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Assessment of the impact of land use on Welsh organo-mineral soils

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Soil Policy Evidence Programme

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Land, Nature and Forestry Division

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Welsh Government

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EXECUTIVE SUMMARY

Introduction

- The aim of this review was to assess the impact of land use on Welsh organo-mineral soil carbon storage and functions, considering the impact of different and competing land uses and land use change. The report focuses on the following land uses: agriculture, conservation designation, mineral extraction and development.
- The following research questions were considered (i) What is the extent and distribution of Welsh organo-mineral soils? (ii) What is the impact of land use (agriculture, mineral extraction and development) on carbon stored in organo-mineral soils? and (iii) What is the impact of land use change on the carbon stored in organo-mineral soils?
- Welsh organo-mineral soils are a substantial carbon store and are estimated to hold c*.* 25% (41 MtC) of the total carbon (159 MtC) stored in the top 15 cm of Welsh soils (Bol *et al.,* 2011). Organo-mineral soils have been estimated to cover 17% - 20.5% of the land area of Wales (Smith *et al.*, 2007; Bol *et al.*, 2011) and to hold 75 MtC which is 19% of the estimated total Welsh carbon stock to depth (Smith *et al.*, 2007). In comparison mineral soils are estimated to cover 80% of the Welsh land area and store 196 MtC, 50% of the total Welsh carbon stock. It has been estimated that deep peats store 121 MtC (31% of the total Welsh carbon stock) despite only covering c. 3% of the Welsh land area (Smith *et al.*, 2007).
- Over half of the estimated total carbon stock of Welsh organo-mineral soils is stored at a depth of 0-15 cm (Bol *et al.,* 2011). This is important when considering vulnerability of soil carbon to land use change as shallow carbon stocks are more likely to be impacted by management practices and environmental changes than deeper carbon stocks. Peats, organo-mineral soils and shallow soils are considered to be the soil types most vulnerable to high rates of soil organic carbon loss.
- Soils have a finite capacity for carbon storage which is determined by the soil type, land use and climate. When land use is changed, soil carbon either increases or decreases towards a new equilibrium value. In general, land uses with permanent vegetation cover and low soil disturbance have the greatest capacity for carbon storage.
- Another consideration is that land use change/management practices which affect soil carbon may also influence emission of nitrous oxide (N_2O) which has a much larger global warming potential than that of CO_2. When considering the impact of land use change on soil carbon, these emissions should also be considered to avoid pollution swapping (i.e. where simultaneously one pollutant is reduced but another increased).
- Most organo-mineral soils in Wales have agricultural or forestry land uses, with around 65% of Welsh organo-mineral soils supporting grassland. Agricultural management practices, conversion from permanent grassland to short term/improved grasslands and particularly conversion of grassland to arable land uses have the potential to cause major loss of soil carbon. Similarly, soil disturbance and removal of vegetation for development and mineral extraction purposes is likely to cause carbon loss. This report has been produced in conjunction with the recent SPEP2019-20/02 report by Berdeni *et al.*, (2020) which reviews current understanding of the impact of tree planting on soil carbon storage of Welsh organo-mineral soils.

Agriculture

- Acid and rough (unimproved) grasslands occupy approximately 49% of the Welsh organo-mineral soil area (Bol *et al.*, 2011). The main threats to grassland soil carbon storage are soil disturbance (for example through ploughing and reseeding) and damage to soil structure (for example from compaction from overstocking or use of heavy machinery on wet soils) which may increase soil erosion. Any management practice which removes surface vegetation and exposes bare soil is likely to have a major impact on soil carbon. This is partly due to (i) reducing organic matter inputs from vegetation (ii) increasing loss of soil (and soil carbon) by erosion (iii) modification of the soil environment e.g. increased temperature which may increase microbial decomposition rates. Consequently, improved and temporary grasslands typically store less carbon than semi-natural grasslands.
- Management of improved grassland including stocking rate, grazing management, frequency of re-seeding and the use of fertilisers and lime are also likely to influence soil carbon storage and functions.
- Arable soils generally have the lowest capacity for carbon storage and annual cultivation along with removal of crop biomass without addition of organic material can deplete soil organic matter. Management practices such as cover cropping and addition of organic material in appropriate circumstances, can help to maintain soil organic matter and soil carbon content, and soil functioning.
- There are clear trade-offs between the ecosystem services provided by different agricultural land uses. Conversion of arable land to permanent grassland will improve SOC storage and sequester carbon but may require changes to the farm business model. Conversely, improvement of semi-natural grassland (e.g. fertiliser and lime addition) has the potential to improve grassland productivity whilst increasing the risk of soil carbon loss and environmental impacts such as nutrient leaching and loss of biodiversity.

Mineral extraction and development

- Soil disturbance and the removal of surface vegetation from organo-mineral soils for purposes such as mineral extraction and development will result in carbon loss by increasing rates of organic matter decomposition and soil vulnerability to erosion.
- Impacts of soil disturbance and compaction on soil structure such as the breakdown of soil aggregates and a reduction in soil pore space will also influence the hydrological functions including infiltration rates and water holding capacity provided by organo-mineral soils.
- Where development is necessary, actions to minimise soil disturbance, exposure of bare soil and the duration for which soil conditions are modified will help to mitigate adverse effects on soil structure and functions however some carbon loss is inevitable. Handling soil at an appropriate moisture content can also reduce impacts on soil structure. However there is a lack of evidence with regard to the capacity and timescale over which soil functions (including carbon storage) of organo-mineral soils may be restored following soil modification for development/mineral extraction purposes.

Regulations effecting Welsh organo-mineral land use and change

- Conservation designations restrict the potential for land use/land management change on over 23% of Welsh organo-mineral soils. Proximity to conservation sites or priority habitats may also influence which land use/land management changes are authorised on other areas of organo-mineral soil due to potential indirect effects on habitat quality (e.g. nutrient runoff to non-target sites) and biodiversity (e.g. modification of adjacent land may impact habitat connectivity and wildlife dispersal between conservation areas). Many areas with organo-mineral soils are adjacent to blanket peat bogs which are designated as priority habitats. On these sites, precautions should be taken to avoid land use change which may indirectly modify habitat quality e.g. causing nutrient enrichment or drying.

- Acid and rough semi-natural grasslands are major land use types and habitats on organo-mineral soils that can be considered for improvement under the Environment Impact Assessment (Agriculture) Regulations. These areas have been considered suitable for forestry establishment and the impact on ecosystem services of converting to forestry was reviewed in the recent SPEP2019-20/02 report by Berdeni *et al.*, (2020). Farms which are registered with Glastir are prevented from improving these grassland types.
- Changes in management or land use change of improved grassland are not regulated in the EIA Assessments or by Glastir regulations (unless grassland management options are specifically chosen). Management practices such as increased frequency of ploughing and reseeding of grassland and particularly the conversion of grassland to tillage (i.e. arable, root crops etc) will result in carbon loss.

Conclusions

- Organo-mineral soils are more carbon rich than mineral soils with most of the carbon stored in the topsoil layers (<40 cm depth). Consequently, the carbon stored in organo-mineral soils is particularly vulnerable to changes in land use and management. In addition, most Welsh organo-mineral soils are located in mountainous upland environments where soil erosion rates may be especially high if soil is exposed. Equivalent land management/land uses on mineral soils will have less of an impact on soil carbon because mineral soils generally store less carbon.
- Land use change may substantially alter the ecosystems services provided by organo-mineral soils. Land use changes which increase the capacity for food production may reduce soil carbon storage and soil organic matter content. Soil organic matter is integral to most ecosystem services provided by soils including food production, biodiversity support, water regulation and climate resilience. Therefore, management to maintain soil organic matter is important for sustaining soil functions under all land uses.

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1 INTRODUCTION

Soils are an integral component of terrestrial ecosystems and provide many important functions including carbon storage, food provision, water regulation, nutrient cycling, climate regulation and support for biodiversity (Gregory *et al.,* 2015). It is estimated that 94.2% (4,019 MtC[1]) of the total UK biocarbon[2] stock (4,266 MtC) is stored within soil whilst only 5.8% (247 MtC) is stored in vegetation (ONS, 2016). Land use, land management practices and land use change, strongly affect soil functions including carbon storage and have the potential to impair soil functioning and increase susceptibility to erosion and degradation.

The Soil Survey of England and Wales defines organo-mineral soils as those with a peat topsoil (with an organic matter content of more than 20%) which is less than 40 cm deep. Organo-mineral soils occupy c. 20% of the Welsh land area (426,000 ha) and are mainly located in areas with altitudes greater than 600 m a.s.l. which typically experience high rainfall and low temperatures thus limiting agricultural productivity (Bol *et al.,* 2011). An estimated 65% of Welsh organo-mineral soils are under grassland with 16% underlying forest (c. 14% coniferous and c. 2% deciduous), 16% underlying heathland and the remainder occupied by cropland, wetland and coastal habitats (Bol *et al.,* 2011).

The Glastir Monitoring and Evaluation Program (GMEP) estimated that in total 382 MtC was stored in the biomass and the top 1 m of soil across Wales (Emmett *et al.*, 2017). Welsh organo-mineral soils are estimated to cover 20.5% of the Welsh land area and hold c. 25% (41 MtC) of the total carbon (159 MtC) stored in the top 15 cm of Welsh soils (Bol *et al.,* 2011) and are an important carbon stock. Estimates of the total soil carbon to depth stored in Welsh organo-mineral soils provided by the ECOSSE project (Smith *et al.*, 2007) reported that organo-mineral soils cover 17 % of the land area of Wales and hold 75 MtC (19% of the total Welsh carbon stock). In comparison mineral soils were estimated to cover 80% of the Welsh land area and store 196 MtC (50% of the total Welsh carbon stock). Deep peats are undoubtedly the most carbon rich soils holding an estimated 121 MtC (31% of the total Welsh carbon stock) despite only covering c. 3% of the Welsh land area (Smith *et al.*, 2007). Land use is an important factor which can impact organo-mineral soil functions including carbon storage, climate regulation, water quality, flood regulation, nutrient cycling and support for biodiversity. It is essential that the impacts of land-use upon soil functions and wider environmental impacts are fully understood as some land use changes can result in adverse environmental impacts including soil carbon losses. Inappropriate land management and land use changes are considered to be principal factors exacerbating soil erosion in Wales (Natural Resources Wales, 2020a).

There are conflicting pressures on land use in Wales including the need for supporting food production, mineral extraction, energy provision, commercial development, conservation and climate change mitigation. Understanding the impact of different land uses on Welsh organo-mineral soils upon soil functions and the environment is essential to make informed policy decisions and to avoid adverse effects upon the environment. For example, the recent SPEP2019-20/02 review by Berdeni *et al.*, (2020) reported that changing land use from moorland to conventional forestry on organo-mineral soils can lead to soil carbon losses of 1.8 - 3.3 t C ha^{-1} yr^{-1} within the first rotation (30-45 years) of Sitka spruce forestry.

The aim of this review was to assess the impact of land use on Welsh organo-mineral soil carbon storage and functions, considering the impact of different and competing land uses and land use change. The report focuses on the following land uses: agriculture, designation, mineral extraction

[1] Million tonnes of Carbon

[2] Carbon stored in soil and vegetation.

and, development. The impact of forestry on Welsh organo-mineral soils has recently been reviewed in the SPEP2019-20/02 report by Berdeni *et al.*, (2020) and is therefore not included in this report.

1.1 Scope of review

To structure the review, the following research questions were considered:

1. What is the extent and distribution of Welsh organo-mineral soils?
2. What is the impact of land use (agriculture, mineral extraction, designation and development) on the carbon storage of Welsh organo-mineral soils?
3. What is the impact of land use change on the carbon stored in organo-mineral soils?

1.2 Welsh Organo-mineral soils

Organo-mineral soils have been broadly described as soils with a surface horizon rich in organic matter which is less than 40 cm thick (in England and Wales), overlying rock or mineral horizons (Smith *et al.*, 2007; Bol *et al.*, 2011). It is important to note that soils with an organic layer <40 cm deep are classed as organo-mineral in England and Wales whilst in Scotland soils with an organic layer <50 cm deep are classed as organo-mineral. Soils are classed as peat where these respective depths are exceeded per country. Organo-minerals soils are sometimes referred to as shallow peats.

Based on the soil classification of England and Wales (Avery, 1980), Bol *et al.,* (2011) identified three categories of organo-mineral soil subgroups. These organo-mineral subgroups are detailed in Table 1 whilst the limiting percentages of organic matter and organic carbon for mineral, organo-mineral and organic soils are presented in Figure 1. Bol *et al.,* (2011) considered that the surface horizon of organo-mineral soils had to contain sufficient organic matter to belong to at least one of the following categories:

1. >15 cm thick humose topsoil.

2. >15 cm thick peaty loam or peaty sand topsoil (<20% organic carbon).

3. Peat (loamy, sandy, fibrous, semi-fibrous or amorphous) <40 cm thick starting at or near the surface or <30 cm thick where peat lies directly on bedrock.

Detailed descriptions of the characteristics and distribution of organo-mineral soil groups provided for England and Wales by the National Soil Research Institute (Cranfield University, 2020) are presented in Table 1.

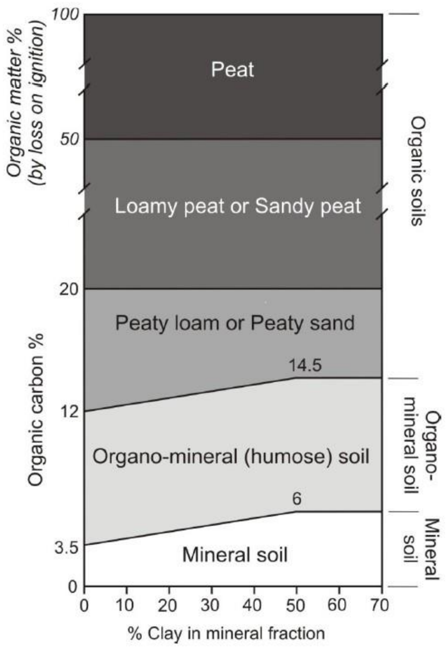


Figure 1. Organic carbon and organic matter content of organic, organo-mineral and mineral soils. From Bol *et al.,* (2011) based on Hodgson, (1997).

Table 1. Soil subgroups from the National Soil Map for England and Wales (Cranfield University, 2020) considered to be organo-mineral soils by Bol *et al.,* (2011). Wetness classes refer to those of Hodgson (1997) (Appendix Table 1). Adapted from Bol *et al.,* (2011).

Category	Description	Wetness class	Soil subgroups	Soil subgroup number	Soil associations
1 17% Welsh organo-mineral soil area	Freely and moderately well drained with humose or thin (<40 cm thick) peaty surface horizon (topsoil)	I, II	Humic Rankers Humic Rendzinas Humic Brown Podzolic soils Humo-ferric Podzols	311 341 612 631	311a Revidge, 311b Skiddaw; 311c Wetton 1; 311d Wetton 2; 311e Bangor 341 Icknield 612a Parc; 612b Moor Gate 631a Anglezarke; 631b Delamere; 631c Shirrell Heath 1; 631d Shirrell Heath 2; 631e Goldstone; 631f Crannymoor
2 44% Welsh organo-mineral soil area	Poorly drained Podzols with humose or thin (<40 cm thick) peaty surface horizon	IV, V, VI	Ferric Podzols Typical-gley Podzols Stagnogley Podzols Ironpan Stagnopodzols Humus-ironpan Stagnopodzols Ferric Stagnopodzols	633 641 643 651 652 654	633 Larkbarrow 641a Sollom 1; 641b Sollom; 641c Holme Moor 643a Hollidays Hill; 643b Poundgate; 643c Bolderwood 651a Bellmont; 651b Hexworthy; 651c Earle 652 Maw 654a Hafren; 654b Lydcott; 654c Gelligaer
3 39% Welsh organo-mineral soil area	Poorly drained Stagnohumic Gleys, Pelo-alluvial Gleys and Humic Gley soils with humose or thin (<40 cm thick) peaty surface horizon	V, VI	Stagnohumic Gley soils Pelo-alluvial Gley soils Typical Humic-alluvial Gley soils Typical Humic-sandy Gley soils Typical Humic Gley soils Argillic Humic Gley soils	721 813 851 861 871 873	721a Princetown, 721b Onecote; 721c Wilcocks 1; 721d Wilcocks 2, 721e Wenallt 813a Midelney; 813f Wallasea 1 851a Downholland 1; 851b Downholland 2; 851c Downholland 3 861a Isleham 1; 861b Isleham 2 871a Laployd; 871b Hense; 871c Hanworth 873 Ireton

Table 2. Organo-mineral soil areas in England and Wales. Data for total land area within Wales and proportion of the total Welsh land area is only available for Welsh specific associations (bold). Data from Rudeforth (1984) and Cranfield University (2021).

Association	Category	Area Wales (km^2)	% Wales	Area England & Wales (km^2)	% England & Wales
311a Revidge	1	82	0.40	103	0.06
311b Skiddaw	1	28	0.14	138	0.09
311c Wetton 1	1	-	-	136	0.09
311d Wetton 2	1	12	0.06	162	0.10
311e Bangor	1	171	0.82	533	0.35
341 Icknield	1	-	-	390	0.25
612a Parc	1	139	0.67	157	0.10
612b Moor Gate	1	132	0.63	379	0.25
631a Anglezarke	1	156	0.75	457	0.30
631b Delamere	1	-	-	80	0.05
631c Shirrell Heath 1	1	-	-	151	0.09
631d Shirrell Heath 2	1	-	-	216	0.14
631e Goldstone	1	10	0.05	115	0.07
633 Larkbarrow	2	-	-	86	0.05
641a Sollom 1	2	-	-	150	0.09
641b Sollom 2	2	-	-	212	0.13
641c Holme Moor	2	-	-	110	0.07
643a Hollidays Hill	2	-	-	256	0.16
643b Poundgate	2	-	-	46	0.03
643c Bolderwood	2	-	-	105	0.06
651a Bellmont	2	-	-	859	0.56
651b Hexworthy	2	70	0.33	370	0.24
651c Earle	2	-	-	64	0.04
652 Maw	2	-	-	215	0.14
654a Hafren	2	1320	6.36	1510	0.99
654b Lydcott	2	174	0.84	283	0.18
654c Gelligaer	2	281	1.36	281	0.18
721a Princetown	3	-	-	135	0.08
721b Onecote	3	-	-	414	0.27
721c Wilcocks 1	3	899	4.33	3822	2.52
721d Wilcocks 2	3	424	2.04	655	0.43
721e Wenallt	3	299	1.10	237	0.15
813a Midelney	3	4	0.02	220	0.14
813f Wallasea 1	3	31	0.15	516	0.34
851a Downholland 1	3	-	-	713	0.47
851b Downholland 2	3	-	-	251	0.16
851c Downholland 3	3	-	-	98	0.06
861a Isleham 1	3	-	-	39	0.02
861b Isleham 2	3	-	-	537	0.35
871a Laployd	3	29	0.14	90	0.05
871b Hense	3	-	-	81	0.05
871c Hanworth	3	-	-	69	0.04
873 Ireton	3	-	-	54	0.03

1.2.1 Distribution

In Wales, organo-mineral soils are estimated to account for 20.5 % (426,048 ha) of the land area based on National Soil Resources Institute data for land cover of individual soil associations shown in Table 1 (Bol *et al.,* 2011) and are typically associated with cold wet upland areas[3]. Similarly, the ECOSSE project estimated that Welsh organo-mineral soils covered 17% of the Welsh land area (Smith *et al.*, 2007) based on a more restrictive definition of organo-mineral soil types[4].

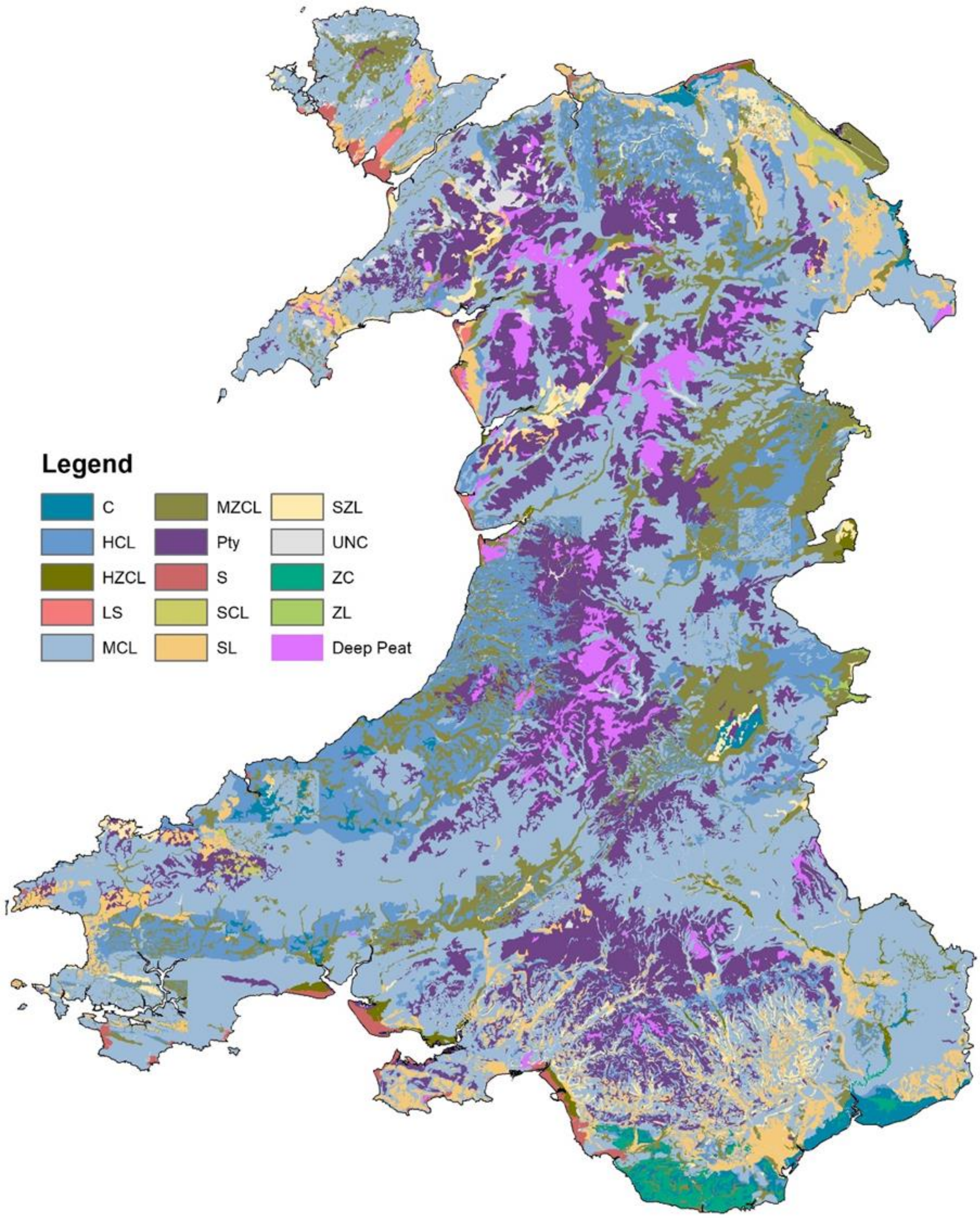
The majority of Welsh organo-mineral soils, 363,118 ha (c. 85 % of total organo-mineral soil area) are located in upland areas including the Cambrian Mountains, Brecon Beacons and Snowdonia, with only 62,900 ha (c. 15 % total organo-mineral soil area) situated in lowland areas (Map 1, Table 3) (Evans *et al.,* 2015). Rainfall in Welsh upland areas typically exceeds 1,500 mm annually although some areas such as Snowdonia may receive over 3,000 mm (Jones & Taylor, 1983).

Table 3. Land cover of organo-mineral soils within Wales as reported by Bol *et al.,* (2011).

Organo-mineral soil category	Lowland Wales: Area (ha) % total organo-mineral soil area	Upland Wales: Area (ha) % total organo-mineral soil area	Total land area within Wales (ha)	% of total area of Wales
Well drained (1)	16647 (3.9%)	55998 (13.1%)	72645	3.5
Podzols (2)	4532 (1.1%)	181664 (42.6%)	186196	9.0
Gley soils (3)	41721 (9.8%)	125456 (29.4%)	167177	8.1
Total	62900 (14.8%)	363118 (85.2%)	426018	20.5

[3] Around 58.5% of the UK uplands are underlain by organo-mineral soils (Bol *et al.,* 2011).

[4] The following soil subgroups were excluded from the ECOSSE classification of organo-mineral: humic rendzinas, humic brown podzolic soils, typical gley podzols, stagnogley podzols, pelo-alluvial gley soils, typical humic alluvial gley soils and typical humic sandy gley soils. In contrast, these soil subgroups were considered to be organo-mineral by Bol *et al*., (2011).



Map 1. The Soils of Wales Map (2019) developed through the Capability, Suitability & Climate Programme (Report CSCP02) classifies soils by soil series. This derived map represents soils by ALC textural categories. Deep peats and shallow peaty (Pty) soils are differentiated and represented by areas coloured light purple and dark purple respectively. This product attempts to identify specific soil series and smaller areas of peat as opposed to soil associations where peats may occur.

1.2.2 Current land use

Table 4. Area (ha) of organo-mineral soil types under different land use within Wales[5], adapted from Bol *et al.,* (2011). Organo-mineral soil categories: (1) well drained; (2) podzols; (3) gleys.

Environmental Zone	Lowland Wales			Upland Wales			Total area (ha)	% of total organo-mineral area
	Soil category			Soil category				
	1	2	3	1	2	3		
Cropland								
Arable cereals	0	10	185	6	48	103		
Horticulture	1295	117	1369	259	522	911		
Non-annual	0	0	0	0	0	0		
Total	*1295*	*127*	*1554*	*265*	*570*	*1015*	*4826*	*1.1%*
Grassland								
Improved grassland	8514	1079	17665	5170	3576	11272		
Set aside	0	0	15	6	0	2		
Rough grass[6]	1147	380	6057	3987	14802	37352		
Calcareous grass	462	42	1641	853	2603	2898		
Acid grass	2153	1385	3393	20676	81842	27669		
Bracken	183	156	349	1031	4186	4194		
Total	*12460*	*3042*	*29121*	*31722*	*107009*	*83388*	*266742*	*65.1%*
Heath								
Dense dwarf shrub heath	326	109	447	7399	16344	5394		
Open dwarf shrub heath	157	137	341	7560	14579	12782		
Total	*483*	*246*	*788*	*14958*	*30922*	*18176*	*65573*	*16%*
Forest								
Broadleaved	660	184	4051	1183	981	2728		
Coniferous	621	784	2058	4443	33794	14986		
Total	1281	968	6610	5625	34775	17713	66972	*16.3%*
Wetland								
Fen, marsh and swamp	0	5	66	109	284	251		
Bog	4	0	4	126	2690	230		
Standing/inland water	41	35	13	385	359	100		
Total	*46*	*40*	*82*	*620*	*3332*	*581*	*4701*	*1.1%*
Coastal								
Saltmarsh	49	6	63	25	24	1		
Supra-littoral rock	0	0	0	0	0	0		
Supra-littoral sediment	50	0	66	0	0	3		
Littoral rock	10	0	1	0	0	0		
Littoral sediment	52	0	41	0	0	2		
Total	*162*	*6*	*171*	*25*	*24*	*6*	*394*	*0.1%*

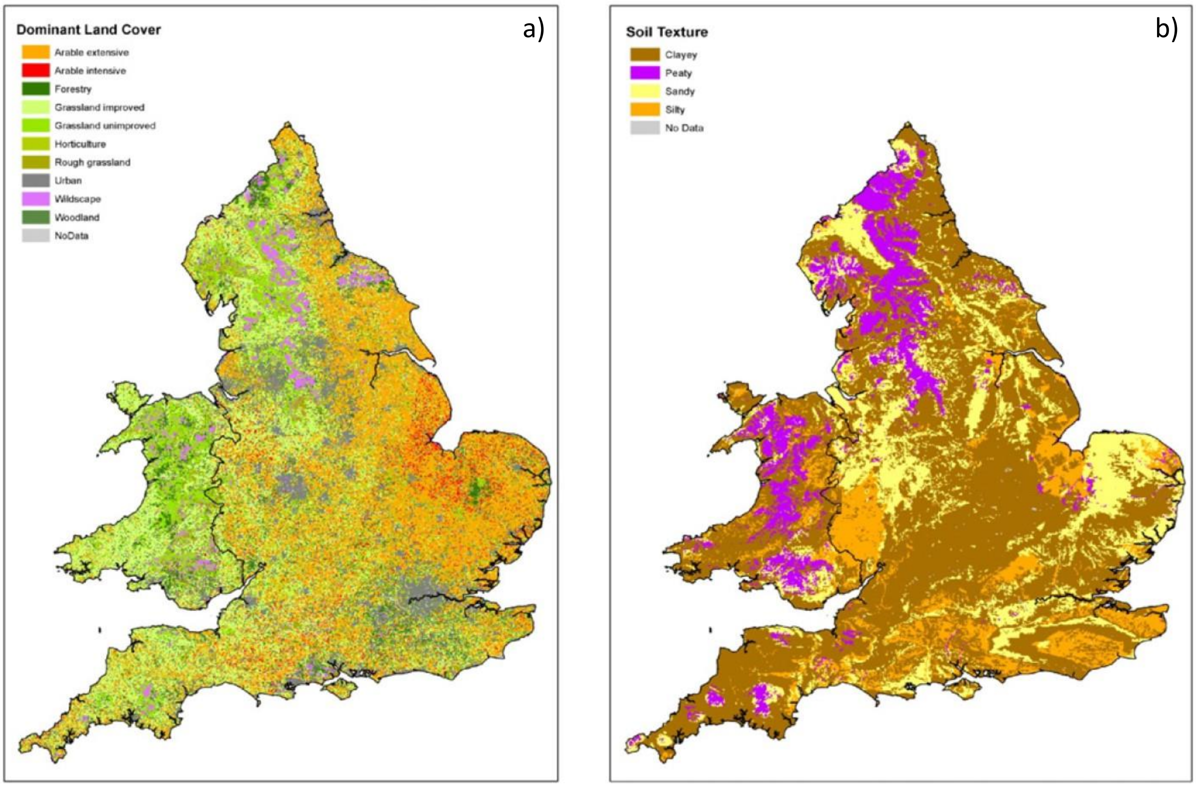
[5] Broad habitat classes are categories developed for the Land Cover Map 2000 (Fuller *et al.,* 2002).

[6] Unimproved neutral grassland

Providing accurate estimates of the land use cover of Welsh organo-mineral soils is challenging due to the extent and distribution of these soil types. Bol *et al.*, (2011) provided estimates of the area of different habitat types underlain by organo-mineral soils in Wales based on the Land Cover Map 2000 (Fuller et al 2002) and data on the cover of organo-mineral soil associations from the Nation Soil Resources Institute (NSRI). To aid interpretation, the extent of organo-mineral soils per land use was presented for the three categories of organo-mineral soils shown in Table 1 , rather than for each of the organo-mineral soil association. To quantify major differences in the extent of organo-mineral soil categories and land use types in upland and lowland areas of Wales, (Bol *et al.*, 2011) used Environmental Zones (EZ8; Lowland Wales and EZ9; Upland Wales) which are amalgamations of the Institute of Terrestrial Ecology (ITE) land classes. ITE land classes are determined based on multiple data relating to the topography, climate and geology of each 1 km square within Great Britain (Bunce *et al.*, 1996) and have been used by the Countryside Survey sampling strategy (Countryside Survey, 2007; Carey *et al.*, 2009). It is important to note that as the ITE classes are defined based on multiple data, the classification of upland and lowland areas used by (Bol *et al.*, (2011) (and the Countryside Survey) may therefore be different to those used elsewhere. For example, uplands are defined by the Countryside Council for Wales as land above the 300 m contour line and the limit of enclosed land. The area of Welsh uplands as defined by the Countryside Council for Wales is therefore a subset of the area classed as upland in the analysis by (Bol *et al.*, 2011) and considerably smaller in area (see comparison of upland extent shown in Appendix Table 2).

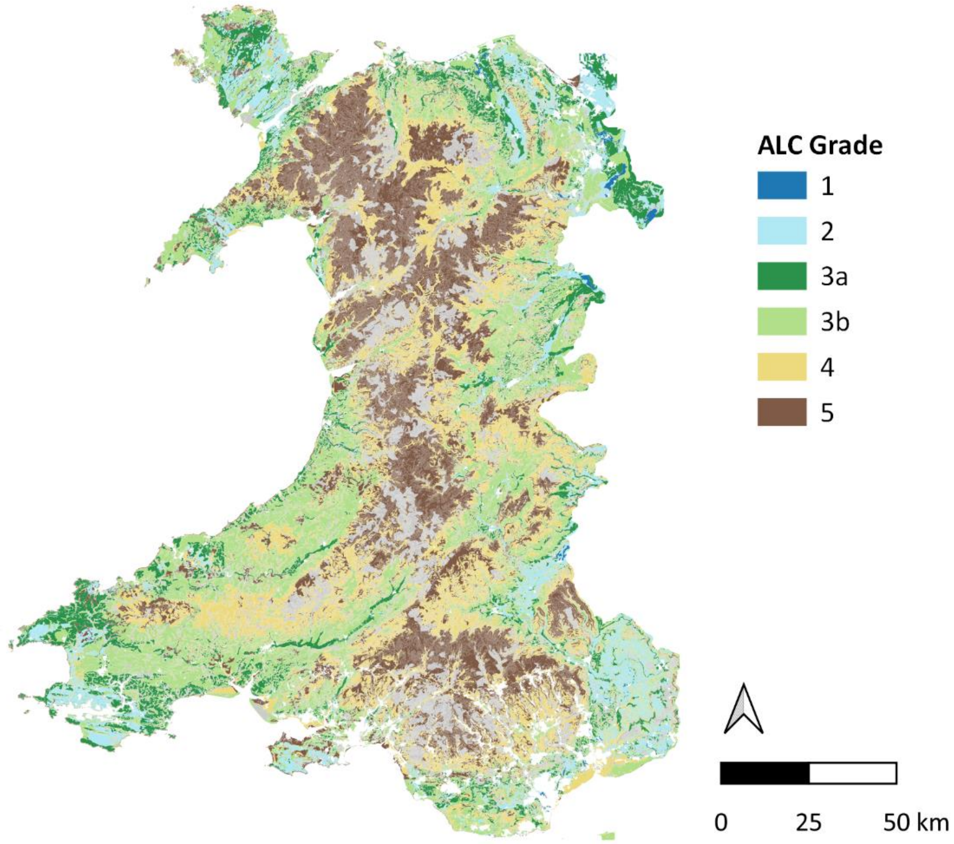
To provide estimates of the habitat types found on Welsh organo-mineral soils, (Bol *et al.*, 2011) used the Land Cover Map 2000 (LCM2000) land classes derived by (Fuller *et al.*, 2002) which categorise Welsh land cover into broad habitat types based on satellite imagery. It is important to note the limitations of quantifying land cover in this way compared to use of phase 1 habitat survey methodology as reported by Blackstock *et al.*, (2010), principally that identification of broad habitats by LCM 2000 is likely to be 85% correct in the mapping of habitats with significant potential for error in defining habitat types. It was particularly noted that distinction between acid, neutral and calcareous grassland and between improved and semi-natural grassland was problematic (Fuller *et al.*, 2002). Further details of how satellite mapping of broad habitat types compare with field survey mapping is provided in Fuller *et al.*, (2002). Never the less, use of LCM2000 to map the extent of broad habitats on organo-mineral soils by Bol *et al.*, (2011) provides a useful estimate of the extent of land cover on Welsh organo-mineral soils.

Grassland currently occupies (65%) of the land area of organo-mineral soils in Wales, most of which is located in upland areas (222,119 ha) compared to lowland areas (44,623 ha) (Map 1, Map 2). Grassland on organo-mineral soils constitutes around 20% of the total area of grassland in Wales. However Welsh organo-mineral soils also support a range of other land use types (Table 4) (Bol *et al.,* 2011; Evans *et al.,* 2015).



Map 2. Dominant land cover and soil texture for England and Wales from Graves *et al.,* (2015). (a) Land cover (based on LCM 2000) and (b) soil texture (type) based on NATMAP vector.

Agricultural productivity is restricted on much of the organo-mineral soil area in Wales due to climatic constraints, topography and soil characteristics which strongly limit the forms of agricultural land use that are suitable. This is reflected in the the Agricultural Land Classification (ALC) system which classes much of the organo-mineral soil area of the Welsh uplands as grade 4 (poor quality) or grade 5 (very poor quality) agricultural land (Map 3). ALC grades are based on assessment of factors limiting agricultural productivity including climate, soil depth, slope, soil wetness, drought, stones and wind exposure (Welsh Government, 2019). Similarly over 97% of Welsh organo-mineral soils are designated under the Less Favoured Area (LFA land) Directive (EU Directive 75/268/EEC 1975) as either disadvantaged or severely disadvantaged (Bol *et al.,* 2011) due to the limited agricultural productivity and profitability of agriculture/forestry based on climatic constraints and soil characteristics (shallow, stony and/or peaty soils).



Map 3. Predictive Agricultural Land Classification (ALC) Map for Wales. Data source: Welsh Government, (2019). ALC land quality categories; Grade 1: excellent, Grade 2: good, Grade 3a: good to moderate, Grade 3b: moderate, Grade 4: poor, Grade 5: very poor. Grey areas are unclassified land. ALC grades are based on assessment of factors limiting agricultural productivity including climate, soil depth, slope, soil wetness, drought, stones and wind exposure.

1.2.3 Soil functions

Soils provide a range of important ecosystem services including carbon sequestration and climate regulation, provision of food, fibre and fuel, water purification and soil contaminant reduction, nutrient cycling, a habitat for organisms, flood regulation and provision of construction materials (Figure 2). Land use and soil management strongly influence the capacity of soils to support these ecosystem services and there are often trade-offs between the services which can be provided by soils dependent on land use. Poor land management can damage soil structure, impairing soil functions and the capacity for supporting agricultural productivity, water regulation, biodiversity and climate change mitigation.

Soil organic matter (SOM) is fundamental to most soil functions and biological processes. SOM is derived from organic matter inputs from plant material (shoot, root and root exudates) and is integral for the formation and stabilisation of soil structure and regulation of soil hydrology as well as providing a source of nutrients and habitat for soil organisms which are key drivers of soil biogeochemical cycles.

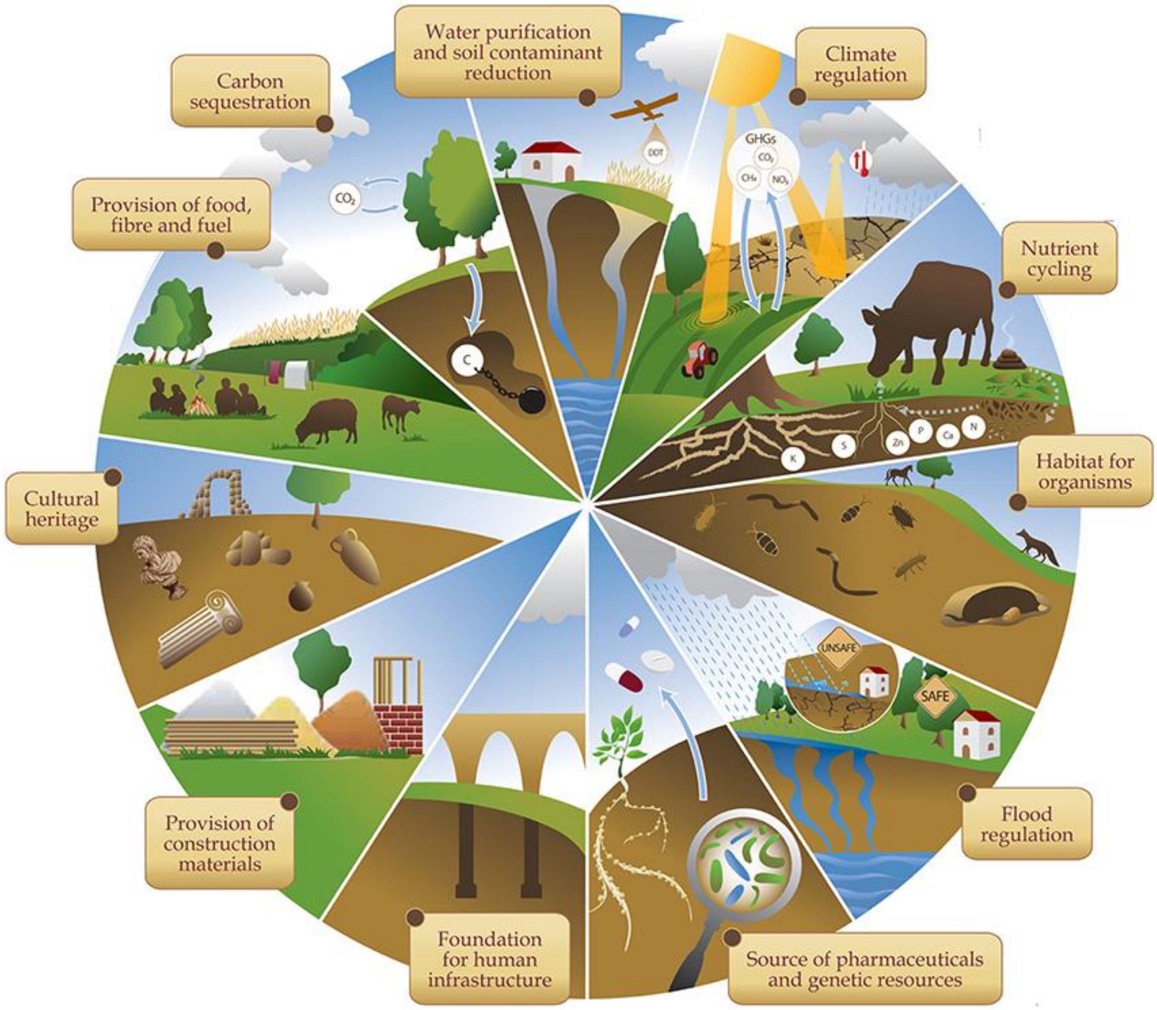


Figure 2. Functions provided by soils. Summary of the functions/ecosystem services delivered by soils which enable life on earth. Source: FAO 2015[7].

Soil organic carbon (SOC)

Soil organic matter is derived from decomposition of plant or animal organic residues including those from shoot material, roots, root exudates and microbial biomass. Decomposition of SOM results in carbon being released into the atmosphere mainly as carbon dioxide, incorporated as SOC within the soil matrix or lost from the soil via erosion or hydrological carbon export via leaching or runoff processes (Ostle *et al.,* 2009) (Figure 3). Net carbon sequestration is dependent on the balance of carbon inputs, the rate of decomposition and losses. These processes are further controlled by soil texture, site, climate and management. Strategies to improve soil carbon focus on improving carbon content by increasing inputs into soils (e.g. by changing land use from arable to permanent grassland or using organic materials and incorporating crop residues), or by reducing losses of soil carbon (e.g by implementing strategies to mitigate soil erosion).

[7] FAO infographics

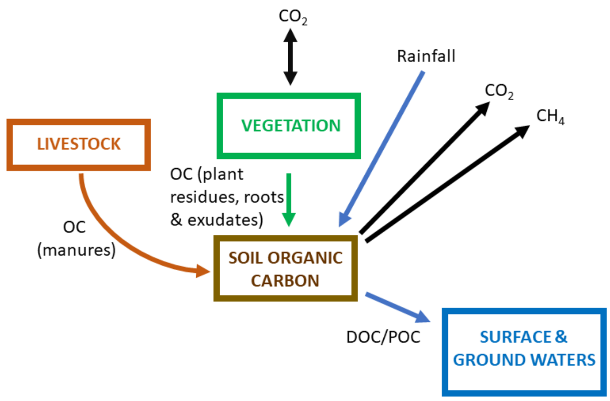


Figure 3. Summary of the major components of the soil carbon budget.

Within the soil matrix SOC can be categorised into fractions which differ in size and turnover rate:

- Labile/active carbon is derived from recent organic residues and the soil microbial community. This is usually a small fraction of the total SOM (1-5%) and has a short turnover rate of 2-3 years. This fraction is important because it can be readily accessed by the soil microbial community and influences plant nutrient supply. Labile carbon is particularly sensitive to management practices.
- Non labile carbon (slow/passive fraction carbon) has a much slower turnover rate. It is comprised of organic compounds which are resistant to decomposition and those which are physically protected from decomposition by soil structure for example within soil aggregates. Passive fraction carbon is chemically stable.

Export of carbon from soil via surface water and ground water contribute to SOC losses. Water erosion is a natural process however rates of soil erosion by water are strongly affected by land use and land management. Water erosion is one of the predominant causes of soil erosion in Wales due to high rainfall and variable topography (McHugh, 2000). Sources of SOC loss via erosion, leaching and runoff include:

- Dissolved Organic Carbon (DOC) mostly consists of humic and fulvic acids and polysaccharides and is mainly produced in upper aerobic organic soil layers (peat and vegetation horizons). DOC accumulates in soil solution and is lost from soils during/following rainfall, when subsurface flow washes DOC into streams. Rainfall is positively associated with DOC loss from peat soils in the UK (Hope *et al.,* 1997; Williamson *et al.,* 2021).
- Particulate Organic Carbon (POC) is primarily produced by surface erosion of peat (e.g. lost via wind and water erosion) and forms a major component of the carbon budget in England and Wales particularly from degraded peaty soils (Evans, 2006; Holden *et al.*, 2007)Vegetation cover of peaty soil has a large effect on POC losses; reduction in vegetation cover is associated with increased POC losses (Holden *et al.,* 2007).
- Dissolved Inorganic Carbon (DIC) is produced as a result of soil respiration and usually only accounts for a small proportion of the carbon flux. Temperature is thought to be an important factor controlling DIC.

Limitations on SOC storage

When considering the impact of land use on soil carbon storage it is important to consider the following limitations on soil carbon sequestration:

- Soils have a finite capacity for carbon storage which is partly determined by the soil type (deep peats and to a lesser extent organo-mineral soils store more carbon per unit area than mineral soils), land use and climate. When land use is changed, soil carbon either increases or decreases towards a new equilibrium value. The time scale for reaching a new equilibrium may be relatively slow (> 100 years) (Johnston *et al.,* 2009). The rate of SOC sequestration is particularly dependent upon land use/soil management, soil texture and structure and climatic factors particularly temperature and rainfall (Lal, 2004; Sowerby *et al.*, 2008).

- Soil carbon storage is not permanent and changing land use/soil management can result in loss of soil carbon. The potential for carbon loss with change in land use/management is much greater for deep peats and to a lesser extent organo-mineral soils, compared to mineral soils due to the greater carbon storage per unit area of the former soil types (Cagnarini *et al.*, 2019). Protecting the carbon stored in these soils has been identified as a priority for reducing carbon emissions in Wales (Natural Resources Wales, 2016a). Rates of soil carbon loss can exceed rates of soil carbon sequestration (Freibauer *et al.,* 2004) therefore protecting existing soil carbon stores particularly that of deep peats and organo-mineral soils should be a priority

- The amount of SOC stored in the soil per land use determines the potential for carbon loss. In general, soils with low disturbance and permanent vegetation cover such as semi-natural woodland, heathland and permanent grasslands store the most carbon (Alonso *et al.,* 2012). Land uses which have a low SOC stock (e.g. arable land) have the greatest potential for sequestering carbon with alteration of land use/management (Minasny *et al.,* 2017; Detheridge *et al.,* 2019).

- Another consideration is that land use change/management practices which affect soil carbon may also influence emission of other greenhouse gases (GHG) such as methane (CH_4) and nitrous oxide (N_2O) which have a much larger global warming potential[8] than that of CO_2. Soils are estimated to emit around two-thirds of N_2O emissions and one third of CH_4 emissions globally (Prather *et al.,* 1995) of which a major contribution is from agricultural soils. When considering the impact of land use change on soil carbon, these emissions should also be considered to avoid pollution swapping (i.e. where simultaneously one pollutant is reduced but another increased).

Carbon storage estimates for Welsh organo-mineral soils

- Estimates of the carbon stock held by Welsh organo-mineral soils vary due to differences in the definition of organo-mineral soil types and method of classifying soil area. Based on data from Emmett *et al.,* (2010), Bol *et al.,* (2011) estimated that organo-mineral soils hold approximately 41 Tg[9] (25%) of the 159 Tg[10] of soil carbon in Wales at 0-15 cm depth although this was based on a relatively small number (48) of sampling locations. This study estimated that organo-mineral soils covered 20.5 % (426,211 ha) of the Welsh land area.
- The first estimates of the total soil carbon to depth stored in Welsh organo-mineral soils have been provided by the ECOSSE project (Smith *et al.*, 2007). The ECOSSE project estimated that organo-mineral soils cover 17 % of the land area of Wales and hold 75 MtC (19% of the total Welsh carbon stock) whilst mineral soils cover 80% of the Welsh land area and store 196 MtC (50% of the total Welsh carbon stock). Deep peats are the most carbon rich soils holding an estimated 121

[8] It is estimated that compared to 1 kg of CO_2 over a 100 year timescale, the global warming potential of 1 Kg of CH_4 is 23 times greater and the global warming potential of 1 kg of N_2O is 300 times greater (Ramaswamy *et al.,* 2001).

[9] 41 million tonnes of soil carbon

[10] 159 million tonnes of soil carbon

MtC (31% of the total Welsh carbon stock) despite only covering c. 3% of the Welsh land area (Smith *et al.*, 2007).

- The differences in carbon stocks estimated by the two studies partly reflect differences in the definition of organo-mineral soil used and thus the estimated organo-mineral soil land area. The ECOSSE project used a more restricted definition of organo-mineral soil types which excluded the following soil sub-groups: humic rendzinas, humic brown podzolic soils, typical gley podzols, stagnogley podzols, pelo-alluvial gley soils, typical humic alluvial gley soils and typical humic sandy gley soils. In contrast these groups were included in the organo-mineral soil definition by Bol *et al.,* 2011. However both projects estimated that over 50% of the total carbon stock of Welsh organo-mineral soils is stored in the top 0-15 cm (Smith *et al.*, 2007; Bol *et al.*, 2011) reflecting the variability of the depth of the peat layer (i.e. <40 cm depth) across the different soil types. This is important when considering vulnerability of soil carbon to land use change as shallow carbon stocks are more vulnerable to environmental and land management/land use pressure (Bol *et al.,* 2011). Peats, organo-mineral soils and shallow soils are considered to be the most vulnerable to high rates of soil organic carbon loss (National Soils Resources Institute, 2004).

1.3 Review methodology

As a starting point for gathering relevant scientific literature for the review, 5 searches were made in the Web of Science search engine using the below listed search strings. The search string for each of the five land uses (red) were each entered with the soil search terms (blue).

Land use search terms:

1. **Agriculture:** **pasture*** OR **grass*** OR **crop*** OR **arable** OR **horticulture** OR **semi-natural**
2. **Designated land:** **conserv*** OR **designate*** OR **SAC** OR **SPA** OR **SSSI** OR **NNR** OR **LFA** OR "**special area* of conservation**" OR "**special protection area***" OR "**site* of special scientific interest**" OR "**national nature reserve***" OR "**less favored area***" OR **wetland*** OR **heath*** OR **moor***
3. **Mineral extraction:** **mine*** OR **mining** OR "**mineral extraction**"
4. **Development:** **develop*** OR **build*** OR **infrastructure** OR "**renewable energy**"
5. **Amenity:** **amenity** OR "**national park***" OR "**green space***" OR "**access land**"

AND

"**organomineral soil***" OR "**organo-mineral soil***" OR "**shallow peat***"

The following exclusion criteria were applied; (1) only include studies published after or including the year 2000, (2) restrict the study location to studies in England, Scotland, Wales, Ireland and Northern Ireland. In total, these searches returned 46 unique articles (agriculture (16), designated land (14), mineral extraction (8), development (3) and amenity (3)). Based on titles and abstracts, studies which were not relevant to the research questions were exclude from the review. All relevant articles were included in the literature review. Due to the paucity of studies quantifying impacts of land use on organo-mineral soils under UK climates, additional more general literature searches were made for relevant material. This includes studies which have quantified impacts of land use and soil management on soil carbon and other functions of mineral or peat soils, but which were considered informative for understanding impacts on organo-mineral soils. This review mainly focuses on the impacts of land management and land use change on soil carbon storage.

Approach for grey literature: Online searches of the grey literature were conducted to identify reports/studies/scientific guidance relating to the impact of the above land uses and land use change on ecosystem service provision by Welsh organo-mineral soils. This initially focused on literature published within the last 20 years and yielded over 50 relevant reports.

2 AGRICULTURE

2.1 Impact of tillage on organo-mineral soils

- Tillage impacts a small proportion (1%) of the total area of organo-mineral soils in Wales (Bol *et al.,* 2011). The majority (93%) of arable land on organo-mineral soils in Wales is used for horticulture[11] (4,473 ha) whilst the remainder (352 ha, 7%) supports cereal production (Bol *et al.,* 2011).
- Effects of soil management on SOM are a balance between inputs (for example from dead plant material or manure) and losses from mineralisation and decomposition. In tillage systems management practices such as drainage, cultivation, and fertiliser or lime application can lead to SOM loss by increasing the rate of SOM decomposition (Kechavarzi *et al.,* 2010). SOM reduction in peaty agricultural soil is mainly caused by mineralization or oxidation of peat layers (Van den Akker *et al.,* 2016). Lack of organic inputs for example return of crop residues or addition of organic inputs (in the form of organic material/manure addition) may also lead to depleted SOM.
- Soil management has a strong influence on soil functions including carbon storage (Reynolds *et al.*, 2013). Agricultural management practices which enhance SOM (and associated soil functions) can be broadly classed as (i) those which reduce soil erosion (e.g. use of winter cover crops, methods to reduce compaction e.g. tyre pressure and weather suitability for land travel), (ii) changes to cultivation practices (reduced soil disturbance e.g. minimal/zero till) and (iii) increased quantity and quality of organic matter inputs. Key management practices and their impacts on SOM and soil functions are examined further in the following sections.

Cultivations

- Cultivation physically disrupts soil structure breaking up soil aggregates and increasing aeration leading to increased rates of SOC decomposition. In contrast zero till management causes less disturbance to soil structure and is therefore promoted as a method of conservation agriculture which can reduce SOM loss, enhance SOC storage and potentially reduce the risk of soil erosion. Similarly, minimal till systems are thought to mitigate damage to soil structure and retain SOC.
- Tillage effects the distribution of SOC within the topsoil due to soil mixing. Whilst zero and min-till systems usually contain a greater concentration on SOC at the soil surface, in tilled systems deeper soil layers (> 30 cm depth) may contain a comparatively higher SOC concentration. Variation in SOC concentration with depth between tillage systems has also been attributed to differences in root growth and distribution within the soil profile arising from the effect of soil management on thermal and physical soil conditions (Baker *et al.,* 2007). Alison *et al.,* (2019) stated that effects of no-till or reduced till management on SOC were variable and often confounded by sampling protocol (lack of consideration of both bulk density and sampling depth). When both bulk density and the distribution of SOC at depths greater than 30 cm are considered, the overall benefit of no-till or reduced till management on SOC storage is small.
- Direct measurements of changes in SOC with reduced tillage on organo-mineral soils have not been quantified. Measurements carried out on mineral soils under UK conditions across six trial sites estimated that switching from conventional to zero tillage may increase soil carbon storage by 1.14 $tCO_2e\ ha^{-1}\ yr^{-1}$ for at least the first 20 years of implementation (Bhogal *et al.,* 2018). Whilst

[11] In the land use categories used by Bol *et al.,* 2011, the category 'horticultural crops' included bare ground, root crops, beans, peas and linseed whilst the 'arable cereal' category included barley, maize, oats and wheat.

Freibauer *et al.,* (2004) estimated that avoiding deep ploughing of organic soils could increase soil carbon sequestration by 1.4 t C ha^{-1} yr^{-1}. In comparison, the same study estimated that conversion of arable land to grassland on organic soils to grassland could increase soil carbon sequestration by around 1.4 t C ha^{-1} yr^{-1} (Freibauer *et al.,* 2004).

- Denitrification rates may be higher in soils under minimal till compared to conventional management due to higher water content and bulk density. Studies of soils in north west Europe have suggested that reduced tillage may increase N_2O emissions due to poorer aeration of soil (Freibauer *et al.,* 2004; Rochette, 2008). In a meta-analysis of 25 studies across soils in mainly cool-humid and semi-arid climates, Rochette, (2008) found that min-till increased N_2O emissions in poorly aerated soils but that N_2O emissions were negligible with min-till on well aerated soil. On average N_2O emissions were 0.06 kg N ha^{-1} lower with min till on well aerated soil but were increased by 0.12 kg ha^{-1} and 2.00 kg ha^{-1} with minimal tillage of soils where soil aeration was medium or poor respectively (Rochette, 2008).
- Other reported environmental benefits of reduced till include reduced soil erosion and nitrate leaching. Studies have suggested that minimal tillage can reduce the amount of soil lost through erosion by 68% and increase infiltration of runoff by over 40% (SMI, 2001). Fuel use is also reduced, however there are challenges to implementing reduced/zero tillage including investment in new machinery which may not be a viable option for some farm businesses. Drier and more stable structured soils are considered most suitable for min-till therefore implementing reduced till cultivation may be challenging in areas which receive high rainfall, including many of the areas where organo-mineral soils are located within Wales.

Nutrient inputs

- Targeted application of organic materials such as manure, composts, crop residues and biosolids can increase SOM in arable soils (Alison *et al.,* 2019b). Methods to increase organic matter additions include use of cover crops and manures, import of materials high in organic carbon, application of manures and incorporation of straw/crop residues (Bhogal *et al.,* 2009).
- The quality of the material added may determine its benefit to SOC storage however there is debate about which materials have the greatest impact on SOM levels. Chenu *et al.,* (2019) suggested that addition of labile, easily degraded compounds may be of greater benefit for SOC storage than lignin rich materials which are more recalcitrant. However other studies have suggested composts and farmyard manures may be more effective at increasing SOM compared to digestates and slurries (WRAP, 2015).
- Lime application to agricultural soils can improve productivity by increasing nutrient availability to crops. However, liming of organic soils can also increase soil respiration and microbial activity resulting in changes in distribution and storage of carbon, ultimately resulting in carbon loss. Impacts of liming on soil carbon are considered further in section 2.2 (grassland).

Crop management

- Bare peat soils are especially vulnerable to water and wind erosion which can be particularly problematic for arable agriculture (Van den Akker *et al.,* 2016). Erosion risks may be partly alleviated by maintaining vegetation cover during autumn and winter to protect soil (Evans & Boardman, 2003). Indeed, Evans, (1998) suggested that 30% vegetation cover was effective at reducing water erosion of soil. Cover cropping may particularly benefit SOC sequestration by providing soil cover and protection from soil erosion (and associated SOC loss) on sloped land. Cover crops also add organic matter to soils from input of above and below ground plant material, root exudates and associated micro-organisms. A recent meta-analysis of 106 studies globally by

Abdalla *et al.,* (2019) found an overall significant increase in SOC sequestration with cover crops. Similarly a meta-analysis effects of cover cropping on SOC sequestration by (McDaniel *et al.,* 2014; Bai *et al.,* 2019) have suggested small but positive effects of cover cropping (and reduced tillage) on SOC.

- Roots and associated micro-organisms (e.g. mycorrhizal fungi) can make a substantial contribution to soil carbon relative to above ground inputs (Menichetti *et al.,* 2015). This is partly because fine roots and mycorrhizal hyphae are able to grow into soil aggregates and pores where the carbon from these sources (after senescence) and their exudates can be physically protected and stabilised (Rasse *et al.,* 2005). Use of cover crops and strategies to lengthen the duration of root growth within the soil may therefore be effective for building/maintain soil carbon.
- Cover crops may also provide additional environmental benefits including reduced leaching loss of nitrogen over winter (Abdalla *et al.,* 2019). Some studies have shown increased N_2O emissions from incorporating cover crop residue into soils (e.g. Wen *et al.,* 2019) however a meta-analysis by Abdalla *et al.,* 2019 suggested that there was not a consistent significant effect on cover cropping on N_2O emission.
- Freibauer *et al.,* (2004) suggested that avoiding growing row crops and tubers on farmed organic soils could reduce carbon losses because these crops are more disruptive to soil structure compared to other crop types such as cereals. However, given the high financial returns for root crops such as sugar beet and potatoes there is little incentive for farmers to adopt this change.

2.2 Impact of grassland management on organo-mineral soils

- Grassland occupies the majority of the organo-mineral soil area in Wales and therefore a large proportion of the Welsh organo-mineral SOC stock is attributed to this land use. Due to the prevalence of this land use on Welsh organo-mineral soils, understanding the optimal management for Welsh grassland to maintain and where possible enhance SOC sequestration is therefore particularly important.
- Of the total area of Welsh grassland underlain by organo-mineral soil (26,742 ha), the majority is upland acid grassland (49 %), followed by upland rough grassland (21%) and improved grassland (10% upland, 8% lowland) with comparatively smaller amounts of upland bracken (4%), lowland rough grassland (3%), lowland acid grassland (3%), calcareous grassland (2% upland, 1% lowland) (Bol *et al.,* 2011) (Figure 4).
- The prevalence of grassland on Welsh organo-mineral soils reflects the high altitude, cool wet climate, often poor drainage and extended periods at field capacity of much of this land area, which limits the potential of organo-mineral soils to support other agricultural land uses. This is reflected in the ALC classification of most Welsh organo-mineral soils as mainly grade 4 or grade 5 land (Map 3).

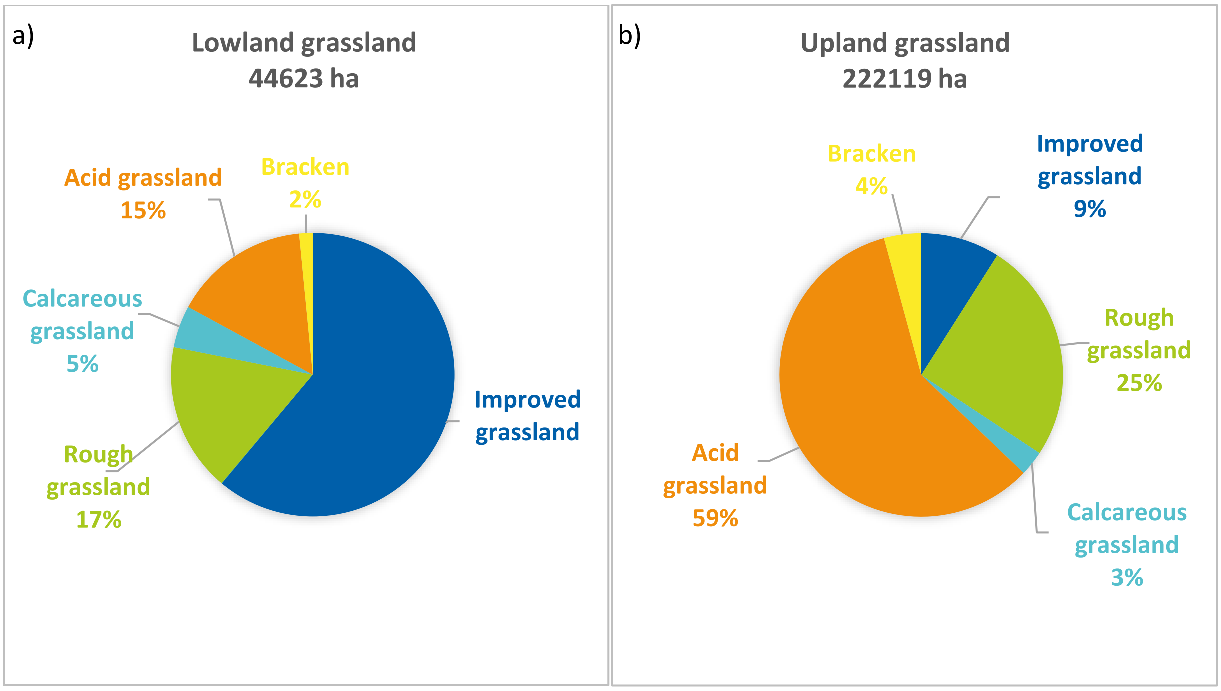


Figure 4. Proportions of grassland types on organo-mineral soils in the Welsh lowlands (a) and uplands (b). Data from Bol *et al.,* (2011).

- Monitoring of topsoil carbon across Wales by the Glastir Monitoring and Evaluation Program (GMEP) recently showed a significant decline in carbon at 0-15 cm depth in upland 'habitat' land (unimproved land which is not woodland) between 2007 and 2016 (Emmett *et al.,* 2017). This was primarily caused by a reduction in the topsoil carbon of acid grassland however, the reasons for recent carbon losses from this land use are currently unclear and being investigated further (Alison *et al.,* 2019a). Similarly, Bellamy *et al.,* (2005) reported declines in topsoil carbon particularly in upland areas with high carbon stocks, across England and Wales between 1978 and 2003.
- SOC stocks on improved grasslands are generally lower than those of upland semi-natural grassland (Reynolds *et al.*, 2013). Moxley *et al.,* (2014) estimated carbon stocks to 1 m depth between land uses in Wales were as follows; arable: 110 t C/ha, grassland pasture: 140 t C/ha; grassland semi-natural: 230 t C/ha. Due to the relatively lower carbon stock of improved grassland, a recent report by Alison *et al.,* (2019) reviewing strategies for improving soil carbon management, stated that management of improved grassland should focus on maintaining and enhancing SOC sequestration (including consideration of conversion to other land use) whilst management of upland acid and rough grasslands should focus on protecting the high existing SOC stock.
- Conversion of grassland to other land use is considered a key threat to SOC storage. Previous work has surmised that the impact of grassland/arable land management on SOC is small compared to the impact of land use change (Conant *et al.,* 2001; Moxley *et al.,* 2014). Optimal grassland management and protection of Welsh grasslands from land use change, are important factors in protecting the important soil functions including SOC storage provided by this land use.

Upland acid and rough grassland

- Much of the Welsh upland grassland on organo-mineral is classed as acidic grassland (semi-natural grassland occurring on acidic substrate) or rough grassland (neutral unimproved grassland). Acidic grassland is the most extensive upland habitat in Wales (Natural Resources Wales, 2020b); the extent of acidic and highly leached soils in upland Wales is due to the combination of high rainfall (usually exceeding 1500 mm annually in upland areas) and prevalence of parent materials with low base content (Jones, 2007).These areas are not generally considered to be of high biodiversity value and therefore are potentially more likely to be considered suitable for conversion to other land uses such as forestry and woodland creation.

- Rates of soil erosion (and associated loss of SOM and SOC) from Welsh grassland and rough grazing has not been quantified but has been generally assumed to be low (Cranfield University, 2016; Natural Resources Wales, 2020a). Newell-Price *et al.,* (2019) stated that extensively managed grasslands in Wales (grasslands receiving ≤ 100 kg N/ha through manure deposition from livestock or spreading) typically have a high organic matter content and are at low risk from compaction and soil erosion. Preventing improvement and maintaining sustainable grazing levels is integral to protecting SOC stocks of these soils.

Improved grassland

- Improved grassland is typically defined at grassland which is managed to increase productivity for example by application of agro-chemical inputs such as inorganic fertilisers and lime, or management such as ploughing and reseeding to maintain high productivity. According to Environmental Impact Assessment general guidance (Welsh Government, 2017) Improved grassland is defined as any land which has greater than 25% coverage of improved agricultural grass species such as perennial rye grass (*Lolium perenne*) and/or white clover (*Trifolium repens*) (whilst grassland with < 25% coverage of improved species is classed as semi-natural). Soil properties and functions of intensively managed grassland soils can be strongly impacted by damage from heavy machinery, (e.g. harvesters/manure spreaders) and poor management of grazing livestock.

Grazing intensity

- Grazing directly impacts grassland soil through livestock trampling and manure deposition, in addition to indirect effects of vegetation removal on soil moisture and plant growth. Numerous studies have examined the impact of grazing intensity on soil properties including carbon storage (Conant *et al.,* 2001, 2017; Abdalla *et al.,* 2018) although fewer have examined impacts specifically on organo-mineral soils (Bardgett *et al.,* 2001). The effects of grazing on organo-mineral SOC stocks are likely to be determined by the site conditions, grazing management and seasonality. Generally the consensus is that moderate to light grazing of semi-natural/natural grassland is optimal for carbon storage (Smith *et al.*, 2007; Bol *et al.*, 2011).
- Overgrazing (whereby excessive grazing results in reduced vegetation cover and a reduction in plant organic matter inputs to soils) can have a severe negative impact on soil functions including carbon storage, by physically causing soil degradation, increasing rates of erosion and subsequent carbon losses and is considered a primary cause of degradation of organic soils in the UK (Holden *et al.,* 2007). This is also partly due to the impact of soil compaction from trampling by livestock which breaks up soil aggregates thus increasing organic matter decomposition rates, in addition to removal of surface vegetation exposing bare soil to wind and water erosion. Heavier livestock such as cattle are able to cause more soil compaction particularly on wet soils and it is therefore recommended that to avoid adverse soil impacts, livestock are excluded/stocking rates are limited particularly at wet sites during winter months (Smith *et al.*, 2007).

- Ward *et al.,* (2016) compared effects of grazing management (number of livestock and duration) on soil carbon to 1 m depth across grasslands in England and found that intensive grazing (≥ 2.0 to >3.5 LU[12] ha^{-1}, generally as rotational/paddock grazing) resulted in decreased SOC at all depths compared to moderate grazing (1.5 LU ha^{-1}, set stocking/continuous stocking) and extensive grazing (> 1 LU ha^{-1} set stocking/continuous stocking). Intensive grazing was shown to reduce carbon in the upper soil layers (7.5 cm depth) as well as increasing bulk density to around 20 cm depth, whilst differences in soil carbon with grazing management were smaller at depth. Total carbon stocks per m^2 on moderately grazed systems were significantly increased by 10.7% and 7.8% respectively compared to both the intensive and extensively grazed sites.
- A study quantifying the effects of overgrazing of ranker and peaty podzol sites in the Welsh uplands found that soil carbon storage was significantly reduced in over-grazed sites compared to un-grazed areas (Smith *et al.*, 2007). Comparison of grazing pressure on topsoil organo-mineral carbon stocks by Bardgett *et al.,* (2001) showed that light grazing (1-2 ewes ha^{-1} yr^{-1}) resulted in higher topsoil carbon compared to heavily grazed (8-16 ewes ha^{-1} yr^{-1}) at upland sites in Snowdonia, the Lake District and Yorkshire Dales, UK (Table 5). Light grazing resulted in significantly increased soil carbon at the Lake District and Snowdonia sites compared to heavy grazing, however did not significantly increase topsoil carbon at the Yorkshire Dales site.

Table 5. Total soil carbon (kg m^{-2}) measured in upland grasslands on organo-mineral soils under contrasting grazing management at three sites. Adapted from Bardgett *et al.,* (2001).

Site	Altitude (m a.s.l)	Ungrazed	Long term ungrazed	Short term ungrazed	Lightly grazed	Moderately grazed	Heavily grazed
Yorkshire Dales	250-300	5.5	4.3	4.6	5.1	5.2	4.7
Lake District	200-300	4.7	5.4	5.8	5.8	5.1	4.5
Snowdonia	300-430	5.9	6.3	6.1	9.3	4.2	3.5

- A meta-analysis of 115 published studies globally by Zhou *et al.,* (2017) showed that grazing intensity strongly affected soil carbon with significant losses in soil carbon resulting from moderate and heavy grazing whilst small increases in soil carbon were found under light grazing. Similarly, another recent meta-analysis study investigating the impacts of extensive grazing system on soil carbon stocks by Abdalla *et al.,* (2018) showed that in moist cool climates SOC was reduced with more intensive grazing systems.
- Overgrazing can also negatively impact other important soil functions. For example, compaction from over-grazing can reduce soil water holding capacity therefore potentially contributing to increased flood risk (Alaoui *et al.,* 2018; Hargreaves *et al.,* 2019).

Fertiliser inputs

- On mineral soils there is consensus that targeted applications of organic inputs to improved grassland can be of benefit for improving SOM content however application timing and rates need to be carefully considered to prevent adverse environmental effects such as leaching and runoff

[12] One livestock unit (LU) is equal to the grazing equivalent of one adult dairy cow producing 3000 kg milk annually without any supplementary consumption of concentrated feed.

of excess nutrients (Alison *et al.,* 2019b). If nutrients are limiting on mineral soils, fertiliser additions can in some cases increase SOC by promoting plant above and below ground growth root growth and subsequent carbon inputs from plant residue and root exudates (Moxley *et al.,* 2014). Freibauer *et al.,* (2004) reported that fertiliser addition to nutrient poor grasslands could improve potential carbon sequestration by 0.2 t C ha^{-1} yr^{-1}.

- The benefits of organic matter addition to organo-mineral soils for increasing soil carbon is less clear (Bhogal *et al.,* 2009) as nutrient additions to organic soils may increase decomposition rates and CO_2 losses particularly in aerobic conditions (Bryne *et al.,* 2004). A review by (Buckingham *et al.,* 2013) suggested that large carbon losses may be caused by intensification of the management of grassland on nutrient poor organic soils. Similarly, Freibauer *et al.,* (2004) estimated that intensification of management of grassland on organic soils would result in carbon losses in the range of 0.9 to 1.1 t C ha^{-1} y^{-1}.

Liming

- The inherent acidity of organic and peaty soils constrains decomposition rates as generally micro-organisms which drive decomposition processes are most active at a soil pH which is close to neutral (Smith *et al.*, 2007). Therefore, acidic conditions promote SOM accumulation. Acidity can also limit plant productivity by reducing nutrient availability in the soil. Consequently, increased soil pH from lime addition can improve productivity of nutrient poor grassland by increasing nutrient availability but also increase the rate of carbon turn over (Rangel-Castro *et al.,* 2004; Foereid *et al.,* 2006; Buckingham *et al.,* 2013). Increased rates of microbial decomposition of SOM can result in carbon loss (Moxley *et al.,* 2014). Due to the pH sensitivity of peatland nutrient cycling and processes, liming is therefore considered to pose a risk to carbon storage on organic soils and is not advised (Holden *et al.,* 2007; Alison *et al.,* 2019b) although it has been noted that there is a paucity of studies quantifying impacts of liming on soil carbon in a Welsh context (Bol *et al.,* 2011).
- Studies investigating the impact of lime addition to a Scottish upland grassland site (brown forest soil on base poor mineral soil) by Foereid *et al.,* (2006) reported net carbon loss due to increased decomposition of SOM despite improved plant productivity. These results are in accord with those of Rangel-Castro *et al.,* (2004) and Lochon *et al.,* (2018). Evans *et al.,* (2012) tested the effect of manipulating pH on organo-mineral soils (peaty podzols) at two sites; Migneint (Wales) (5-28 cm depth organic horizon, dominated by Graminoids *Juncus squarrosus* and *Festuca ovina*, 486 m a.s.l) and the Peak District (England) (5-8 cm depth organic horizon, vegetation mainly *Festuca ovina* and *Vaccinium myrtillus,* 440 m a.s.l). This study reported that DOC losses were significantly increased at both sites when pH was experimentally raised by application of sodium hydroxide solution.

2.3 Wider impacts of agriculture on the Welsh environment

2.3.1 Grassland

Welsh grasslands support many important ecosystem services besides climate regulation and food production, for example water regulation and habitat provision for above and below ground biodiversity. Impacts of grassland management on organo-mineral soils on the provision of these services are outlined in further detail.

Water regulation

- Upland grasslands have a vital role in water management including provision of drinking water and flood regulation. Around 70% of UK water resources are sourced from upland sites of which approximately 58% are underlain by organo-mineral soils (Stevens *et al.,* 2008; Bol *et al.,* 2011). Upland grassland management impacts water quality and provisioning of flood regulation. Soil management can strongly affect soil hydrological functioning, for example loss of macropore structure caused by compaction from livestock, may result in reduced soil water holding capacity and infiltration rates, consequently increasing overland flow. Other key factors influencing upland water quality include soil type, vegetation cover, location and climate.

- Stevens *et al.,* (2008) reviewed impacts of upland grassland management on water quality. Aspects of livestock management including stocking rates, sheep dipping, outdoor lambing, static supplementary feeding and access of livestock to streams, were considered to have an important impact on upland water quality for example by increasing nutrient and sediment loads to water courses and introducing chemical contaminants from veterinary medicines. Detrimental impacts of poor slurry and nutrient management and land improvement such as draining and management of riparian vegetation upon water quality were also highlighted.
- Studies of the effect of upland grassland management on hydrological functions have reported effects of grazing (Meyles *et al.,* 2006) ploughing (Wallace & Chappell, 2020) aeration (Wallace & Chappell, 2019), and underdrainage on soil moisture and permeability which influence overland flow rates.
- Vegetation type also has a strong influence on water regulation in upland catchments. Bond *et al.,* (2020) compared overland flow rates between four common upland grassland vegetation communities (hay meadow, low density grazing, rush pasture and rank grassland[13]) at an organo-mineral site in the Lake District, UK (270-430 m a.s.l). Grassland vegetation composition had a strong influence on overland flow rates and flood peaks were significantly delayed with rougher vegetation cover (rank grassland compared to hay meadows). In this study, grazing and cutting management also significantly affected overland flow seasonally due to effects on vegetation growth.

Biodiversity provision

- Grasslands provide unique ecological habitats and have high biodiversity value (Stevens *et al.*, 2008, 2010). The process of plant diversity loss from species rich nutrient poor grassland with agricultural improvement is well understood (Stevens *et al.,* 2004). Grassland species adapted to nutrient poor soils quickly become outcompeted by faster growing more productive species when nutrient availability is increased. It is estimated that 91% of lowland semi-natural grassland in Wales has been lost between 1930 and 1990 mainly due to agricultural improvement (Natural Resources Wales, 2016b).
- Studies in the Welsh uplands have reported adverse effects on water quality with liming of upland catchments. Bradley & Ormerod, (2002) assessed the impact of catchment liming on freshwater invertebrates, 10 years after lime application at three streams in Wales and showed that invertebrate communities were sensitive to changes in pH. Holden *et al.,* (2007) reported that surveys of upland vegetation communities (grassland, heath and mire) and above ground biodiversity surveys (mammals, birds, amphibians and invertebrates) across 20 Welsh catchments

[13] Hay meadow (species rich meadow managed by cutting and light season grazing); low density grazing (2.6 ewes ha^{-1} yr^{-1}); rush pasture (2.6 ewes ha^{-1} yr^{-1}); rank grassland (dominated by tall tussocky and coarse grass species, ungrazed for 6 years).

in 1994 showed significant effects of liming on biodiversity. Limed sites had fewer invertebrate orders, fewer amphibians, and reduced cover of Sphagnum species.

- Extensive grassland management generally have a reduced environmental impact compared to more intensive systems. Nutrient leaching losses from extensive upland beef and sheep enterprises are low as few (if any) inputs are made (Williams *et al.,* 2019). Nutrient applications are lower to grade 4 and 5 land as the productivity is primarily limited by factors such as climate, soil depth and topography.

2.3.2 Arable agriculture

- There are numerous environmental impacts associated with agriculture both on and off farm. Key impacts include diffuse pollution of water and air, fossil fuel consumption (for example for synthesis of inorganic fertilisers and fuel for mechanisation) and impacts of habitat loss/modification, degradation or fragmentation on biodiversity (Graves *et al.,* 2015). Agriculture (primarily the dairy industry) accounted for almost 25% of the freshwater pollution incidents in Wales between 2014-2019 (Natural resources Wales 2020b).
- Depending upon the soil, site and climatic factors, cultivation methods may lead to compaction and effect soil erosion rates and soil organic matter. A recent report assessing threats to Welsh soils by Rollet & Williams, (2019) stated that the main threats to arable soils in Wales were soil compaction, soil erosion, loss of SOM and loss of biodiversity, soil loss to development/soil sealing and soil contamination.

Impact of land use change on ecosystem services

- Due to inherent constraints on productivity such as relief, altitude and temperature, around 92% of Welsh organo-mineral soils are designated as Less Favoured Areas which are ‘Severely Disadvantaged’ and a further 5% are classed as ‘Disadvantaged’ (Bol *et al.,* 2011). This means that over 97% of Welsh organo-mineral soils are unsuitable for supporting productive arable agriculture and therefore limits the potential for converting grassland to arable agriculture.
- There are clear trade-offs between the ecosystem services provided by different agricultural land uses. Conversion of arable land to permanent grassland will improve SOC storage and sequester carbon but would also reduce agricultural productivity. Conversely, improvement of semi-natural grassland (e.g. fertiliser and lime addition) will increase grassland productivity and capacity to support food production however is likely to also result in soil carbon loss and environmental impacts such as nutrient leaching and loss of biodiversity.
- Relative benefits/disbenefits of some land management practices to conserve soil carbon and potential environmental impacts are summarised in Table 6.

Table 6. Summary matrix of relative benefits/disbenefits of best practice methods for managing SOM in lowland agriculture on organic/peaty soils. Adapted from Bhogal *et al.,* (2009).

Method	Impact	Environmental Impact	
Methods to maintain SOM by reducing soil erosion		**+ve**	**-ve**
Cultivate compacted tillage soil	*	↑	↓
Leave autumn seedbeds rough	*	↑	~
Cultivate across the slope		↑	~
Manage over winter-tramlines	*	↑	↓
Early establishment of winter crops	*	↑	~
Fence off rivers and streams from livestock	*	↑	~

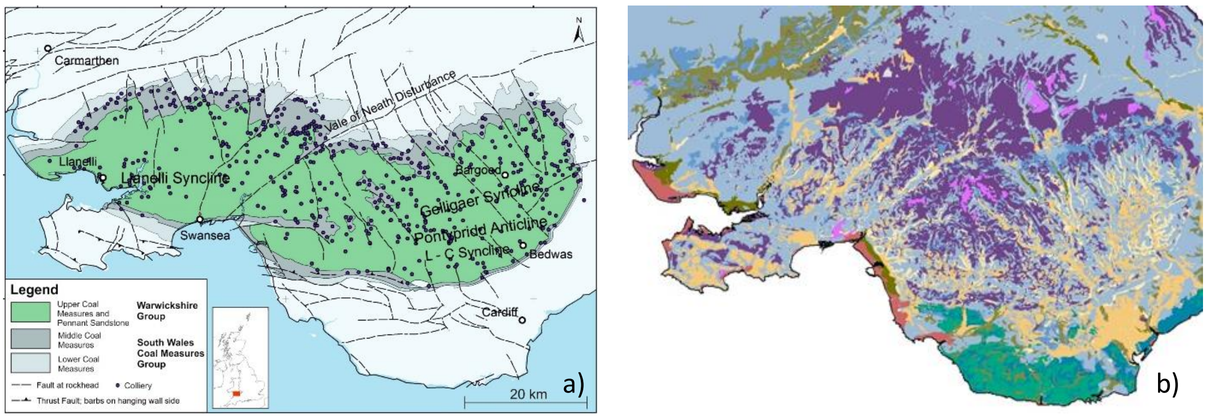
Move feed/water troughs at regular intervals	*	↑	~
Loosen compacted soil layers in grassland	*	↑	~
Reduce stocking density	*	↑	~
Methods to maintain SOM and enhance SOC storage:			
Reduced/zero till	*	↑	↓
Establish cover crop/green manure	*	↑	~
Straw/crop residue incorporation	*	~	~
Encourage use of livestock manures	*	↑	↓
Apply high OC materials	*	↑	↓
Methods that enhance SOM and SOC by land use change			
Introduce buffer strips	***	↑	~
Introduce rotational grass	***	↑	↓
Establish hedges and shelter belts	**	↑	~
Water table management	**	↑	↓
Convert tilled land to permanent grassland	***	↑↑	~
Establish permanent woodlands	**	↑↑	~

Carbon storage effectiveness: * Some effect; ** moderately effective; *** very effective
Environmental impact (+ve): ↑small/medium benefit; ↑↑ highly beneficial/benefit over large area
Environmental impact (-ve): ~ no risk; ↓ risk of pollution swapping
Relative benefit to SOM broadly quantified using carbon storage estimates

3 MINERAL EXTRACTION

3.1 Impact of mineral extraction on organo-mineral soils

- Minerals are extracted from many areas of Wales and the areas affected often coincide with areas of organo-mineral soil (Bol *et al.,* 2011). For example, areas of organo-mineral soil are found across the South Wales Coalfield which was one of the main locations of coal mining activity in Wales (Map 4).
- The effects of mineral extraction on organo-mineral soils are either temporary if the land is returned to agriculture or other green land uses or permanent if the site is restored to water. Carbon loss to atmosphere or water is considered to be the most significant effect of mineral extraction on these soils. The quality of soil restoration and aftercare will determine the land uses which may be supported on former mineral extraction sites.
- The extraction of minerals requires either the digging of underground tunnels for deep coal, slate and metal extraction or the digging of large pits and quarries for extraction of open cast coal, sand and gravel or limestone and clay. Whilst the extraction from deep mines does not directly affect the surface of the land, it does generate large quantities of spoil which is normally spread adjacent to the mine and consequently large areas of soil around the workings may be impacted. Soils are normally stripped and stored in soil bunds for the duration of the work. Ultimately soils are restored over the original area and returned to agriculture or another land uses e.g., amenity or forestry.
- There is a deficit of research looking at the effect of mineral extraction on organo-mineral soils in the UK. The literature search undertaken suggests that there are few references on the direct effect of mineral extraction on organo-mineral soils, therefore much of the material summarised here is based on information inferred from papers about mineral or peat soil, or on opinion and prior observations on mineral sites.



Map 4. Maps of the South Wales Coalfield (a) Location of collieries (black circles) source Bateson *et al.,* (2015), (b) Corresponding land area from the The Soils of Wales Map (2019 showing location of organo-mineral soils (dark purple) and deep peat (pink) source: Keay (2019).

- In areas where the extraction of minerals coincides with organo-mineral soils there is a strong likelihood that the organic horizon will be subjected to changes in soil chemistry and biota as it is disturbed. Excavation and transportation of soil to bunds results in drying of the soil. As the bund dries the organic soil will begin to release carbon and on completion of extraction the soil is usually re-spread over the original area or spread over the spoil mounds to provide a growing medium. Each phase of disturbance has an impact on the organic layer of soil, particularly with reference to carbon release and water quality.

Soil stripping

- The removal of soil from a field will result in a loss of agricultural production, either permanently or temporarily and increased erosion risk due to trafficking. Soil removal can also affect water quality and carbon storage because excavation of peat will result in large carbon losses (SEPA, 2017). The moisture content of the organic layer will determine how the soils are handled; for example saturated soils are often placed in a lagoon to dewater prior to being placed in bunds for storage. When the peat is drier and more humified it is bunded as soon as excavated. Shallow water tables protect peatlands and their carbon stock from aerobic decomposition (Morris *et al.,* 2019) but once the water table is controlled by drainage as part of site preparation, the organic layer will start to dry and so shrink and lose carbon.
- Soil stripping typically removes, either temporarily or permanently, the organic carbon and water storage capacity of the organic soil fraction and compacts the surface of the mineral subsoil if it remains in situ, whilst vegetation removal reduces surface roughness. It has been noted that surface roughness in grasslands modifies overland flow and can have a large impact on downstream flood peak and timing (Bond *et al.,* 2020). The removal of the organic layer protecting the mineral material will further exacerbate this flood risk.

Soil storage

- Soils are typically stored in bunds up to 3 m high for topsoil and 5 m for subsoil (MAFF, 2000; Defra, 2004, 2009) although peat bunds (where the soils are sufficiently dry to be bunded) are often lower than this to preserve their stability. Soils in store are initially compacted at the surface to seal them to keep them drier, which helps prevent slumping and reduce erosion by wind or water. Over time the soils will also settle and become compacted under their own weight leading to the development of anaerobic conditions in the core of the mound. The development of anaerobic conditions can lead to the release of methane, thereby increasing greenhouse gas emissions. On an organic soil the weight of the stacked soil is likely to expel water from the store and shrink the bunds further. The elevated position of the soil in a bund increases the drying potential leading to the loss of carbon and nitrogen from the store.
- Soil not required for restoration of the site is usually classed as waste or treated and reused on other sites (Scottish Renewables & SEPA, 2012) without being placed in soil bunds as this helps to reduce the land take required for storage.

Settlement

- Surface settlement can affect land levels in mined areas as the land above the shafts subsides, leading to waterlogging of previously dry sites. The increased wetness will lead to a build-up of the organic layer in these areas, but the effects are usually local and likely to cover small areas.

Soil reinstatement

- Re-spreading the stored soils over the worked-out quarry (sand and gravel or rock) or over the spoil mounds (coal) may gradually reinstate the main soil functions that were lost during storage, but time is required to ameliorate soil conditions and an aftercare period is usually necessary. During the aftercare period soil structure and drainage can be improved by careful management and cultivation to encourage a dense vegetative cover (Defra 2009). The addition of inorganic fertilizers to the newly placed soils, help increase plant biomass production so long as soil structure and drainage is sufficiently ameliorated. Fertiliser applications will also influence key regulatory services such as soil carbon sequestration, soil nutrient cycling, and greenhouse gas emissions (Smith *et al.,* 2013).

3.2 Wider impact of mineral extraction on the Welsh environment

- Disturbance of the soil as a result of mineral extraction activities leads to an increase in carbon loss both to atmosphere and water. In local water, levels of dissolved organic carbon increase (Billett *et al.,* 2006). The disturbance also releases inorganic compounds from the soil into drainage water, particularly phosphorus, iron and aluminium, with levels of sodium, calcium, magnesium and manganese being affected by rainfall events (Muller *et al.,* 2015); all of these will impact on water quality.
- The presence of ferrous iron in the soil stores can lead to the formation of iron ochre in water seeping out of the mounds which can also contribute reduce water quality unless the water is manged on site. In addition changes in soil acidity may have wider impacts on ecosystem carbon balances (Evans *et al.,* 2012).
- Land restoration at former coal fields in Wales has the potential for providing carbon sequestration benefits. Based on surveys of restored mine soil in the South Wales Coalfield, 20-30 years after land use conversion, Detheridge *et al.,* (2019) calculated that restored mine soil to 30 cm depth under grassland and deciduous temperate woodland land use held 60 (± 7.0) and 99 (± 14.2) t C ha^{-1} respectively. In comparison adjacent undisturbed grassland and woodland sites contained 99 (± 8.6) and 106 (± 8.1) t C ha^{-1} to 30 cm depth respectively. This suggests that within 20-30 years, restoration of soil at the mining sites particularly to woodland land use was effective at restoring soil carbon. Furthermore, the sites restored to native woodland were estimated to have sequestered an additional 83 t C ha^{-1} in above ground biomass since restoration. However subsequent land restoration projects may be inadequate to compensate for larger carbon losses caused by disturbance of soils with a deeper peat layer for mineral extraction activities.
- The majority of historic coal extraction sites will not have any stored soil and will have to rely on soil forming materials (e.g. shales) for restoration. In this case the options for land use post restoration are limited however these sites may be utilised for supporting amenity land uses (e.g. nature parks, fisheries, golf course), land fill sites and wildlife habitats (ERM, 2014). Many Welsh mineral extraction sites which were previously under agricultural land use have been heavily modified by the site operations and it will not be possible to restore them to agricultural land use, therefore resulting in a reduction in the utilisable agricultural area. The challenges associated with the lack of suitable soil materials has made it impossible to fully restore many former opencast sites in Wales (ERM, 2014).

4 DEVELOPMENT

4.1 Impact of development on organo-mineral soils

- Development on Welsh organo-mineral soils for example for installation of renewable energy and infrastructure or commercial/industrial purposes, will inevitably impact soil functions including carbon storage, water regulation, and biodiversity support.
- The most comprehensive guidance to date on best practice for handling UK soils during development is covered by Construction Code of Practice for the Sustainable Use of Soils on Construction Sites (Defra, 2009). However, the code is not legislatively binding and whilst it is relevant to the UK it is specifically targeted at England. Land development can cause multiple risks to soil properties and functions (Table 7) however careful planning of soil management on site can mitigate some of these risks. Most substantial planning applications (particularly for development on greenfield sites) need to include a soil resource plan which records the areas, types and characteristics of soils on site. Producing a soil management plan which details how to handle the soil over the course of the development project including recovering, storing and re-using soil resources can reduce impacts on soil properties and functions.

Table 7. Summary of the main potential risks to soils which will impact soil function, caused by development. Adapted from The Construction Code of Practice for the Sustainable Use of Soils on Construction Sites (Defra, 2009).

Impact on soil	Cause during development
Soil sealing	Covering soil with an impermeable material will impact soil physical chemical and biological properties. Soil sealing particularly reduces the hydrological functioning soil.
Soil compaction	Caused by soil mismanagement for example use of heavy machinery, handling wet soil or storage of construction materials.
Soil contamination	Chemical applications or accidental spillage of chemicals.
Reduced soil quality	May be caused by soil handling for example mixing topsoil with construction materials or the mixing of topsoil and subsoil.
Soil erosion	Erosion may occur during soil storage after soil structure has been physically disrupted and vegetation cover has been removed. Compacted soils are at greater risk from water and wind erosion.

- The recent Planning Policy Wales guidance (Welsh Government, 2021) states the importance of protecting peat soils and a requirement for planning authorities to consider impacts on priority habitats and priority species within Wales as listed by Section 7 of the Environment (Wales) Act 2016. However, no reference is made to protecting organo-mineral soils and these are only considered a priority habitat where specific vegetation communities are present (see Table 10).
- Compared to mineral soils, organo-mineral soils have a greater capacity for carbons storage Therefore any disturbance, handling or alteration of organo-mineral soil properties or indirect effects on the soil environment during development has the potential to result in a larger amount of carbon loss comparative to treatment of mineral soils. The main impacts of development on organo-mineral soil functions are summarised in Table 8. Due to the paucity of studies which have directly measured impacts of soil management during development on organo-mineral soil

properties and functions the impacts outlined are based on an understanding of how organo-mineral soils have been shown to respond to modification in other situations (mainly modification for agriculture and forestry purposes).

Table 8. Summary of potential impacts of soil handling during land development on organo-mineral soil carbon storage and functions.

Soil management during development	Summary	Potential impacts on organo-mineral carbon storage and other functions
Soil stripping	Removal of soil from areas of the development site.	- Loss of soil structure may increase microbial oxidation and carbon losses. - Surface vegetation is the main source of carbon input to soil therefore removal of vegetation prevents carbon input. - Loss/changes in soil biodiversity due to soil disturbance and altered soil conditions (temperature, moisture, pH, aeration) impacts microbial functioning and carbon cycling. - Disruption to soil structure impacts hydrological functions. Impacts on macropore/micropore distribution reduce infiltration rates, loss of OM content (by decomposition) and pore space (by compaction) reduces soil water holding capacity. - Loss of palaeoevironmental archive.
Soil stock piling	Soil storage during development.	- Altered soil conditions (e.g. temperature, moisture, aeration) impact soil microbial functioning and carbon cycling for example, the centre of a stockpile may become anaerobic. - Reduced surfaces area for interaction, notably water and gas exchange between soil and atmosphere. - Lack of vegetation cover increases risk of water/wind erosion.
Soil translocation	Removal of soil to new location.	- Changes in soil environmental conditions effect soil microbial functioning. Drier, warmer conditions favour decomposition of organic matter and carbon loss.
Soil sealing	Covering soil with an impermeable or partly impermeably material (e.g. concrete).	- Prevents gas and water exchange with the atmosphere preventing carbon sequestration and hydrological functioning. - Greatly reduced capacity to support soil biodiversity.
Modification of the soil environment	Any activity which directly or indirectly impacts soil conditions such as moisture, temperature, pH, vegetation cover.	- Potential to impact carbon cycling: warmer drier conditions and more neutral pH generally favour microbial decomposition of organic matter and carbon loss.

- Soil sealing is defined as covering soil with completely or partly impermeable artificial material for example asphalt or concrete. Depending upon the permeability of material used, soil sealing partly or completely prevents the exchange of air and water with the atmosphere and the ability to support ecosystem services. Soil sealing particularly reduces the capacity for hydrological functioning of soil as water from rainfall or overland flow is unable to drain into the soil (Wood *et al.,* 2005; Scalenghe & Marsan, 2009). By reducing infiltration, soil sealing increases the volume of surface water run-off and peak discharge rates. This puts more pressure on adjacent un-sealed soil to absorb water and may increase flood risk (National Soils Resources Institute, 2006).
- Vehicular access tracks may also impact soil functions including carbon storage. Access tracks across peat soils in the UK uplands are mainly created for agriculture, forestry, wind farms or sporting purposes and may be constructed in different ways, for example floating roads and cut and fill tracks. These road networks may cause soil compaction and removal or alteration of vegetation cover thus impacting soil structural properties, microbiological functioning, carbon cycling and vegetation community structure (Williams-Mounsey *et al.,* 2021). In a recent literature review of the impact of vehicular access tracks on peatland ecohydrological processes Williams-Mounsey *et al.,* (2021) concluded it was likely that tracks had long terms impacts on carbon and methane cycling, vegetation community structure and hydrological functioning which could persist following the removal of temporary tracks. However, further research was needed to quantify these effects. This is of importance because at present, consent for temporary construction tracks in the UK is only required if the track crosses a designated conservation area such as an SSSI. Additionally, the material used for track construction (even temporarily) could have an environmental impact (e.g. construction of tracks using non-biodegradable materials such as plastic mesh, could potentially introduce micro-plastic pollutants and have ecotoxicological effects (Williams-Mounsey *et al.,* 2021). Surface placed mineral roads have been found to impact the pH of adjacent soil in peat systems (Pouliot *et al.,* 2019) which may indirectly impact soil microbial activity and plant community composition.
- Overall, development poses a risk to organo-mineral soil carbon storage and functions. Any action which removes the vegetation cover from organo-mineral soils is likely to result in carbon losses by (i) reducing carbon inputs to the soil, (ii) exposing the soil to erosion, (iii) impacting soil microbial functioning by modifying the soil environment (e.g. changes in moisture, temperature and aeration) and (iv) impacting soil structure. Any action which dries, warms or aerates the soil is likely to increase the rate of organic matter decomposition and carbon loss by influencing soil microbial functioning. Due to the substantial impact of development on soil structural properties, effects on soil hydrological functions and biodiversity support may also be substantial.

4.2 Wider impact of development on the Welsh environment

- As with all land use change, development impacts and alters the capacity for ecosystem service provision by soils. On organo-mineral soils, development of grassland (particularly improved grassland) or arable land will clearly have the largest impact on the capacity to support food production. However, in terms of carbon storage, the impact of development is likely to be greatest on semi-natural grassland, woodland and heathland because of the large carbon stock usually associated with these land uses.
- All development activities will to some extent impact habitat provision and the capacity to support biodiversity. The development of priority habitats is regulated to prevent/mitigate adverse environmental impacts. Development of organo-mineral soils is likely to impair soil hydrological functioning due to impacts on soil structure (effecting infiltration rates and water holding

capacity) and the effect of soil sealing which prevents/reduces water infiltration. This may be particularly important in upland areas which have a vital role in water provision and flood regulation.

5 REGULATION AND LAND DESIGNATION

5.1 Impact of land designation on organo-mineral soils

- Land designations limit the range of management options available and may prevent certain areas from being considered as suitable for land use change. Organo-mineral soils are an important soil type for Welsh conservation with between 40-45% of the total area of Welsh Sites of Special Scientific Interest (SSSI), Special Protection Areas (SPA) and Special Areas of Conservation (SAC) underlain by organo-mineral soils. This equates to approximately 57,000 ha, 34,000 ha and 97,000 of land under the respective designations, underlain by organo-mineral soils. Approximately 23% of the total organo-mineral soil area of Wales is designated as land supporting Sites of Special Scientific Interest (SSSI) (Bol *et al.,* 2011) (Table 9). A detailed analysis of the classification of Welsh organo-mineral soils into different land use categories is provided by Bol *et al.,* (2011). It is important to note that land may be under multiple designations for example National Nature Reserves and Special Protection Areas in Wales are also designated as SSSI sites.
- A large proportion (80%) of the Welsh land area is designated as Less Favoured Area (LFA) land due to environmental constraints on productivity (principally due to mountainous topography and wet climate). Over 97% (415,754 ha) of the total area of organo-mineral soils in Wales is classed as LFA land and organo-mineral soils constitute 25% of the total Welsh LFA area (Table 9). Therefore, the potential options for land use change are limited by environmental/geographic constraints on the land. Upland LFA land can support livestock farming and pasture with the most mountainous areas best suited to sheep farming, whilst some of the lower lying more productive areas are able to support dairy farming.
- Sites designated as SSSI each have a management plan agreed by Natural Resources Wales and the landowner which details the scientific importance of the site and how the site should be managed to maintain its environmental quality. The landowner is required to follow the agreed management plan and any change in management should have consent from Natural Resources Wales.

Table 9. Area of organo-mineral soils in Wales under designation, total land area under different designation classes within Wales and the proportion of the total designated area within Wales that is on organo-mineral soils. Designation classes; SAC: Special Areas of Conservation; SPA: Special Protection Areas; SSSI: Site of Special Scientific Interest; NNR: National Nature Reserve; ESA: Environmental stewardship agreements; LFA: Less Favoured Area. Adapted from Bol *et al.,* (2011).

Land Designation	1 Well drained	2 Podzols	3 Gley Soils	Total area on organ-mineral soil (ha)	% of total area on organo-mineral soil	Total area designated (all soil types) (ha)	% of total area designated on organo-mineral soil
	Area (ha)						
SAC	19242	26632	10918	56792	13.3	138902	41
SPA	5504	23907	4266	33677	7.9	81319	41
SSSI	25018	49781	22415	97214	22.8	217306	45
NNR	2950	2504	1350	6804	1.6	21260	32
ESA	1795	12337	4127	18259	4.3	80302	23
LFA (total)	68767	186074	160913	415754	97.6	1634970	25

Land Designation	1 Well drained	2 Podzols	3 Gley Soils	Total area on organ-mineral soil (ha)	% of total area on organo-mineral soil	Total area designated (all soil types) (ha)	% of total area designated on organo-mineral soil
LFA (disadvantaged)	6733	23	14997	21753	5.1	473938	5
LFA (severely disadvantaged)	62034	186051	145916	394001	92.5	1161032	34

5.2 Regulations impacting land use change on organo-mineral soils

Environmental Impact Assessment (Agriculture) Wales Regulations (2017)

- For land which is not protected by designation, Environmental Impact Assessment (Agriculture) Regulations (2017) control the conversion of semi-natural habitats to improved agricultural land use. The Environmental Impact Assessment (EIA) Agriculture Regulations consider whether any semi-natural land being developed for agricultural purposes has significant environmental value (such as impacting habitats or species) or historic/cultural value and generally permit agricultural projects which do not have significant adverse effects on the environment (including effects on soil, land, water and biodiversity).
- According to Environmental Impact Assessment general guidance (Welsh Government, 2017) any land which has less than 25% coverage of improved agricultural grass species and/or white clover is classed as semi-natural. A summary of semi-natural habitats found in Wales and descriptions of habitat characteristics is shown in columns 1 and 2 of Table 10. If considered semi-natural, in compliance with the EIA regulation, a Screening Application must be made and approved before agricultural projects can take place on the land.
- Agricultural projects are defined as those which increase agricultural productivity of semi-natural land by either (i) changing the way the land is farmed to a more intensive method of management, (ii) causing long term change in species composition of the surface vegetation. The regulation is not needed for improvement of arable land, short term grass leys or agricultural land that has recently been cultivated intensively or received fertiliser applications.
- The decision making process regarding whether or not the proposed agricultural project will have a ‘significant’ adverse effect on the environment is fully detailed in (Welsh Government, 2020). In brief, the decision on the significance of the environmental impact is based on the characteristics of the land under consideration including habitat size, species diversity, habitat mosaics, species, ecological resilience, local context and designated sites.

Key issues relevant to the application of the EIA (Agriculture) Regulations for agricultural improvement of Welsh organo-mineral soils

- Habitats classed as priority habitats under Section 7 of the Environment (Wales) Act 2016 are considered to be a ‘significant’ environment and therefore will be protected from agricultural improvement (Welsh Government, 2020). Table 8 shows a list of semi-natural habitats which are commonly found on Welsh organo-mineral soils (and cover more than c. 1% of total Welsh organo-mineral soil area according to Bol *et al.,* (2011)) and the specific priority habitats which are found within these classes. A full list of semi-natural habitat descriptions according to the EIA Wales

Regulations (2017) is provided in Appendix Table 3 and further details of terrestrial, coastal and freshwater priority habitats are provided in Appendix Table 4.

- Priority habitats which are particularly extensive on organo-mineral soils include lowland and upland dwarf shrub heath (65,573 ha, 16% of the organo-mineral land area), and to a lesser extent upland and lowland calcareous grassland (Bol *et al.*, 2011).
- Most acid grasslands and rough grasslands underlain by organo-mineral soils in Wales are not considered a priority habitat and may be considered suitable for improvement under the EIA (Agriculture) Regulations. Acid grassland covers 137,118 ha (32%) of Welsh organo-mineral soil area (Bol *et al.*, 2011) and (with the exception of lowland dry acid grassland which covers less than 2%) is not considered a priority habitat. Rough grassland (neutral unimproved grassland) covers c. 16 % of the Welsh organo-mineral soil area (Bol *et al.*, 2011) and of this, only lowland meadows (< 2%) are considered a priority habitat.
- Designated sites such as SSSIs, SACs, SPAs and NNR are protected from agricultural improvement under EIA (Agriculture) Regulations. This amounts to c. 23 % of the Welsh organo-mineral land area.
- Land use change of semi-natural land adjacent to priority habitats may indirectly impact the habitat quality of adjacent habitat (for example runoff of agricultural fertilisers). Organo-mineral soils are often found in proximity to or in a mosaic with blanket peat bog which is a priority habitat. Similarly, issues around connectivity between wildlife habitats may be relevant to organo-mineral soils adjacent to protected sites such as SSSIs and NNRs. Note that broadleaf and coniferous woodland (which covers approximately 66,971 ha (16 %) of the Welsh organo-mineral soil area) and woodland creation and deforestation is controlled separately according to EIA (Forestry) Regulations.

Table 10. Description of semi-natural habitats from (Welsh Government, 2017). Priority habitats associated within each broad habitat according to Section 7 of the Environment (Wales) Act 2016, are also presented. Priority habitats are habitats considered to be of principal importance for maintaining and enhancing biodiversity in Wales. Column one shows the % of the total area of Welsh organo-mineral soils occupied by each habitat type as reported by Bol *et al.*, (2011). Land cover of habitats is derived from LCM2000 (Fuller *et al.*, 2002).

Semi natural habitat	Brief habitat description	Priority habitats
Acid grassland (33%) Upland: (31%) Lowland: (2%)	Typically found on dry acid soils in the lowlands or damp acid grasses on gleys or shallow peats elsewhere, usually with a pH less than 5.5. Includes moorland that has been heavily grazed to the exclusion of heather cover. Acid tolerant plants such as heath bedstraw (*Galium saxatile*), tormentil (*Potentilla* sp.) and sheep sorrel (*Rumex acetosella*) are characteristic.	Lowland dry acid grassland
Neutral grassland (16%) Upland: (14%) Lowland: (2%)	Vegetation dominated by grasses and herbs on a range of soils (usually pH of 4.5-6.5). Includes enclosed dry hay meadows or pastures that have been managed with the annual or periodic	Lowland meadows

Semi natural habitat	Brief habitat description	Priority habitats
	addition of manures or low levels of inorganic fertilisers in both uplands and lowlands.	
Calcareous grassland (2%) Upland: (>1%) Lowland: (<1%)	Well drained soils rich in limestone or other lime-rich rocks, usually with a pH > 6. Characteristic vegetation: lime loving plants such as salad burnet (*Sanguisorba minor*), wild thyme (*Thymus polytrichus*), common rockrose (*Helianthemum nummularium*) and lady's bedstraw (*Galium verum*) are largely confined to this type of grassland.	Lowland calcareous meadows Upland calcareous meadows
Dwarf shrub heath 16%) Upland: (15%) Lowland: (<1%)	Characterised by at least 25% cover of dwarf shrubs including ling heather (*Calluna vulgaris*), bilberry (*Vaccinium myrtillus*) and western gorse (*Ulex gallii*). Includes heathland in both the uplands and lowlands.	Lowland heath Upland heath
Bracken (2%)	Areas with a continuous canopy cover of bracken at the height of the growing season.	
Fen, swamp and marsh/marshy grassland (~1%)	Found on groundwater fed, permanently or periodically waterlogged peats or mineral soils. Fens occur on peats where rainfall, ground water and run-off maintain waterlogged conditions for most of the year. Swamps are characterised by tall stands of emergent vegetation (standing in water for part of the year) including reed beds. Marshes refer to fen meadows and rush pasture which may have the appearance of species-rich grassland but will be waterlogged at least for the winter period. Marshy grassland is typically dominated by rushes (*Juncus* sp.), purple moor grass (M*olinia caerulea*), meadowsweet (*Filipendula ulmaria*) or yellow flag iris (*Iris pseudacorus*). Typically have a taller structure than drier grassland habitats.	Upland flushes, fens and swamps Lowland fens Purple moor grass and rush pastures Reedbeds
Bog[14]	Vegetation associated with Sphagnum (bog) mosses and hare's-tail cottongrass (*Eriophorum vaginatum*).	Lowland raised bog Blanket bog

Glastir sustainable land management scheme for Wales regulations and implications for land use change on organo-mineral soils

- The Glastir sustainable land management scheme for Wales is a whole farm voluntary incentive scheme to pay for sustainable land management practices which are above and beyond the legal

[14] Deep peat (rather than organo-mineral) but often occur in close proximity to organo-mineral semi-natural habitats.

minimum. Key objectives of Glastir include managing soils to prevent erosion and conserve carbon stocks, improving water quality, reducing flood risk, conservation of wildlife and biodiversity, protecting landscapes and the historic environment and improving access to the countryside.

- Within the scheme all farms must comply to the Whole Farm Code which is a set of compulsory requirements which must be followed for the full five years of the scheme (Welsh Government, 2013a). Under the Whole Farm Code, the Welsh Government, (2015b) defines habitat land as "Any vegetation which has a composition of less than 25% sown agricultural species as per the Environment Impact Assessment (Agriculture) (Wales) (EIA) Regulations 2007". The Whole Farm Code rules state that agricultural improvement of habitat land is prohibited including the following management practices: (i) damage to habitat land which causes loss of the vegetation typical of the habitat (e.g. over or under grazing, poaching of soil by livestock or soil rutting by machinery), (ii) any agricultural improvement including ploughing, cultivating or re-seeding or installation of drainage or (iii) any application of fertilisers (inorganic or organic[15]). The Whole Farm Code rules state that agricultural projects permitted on semi-natural habitats under the EIA Wales Regulations 2007, are not allowed to be made while the land is entered into the Glastir sustainable land management. These rules preventing improvement of habitat land apply to the whole farm and all farms entered into both the Entry and Advanced Glastir scheme for the full term of the contract.
- Improved grassland (i.e. grassland with >25% sown agricultural species) is not classed as habitat land under the Glastir scheme and is therefore not protected from further agricultural improvement (e.g. ploughing, reseeding or fertiliser application) or conversion to arable agriculture. The Glastir scheme (both entry and advanced) does include grassland management options such as Management Option 15B (Grazed permanent pasture with low inputs), 15C (grazed permanent pasture with no inputs and mixed grazing) and 15D (Grazed permanent pasture with low inputs and mixed grazing) (Welsh Government, 2013b) which promote extensive grassland management. Whilst the Glastir regulations prevent improvement of semi-natural habitats on organo-mineral soils such as acid grassland, the management of improved grassland for example ploughing and re-seeding or conversion to arable is not controlled. Improved grassland on organo-mineral soil occupies 47,276 ha of land in Wales (~11.5%) of the total organo-mineral land area of Wales. Whilst improved grassland generally does not store as much carbon as semi-natural grassland (Table 11), intensive management of improved grassland (such as ploughing and reseeding) and in particular the conversion of grassland to arable cropping is likely to result in substantial carbon loss.

Table 11. Carbon stock average estimates by broad habitat from Alonso *et al.,* (2012) based on sampling in England. It is important to note that these carbon stocks are calculated from 0-15 cm depth soil samples and therefore provide a comparison of carbon storage in the top 15 cm of the soil rather than the entire topsoil layer.

Habitat	Carbon stock in soils (t C/ha)	Carbon stock in vegetation (t C/ha)
Dwarf shrub heath	88	2
Acid grassland	87	1

[15] With the exception of application of farmyard manures where these are specifically permitted by Glastir habitat management options.

Habitat	Carbon stock in soils (t C/ha)	Carbon stock in vegetation (t C/ha)
Fen, marsh and swamp	76	-
Bog	74	2
Coniferous woodland	70	70
Broad leaf, mixed & yew wood	63	70
Neutral grasslands	60	1
Improved grasslands	59	1
Arable and horticulture	43	1

Conclusions

- Grasslands on organo-mineral soils represent a substantial carbon stock and increasing the intensity of management of Welsh grasslands is a key threat to soil carbon storage.
- Acid and rough upland grasslands cover a large proportion of the Welsh organo-mineral soil area in Wales (together accounting for approximately 49% of the Welsh organo-mineral soil area). Under the EIA (Agriculture) Regulation these habitats are likely to be considered suitable for agricultural improvement (fertiliser addition, ploughing and reseeding). However, grassland improvement particularly soil disturbance by ploughing and reseeding is likely to cause a substantial carbon loss from these soils. Farms entered into the Glastir agri-environment scheme are prohibited from agricultural improvement of semi-natural habitats (including acid and rough grassland).
- The intensification of grassland management including that of improved grassland (>25% sown agricultural species), such as ploughing and conversion to arable cropping is likely to result in carbon loss.
- The potential for land use change of designated land is limited due to protected status (e.g. SSSI, NNR, SPA, SAC). This means that land use change of at least 23% of the organo-mineral soil area in Wales is restricted.

6 CONCLUSIONS

- Soils are an integral part of the terrestrial ecosystem and support many essential functions including carbon storage, food provision, water regulation, nutrient cycling and biodiversity. Land use and land management practices strongly affect soil functions.
- Welsh organo-mineral soils are a substantial carbon store and estimated to hold 19% of the total carbon in Welsh soils (Smith *et al.*, 2007). Furthermore it is estimated that over half of the total carbon stock of Welsh organo-mineral soils is stored at a depth of 0-15 cm which reflects the variability of the peat layer (≤ 40 cm depth) across Welsh organo-mineral soils (Bol *et al.,* 2011). This is important when considering vulnerability of soil carbon to land use change as shallow carbon stocks are more likely to be impacted by management practices and environmental changes than deeper carbon stock. Peats, organo-mineral soils and shallow soils are considered to be the soil types most vulnerable to high rates of soil organic carbon loss.
- Results from the literature review suggest that soils have a finite capacity for carbon storage which is determined by soil type, land use and climate. When land use is changed, soil carbon either increases or decreases towards a new equilibrium value. In general, land uses with permanent vegetation cover and low soil disturbance have the greatest capacity for carbon storage.
- The review also highlighted that land use change/management practices which affect soil carbon may also influence emission of nitrous oxide (N_2O) which has a much larger global warming potential than that of CO_2. When considering the impact of land use change on soil carbon, these emissions should also be considered to avoid pollution swapping (i.e. where simultaneously one pollutant is reduced but another increased).
- Within Wales, most organo-mineral soils are occupied by agricultural or forestry land uses with round 65% of welsh organo-mineral soils supporting grassland. Agricultural management practices, conversion from permanent grassland to short term/improved grasslands and particularly conversion of grassland to arable land uses have the potential to cause major loss of soil carbon. Similarly, soil disturbance and removal of vegetation for development and mineral extraction purposes is likely to cause carbon loss.

Agriculture

- Acid and rough grasslands occupy 49% of the Welsh organo-mineral soils. The main threats to grassland soil carbon storage are soil disturbance (for example through ploughing and reseeding) and damage to soil structure (for example from compaction from overstocking or use of heavy machinery on wet soils) which may increase soil erosion. Improved and temporary grasslands store less carbon than semi-natural grasslands. Any management practice which removes surface vegetation and exposes bare soil is likely to have a major impact on soil carbon. This is partly due to (i) reducing organic matter inputs from vegetation, (ii) increasing loss of soil (and soil carbon) by erosion, and (iii) modification of the soil environment e.g. increased temperature which may increase microbial decomposition rates. Consequently, improved and temporary grasslands typically store less carbon than semi-natural grasslands.
- Management of improved grassland including stocking rate, grazing management, frequency of re-seeding and the use of fertilisers and lime are also likely to influence soil carbon storage and functions.
- Arable soils generally have the lowest capacity for carbon storage and annual cultivation and removal of crop biomass without addition of organic material can deplete soil organic matter. Management practices such as, introducing grass leys, cover cropping and addition of organic

material in appropriate circumstances, can help to maintain soil organic matter and soil carbon content, and soil functioning.

- There are clear trade-offs between the ecosystem services provided by different agricultural land uses. Conversion of arable land to permanent grassland will improve SOC storage and sequester carbon but would also impact on the structure of farm businesses. Conversely, improvement of semi-natural grassland (e.g. fertiliser and lime addition) has the potential to improve grassland productivity whilst increasing the risk of soil carbon loss and environmental impacts such as nutrient leaching and loss of biodiversity.

Mineral extraction and development

- Soil disturbance and the removal of surface vegetation from organo-mineral soils for purposes such as mineral extraction and development will result in carbon loss by increasing rates of organic matter decomposition and soil vulnerability to erosion.
- Impacts of soil disturbance and compaction on soil structure such as the breakdown of soil aggregates and a reduction in soil pore space will also influence the hydrological functions including infiltration rates and water holding capacity provided by organo-mineral soils.
- Where development is necessary, actions to minimise soil disturbance, exposure of bare soil and the duration for which soil conditions are modified will help to mitigate adverse effects on soil structure and functions however some carbon loss is inevitable. Handling soil at appropriate moisture contents can also reduce impacts on soil structure.

Regulations effecting Welsh organo-mineral land use and change

- Conservation designations restrict the potential for land use/land management change to some extent on over 23% of Welsh organo-mineral soils. Proximity to conservation sites or priority habitats may also influence which land use/land management changes are authorised on other areas of organo-mineral soil due to potential indirect effects on habitat quality (e.g. nutrient runoff to non-target sites) and biodiversity (e.g. modification of adjacent land may impact habitat connectivity and wildlife dispersal between conservation areas). Many areas with organo-mineral soils are adjacent to blanket peat bogs which are designated as priority habitats. On these sites, precautions should be taken to avoid land use change which may indirectly modify habitat quality e.g. causing nutrient enrichment or drying.
- Acid and rough semi-natural grasslands are major land use types and habitats on organo-mineral soils that can be considered for improvement under the Environment Impact Assessment (Agriculture) Regulations. However, farms which are registered with Glastir are prevented from improving these grassland types.
- Changes in management or land use of improved grassland are not regulated in the EIA (Agriculture) Assessments or by Glastir regulations (unless grassland management options are specifically chosen). Management practices such as increased frequency of ploughing and reseeding of grassland and particularly the conversion of grassland to arable crop land all will result in carbon loss.

Conclusions

- Organo-mineral soils are more carbon rich than mineral soils and most of the carbon is stored in the topsoil layers (<40 cm depth). Consequently, the carbon stored in organo-mineral soils is particularly vulnerable to changes in land use and management. In addition, most Welsh organo-mineral soils are located in mountainous upland environments where soil erosion rates may be especially high if soil is exposed. Equivalent land management/land uses on mineral soils will have less of an impact on soil carbon because mineral soils generally store less carbon.

- Land use change may substantially alter the ecosystems services provided by organo-mineral soils. Land use changes which increase the capacity for food production may reduce soil carbon storage and soil organic matter content. Soil organic matter is integral to most ecosystem services provided by soils including food production, biodiversity support, water regulation and climate resilience. Therefore, management to maintain soil organic matter is important for sustaining soil functions under all land uses.

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APPENDIX

Table 1. Definitions of Soil wetness classes from (Hodgson, 1997). The number of days specified is not necessarily a continuous period.

Wetness class	Definition
I	The soil profile is not wet within 70 cm depth for more than 30 days in most years*.
II	The soil profile is wet within 70 cm depth for 31-90 days in most years or, if there is no slowly permeable layer within 80 cm depth, it is wet within 70 cm for more than 90 days, but not wet within 40 cm depth for more than 30 days in most years.
III	The soil profile is wet within 70 cm depth for 91-180 days in most years or, if there is no slowly permeable layer within 80 cm depth, it is wet within 70 cm for more than 180 days, but only wet within 40 cm depth for between 31 and 90 days in most years.
V	The soil profile is wet within 40 cm depth for 211-335 days in most years.
VI	The soil profile is wet within 40 cm depth for more than 335 days in most years.

*'In most years' is defined as more than 10 out of 20 years.

Table 2. Comparison of extent of Welsh upland and lowland as defined by the Countryside Survey and the Countryside Council for Wales.

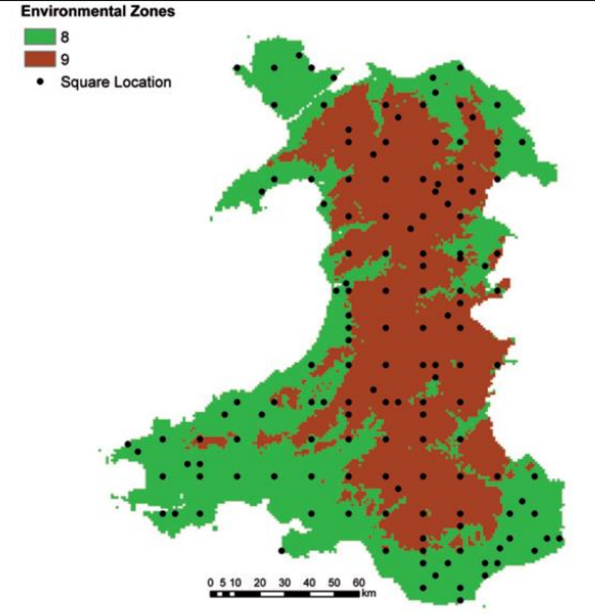
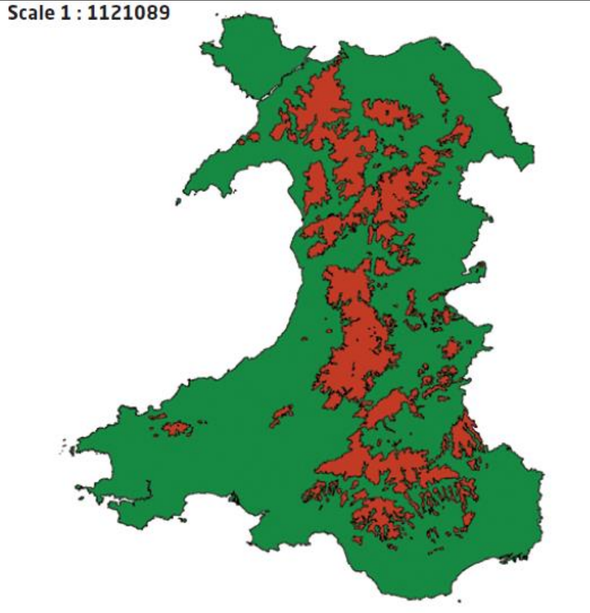
a) Division of Wales in two environmental zones; EZ8 lowland Wales (green) and EZ9 upland Wales (brown) as used by the Countryside Survey, (2007) and Bol *et al.*, (2011). Map sourced from Countryside Survey, (2007).	b) Welsh upland (red) defined as land over the 300 m contour and the limit of enclosed land, and lowland (green). (definition used by Countryside Council for Wales. Map sourced from Countryside Survey, (2007).
	

Table 3. Semi-natural habitat descriptions according to the EIA (Agriculture) 2017 regulations.

Semi natural habitat	Brief habitat description	Priority habitats
Acid grassland	Typically found on dry acid soils in the lowlands or damp acid grasses on gleys or shallow peats elsewhere, usually with a pH less than 5.5. Includes moorland that has been heavily grazed to the exclusion of heather cover. Acid tolerant plants such as heath bedstraw, tormentil and sheep sorrel are characteristic.	Lowland dry acid grassland
Calcareous grassland	Well drained soils rich in limestone or other lime-rich rocks, usually with a pH > 6. Characteristic vegetation: lime loving plants such as salad burnet, wild thyme, common rockrose and lady's bedstraw are largely confined to this type of grassland.	Lowland calcareous meadows Upland calcareous meadows
Neutral grassland and hay meadow	Vegetation dominated by grasses and herbs on a range of soils (usually pH of 4.5-6.5). Includes enclosed dry hay meadows or pastures that have been managed with the annual or periodic addition of manures or low levels of inorganic fertilisers in both uplands and lowlands. *Does not include improved or some semi-improved grassland types which have been recently modified by management (e.g. reseeding, inorganic fertilisers).*	Lowland meadows
Dwarf shrub heath	Characterised by at least 25% cover of dwarf shrubs including ling heather, bilberry and western gorse. Includes heathland in both the uplands and lowlands.	Lowland heath Upland heath
Bracken	Areas with a continuous canopy cover of bracken at the height of the growing season.	
Fen, marsh and swamp	Found on groundwater fed, permanently or periodically waterlogged peats or mineral soils. Fens occur on peats where rainfall, ground water and run-off maintain waterlogged conditions for most of the year. Swamps are characterised by tall stands of emergent vegetation (standing in water for part of the year) including reed beds. Marshes refer to fen meadows and rush pasture which may have the appearance of species-rich grassland but will be waterlogged at least for the winter period.	Upland flushes, fens and swamps Lowland fens Purple moorgrass and rush pastures Reedbeds
Marshy grassland	Wet grasslands typically dominated by rushes, purple moor grass meadowsweet or yellow flag iris. Typically have a taller structure than drier grassland habitats. May occur on shallow peats (but not deep peat).	

Bog	Peat forming vegetation associated with Sphagnum (bog) mosses and Hares-tail cotton grass	Lowland raised bog Blanket bog
Coastal habitats	Saltmarshes, sand dunes, coastal cliffs and slopes	Maritime cliff and slopes Coastal sand dunes Coastal vegetated shingle
Broadleaved mixed and yew woodland (scrub)	Areas of semi-natural scrub (having colonised naturally) are included as semi-natural areas. Woodland above a certain threshold is considered under the EIA (Forestry) (England and Wales) Regulations 1990.	
Scrub	Vegetation dominated by shrubs for example common gorse, hawthorn, blackthorn or bramble.	
Montane habitats	Vegetation above the tree line (usually > 600 m above sea level).	Mountain heaths and willow scrubs
Standing water and canals	Includes natural systems such as lakes, meres and pools as well as man-made waters such as reservoirs, canals, ponds and gravel pits. Includes the open water zone (which may contain submerged, free-floating or floating-leaved vegetation and water fringe vegetation. Ditches with open water (for at least the majority of the year) are also included in this habitat.	Oligotrophic and dystrophic lakes Ponds Mesotrophic lakes Eutrophic standing waters Aquifer-fed naturally fluctuating water bodies

Table 4. List of terrestrial, coastal and freshwater priority habitats according to Section 7 of the Environment (Wales) Act 2016. Priority habitats are habitats of principal importance for maintaining and enhancing biodiversity in Wales.

Habitats	Priority habitats
Broadleaved, mixed and yew woodland	Traditional orchards Wood pasture and parkland Upland oak woodland Lowland beech and yew woodland Wet woodland Lowland mixed deciduous woodland
Boundary and linear features	Hedgerows
Arable and horticulture	Arable field margins
Improved grassland	Coastal and floodplain grazing marsh
Neutral grassland	Lowland meadows
Calcareous grassland	Lowland calcareous meadows Upland calcareous meadows
Acid grassland	Lowland dry acid grassland
Dwarf shrub heath	Lowland heath Upland heath
Fen, marsh and swamp	Upland flushes, fens and swamps Lowland fens Purple moorgrass and rush pastures Reedbeds
Bogs	Lowland raised bog Blanket bog
Montane habitats	Mountain heaths and willow scrubs
Rivers and streams	Rivers
Standing open waters and canals	Oligotrophic and dystrophic lakes Ponds Mesotrophic lakes Eutrophic standing waters Aquifer-fed naturally fluctuating water bodies
Inland rock	Inland rock outcrop and scree habitats Calaminarian grasslands Open mosaic habitats on previously developed land Limestone pavement
Supralittoral rock	Maritime cliff and slopes
Supralittoral sediment	Coastal sand dunes Coastal vegetated shingle