil biology has on soil formation, and the extent and rate at which land-use change destroys horizonation but also reduces the pre-existing biology and biodiversity.

Whilst soil parent material is a critical starting point for soil formation, its properties determining the rates of weathering and pedological processes and resultant soil properties, it is the Welsh climate, relief and, latterly human impacts that has modulated soil formation processes. As a result of climate and relief being such strong controls on Welsh soil diversity, the role of future climate change, along with land-use and management change will be key drivers on future soil formation and the maintenance and the ability to both safeguard and enhance the natural capital and the ecosystem services that the soils of Wales can deliver. These services may include the storage of carbon and water, and the ability to moderate stream hydrographs to reduce flooding under extreme events along with the maintenance and improvement of soil biodiversity. One aspect of soil formation that responds rapidly and is important in Welsh soils is organic carbon. A key feature of organo-mineral soils with respect to soil formation is the upbuilding of organic matter horizons. Best practice management options were discussed (Defra 2011) to maintain carbon stores and include for semi-natural grassland (i) reducing stocking density and grazing, (ii) introducing permanent forest but the latter has the potential for influencing water table levels; for improved grassland (i) water table management (ii) introducing permanent forest (iii) reducing stocking density and grazing and (iv) and encouraging the use of organic materials.

Key climate driven issues are the maintenance of soil organic carbon levels in mineral, organo-mineral and peat soils. Not only critical as a carbon store, OC is important for soil structure. Dryer conditions may increase organic matter oxidation rates and changes in hydrological properties of organo-mineral soils (see section ?.?). Reforestation may increase carbon stocks but may also influence water table levels, affecting oxidation rates. Commercial forestry may increase soil erosion.

- **Are there spatial differences between (e.g.) soil types, parent materials, climate and land use that affect soil formation rates? What level of granularity is possible?**

Soil formation and production in Wales demonstrates the interactions of the state variables of relief, organisms, climate, parent material and time to produce a distinct array of soil types. It is evident from the global review of methods and formation rates that soil formation or pedological processes may be driven at faster rates by both water and temperature. For example, from Table 18 it would appear that horizonation in arctic gleys occurs rapidly, and that from section 4.7.4.1, there is a global rate of soil deepening and feldspar weathering driven by moisture and warmth. Indeed, the Koppen climate classification shows that soil production is fastest in Aww and Cfb (similar to Wales) climates (Figure 10). Whereas global differences in soil formation and pedological processes can be identified, can a similar analysis be made for Wales that would increase the granularity and knowledge of soil formation?

As discussed previously, spatial mapping using soil maps, instead of soil parent material maps, may provide greater resolution, but can the other state variables Jenny identified (e.g. climate, vegetation or relief) be considered for increasing granularity using soil Association / series maps. Qualitative assessments may be made (e.g. based on rainfall therefore process (a) may be quicker) but the global and Welsh inventories of soil production and horizonation are relatively small at the moment, therefore making assumptions on quantitative rates difficult, particularly across a relatively small area such as Wales. For example, it is known that the formation of podzols on both sandstone and siltstone parent materials require organic acids from the breakdown of vegetation in processes moderated by localised climate and relief. When focusing at higher resolution, more local variations such as position of slope and water table position will increase local variation in horizonation and production rates as described, along with parent material variations. These are the types of complexities that may start arising as greater granularity is explored. When we consider that the formation of a mature soil profile may be ~thousand years, it then seems difficult to consider small variations in formation rates.

However, with an increase in the database of formation and production rates small incremental steps may be taken.

- **How well does international or UK research findings translate to Wales? Are the bioclimatic situations comparable between countries?**

The complexity and time scales over which soils form mean that measuring soil formation and production rates have not attracted as much attention as soil erosion where impacts can often be visually compelling and readily observable. The dataset from global soil production assessments is still small compared to soil erosion. Our study included results from only 15 soil production studies and extends back ~20 years. A Scopus literature search using 'soil erosion' as a key word for the last 20 years produced a total of 41,198 documents, demonstrating the bias towards soil erosion studies rather than soil formation globally. However, in recent years the soil community has developed new methods to assess the rates at which soil formation / production occurs. Currently, the community has an overview of rates, which can be used to estimate the rates of processes reasonably, but largely on an order of magnitude basis. For Wales, the closest assessments are those from studies in England and Wales which cover the range of soft sedimentary sandstone (n=4) to granite (n=1). However, this is still only five sites in England, so the dataset is extremely limited, but does cover the range of hard to very soft rock, in a climate not dissimilar to Wales. Parent material, vegetation and climate are key controls as demonstrated and these are often cited as being test variables in studies. Thus, on a 'first-order' basis these values can be applied to Welsh soils.

- **How comprehensive and robust is the evidence to support soil formation rates in Wales? This is important in terms of defensibility for any possible future incentives or controls.**

Robust evidence to support soil formation rates on a 'first order' basis exists as the Welsh soil map. This statement assumes that all the Welsh soil diversity has occurred since the retreat of the last glacial ice-sheet (Time being one of Jenny's state variables) and demonstrates the extent of formation in ~10000 yrs. The global review of soil formation rates has placed further resolution on soil production and pedological processes and these have been applied to Wales (Tables 19 and 20). Whilst, little information was generated in Wales, data can be used (e.g. soil production rates from Dartmoor and English Midlands) which appears to be robust, fitting in with global patterns of production rates based on the Köppen climate classifications. Distinct time trends in soil horizonation processes are evident (e.g. podzolization processes in the Baltic). On an order of magnitude basis these would fit into the Welsh landscape, and come from regions with reasonably similar climates. Thus 10-100yrs for horizons, with organic carbon being the most responsive variable, to start being recognizable and low 1000's of years for profile maturity. There is a need for more work to be directed specifically for Wales to address issues of defensibility and greater legitimacy, particularly to address where trade-offs between land-use change and soil formation / production are acceptable. However, results from Wales would be expected to fit within the ranges of rates obtained from the global database from studies where the climate and soil parent material was similar to Wales.

CENTRES OF EXCELLENCE

This section reports on those researchers and their affiliations who have been undertaking work on soil formation within recent years, and provide the national expertise, within this subject area. Please see Appendix 1 for reference list pertaining to this table.

	Soil formation (Genesis)	**Soil production (Rock weathering)**	**Peat**
BGS	Andy Tye Simon J. Kemp Russell Lawley (Soil Parent material model)	Andy Tye Simon J. Kemp	
	Research emphasis: BGS produces the soil parent material model for Great Britain and led one of the first cosmogenic radionuclide-based studies of soil production rates in the UK. They have also been involved in recent research measuring soil formation in arable and woodland settings using cosmogenic		

<table>
<tr><td rowspan="2"></td><td colspan="3">radionuclide analysis. BGS has also been involved in testing the sensitivity of cosmogenic radionuclide production to changes in soil bulk density.</td></tr>
<tr><td colspan="3">Publications (1-4, 26)</td></tr>
<tr><td rowspan="3">Forest Research</td><td>Elena Vanguelova</td><td></td><td></td></tr>
<tr><td colspan="3">Research emphasis: Forest soils with a particular interest in soil formation of organo-mineral soils; this has involved chronosequence studies.</td></tr>
<tr><td colspan="3">Publications (5-8)</td></tr>
<tr><td rowspan="3">JHI</td><td>Alan Lilly
Stephen James Chapman</td><td></td><td>Stephen James Chapman</td></tr>
<tr><td colspan="3">Research emphasis: Hydropedology</td></tr>
<tr><td colspan="3">Publications (9, 10)</td></tr>
<tr><td rowspan="3">Rothamsted</td><td>Steve McGrath</td><td></td><td></td></tr>
<tr><td colspan="3">Research emphasis: Rothamsted is home to some of the world's oldest long-term agricultural experiments. Primarily focused on arable mineral soils they provide unique insight into how soils change and evolve with different management practices.</td></tr>
<tr><td colspan="3">Publications (11, 12)</td></tr>
<tr><td rowspan="3">Scottish Universities Environmental Research Centre, East Kilbride, UK</td><td></td><td>Ángel Rodés
Derek Fabel</td><td></td></tr>
<tr><td colspan="3">Research emphasis: Scottish Universities Environmental Research Centre (SUERC) is home to one of the UK's only facilities that can prepare samples for cosmogenic radionuclide analysis. SUERC has been a major part of recent work in the UK that has measured the rate of soil production down arable and woodland hillslopes. Recently, they produced the CoSOILcal model that accounts for soil bulk density in cosmogenic radionuclide analysis.</td></tr>
<tr><td colspan="3">Publications</td></tr>
<tr><td rowspan="2">UKCEH</td><td>Ed Rowe (M - OPRAS)
David Robinson
Jack Cosby (M – Magic)
Laurence Jones</td><td>Jack Cosby</td><td>Chris Evans
Jenny Williamson
Annette Burden</td></tr>
<tr><td colspan="3">Research emphasis: Soil formation research tends to focus on the role of soil carbon and nitrogen dynamics including peat and organo-mineral soil formation, but mineral soil work is also conducted. The OPRAS model predicts organic matter accumulation in organo-mineral soils and peat. Long-term experiments in Wales are used to understand hydropedology and organo-mineral soil formation and change in response to climate change. UKCEH runs the Plynlimon observatory where a variety of soil production rate research on shale has been</td></tr>
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<tr><td></td><td colspan="3">conducted in the last 10 years as part of the critical zone network (SoilTrec) including through the use of cosmogenics and water.</td></tr>
<tr><td></td><td colspan="3">Publications (3, 4, 8, 13-24)</td></tr>
<tr><td rowspan="3">Aberdeen</td><td></td><td></td><td>Pete Smith (M – ECOSSE)</td></tr>
<tr><td colspan="3">Research emphasis: Aberdeen produces the ECOSSE model that has been used to study soil formation and biological carbon sequestration.</td></tr>
<tr><td colspan="3">Publications (8, 10, 25)</td></tr>
<tr><td rowspan="2">Cranfield</td><td>Dan Evans
Jacqueline Hannam
Jane Rickson</td><td>Dan Evans</td><td></td></tr>
<tr><td colspan="3">Research emphasis: Dan Evans conducted the world's first cosmogenically-derived measurements of soil formation for arable soils, and only the second study of soil formation based in the UK. Moreover, he compared these formation rates with those of soil erosion for four sites across the UK to calculate soil lifespans. Having developed this, he also compiled one of the largest global inventories of soil formation and soil erosion rates to produce the first globally relevant, evidence-backed estimates of soil lifespans. Dan was also involved in the production of the CoSOILcal model, which accounts for soil bulk density in cosmogenic radionuclide analysis and led a sensitivity analysis that demonstrates the impact of using this model on previously published rates of soil formation. His recent work has included studying how bedrock lithology affects rates of soil production from bedrock, combining cosmogenic radionuclide analysis with scanning electron microscopy (SEM) to investigate how bedrock burial depth and bedrock matrix impacts weathering rates. Dan Evans currently holds a 75th Anniversary Research Fellowship at Cranfield University, and is leading research at the zone between soil and saprolite (weathered bedrock). His research aims to understand the processes that occur across this interface, particularly in contexts with shallow and near-absent soils. This understanding will help to enhance the potential of saprolite to support soil functioning, in order to sustain the local delivery of ecosystem services, and to tackle global environmental challenges. He is currently leading a Global Challenges Research Fund (GCRF) project in Brazil to pioneer the use of drones to detect and measure erosion and colluviation (upbuilding) of soil and saprolite. Moreover, Dan is also involved in a couple of industry-based projects that aim to investigate soil formation on degraded soils and exposed bedrock, as well as the growth of soil in urban spaces.

For more than 50 years Cranfield University has been working to enhance natural capital and to ensure that global food systems are more resilient for the future. It holds the Land Information System (LandIS) which is designed to contain soil and soil-related information for England and Wales, including spatial mapping of soils at a variety of scales, as well as corresponding soil property and agro-climatological data. LandIS is the largest system of its kind in Europe and is</td></tr>
</table>

	recognised by UK Government as the definitive source of national soils information.		
	Publications (1, 2, 26, 27, 39, 40)		
Durham			Fred Worrall (M - Durham carbon model)
	Research emphasis: Peat formation		
	Publications (8, 10, 25, 28)		
Edinburgh	Simon M. Mudd	Simon M. Mudd	
	Research emphasis: The school of geoscience has a broad range of geoscience research. Simon Mudd in particular conducts research on hillslope geomorphology, sediment transport processes, chemical weathering within soils and soil development with saltmarshes a particular recent focus. Recently, Simon has been involved in the measurement of soil production in arable and woodland soils in the UK.		
	Publications (2, 29-32)		
Lancaster	John Quinton Jess Davies	John Quinton Jess Davies	Nick Ostle
	Research emphasis: Recent research has focused on measuring rates of soil production in arable and woodland soils in the UK, and comparing these with rates of soil erosion. Modelling work has investigated biogeochemical cycling during soil formation and soil erosion.		
	Publications (2, 21, 39)		
Leeds	Steve Banwart	Steve Banwart	
	Research emphasis: Steve Banwart led the EU critical zone observatory project (SoilTrEC) on soil formation and also works on biogeochemical cycling and geochemical weathering. Soil carbon is an important part of the research portfolio and the interaction between roots, mycorrhizae and minerals in the weathering cycle.		
	Publications (20, 33, 34)		
Newcastle	David Manning		
	Research emphasis: The school of Natural and Environmental sciences at Newcastle has a range of expertise. David Manning's research focuses on how soils and their constituent minerals interact with the biosphere in two contexts: 1) carbon capture (through carbonate precipitation or biochar addition), and 2) plant nutrient supply (especially novel sources of K). It is the former that includes work on soil formation, especially inorganic carbon and urban soils.		
	Publications (35, 36)		

Reading			Jo Clarke
	Research emphasis: The soil research centre in Reading has a range of soils expertise. In particular peat development and formation rates.		
	Publications (8, 21, 37)		
York			Andreas Heinemeyer (M – Millennia)
	Research emphasis: York university has a range of soils expertise. With regard to soil formation they have developed the Millennia model used for assessing peat development.		
	Publications (8, 38)		

OPTIONS TO DEVELOPING KNOWLEDGE OF SOIL FORMATION IN WALES

Working towards developing spatial knowledge of soil formation in Wales it is possible that different levels of information could be produced. All would use information obtained in the previous tasks, with the aim of being able to produce a national soil formation dataset that could be used with complementary erosion data to calculate net soil loss and soil lifespans at a later stage.

Option 1: Approach based on mapping current evidence (Low cost option)

Using BGS parent material (1km) and NSI NatMap, the spatial extent of soil production / formation based on different parent material types will be identified. This would be based on the parent material types explored within this review and the greater detail contained in NatMap. Soil formation rates (e.g. Tables 19 and 20) and estimates for full profile development or specific horizon development could be attributed to the polygons of parent materials. In addition, features of horizonation of benefit to society (e.g. carbon storage) could have specific GIS layers or aspects. Further information could be added regarding soil production / formation rates based on a matrix of additional variables identified in this review as being important including geological hardness, soil thickness (depth to rockhead), relief and climate as to indicate whether the expected rate may be higher or lower than the attributed rate. A key factor would be to convene appropriate people to assess soil formation rates from the evidence base.

Cost and Time frame:

This could be done relatively quickly, as datasets required would be available (parent material (1km), Natmap, climate, relief, land cover). Some may require licencing if unavailable such as BGS Depth to Rockhead and their use was considered essential and cost justified. A project of this type would be expected to cost ~£30000 - £40000 and could be done in ~6 months

Outputs

A series of GIS layers highlighting relative soil formation rates as a traffic light system:

Red – Soil formation low relative to the expected for the soil parent material type

Amber – Soil formation about average compared to expected for the soil parent material type

Green – Soil formation above expected for the soil parent material type

Option 2: Approach based on calculating mass balances (Medium cost option):

Option 2 would again be a GIS based approach. Building on the low-cost option, simple mass balance and lifespan assessments (Robinson et al. 2017) based on appropriate soil formation rates would be undertaken for Wales. Soil erosion could be derived from the use of 'Universal Soil Loss Equation' or similar soil erosion models. The number of soil parent material types would be expanded to the 10 - 15 major soil parent material types derived from the BGS Soil parent Material Map (using the 1 km version) and assessments compared to the use of NSI Natmap Soil formation rates would be assigned using a similar methodology to Option 1. Different lithologies will have different erosion rates based on additional factors such as soil depth and climate, enabling a +/- mass balance (formation-erosion) map to be created across Wales. The attraction of combining the formation and erosion approach is that using erosion models land-use and climate change scenarios could be introduced. Some assessment of the role erosion may play on soil horizonation would be included

Costs and Time frame:

This could be done relatively quickly, as datasets required would be available (parent material (1km), Natmap, climate, relief, land cover, lidar, soil texture, precipitation and land cover). Some may require licencing if unavailable such as BGS Depth to Rockhead and their use was considered essential and cost justified. This could be done in ~6 months and would cost in ~£50 000 - 60 000

Option 3: Approach based on a new measurement campaign (High Cost option)

This approach would take the approach of Option 2 but include Wales specific assessments of the soil formation and production of soils. This may include measured estimates of soil formation such as those derived from the measurement of cosmogenic radionuclides on soil parent materials containing quartz, the use of meteoric ^{10}Be for soil residence times on unconsolidated and organo-mineral soils and ^{14}C dating for peat and organo-mineral soils to assess the age of the organic rich horizon.

The final cost of the high cost option is of course dependent on the number of sites sampled. In this costing for field work on soil formation in Wales we would select high and low precipitation areas and also the major soil parent material types to account for as much of the potential variation across Wales, but still within a reasonable sampling programme, to allow results to be translated into the GIS analysis.

Table 21 shows a possible sampling programme in terms of numbers. The intention would be to sample 2 sites for soil production at consolidated parent material types. Four sites for unconsolidated parent materials at which 4 samples would also be taken down a slope accounting for potential differences for depth. In addition, the organic carbon of peat and organo-mineral soils would be sampled four times. Methodologies would probably require 2 analyses for each sample taken. Organic carbon in blanket peat and organo-mineral soils would be sampled to assess the rate of organic carbon build up.

Table 21: Breakdown of analyses required for High Cost option

Material	Method	Precipitation		Number of samples on slope	Parent material	Total number of samples per site	Number of sites	Total samples	Cost Per sample	Analysis costs
Consolidated	Cosmos	High	Low	4	Sandstone	8	2	16	£2000 incl. vat	£32000
	Cosmos	High	Low	4	Granite	8	2	16	£2000 incl. vat	£32000
	Meteoric ^{10}Be	High	Low	4	Shale	8	4	16	£1500	£24000
Unconsolidated	Meteoric ^{10}Be	High	Low	4	Till	8	4	16	£1500	£24000
	Meteoric ^{10}Be	High	Low	4	Organo-mineral	8	4	16	£1500	£24000
Peat	^{14}C	High	High	4	Peat	8	4	36	£350	£12600
Organo-mineral	^{14}C	Low	Low	4	various	8	4	36	£350	£12600
Totals							24	152		£161, 200

Associated with the analyses are a range of other costs

<u>Costs and time frame:</u>

This would take longer because of the planning and execution of the field programme. For obtaining samples and analysis of samples, combined with Option 2 GIS capabilities, the cost would be in the region of £250000 and would take a year to 18 months to deliver (depending on the speed of analysis at the specialist facilities.

APPENDIX 1: REFERENCES

Aaby, B. and Tauber, H. 1975. Rates of peat formation in relation to degree of humification and local environment, as shown by studies of a raised bog in Denmark. Boreas, 4(1), pp.1-17.

Adams, W.A. and Raza, M.A. 1978. The significance of truncation in the evolution of slope soils in mid-Wales. Journal of Soil Science, 29(2), pp.243-257.

ADAS 2020a. Soil Policy Evidence Programme SPEP2018-19/12: ALC Technical Review (Part 1)

ADAS 2020b. An assessment of the impact of tree planting on Welsh organo-mineral soils (SPEP 2019 – 20 / 02)

Aitken, M. J. 1998. An Introduction to Optical Dating. The Dating of Quaternary Sediments by the use of Photon-Stimulated Luminescence. 267 pp. Oxford, New York, Tokyo: Oxford University Press.

Alexandrovskiy, A.L. 2007. Rates of soil-forming processes in three main models of pedogenesis. Revista Mexicana de Ciencias Geologicas, 24, 283-292.

Anderson, D.E., 2002. Carbon accumulation and C/N ratios of peat bogs in North-West Scotland. Scottish Geographical Journal, 118(4), pp.323-341.

Avery, B.W. 1973. Soil classification of England and Wales. Journal of Soil Science, 24, 324-338.

Avery, B.W. 1980. Soil classification of England and Wales (higher categories). Soil Survey Technical Monograph No. 14. Harpenden.

Bain, D.C., Mellor, A., Robertson-Rintoul, M.S.E., Buckland, S.T. 1993. Variations in weathering processes and rates with time in a chronosequence of soils from Glen Feshie, Scotland. Geoderma, 57, 275-293.

Balco, G., Stone, J. O., Lifton, N. A. and Dunai, T. J. (2008) 'A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements', Quaternary Geochronology, 3, pp. 174-195.

Barrett, L.R., Schaetzl, R.J. 1998. Regressive pedogenesis following a century of deforestation: Evidence for depodzolization. Soil Science, 163, 482-497.

Belyea, L.R., Clymo, R.S. 2001. Feedback Control of the Rate of Peat Formation Author(s): Proceedings: Biological Sciences, Vol. 268, No. 1473, pp. 1315-1321.

Beier, C., Emmett, B., Gundersen, P., Tietema, A., Penuelas, J., Estiarte, M., Gordon, C., Gorissen, A., Llorens, L., Roda, F. and Williams, D., 2004. Novel approaches to study climate change effects on terrestrial ecosystems in the field: drought and passive night time warming. Ecosystems, 7(6), pp.583-597.

Bell, J., 2005. The soil hydrology of the Plynlimon catchments. Centre for Ecology and Hydrology.

Benito, G., Macklin, M., Panin, A. et al. Recurring flood distribution patterns related to short-term Holocene climatic variability. Sci Rep **5,** 16398 (2015). https://doi.org/10.1038/srep16398

Blum, W.E.H. Functions of Soil for Society and the Environment. Rev Environ Sci Biotechnol **4,** 75–79 (2005). https://doi.org/10.1007/s11157-005-2236-x

Bol, R., Blackwell, M., Emmett, B., Reynolds, B., Hall, J., Bhogal, A., Ritz, K. 2011. Assessment of the response of organo-mineral soils to change in management practices. In: Sub-Project ii of Defra Project SP1106: Soil carbon: studies to explore greenhouse gas emissions and mitigation

Boschi, V., Willenbring, J.K., 2016. The effect of pH, organic ligand chemistry and mineralogy on the sorption of beryllium over time. Environ. Chem.http://dx.doi.org/10.1071/EN15107.

Bot, A., Nachtergaele, F., Young, A. 2000. Land resource potential and constraints at regional and country levels. (Food & Agriculture Org., 2000)

Bradley, R.I., Milne, R., Bell, J., Lilly, A., Jordan, C., Higgins, A. 2005. A soil carbon land use database for the United Kingdom. Soil Use and management, 21, 363-369.

Brady, N.C. and Weil, R.R. (2008) The Nature and Properties of Soils. Prentice-Hall Inc., New Jersey.

Bridgland, D., 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation. Quaternary Science Reviews, 19(13), 1293-1303.

Brimhall, G.H., Dietrich, W.E. 1987. Constitutive Mass Balance Relations between Chemical Composition, Volume, Density, Porosity, and Strain in Metasomatic Hydrochemical Systems: Results on Weathering and Pedogenesis. Geochimica Cosmochimica Acta, Vol. 51, No. 3, 1987, pp. 561-581.

Bunce, R.G.H., Barr, C.J., Gillespie, M.K. and Howard, D.C., 1996. The ITE Land Classification: providing an environmental stratification of Great Britain. Environmental monitoring and assessment, 39(1-3), pp.39-46.

Bunemann, E. K., Bongiorno, G., Bai, Z. G., Creamer, R. E., De Deyn, G., de Goede, R., et al. (2018). Soil quality-a critical review. Soil Biol. Biochem. 120, 105–125. doi: 10.1016/j.soilbio.2018.01.030

Butler, B.E. 1982. A new system for soil studies. Journal of Soil Science 1982, 33, 5 8 1-595

Cagnarini, C., Blyth, E., Emmett, B.A., Evans, C.D., Griffiths, R.I., Keith, A., Jones, L., Lebron, I., McNamara, N.P., Puissant, J. and Reinsch, S., 2019. Zones of influence for soil organic matter dynamics: A conceptual framework for data and models. Global change biology, 25(12), pp.3996-4007.

Chambers, F.M., 1982. Two radiocarbon-dated pollen diagrams from high-altitude blanket peats in South Wales. The Journal of Ecology, pp.445-459.

Charman, D. 2002. Peatlands and environmental change. Wiley, Chichester

Chiverrell, R.C., Harvey, A.M., Foster, G.C. 2007. Hillslope gullying in the Solway Firth - Morecambe Bay region, Great Britain: Responses to human impact and/or climatic deterioration? Geomorphology, 84, 317-343.

Clayden, B., Hollis, J.M. 1984. Criteria for differentiating soil series. Soil Survey Technical Monograph No. 17, Harpenden.

Cornu, S., Montagne, D., Vasconcelos, P.M. 2009. Dating constituent formation in soils to determine rates of soil processes: A review. Geoderma, 293-303.

Craft 2015. Creating and Restoring Wetlands: From Theory to Practice. Elsevier

Crompton, E. 1960. The significance of the weathering/leaching ratio in the differentiation of major soil groups with reference to some very strongly leached brown earths on the hills of Britain. Trans. 7th int. Cong. Soil Sci, 4, 406-12.

Darmody, R.G., Allen, C.E., Thorn, C.E. 2005. Soil Topochronosequences at Storbreen, Jutunheimen, Norway. Soil Science Society America Journal, 69, 1275-1287.

deB. Richter, D., Yaalon, D.H. 2012. 'The changing model of soil' revisited. Soil Sci. Soc. Am. J., 76, 766-778.

DEFRA, 2002. Development of a database of agricultural drainage. DEFRA project ES0111.

DEFRA, 2007. Vulnerability of organic soils in England and Wales: Final technical report to DEFRA and Countryside Council for Wales, DEFRA Project SP0532.

Defra, 2011. Developing a cost effective framework for monitoring soil erosion in England and Wales. DEFRA project SP1303

Dere A.L. 2014. Shale weathering across a latitudinal climosequence. PhD thesis Penn State University. https://etda.libraries.psu.edu/catalog/22514

Dere Ashlee L., Timothy S. White, Richard April, and Susan L. Brantley 2016. Mineralogical transformations and soil development in shale across a latitudinal climosequence. Soil Science Society of America, 80, 623–636

Dixon, J. I., Heimsath, A. M. and Amundson, R. (2009) 'The critical role of climate and saprolite weathering in landscape evolution', Earth Surface Processes and Landforms, 34, pp. 1507-1521.

Dixon, J.L., von Blanckenburg, F. 2012. Soils as pacemakers and limiters of global silicate weathering. C.R. Science, 344, 597-609.

Domínguez, M.T., Sowerby, A., Smith, A.R., Robinson, D.A., Van Baarsel, S., Mills, R.T., Marshall, M.R., Koller, E., Lebron, I., Hall, J. and Emmett, B.A., 2015. Sustained impact of drought on wet shrublands mediated by soil physical changes. Biogeochemistry, 122(2), pp.151-163.

Dominguez, M.T., Smith, A.R., Reinsch, S. and Emmett, B.A., 2017. Inter-annual variability of soil respiration in wet shrublands: Do plants modulate its sensitivity to climate? Ecosystems, 20(4), pp.796-812.

Dosseto, A., Bourdon, B., Gaillardet, J., Allegre, C. J. and Filizola, N. (2006) 'Time scale and conditions of weathering under tropical climate: Study of the Amazon basin with U-series', Geochimica et Cosmochimica Acta, 70(1), pp. 71-89.

Dosseto, A., Buss, H. and Suresh, P. O. (2011) 'The delicate balance between soil production and erosion, and its role on landscape evolution', Applied Geochemistry, 26, doi: 10.1016/j.apgeochem.2011.03.020

Droogers, P. and Bouma, J., 1997. Soil survey input in exploratory modeling of sustainable soil management practices. Soil Science Society of America Journal, 61(6), pp.1704-1710.

Du, P., Walling, D., 2012. Using ^{210}Pb measurements to estimate sedimentation rates on river floodplains. Journal of Environmental Radioactivity, 103(1), 59-75.

Dudal, R., F. Nachtergaele, and M. F. Purnell. 2002.The human factor of soil formation. In: 17th World Congress of Soil Science, CD-ROM, paper 93. Intern. Union Soil Sci., Bangkok, Thailand
Dunne, J., Elmore, D. and Muzikar, P. (1999) 'Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces', Geomorphology, 27, pp. 3-11.

Egli, M., Fitze, P., Mirabella, A. 2001. Weathering and evolution of soils formed on granitic, glacial deposits: results from chronosequences of Swiss alpine environments. Catena, 45, 19-47.

Egli, M., Dahms, D. and Norton, K. (2014) 'Soil formation rates on silicate parent material in alpine environments: Different approaches- different results?', Geoderma, 213, 320-333.

Ellis, C.J. and Tallis, J.H., 2001. Climatic control of peat erosion in a North Wales blanket mire. New Phytologist, pp.313-324.

Emmet, B.A. & the GMEP Team. 2015. Glastir Monitoring and Eavluation programme. Final Report to Welsh Government (Contract ref: C147/2010/11. NERC/Centre of Ecology and Hydrology (CEH Project: NEC04780/NEC05371/NEC05782).

Emmett, B.A. et al. (2019) ERAMMP Report 11: Year 1 Summary. Report to Welsh Government (Contract C210/2016/2017)(CEH NEC06297)

Evans, C.D., Williamson, J.M., Kacaribu, F., Irawan, D., Suardiwerianto, Y, Fikky Hidayat, M., Laurén, A., Page, S.E. 2019. Rates and spatial variability of peat subsidence in Acacia plantation and forest landscapes in Sumatra, Indonesia. Geoderma, 338, 410-421

Evans, C., Rawlins, B., Grebby, S., Scholefield, P., Jones, P. (2015) Glastir Monitoring & Evaluation Programme. Mapping the extent and condition of Welsh peat. Welsh Government (Contract reference: C147/2010/11). NERC/Centre for Ecology & Hydrology (CEH Project: NEC04780).

Evans, D. L., Quinton, J. N., Tye, A. M., Rodés, Á., Davies, J. A. C., Mudd, S. M. and Quine, T. (2019) 'Arable soil formation and erosion: a hillslope-based cosmogenic-nuclide study in the United Kingdom', SOIL, 5, pp. 253-263.

Evans, D.L. 2020. New Insights into the rates of soil formation and their contribution to our understanding of soil lifespans. PhD Thesis. Lancaster University. Available at: http://www.research.lancs.ac.uk/portal/en/publications/new-insights-into-the-rates-of-soil-formation-and-their-contribution-to-our-understanding-of-soil-lifespans(fd2456ce-c4e1-4145-a676-7b3ac8bdd44e).html

Evans, D., Rodés, Á., Tye, A. 2021. The sensitivity of cosmogenic radionuclide analysis to soil bulk density: Implications for soil formation rates. European Journal of Soil Science **72**, 174-182 (2021).

Evans, D. L., Quinton, J. N., Tye, A. M., Rodés, Á., Rushton, J. C., Davies, J. A. C. and Mudd, S. M. (in review) 'The matrix effect: how the composition and petrographic structure of sandstone affects rates of soil formation and the implications for soil sustainability', in review for Geoderma.

Evans, R. 1990. Soils at risk of accelerated erosion in England and Wales. Soil Use Manage. 6, 125– 131.

Evans, R. 2002. An alternative way to assess water erosion of cultivated land – field-based measurements and analysis of some results. Applied Geography, 22, 187-208

Evans, R., Collins, A.L., Zhang, Y., Fioster, I.D.L., Boardman, J., Sint, H., Lee, M.R.F., Griffth, B.A. 2017. A comparison of conventional and 137Cs based estimates of soil erosion rates on arable and grassland across lowland England and Wales. Earth Science Reviews, 173, 49-64.

Forrest, G.I., Smith, R.A.H. 1975. The productivity of a range of blanket bog types in the northern Pennines. J Ecol 63:173–202

George, P.B., L, Lallias, D., Creer, S., Seaton, F.M., Kenny, J.G., Eccles, R.M., Griffiths, R.I., Lebron, I., Emmett, B.A., Robinson, D.A., Jones, D.L. 2019. Divergent national-scale trends of microbial and animal biodiversity revealed across diverse temperate soil ecosystem. Nature Communications, 10, 1107

Graves, A.R., Morris, J., Deeks, L.K., Rickson, R.J., Kibblewhite, M.G., Harris, J.A., Farewell, T.S., Truckle, I. 2015. The total costs of soil degradation in England and Wales. Ecological Economics, 119, 399-413.

Green E.G., Dietrich W.E., Banfield J.F. Quantification of chemical weathering rates across an actively eroding hillslope. Earth Planet. Sci. Lett., 242 (2006), pp. 155-169

Gov.Wales. 2020: Capability, Suitability & Climate Programme Volume 3 - Predictive ALC Map of Wales v2. https://gov.wales/sites/default/files/publications/2020-06/agricultural-land-classification-predictive-map-guidance.pdf

Gov.Wales, 2020b: Capability, Suitability & Climate Programme Volume 2 – Soils of Wales – series map. https://gov.wales/sites/default/files/publications/2020-12/soils-of-wales-map.pdf

Great Fen. 2021. https://www.greatfen.org.uk/about-great-fen/heritage/holme-fen-posts

Hallett, S.H., Sakrabani, R., Keay, C.A. and Hannam, J.A. 2017. Developments in Land Information Systems: Case studies in land resource management capabilities and options. Soil Use and Management. 33(4), December 2017, 514-529. https://doi.org/10.1111/sum.12380.

Harrison, S., Bailey, R.M., Anderson, E., Arnold, L., Douglas, T., 2010. Optical Dates from British Isles 'Solifluction Sheets' Suggests Rapid Landscape Response to Late Pleistocene Climate Change. Scottish Geographical Journal, 126(2), 101-111.

Heimsath, A. M., Dietrich, W. E., Nishiizumi, K. and Finkal, R. C. 1997. The Soil Production Function and Landscape Equilibrium', Nature, 388, pp. 358-361.

Heimsath, A. M., Dietrich, W. E., Nishiizumi, K. and Finkel, R. C. 1999. Cosmogenic nuclides, topography and the spatial variation of soil depth, Geomorphology, 27, pp. 151-171.

Heimsath, A. M., Chappell, J., Dietrich, W. E., Nishiizumi, K. and Finkel, R. C. 2000. Soil production on a retreating escarpment in south-eastern Australia, Geology, 28(3), pp. 787-790.

Heimsath, A. M., Chappell, J., Dietrich, W. E., Nishiizumi, K. and Finkel, R. C. (2001a) 'Late Quaternary erosion in south-eastern Australia: a field example using cosmogenic nuclides', Quaternary International, 83, pp. 169-185.

Heimsath, A. M., Dietrich, W. E., Nishiizumi, K. and Finkel, R. C. (2001b) 'Stochastic processes of soil production and transport: erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range', Earth Surface Processes and Landforms, 26, pp. 531-532.

Heimsath, A. M., Furbish, D. J. and Dietrich, W. E. (2005) 'The illusion of diffusion: field evidence for depth-dependent sediment transport', Geology, 33(12), pp. 949-952.

Heimsath, A. M., DiBiase, R. A. and Whipple, K. X. (2012) 'Soil production limits and the transition to bedrock-dominated landscapes', Nature Geoscience, 5(3), pp. 210-214.

Herrmann, D.L., Schifman, L.A., Shuster, W.D. 2018. Widespread loss on intermediate soil horizons in urban landscapes. PNAS, 115, 6751-6755.

Hooke, R.L., 2000. On the history of humans as geomorphic agents. Geology 28, 843–846.

https://naturalresources.wales/about-us/our-projects/nature-projects/new-life-for-welsh-raised-bogs/?lang=en

Hudson, J.A., 1988. The contribution of soil moisture storage to the water balances of upland forested and grassland catchments. Hydrological sciences journal, 33(3), pp.289-309.

Jenny, H. 1941. Factors of Soil Formation: A System of Quantitative Pedology. Dover Publications, New York, 281 p.

Jenny, H. 1980. The soil resource: Origin and behaviour. Ecological Studies Vol. 37, Springer-Verlag.

Jones, M.L.M., Sowerby, A., Williams, D.L. and Jones, R.E., 2008. Factors controlling soil development in sand dunes: evidence from a coastal dune soil chronosequence. Plant and Soil, 307(1), pp.219-234.
Jones and Thomasson (1985) An Agroclimatic databank for England and Wales – Soil Survey Technical Monograph No16.

Kurganova, I., Merino, A., Lopes de Gerenyu, V., Barros, N., Kalinina, O., Giani, L., Kuzyakov, Y. 2019. Mechanisms of carbon sequestration and stabilization by restoration of arable soils after abandonment: A chronosequence study on Phaeozems and Chernozems. Geoderma, 354, 113882.

Labaz, B., Kabala, C. 2016. Human-induced development of mollic and umbric horizons in drained and farmed swampy alluvial soils. Catena, 139, 117-126.

Lal, D. (1991) 'Cosmic ray labelling of erosion surfaces: in situ nuclide production rates and erosion models', Earth and Planetary Science Letters, 104, pp. 424-439.

Lawley, R. 2014 *User guide: soil parent material 1 kilometre dataset.* Nottingham, UK, British Geological Survey, 15pp. (OR/14/025) (Unpublished)

Lindsay R, Birnie R, Clough J (2014) Peatbog Ecosystems: Key Definitions IUCN UK Committee Peatland Programme briefing note No.1. Retrieved from:
https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2019-07/1%20Definitions%20final%20-%205th%20November%202014.pdf

Lundström, U.S., van Breemen, N. and Bain, D., 2000. The podzolization process. A review. Geoderma, 94(2-4), pp.91-107.

Maejima, Y., Matsuzaki, H., Higashi, T., 2005. Application of cosmogenic 10Be to dating soils on the raised coral reef terraces of Kikai Island, southwest Japan. Geoderma 126, 389–399.

MAFF. 1988. Agricultural Land Classification of England and Wales: Revised guidelines and criteria for grading the quality of agricultural land.

McMillan, A.A., Hamblin, R.J.O., Merritt, J.W., 2011. A lithostratigraphical framework for onshore Quaternary and Neogene (Tertiary) superficial deposits of Great Britain and the Isle of Man. British Geological Survey Research Report, RR/10/03, 343pp.

MEA, 2005. Millennium ecosystem assessment. Washington, DC: New Island, 13, p.520.

Met Office. 2016.
https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/wales_-climate---met-office.pdf

Mitsch and Gosselink 2000. Wetlands 3rd edition

Mokma, D.L., Yli-Halla, M., Lindqvist. 2004. Podzol formation in sandy soils of Finland. Geoderma, 120, 259-272.

Montagne, D, Cornu, S., Le Forestier, L., Hardy, M., Josière, O., Caner, L., Cousin, I. 2008. Impact of drainage on soil-forming mechanisms in a French Albeluvisol: Input of mineralogical data in mass-balance modelling. Geoderma 145, 426-438

Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R. and Simpson, I., 2011. Final report for LCM2007-the new UK land cover map. Countryside survey technical report no 11/07.

Natural Resources Wales, 2021. https://naturalresources.wales/about-us/our-projects/nature-projects/new-life-for-welsh-raised-bogs/?lang=en

ONS 2016, UK Natural Capital: Experimental carbon stock accounts, preliminary estimates.
https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/experimentalcarbonstockaccountspreliminaryestimates

ONS, 2017. UK natural capital: ecosystem accounts for freshwater, farmland and woodland.
https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/landandhabitatecosystemaccounts

Owen, J. J., Amundson, R., Dietrich, W. E., Nishiizumi, K., Sutter, B. and Chong, G. (2011) 'The sensitivity of hillslope bedrock erosion to precipitation', Earth Surface Processes and Landforms, 36(1), pp. 117-135.

Owens, P.N., Walling, D.E., Leeks, G.J., 1999. Use of floodplain sediment cores to investigate recent historical changes in overbank sedimentation rates and sediment sources in the catchment of the River Ouse, Yorkshire, UK. CATENA, 36(1), 21-47.

Owens, P.N., Walling, D.E., 2002. Changes in sediment sources and floodplain deposition rates in the catchment of the River Tweed, Scotland, over the last 100 years: the impact of climate and land use change. Earth Surface Processes and Landforms, 27(4), 403-423.

Parry, SA, Hodson, ME, Kemp, S & Oelkers, EH 2015, 'The surface area and reactivity of granitic soils: I. Dissolution rates of primary minerals as a function of depth and age deduced from field observations', Geoderma, vol. 237-238, pp. 21-35. https://doi.org/10.1016/j.geoderma.2014.08.004

Phillips, J. D. (2005) 'Weathering instability and landscape evolution', Geomorphology, 67, 255-272.

Piotrowska, N., Blaauw, M., Mauquoy, D. and Chambers, F.M., 2011. Constructing deposition chronologies for peat deposits using radiocarbon dating. Mires and Peat, 7(10), pp.1-14.

Portenga, E. W. and Bierman, P. R. (2011) 'Understanding Earth's eroding surface with ^{10}Be', GSA Today, 21(8), pp. 4-10.

Preece, R.C., Bridgland, D.R., 1999. Holywell Coombe, Folkestone: A 13,000 year history of an English Chalkland Valley. Quaternary Science Reviews, 18(8–9), 1075-1125.

Ramsey, C. 2008. Deposition models for chronological records. Quaternary Science Reviews 27:42–60.

Razauskaite, R., Vanguelova, E., Cornulier, T., Smith, P., Randle, T. and Smith, J.U., 2020. A New Approach Using Modeling to Interpret Measured Changes in Soil Organic Carbon in Forests: The Case of a 200 Year Pine Chronosequence on a Podzolic Soil in Scotland. Frontiers in Environmental Science.

Reynolds, B., Chamberlain, P. M., Poskitt, J., Woods, C., Scott, W. A., Rowe, E. C., Robinson, D. A., Frogbrook, Z. L., Keith, A. M., Henrys, P. A., & Black, H. I. J. (2013). Countryside Survey: National Soil Change 1978–2007 for Topsoils in Great Britain—acidity, carbon, and total nitrogen status. Vadose Zone Journal, 12(2), 1– 15.

Richter, D.D., and D. Markewitz, 2001. Understanding Soil Change: Soil Sustainability over Millennia, Centuries, and Decades. Cambridge University Press, New York, 255 pp.

Richter, Daniel deB., and Dan H. Yaalon (2012): "The Changing Model of Soil" Revisited. Soil Science Society of America Journal 76 (3):766-778. DOI: 10.2136/sssaj2011.0407

Riebe, C.S., Kirchner, J.W., Finkel, R.C. 2003. Long term rates of chemical weathering and physical erosion using cosmogenic nuclides and geochemical mass balance. Geochimica et Cosmochimca Acta. 67, 4411-4427.

Riggins, S. G., Anderson, R. S., Anderson, S. P. and Tye, A. M. (2011) 'Solving a conundrum of a steady-state hilltop with variable soil depths and production rates, Bodmin Moor, UK', Geomorphology, 128, pp. 73-84.

Robinson, M. 1986. The Extent of Farm Underdrainage in England and Wales, Prior to 1939. The Agricultural History Review, 34, 79-85

Robinson, D.A., Jones, S.B., Lebron, I., Reinsch, S., Domínguez, M.T., Smith, A.R., Jones, D.L., Marshall, M.R. and Emmett, B.A., 2016. Experimental evidence for drought induced alternative stable states of soil moisture. Scientific reports, 6(1), pp.1-6.

Robinson, D.A., Panagos, P., Borrelli, P., Jones, A., Montanarella, L., Tye, A. and Obst, C.G., 2017. Soil natural capital in Europe; a framework for state and change assessment. Scientific Reports, 7.

Robinson, G.W., 1924. Pedology as a Branch of Geology. Geological Magazine, 61(10), pp.444-455.

Robinson, G.W., 1930. The development of the soil profile in North Wales as illustrated by the character of the clay fraction. The Journal of Agricultural Science, 20(4), pp.618-639.

Robinson, G.W., 1936. Normal erosion as a factor in soil profile development. Nature, 137(3475), pp.950-950.

Rudeforth, C.C., Hartnup, R., Lea, J.W., Thompson, T.R.E., Wright, P.S. 1984. Sols and their use in Wales. Soil Survey of England and Wales Bulletin No.11 Harpenden.

Sauer, D., Sponagel, H., Sommer, M., Giani, L., Jahn, R. and Stahr, K., 2007. Podzol: Soil of the year 2007. A review on its genesis, occurrence, and functions. Journal of Plant Nutrition and Soil Science, 170(5), pp.581-597.

Sauer, D., Schülli-Maurer, I., Wagner, S., Scarciglia, F., Sperstad, R., Svendgård-Stokke, Sørensen, R., Schellmann, G. 2015. Soil development over millennial timescales – a comparison of soil chronosequences of different climates and lithologies. IOP Conf.ser.: Earth Environment Science, 25, 012009.

Schaetzel, R. J., Barrett, L. R., & Winkler, J. A. (1994). Choosing models for soil chronofunctions and fitting them to data. European Journal of Soil Science, 45, 219-232

Schaetzl, R. J. and Thompson, M. L. (2005) Soils Genesis and Geomorphology. 2nd edn. New York: Cambridge University Press.

Seaton, F.M., George, P.B.L., Lebron, I., Jones, D.L., Creer, S., Robinson, D.A. 2020. Soil textural heterogeneity impacts bacterial but not fungal diversity. Soil Biology and Biochemistry, 144, 107766.

Seybold, C.A., Herrick, J.E. and Brejda, J.J., 1999. Soil resilience: a fundamental component of soil quality. Soil Science, 164(4), pp.224-234.

Sloan, T.J., Payne, R.J., Anderson, A.R., Bain, C., Chapman, S., Cowie, N., Gilbert, P., Lindsay, R., Mauquoy, D., Newton, A.J., Andersen, R. 2018/19. Peatland afforestation in the UK and consequences for carbon storage Mires and Peat, Volume 23, Article 01, 1–17,

Smith P, Smith J, Flynn H, Killham K and others (2007) ECOSSE: Estimating Carbon in Organic Soils — Sequestration and Emissions. Scottish Executive, Edinburgh.

Sommer, M., Schlichting, E. 1997. Archetypes of catenas in respect to matter - a concept for structuring and grouping catenas. Geoderma, 76, 1-33.

SoNaRR. 2020. https://naturalresources.wales/evidence-and-data/research-and-reports/state-of-natural-resources-report-sonarr-for-wales-2020/sonarr2020-our-assessment/ecosystems/?lang=en

Sowerby, A., Emmett, B.A., Tietema, A., Beier, C., 2008. Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. Global Change Biology 14, 2388e2404.

Small, E. E., Anderson, R. S., Hancock, G. S. (1999) 'Estimates of the rate of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope', Geomorphology, 27, pp. 131-150.

Stockmann, U., Misasny, B., NcBratney, A.B. 2011. Quantifying processes of pedogenesis. Advances in Agronomy, 113, 1-71.

Stockmann, U., Minasny, B. and McBratney, A. B. (2014) 'How fast does soil grow?', Geoderma, 216, pp. 48-61.

Stone, J. O. (2000) 'Air pressure and cosmogenic isotope production', Journal of Geophysical Research, 105, pp. 23753-23759.

Stivrins, N, Ozola, I, Galka, M, Kuske, E, Alliksaar, T, Andersen, T.J., Lamentowicz, M, Wulf, S, Reitalu, T. 2017. Drivers of peat accumulation rate in a raised bog : impact of drainage, climate, and local vegetation composition Mires and Peat , vol. 19 , 08 . DOI: 10.19189/MaP.2016.OMB.262

Stützer, A. (1998): Early stages of podzolisation in young aeolian sediments, western Jutland. Catena 32, 115–129.

Thormann, M. N., Currah, R. S. & Bayley, S. E. (1999) The mycorrhizal status of the dominant vegetation along a peatland gradient in southern boreal Alberta, Canada. Wetlands 19: 438–450.

Tipping, E., Davies, J.A., Henrys, P.A., Jarvis, S.G., Rowe, E.C., Smart, S.M., Le Duc, M.G., Marrs, R.H. and Pakeman, R.J., 2019. Measured estimates of semi-natural terrestrial NPP in Great Britain: comparison with modelled values, and dependence on atmospheric nitrogen deposition. Biogeochemistry, 144(2), 215-227.

Tsai, H., Maejima, Y., Hseu, Z.-Y., 2008. Meteoric 10Be dating of highly weathered soils from fluvial terraces in Taiwan. Quaternary International 188, 185–196.

Turk, J.K., Goforth, B.R., Graham, R.C., Kendrick, K.J. 2008. Soil morphology of a debris flow chronosequence in a coniferous forest, southern California. Geoderma, 146, 157-165.

Tye, A.M. & Robinson, D.A. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-45: Soil Degradation: Erosion & Compaction Phase-1. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

United-Nations. 2014a System of Environmental-Economic Accounting (SEEA). Experimental ecosystem accounting. https://unstats.
un.org/unsd/envaccounting/eea_white_cover.pdf.

United Nations. 2014b. System of Environmental-Economic Accounting 2012 : Experimental Ecosystem Accounting. New York: United Nations. © United Nations, European Union, Food and Agriculture Organization, Organisation for Economic Co-operation and Development, World Bank Grop. https://openknowledge.worldbank.org/handle/10986/23959 License: CC BY-NC-ND 3.0 IGO.

Van Es 2017. A new definition of soil.
https://acsess.onlinelibrary.wiley.com/doi/full/10.2134/csa2017.62.1016

Vreeken, W.J. 1984. Soil-Landscape chronograms for pedochronological analysis. Geoderma, 34, 149-164.

Walling, D.E., Owens, P.N. & Leeks, G.J.L. 1999. Rates of contemporary overbank sedimentation and sediment storage on the floodplains of the main channel systems of the Yorkshire Ouse and Tweed, UK. Hydrological Processes, 13, 993-1009.

White, A.F., Schulz, M.S., Davison, V.V., Blum, A.E., Stonestrom, D.A., Harden, J.W. 2005. Chemical weathering rates of a soil chronosequence in grantic alluvium: III. Hydrocemical evolution and contemporary solute fluxes and rates. Geochimica et Cosmochimica Acta, 69, 1975-1996.

Wilkinson, M. T., Chappell, J., Humphreys, G. S., Fifield, K., Smith, B., Hesse, P., Heimsath, A. M. and Ehlers, T. A. (2005) 'Soil production in heath and forest, Blue Mountains, Australia: influence of lithology and paleoclimate', Earth Surface Processes and Landforms, 30(8), pp. 923-934.

Willis, K.J., Braun, M., Sumegi, P., To´th, A., 1997. Does soil change cause vegetation change or vice versa? A temporal perspective from Hungary. Ecology 78, 740–750.

Wong, James. "Are there really only 100 harvests left?." (2019): New Scientist, Volume 242, Issue 3229, 11 May 2019, Page 24

WRB. 2001. http://www.fao.org/3/y1899e/y1899e03.htm

You, C.F., Lee, T., Li, Y.H., 1989. The partition of Be between soil and water. Chem. Geol. 77, 105.http://dx.doi.org/10.1016/0009-2541(89)90136-8.58V. Boschi, J.K. Willenbring / Chemical Geology 439 (2016) 52–58

Appendix 2: Reference list for section 5.3

1. D. Evans, Á. Rodés, A. Tye, The sensitivity of cosmogenic radionuclide analysis to soil bulk density: Implications for soil formation rates. European Journal of Soil Science **72**, 174-182 (2021).
2. D. L. Evans et al., Arable soil formation and erosion: a hillslope-based cosmogenic nuclide study in the United Kingdom. Soil **5**, 253-263 (2019).
3. D. A. Robinson et al., Soil natural capital in Europe; a framework for state and change assessment. Scientific reports **7**, 1-14 (2017).
4. A. Tye, D. Robinson, R. Lark, Gradual and anthropogenic soil change for fertility and carbon on marginal sandy soils. Geoderma **207**, 35-48 (2013).
5. R. Razauskaite et al., A New Approach Using Modeling to Interpret Measured Changes in Soil Organic Carbon in Forests: The Case of a 200 Year Pine Chronosequence on a Podzolic Soil in Scotland. Frontiers in Environmental Science (2020).
6. M. Mayer et al., Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. Forest Ecology and Management **466**, 118127 (2020).
7. N. Cools, L. Vesterdal, B. De Vos, E. Vanguelova, K. Hansen, Tree species is the major factor explaining C: N ratios in European forest soils. Forest Ecology and Management **311**, 3-16 (2014).
8. J. Clark et al., Model inter-comparison between statistical and dynamic model assessments of the long-term stability of blanket peat in Great Britain (1940–2099). Climate Research **45**, 227-248 (2010).
9. H. Lin et al., Hydropedology: Synergistic integration of pedology and hydrology. Water Resources Research **42** (2006).
10. M. Bell et al., UK land-use change and its impact on SOC: 1925–2007. Global Biogeochemical Cycles **25** (2011).
11. G. Yu et al., Mineral availability as a key regulator of soil carbon storage. Environmental Science & Technology **51**, 4960-4969 (2017).
12. A. Macdonald et al., The Rothamsted long-term experiments. Aspects of Applied Biology, 1-10 (2015).
13. D. A. Robinson et al., Experimental evidence for drought induced alternative stable states of soil moisture. Scientific reports **6**, 1-6 (2016).
14. A. L. Dere, Shale Weathering across a latitudinal climosequence. PhD thesis PSU https://etda.libraries.psu.edu/files/final_submissions/9948 (2014).
15. M. Jones, A. Sowerby, D. Williams, R. Jones, Factors controlling soil development in sand dunes: evidence from a coastal dune soil chronosequence. Plant and Soil **307**, 219-234 (2008).
16. E. Tipping, E. Rowe, Modelling the physical states, element stoichiometries and residence times of topsoil organic matter. European Journal of Soil Science **70**, 321-337 (2019).
17. J. Williamson et al., Historical peat loss explains limited short-term response of drained blanket bogs to rewetting. Journal of environmental management **188**, 278-286 (2017).
18. D. M. Young et al., Misinterpreting carbon accumulation rates in records from near-surface peat. Scientific reports **9**, 1-8 (2019).
19. R. J. Payne et al., Peatland initiation and carbon accumulation in the Falkland Islands. Quaternary Science Reviews **212**, 213-218 (2019).
20. S. A. Banwart et al., "Soil functions in Earth's critical zone: key results and conclusions" in Advances in agronomy. (Elsevier, 2017), vol. 142, pp. 1-27.
21. M. Billett et al., Carbon balance of UK peatlands: current state of knowledge and future research challenges. Climate Research **45**, 13-29 (2010).
22. N. A. Povak et al., Machine learning and linear regression models to predict catchment-level base cation weathering rates across the southern Appalachian Mountain region, USA. Water Resources Research **50**, 2798-2814 (2014).
23. J. Reuss, B. Cosby, R. Wright, Chemical processes governing soil and water acidification. Nature **329**, 27-32 (1987).

24. C. Cagnarini et al., Zones of influence for soil organic matter dynamics: A conceptual framework for data and models. Global change biology **25**, 3996-4007 (2019).
25. D. Barraclough, P. Smith, F. Worrall, H. Black, A. Bhogal, Is there an impact of climate change on soil carbon contents in E ngland and W ales? European Journal of Soil Science **66**, 451-462 (2015).
26. Á. Rodés, D. L. Evans, Cosmogenic soil production rate calculator. MethodsX **7**, 100753 (2020).
27. F. G. Verheijen, R. J. Jones, R. Rickson, C. Smith, Tolerable versus actual soil erosion rates in Europe. Earth-Science Reviews **94**, 23-38 (2009).
28. F. Worrall et al., Can carbon offsetting pay for upland ecological restoration? Science of the Total Environment **408**, 26-36 (2009).
29. K. Yoo, S. M. Mudd, Toward process-based modeling of geochemical soil formation across diverse landforms: A new mathematical framework. Geoderma **146**, 248-260 (2008).
30. K. Yoo, S. M. Mudd, Discrepancy between mineral residence time and soil age: Implications for the interpretation of chemical weathering rates. Geology **36**, 35-38 (2008).
31. S. M. Mudd, K. Yoo, Reservoir theory for studying the geochemical evolution of soils. Journal of Geophysical Research: Earth Surface **115** (2010).
32. K. Yoo, S. M. Mudd, J. Sanderman, R. Amundson, A. Blum, Spatial patterns and controls of soil chemical weathering rates along a transient hillslope. Earth and Planetary Science Letters **288**, 184-193 (2009).
33. R. M. Thorley, L. L. Taylor, S. A. Banwart, J. R. Leake, D. J. Beerling, The role of forest trees and their mycorrhizal fungi in carbonate rock weathering and its significance for global carbon cycling. Plant, cell & environment **38**, 1947-1961 (2015).
34. M. Goldhaber, S. A. Banwart, Soil formation. Soil Carbon: Science, Management, and Policy for Multiple Benefits, 82-97 (2015).
35. B. W. Kolosz, P. Manning, J. M. Ehsan, S. P. Sohi, D. A. Manning, A Multipurpose Soil Inorganic Carbon Prediction Model. (2016).
36. J. L. Edmondson et al., Black carbon contribution to organic carbon stocks in urban soil. Environmental science & technology **49**, 8339-8346 (2015).
37. J. M. Clark et al., Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models. Climate Research **45**, 131-150 (2010).
38. A. Heinemeyer et al., The MILLENNIA peat cohort model: predicting past, present and future soil carbon budgets and fluxes under changing climates in peatlands. Climate Research **45**, 207-226 (2010).
39. D. L. Evans, J. N. Quinton, J. A. C. Davies, J. Zhao, G. Govers (2020) Soil lifespans and how they can be extended by land use and management change', Environmental Research Letters, 15(9), doi: 10.1088/1748-9326/aba2fd
40. D. L. Evans (2020) New Insights into the rates of soil formation and their contribution to our understanding of soil lifespans. PhD Thesis. Lancaster University. Available at: http://www.research.lancs.ac.uk/portal/en/publications/new-insights-into-the-rates-of-soil-formation-and-their-contribution-to-our-understanding-of-soil-lifespans(fd2456ce-c4e1-4145-a676-7b3ac8bdd44e).html