Changing Carbon Stores in Peatlands Over Time

A Level Geography Teacher Resource

[Specifically featuring Welsh examples taken from the Teifi Catchment.]

Tim Wright

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Amended August 2024

This set of resources was prepared for former colleagues teaching in Carmarthen, Ceredigion and Pembrokeshire schools. It was intended to introduce A level teachers to the important role peat mires/bogs play in carbon capture.

It also includes an introduction to peat bog formation, degradation and restoration and where possible, examples from within the Teifi catchment are reported. Related issues such as carbon management and climate change impacts were appended for those colleagues who had not had the opportunity to study this topic first hand.

This document is underpinned by material from a wide range of sources, links to which appear within the text and in the source section at the end. The most important however, are the IUCN UK Committee, Peatland Programme's Briefing Notes. [No doubt, colleagues will have added to this resource and improved on the content over the years.]

If you wish to reproduce parts of this work that's fine, but please **ensure you credit the original authors/sources.**

Those wanting to access Teifi catchment information only, should focus on sections 6 to 10.

Acknowledgement - My background is in the Quaternary sciences and I am mainly interested in what bogs reveal about landscape evolution and past climates, rather than their fauna and flora. Consequently, I would anticipate that those of you with a deeper knowledge and understanding in ecosystems fauna and flora will "beef-up" any deficiencies.

Most of my Teifi catchment knowledge comes from fieldwork in West Wales over the past 35 years. Some in the company of Mike Walker *[Emeritus Professor of Quaternary Science in the University of Wales, Lampeter]* who along with, one of Mike's former PhD students, Sean Buckley, introduced me to many of the secrets contained within the upland blanket bogs above the Teifi valley. Further, detailed information on the Tregaron raised bog system came courtesy of a Quaternary Research Association fieldwork meeting led by Keith Barber, Paul Hughes and Jenni Shultz of Southampton University. [2001]

The use of satellite and Lidar data in terms of landscape interpretation is an area of study, which I have applied successfully over the years and particularly, in a long running Teifi estuary research programme. I would encourage colleagues to introduce their students to this geospatial resource, as much of the data is freely available and is easily manipulated on school IT systems.

TDW February 2017, [*Amended in part, August 2024*]

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Important Definitions

Acrotelm – the surface layer of an active mire where bog plants photosynthesise and grow. The plant supply zone.

Anoxic – severely depleted or without oxygen.

Archaic peat - Term used to describe degraded peatlands covered by agriculturally improved grassland or crops, or under the built environment.

Autotrophs - A organism capable of making nutritive organic molecules from inorganic sources via photosynthesis (involving light energy) or chemosynthesis (involving chemical energy)

Bare peat - Term used to describe areas of exposed peat.

Catotelm – relatively inert, permanently waterlogged peat forming zone.

Grips – artificial drains dug across upland peatlands for agricultural and game management.

Labile – chemically unstable

Macrofossils - with reference to peat this term applies to plant remains.

Microfossils - with reference to peat this term applies to pollen and invertebrates such as testate amoebae.

Microtopography - The patterned mosaic of pools, hummocks and lawns on the bog surface, created in part by the growth of the plants themselves.

Mire – is a peat-forming system

Moorland - A term used to describe unenclosed upland areas dominated by a range of semi-natural vegetation. **Not synonymous with peatlands**.

Oligotrophic - Low fertility, nutrient poor.

Ombrogenous - Derived from a water supply comprising only of precipitation.

Ombrotrophic - Where nutrient supply is derived from precipitation [rain, snow or mist], also referred to as rain-fed.

Peat - a relatively amorphous organic deposit consisting of semi-decomposed plant material mixed with varying amounts of inorganic, matter. In the case of UK peat bogs the mineral content may be as low as 2% by weight. Fen peat generally has higher mineral contents because it is waterlogged by mineral-enriched groundwater.

> **Limnic** peats form beneath the water table. [Lakes]
>
> **Telematic** peats form in the swamp zone between high and low water levels. [Swamps]
>
> **Terrestrial** peats accumulate at, or above the high water level. [Mires]

Recalcitrant - resistant to microbial attack, or chemical breakdown

Soil Organic Matter – [SOM] refers to all organic material present in the soil including the remains of plants and animals at varying stages of decomposition and the living plant and animal material on and below the soil surface.

Soil Organic Carbon – [SOC] refers to the amount of carbon stored in the soil. It is often expressed as a percentage by weight or as ***g C/kg*** soil. SOC can be expressed into SOM through a simple multiplication factor, usually taken as equal to 1.72 in mineral soils and closer to 1.92 in organic soils.

Soil profile - Vertical arrangement of soil layers forming the basis of all UK soil classification system.

Soil series - Group of soil profiles developed under similar conditions and similar parental material in UK soil classification. Also the smallest unit of soil mapping.

Soil association - A characteristic grouping of soil series, used to map larger areas and normally bearing the name of the dominant series.

Waterlogging - Permanent or temporary saturation of the soil from high precipitation and poor drainage, or where there is a more or less constant supply of ground water and/or surface runoff, in basins, floodplains or springs.

List of Abbreviations often used in literature discussing bogs/peat

µm	Micro (10-6) metre
C	Carbon
C:N	Carbon to Nitrogen ratio
CCW	Countryside Council for Wales now Natural Resource Wales [NRW]
DOC	Dissolved Organic Carbon
ER	Ecosystem Respiration
GHG	Greenhouse Gases
GJ	Giga [10^9]Joules
GPP	Gross Primary Productivity
Gt	Giga (10^9) Tons*
ha	Hectare
kyr	Thousand Years
Mg	Mega (10^6) Grams
MJ	Mega (10^6) Joules
Mt	Mega (10^6) Tons
N	Nitrogen
NECB	Net Ecosystem Carbon Budget
NEP	Net Ecosystem Productivity
ppmv	Parts per Million by Volume
POC	Particulate Organic Carbon
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
t	Tons
UV	Ultra Violet
WAG	Welsh Assembly Government
yr	Year

* Tons are usually metric tonnes in UK & European literature. US use tons [Short ton]

1 US Ton = 0.90718 Metric Tonnes

1. Peatlands – An Overview

[UK Peatlands Programme] [International Peatland Society]

Peatlands – This is a generic term that incorporates areas of peat accumulation and peat soils in both the uplands and lowlands. There is **no universal definition of peat** and **peatland in terms of soil.** Differing interest groups adopting specific definitions.

The proportion of mineral content also varies between definitions, with some allowing as much as 70%! **Important to note**: a 30% organic matter content is higher than is found in most other soil types.

Some peatland surveys refer to areas of all peat soils whereas others only consider peat-forming mire habitats. Consequently **estimated values for the extent of peatland in the UK are entirely dependent upon the definition used**. If the ecologists' definition is used, peatland is much more extensive in the UK than if the geological definition were to be used for example.

***Depth?* -** Ecologists use a minimum peat depth of 30 cm as the threshold, while geological surveys use 1 m. The Soil Survey of Scotland uses a minimum depth of 40 cm for pure-peat soils, whereas the limit for the Soil Survey for England and Wales ranges from 30 cm to 50 cm.

	Soil Data		UK Biodiversity Action Plan – Mire Areas*	
	Shallow Peaty or Organo-mineral soils [km²]	Deep Peaty or Organic Soils [km²]	Peat-forming Mires [km²]	Peat-forming Fens [km²]
England	7,386	6,799	2,727	80
Wales	3,592	706	718	62
Northern Ireland	1,417	2,064	1,069	30
Scotland	34,612	17,269	17,720	86
Total Area	**47,007**	**26,838**	**22,775**	**258**
UK Cover [%]	**19.3%**	**11%**	**9.35%**	**0.11%**

*Existing or planned restoration

Table 1. Peatland distribution and state across the UK Source:(adapted from JNCC, 'Towards an assessment of the state of UK peatlands' (2011).

Blanket bog is a type of peatland found in the uplands, while the **raised-bog** is found in the lowlands. [Floodplain raised bogs, estuarine raised bogs and isolated basin raised bog are common examples.] A **fen** is another bog-like wetland that has peat deposits. However, unlike bogs, fens have greater water exchange and are less acidic. Therefore, the soil and water are richer in nutrients. Fens are often found near bogs and over time most fens become bogs. [Marshes and swamps are terms reserved for wetlands that are more nutrient rich and hold a wider bio-diversity. Marshes support grasses and swamps support some trees]. However, contrary to popular belief, a **bog supports a wide range of species** and **is not a species-poor habitat**. **It is important to note that the bog ecosystem is poorly understood.**

Peatlands have only recently started to receive wider public attention in the discussion of how best to tackle the issue of climate change. Initial interest was restricted to a small academic group.

Governments and NGOs around the world have woken up to the fact that they contain twice as much carbon as all the world's forests put together! **Peatlands cover just 3% of the world's surface, but contain nearly a third of all organic carbon.** They're second only to oceanic deposits as the world's most important store of carbon.

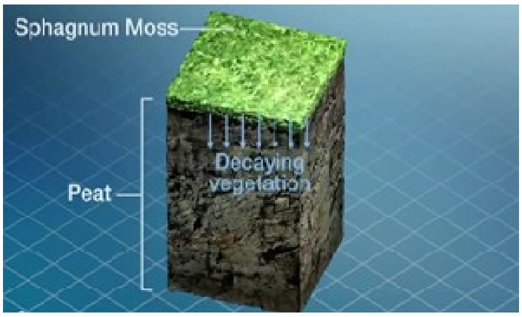
Peatlands are very efficient at absorbing carbon from the carbon cycle and locking it away – a process called **sequestration**.

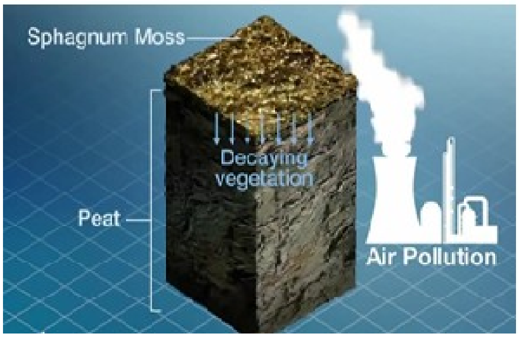
In their natural state, most peat bogs function as carbon 'sinks'. A '**sink**' is the term applied when a natural process absorbs and stores more carbon than it releases.

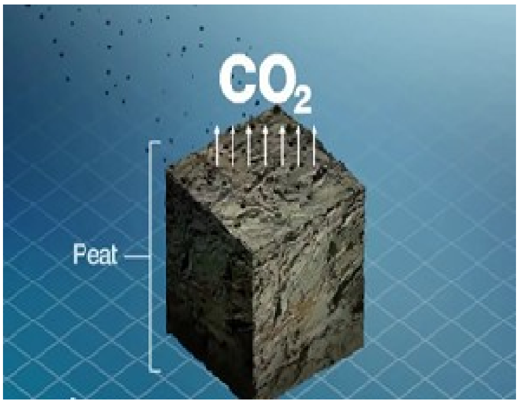
Importantly, peat bogs reduce the amount of carbon entering the atmosphere as carbon dioxide and methane. Both of which are major greenhouse gasses [GHGs] and contributors to climate change.

In the UK, more carbon is locked up in peatlands than is stored within the combined tree population of Britain and France. It represents 42 per cent of our entire carbon stock.

Problem - Many peatlands are degrading and have become carbon 'sources, – they release more carbon than they sequester. Given how much carbon is locked up in the world's peatlands, this is a significant threat to climate stability.







Sphagnum Moss [The Bog Builder] is sensitive to changes in air quality. In the last 200 years, areas of Sphagnum moss downwind of industrial areas have been killed.

First by pollution from the industrial revolution and more recently by government incentivised programmes to drain and manage upland to make it more suitable for grazing and game management.

Once the sphagnum is gone, and the peat exposed, it is free to degrade in the open atmosphere releasing back all the carbon that has been sequestered over thousands of years.

Image source: BeadaMoss®

The cause of the Threat is principally **human activity** and it's global - Peatland degradation over many years by humans includes:-

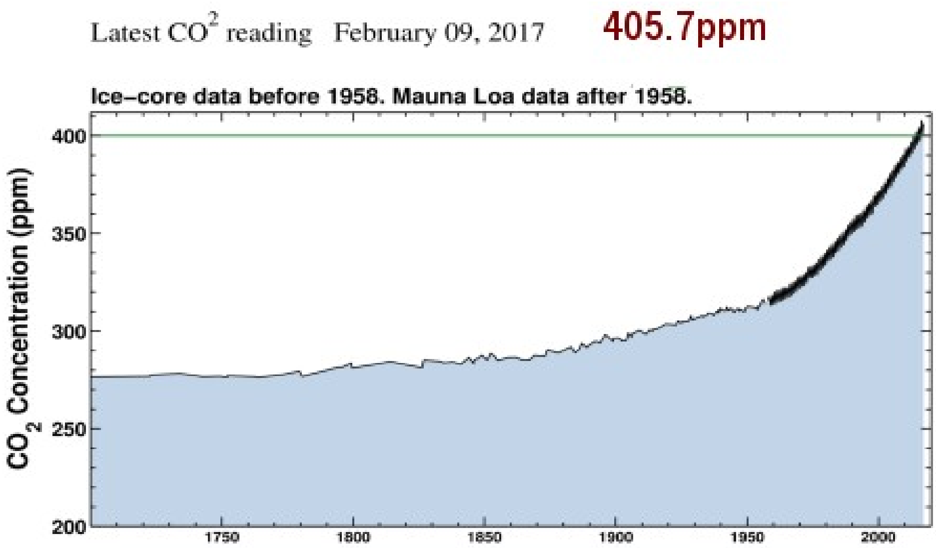
- Afforestation,
- Drainage,
- Burning,
- Cutting for fuel
- Fertilizer/compost production
- Grazing.
- Seeding and fertilising
- Trampling
- Atmospheric pollution
- Palm oil production

Peatlands are very delicate systems. They are referred to as 'unbalanced ecosystems', because organic matter is produced faster than it decays. Hence their usefulness as carbon sinks. When bogs are damaged by humans, this delicate balance is upset and the rate of decay increases, further increasing the amount of GHGs released to the atmosphere. Estimates suggest that 3,000 Mt of carbon dioxide is being released into the atmosphere from bogs damaged by human activity. This is **equivalent to ~10% of the world's fossil fuel emissions**.

Problem - Climate change itself reinforces the pressure on peatlands and causes them to increase their GHG emissions. Climate scientists point out that as many areas of the world are likely to experience warmer, drier conditions as a result of climatic changes, peat bogs will become drier and decompose more quickly. Decomposing peat releases more GHGs into the atmosphere.

Problem – Another climate change related threat facing peat bogs and their potential to store carbon relates to the current warming trend in subarctic and arctic regions. As temperatures increase towards the poles, peat that is currently part of the permafrost [A zone frozen all year round] will start to thaw. This thawing will allow bogs distributed across the northern tundra to degrade, releasing the carbon and methane locked up inside.

Change - Although initially, the benefit of restoring and conserving peatlands was not recognised by climate policy makers, this is changing. A galvanising factor came in May 2013. An atmospheric carbon dioxide concentration of **400 parts per million** was measured at Mauna Loa Observatory in Hawaii. This was the highest recorded level in human history at the time. [Now 404.7ppm]. The diagram below demonstrates how fast carbon dioxide levels have accelerated since the industrial revolution.



Source: Scripps Institution of Oceanography, UC San Diego - 2017

The Kyoto Protocol – [An international treaty adopted in 1997, setting targets for developed countries to reduce their GHG emissions.] Recent modifications acknowledge the role peatlands play in mitigating against climate change. It has now been agreed that reductions in emissions resulting from peatland restoration and conservation programmes can count towards targets.

The Economic Value of Peat Bogs – If countries are able to do better than their target, they can sell the remainder of their emission 'allowance' to other countries. This system has become known as '**carbon-trading'**. The 'currency' in this new system is often referred to as **carbon-credits**. It is hoped that assigning a real economic value to the restoration and conservation of peatlands will provide an incentive to preserve bogs.

The International Union for Conservation of Nature [IUCN] Peatland Programme suggests that peatland conservation projects represent a cost-effective method of addressing climate change. **It is estimated that UK peatlands have the potential to sequester 3 Mt of carbon dioxide every year!**

As it is now possible to trade carbon credits between nations, it is also possible to put a monetary value on the world's peatlands. Clearly, many believe that these precious ecosystems should be saved, regardless of any financial gain. However, we live in a world where money talks! Current valuations range greatly [US$1000 and US$45,000 per hectare]. At a global level, the world's 400 million hectares of peatland, are worth between US$400,000 million and US$18 billion per year. Financial experts argue that if the market for peat-based carbon-credits takes off, this price will rise. **That makes the UK's 2.3 million hectares of peat forming mires and fens worth how much**?

Defra's - Ecosystem Services of Peat

Complexity – **Scientists** have found that re-wetting drained peat bogs as part of the restoration programme, results in increased methane production. This increase, although small in relation to the overall GHG emissions of a degrading peat bog still requires thorough investigation.

The Economy – The horticultural industry and gardeners still buy peat derived compost and forestry plantations are planted and replanted in our uplands. Changes to either will impact upon other industries, inflicting costs and impacting upon jobs in regions where work is often hard to find. Of note; an equivalent peat free compost is proving hard to find.

A Question of Choice - Peatlands will play one of two roles in the future of human-induced climate change: -

- They can become part of the problem through continued damage and the subsequent release of millions of tonnes of GHGs.
- Or alternatively, they can be made part of the solution, by conservation and restoration.

Allowing bogs to function as they have for thousands of years provides a steady and reliable extraction of carbon from the carbon cycle, which is locked up for years to come.

A Natural England report stated that in England less than 1% of peatlands are now 'undisturbed'. More schemes are being started here and around the world to restore and preserve peatlands. One UK example, is aiming to restore nearly 1 million hectares of bog. The UK Biodiversity Action Plan estimates that 1.5 Mt of carbon dioxide emissions will be saved by 2015 as a result.

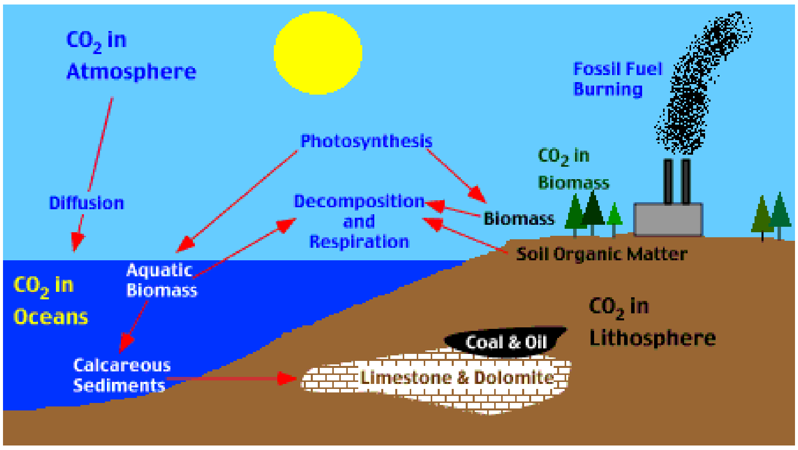
CEH scientists give evidence to peatlands inquiry BBC's Bitesize Peat Bogs

2. The Carbon Cycle

Carbon is the central element in the compounds which form organisms and is derived from carbon dioxide found in the air or dissolved in water. Plants incorporate carbon into carbohydrates and other complex organic molecules by means of photosynthesis. During respiration, they combine oxygen with portions of the carbohydrate molecule, releasing carbon in the form of carbon dioxide and water.

The Carbon Cycle

Source: Original image, at https//cied.ucar.edu/image/carbon-cycle-diagram-nasa



Carbon is **stored** on Earth in the following sinks:-

1. Organic molecules in living and dead organisms found in the biosphere.

2. Gases in the atmosphere, principally carbon dioxide but also methane.

3. Organic matter in soils.

4. Within the lithosphere as fossil fuels and sedimentary rocks like limestone and chalk.

5. In the oceans as dissolved atmospheric carbon dioxide in water. Also as calcium carbonate shells in marine organisms and calcium carbonate oozes on the ocean floor.

Carbon transfers - Most of the carbon found in ecosystems entered as atmospheric carbon dioxide, which passes through the leaves or other photosynthetic parts of **autotrophs**. Photosynthesis produces complex organic material using carbon dioxide, water, inorganic salts, and solar radiation captured by light-absorbing pigments, such as chlorophyll. These molecules can then be combined with other nutrients to produce more complex compounds like proteins, cellulose, and amino acids, etc.

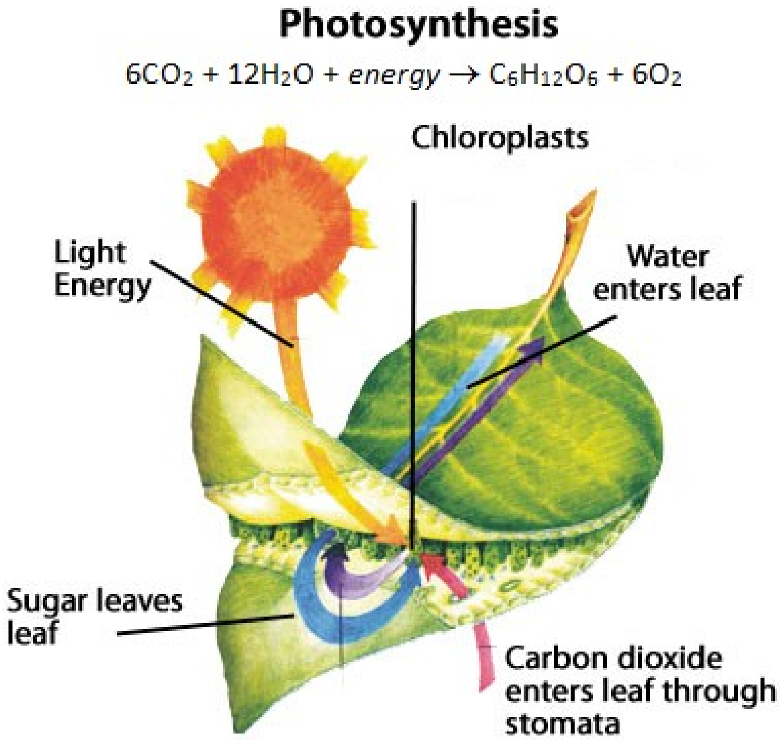
Some of the organic matter produced by photosynthesis is passed through the food chain by consumption. Carbon is transferred from organism to organism when plants are eaten by herbivores, which are in turn are eaten by carnivores. All these organisms respire, excrete organic waste, and eventually die and decompose, which releases carbon into the soil. Carbon is released from ecosystems as carbon dioxide when respiration takes place in both plants and animals. It re-enters the atmosphere where it can be reused by plants.

Decomposition is carried out mainly by bacteria and detritivores [microorganisms that feed on dead animal/plant material]. If decomposition occurs in aerobic conditions, carbon dioxide is released back into the atmosphere. However, if it occurs in anaerobic conditions, methane is released to the atmosphere. Organic forms of carbon in the biosphere include litter, organic matter, and humic materials found in soils. Carbon is also stored in soil as inorganic or organic carbon [carbonate salts].

Inorganic deposits of carbon in the lithosphere include fossil fuels like coal, oil, natural gas, oil shale and peat; and carbonate based sediments [e.g. limestone]. Some carbon is released as carbon dioxide from volcanoes and geysers.

Human Activity - In recent years, humans have greatly increased the rate at which carbon passes from the sedimentary store to atmospheric carbon dioxide. Burning fossil fuels inputs sedimentary carbon into the atmosphere much faster than natural weathering as does the manufacture of cement to a lesser degree.

Some carbon, especially in the sea, is found not as organically fixed carbon, but rather as the carbonate ion [$CO^{2-}{}_3$]. The carbonate ion combines with calcium ions to form calcium carbonate [$CaCO_3$]. Animals such as coral, molluscs, some protozoa, and some algae construct shells calcium carbonate.



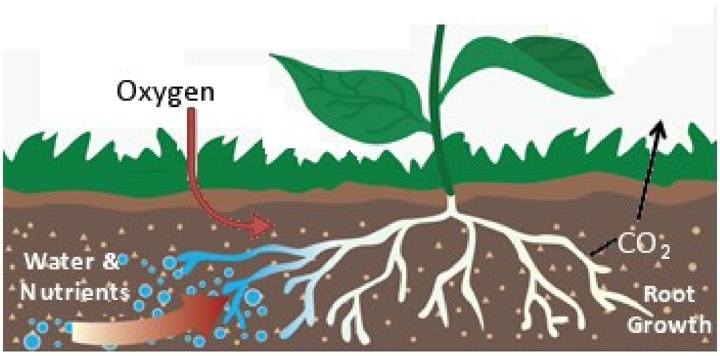


Image source: http://msascienceonline.weebly.com/photosynthesis.html

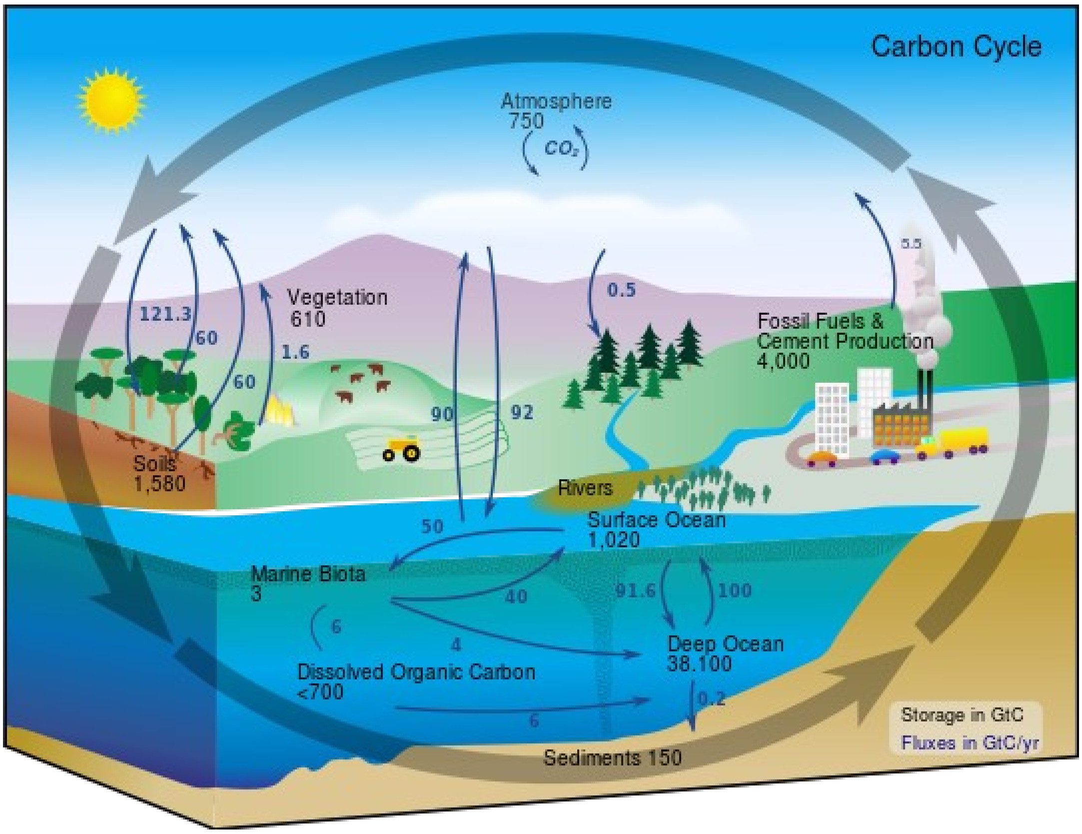
Carbon and oxygen cycling are vital functions of the ecosystem. It is estimated that each year, the Earth's land plants extract some 120 billion tonnes of carbon in the form of CO_2 from the atmosphere. As we know, oxygen is a by-product of photosynthesis and this process is the means by which the essential supply of oxygen in the Earth's atmosphere is maintained at around 21%. However, respiration and the decay of organic matter, effectively reverse photosynthesis. Oxygen is taken from the air and used to release energy and CO_2 stored by plant material. Respiration in an organic cell is represented chemically as:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \textit{energy}$$

If respiration and decomposition were to cease then much of the Earth's supply of carbon would be tied up in dead organic matter. Photosynthesis would slow down as a result, since insufficient CO_2 would be available for the process to take place.

In practice, there is a natural balance which maintains approximate proportions of gases in the atmosphere. However, due to the burning of fossil fuels, the energy and CO_2 that was locked up during photosynthesis millions of years ago is now being 'suddenly' released. The huge quantity of CO_2 now being returned to the atmosphere is upsetting the natural balance. CO_2 is one of several greenhouse gases whose increase is responsible for rapid global warming.

Must Watch - [The Peatbog Problem - Ecosystems: The Carbon Cycle] [3/3] – OU YouTube Video
[Recycling Carbon - Ecosystems: The Carbon Cycle] [2/3] – OU YouTube Video
[The Carbon Cycle]



Source: The Carbon Cycle. Kevin Saff via Wikimedia Commons

3. Classification of Bogs

There are lots of wetland environments. Here we are focussed on just those wetlands where peat is formed.

There are several methods -

- Classification based on the method of water supply:-
  - **Ombrotrophic** bogs receive water only from precipitation
  - **Geotrophic/ minerotrophic** bogs receive moisture from surface water or groundwater. *The flux of nutrients and minerals are much greater than in an ombrotrophic bog.
- Classification based on the landforms where the bog development occurs:-
  - Surface depressions
  - Lakes
  - Valley sides
- Classification based on the landform produced by the bog:-
  - Peat bog lake system
  - Perched water bogs
  - Ombrogenous Bog Systems

The term mire will also occur commonly within the literature. Simply, a **mire** is defined as a peatland where peat is actively being formed. [Joosten, H. & Clarke, D. 2002] Consequently, the raised and blanket bogs of the Teifi catchment can also be referred to as mires.

Bogs however, are not simple to categorise as they are three dimensional in space and time. For example, as will become evident below, the two ombrogenous bog systems in the Teifi catchment are associated with very different landscapes in West Wales. They have also experienced different conditions at various stages during their formation. For example as early peatlands situated in a depression and receiving water that has been in contact with mineral bedrock or soil, then that stage is described as **fen** or a **geotrophic mire.**

A sphagnum mat

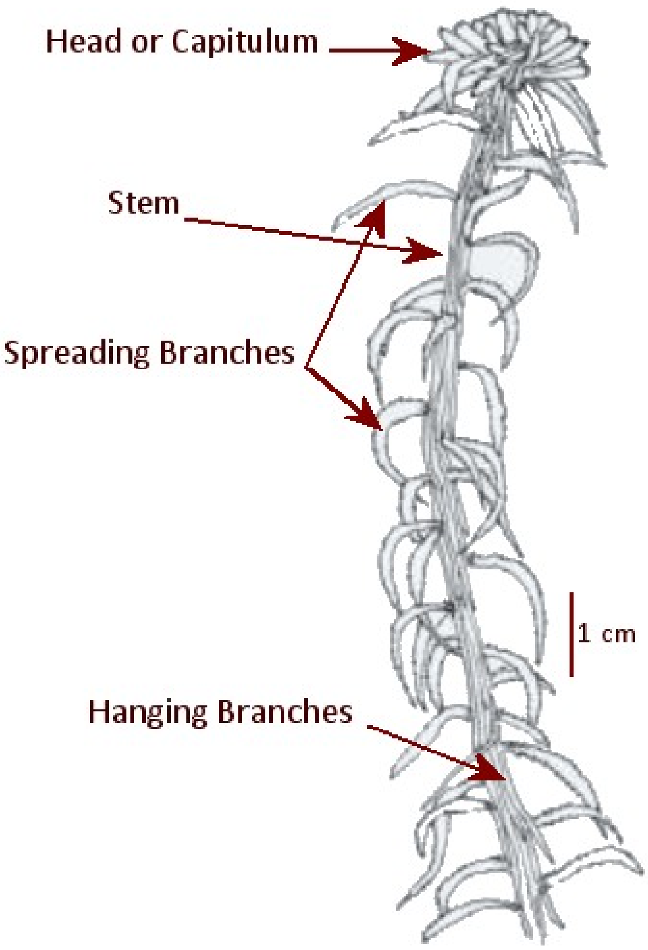
4. The Bog Builder - Sphagnum Moss

All plants in the bog community will contribute to peat production. However, one species predominates. - ***Sphagnum*** covers more of the world's land surface than any other single plant genus. A single *Sphagnum* plant is very small. Up to 50,000 individual plants can be found per square metre.

All growth takes place in the head extending the plant upwards; making the plant very sensitive to grazing/trampling and burning. As a *sphagnum* plant is constantly growing at the head, the capitula have been described as potentially "immortal" and there is evidence of *Sphagnum* plants that have been growing for a thousand years.

Attached to the stem are two types of branches – the spreading branches stick out and give the plant structure. This branch structure supports the hummocky structure that is typical of many bogs.

Sphagnum mosses can hold up to 20 times their own weight in water. The hanging branches are pressed to the stem and help to draw up water, but water is also stored inside dead cells within the plant itself. Surprisingly, sphagnum does not have leaf stomata and so is poor at controlling water loss. Water is also trapped between plants in a hummock and that helps maintain the high water table. Maintaining this high surrounding water content gives the sphagnum an advantage as it helps reduce competition from other plant species that are less well adapted to waterlogged conditions.



The lower parts of the plant are dead and partially decayed. Sphagnum decays much more slowly than other plants.

Sphagnum does not have roots. Minerals, such as calcium and magnesium are absorbed by its cell walls from rainwater.

The moss also takes in more nutrients than it needs, which further depletes the nutrient supply for the rest of the bog. So it is hard for other plants to grow in bogs. Further, sphagnum creates acidic conditions by giving up hydrogen ions in exchange for mineral ions like calcium, potassium and magnesium. Consequently, it is the keystone species in this habitat.

Growth rates and colony expansion are determined by species, but on the whole are pretty slow. A study into the growth of *Sphagnum* colonies found annual, radial growth rates of between 0.5 cm and 13 cms, with a mean value of 3.6 cms.

The common peat forming varieties in the UK are …***Sphagnum capillifolium*** ***Sphagnum fuscum*** ***Sphagnum fallax*** ***Sphagnum papillosum*** ***Sphagnum magellanicum***

Source: Original image … At Irish Peatland Conservation Council.
http://www.ipcc.ie/wp/wp-content/uploads/2012/07/sphagplant.jpeg

5. Raised and Blanket Bogs – Poorly understood ecosystems

[Reminder - Bogs that are active [peat forming] are referred to as **mires**.]

The nature of the water supply is an important factor in bog formation. The raised bog at Tregaron occurs where rainfall is in plentiful supply; between 900mm and 1100mm per year. The blanket bog found on the glaciated upland plateau around Teifi Pools receives a higher annual precipitation total in excess of 1800mm per year.

These types of bog represent one of the most nutrient-poor and acidic rich environments in the natural landscape with pH values between 3.2 and 5.5. They are often referred to as **ombrotrophic mires** because they receive their water and nutrient supply exclusively from precipitation. It is important to note that precipitation is a poor source of both minerals and nutrients.

Natural change in the hydrology of the bog is directly related to climate. Principally, precipitation but also temperature because that affects how much water evaporates. This contrasts with fens, which are also peatlands, but which receive at least some of their water supply and nutrients from mineral rich groundwater [G**eotrophic/mineratrophic mires**].

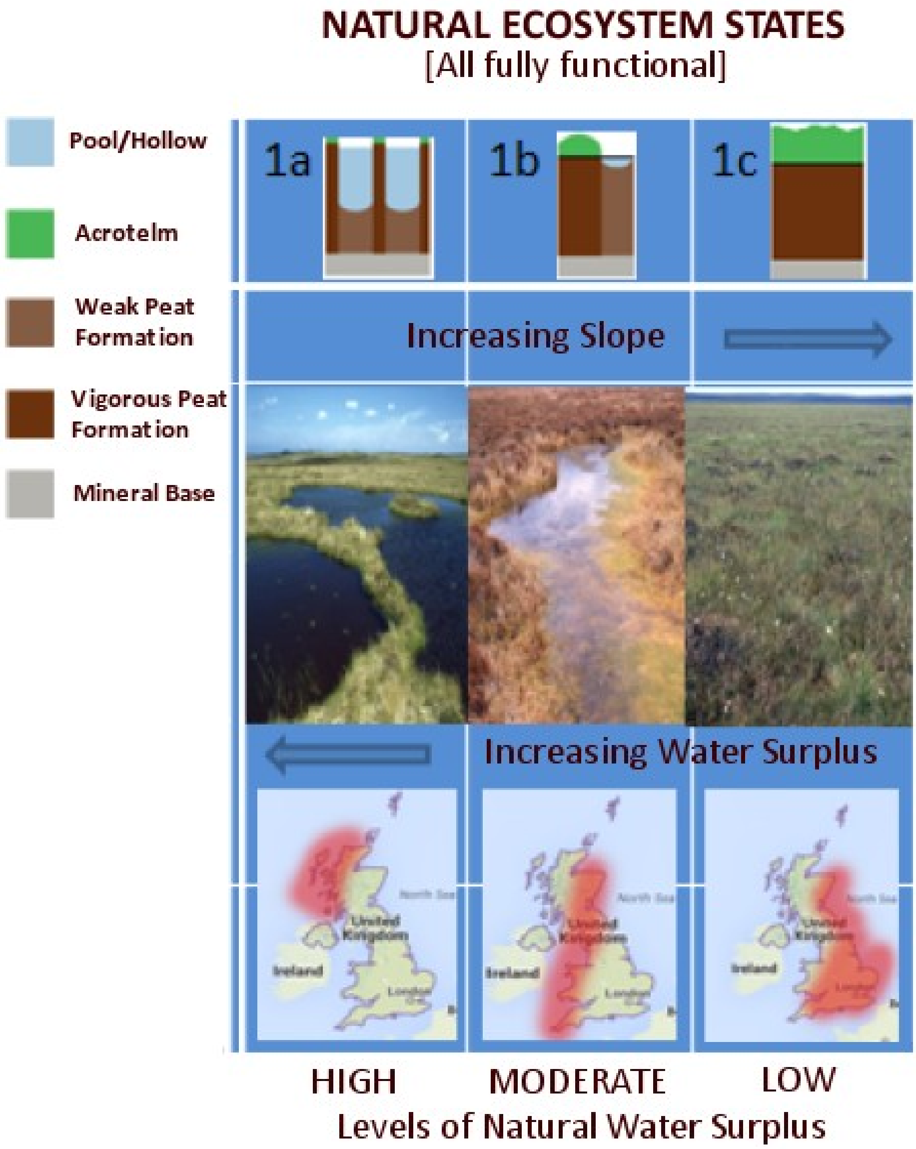
Ombrotrophic bogs tend to have three main surface features [**microtopography**]. The pools and lawns are flat areas of moss and these are interspersed with hummocks. These features are formed at least in part by the plants themselves and produce a gently rolling landscape. Hummocks form out of lumps of moss and other plants.

Over thousands of years, ombrotrophic bogs accumulate peat. They are acidic and dead plant remains do not fully decay. This is because they are mainly an oxygen free environment, except very near the surface. Slowly, they are gradually overgrown by new plant communities. As the bog grows upwards, a record of any change in the plant communities will be preserved. Taking a core down through all the accumulated layers gives an insight into those changes over thousands of years. Sometimes these cores can be over 10 metres deep.

5.1. Natural Ecosystem States – In the UK there are three typical natural bog ecosystem states which reflect the regional climatic conditions. The bog is fully functional in its own respective state.

For a given surface gradient the micro-topography of a bog is determined by the water surplus of the regional and local climate. In the diagram below, the micro-topographic patterns labelled 1a. 1b and 1c represent the maximum likely to be found in the general water-surplus zones shaded in red.

With no human intervention, changes from one state to another are only driven by climate shifts that impact on water surplus. In all three states the important ecosystem functions of peat formation and storage, along with water retention within the peat are maintained.



Source: Lindsay, Birnie & Clough IUCN UK Peatland Programme, Briefing Note No. 2 2014 [Uni East London]

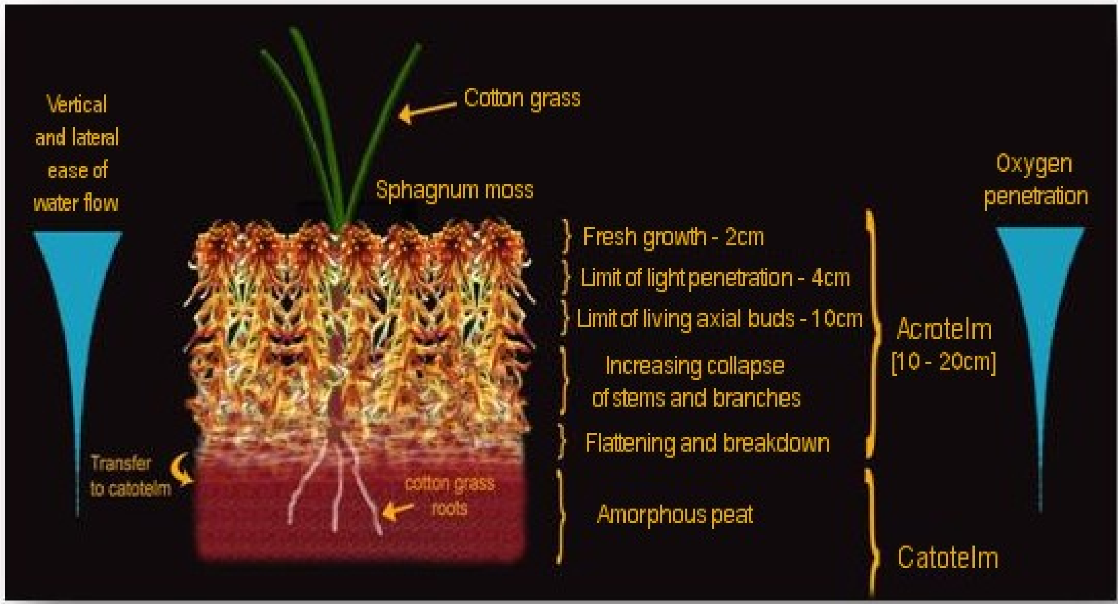
5.2 What is Peat? - Peat is brownish-black in colour and in its natural state is composed of 90% water and 10% solid material. It consists of Sphagnum moss along with the roots, leaves, flowers and seeds of heathers, grasses and sedges. Occasionally the trunks and roots of trees such as pine, oak alder, hazel and birch are present in the peat. Peat is not considered a soil by some soil scientists due to its waterlogged nature, lack of vertical exchanges and poor mineral content. ***Simply, peat consists of the partially decomposed remains of dead plants.***

Humification - This is a process that occurs in soils and peats as organic materials decompose and break down.

Peat bogs have two layers:

- **Acrotelm -** upper biologically active layer, which gets oxygen from the air aiding partial decomposition.

- **Catotelm -** lower permanently saturated layer. Here the water keeps oxygen away. Consequently, low oxygen and low pH values make it relatively inactive and limit the breakdown of peat. **Anoxic environment**



Source: Lindsay, Birnie & Clough IUCN UK Peatland Programme Briefing Note No. 2. 2014 [Uni East London]

Catotelm Layer Chemistry - In most ecosystems the three primary nutrients [nitrogen [N], phosphorus [P], and potassium [K]] needed by plants are recycled. They are leached from decaying vegetation and the soluble nutrients are then available to the growing vegetation. In bog environments nutrient recycling is limited by the chemical and biological properties of the bog.

Decay and leaching occur slowly in the bog.

The most common form of available nitrogen for uptake by plants is the nitrate [NO_3^-]. However, in the absence of oxygen, bacteria break down the nitrate. Using the available carbon provided by the vegetation to serve as an energy source, the bacteria reduce the nitrate to nitrogen gas. The carbon source is represented by a simple carbohydrate [CH_2O] in the equation below.

$$\mathbf{4NO_3^- + 5[CH_2O] + 4H^+ \longrightarrow 2N_2 + 5CO_2 + 7H_2O}$$

The nitrogen gas [N_2] and carbon dioxide [CO_2] are lost to the atmosphere. The reaction can only occur in an anaerobic reducing environment.

The water contained in bogs generally has a low pH around 5.5. The pH scale is logarithmic so a change of one pH unit represents a 10-fold change. The factors that contribute to the low pH are:

- Decaying vegetation produces humic and fulvic acids
- Dissolved carbon dioxide in the water forms carbonic acid.
- In industrial/volcanic areas, rainwater may have a low pH due to atmospheric sulphur combining with the rain water to form sulphuric acid.
- Tannins released by vegetation [adding to the brown colour common in bogs] can also lower the pH.

The complex chemistry of bogs contributes to making them a nutrient poor environment.

There are other important chemical processes as well, such as carbon absorption and cation exchange that create and stabilize the environment. [See Soil PowerPoint]

In Summary - The degree of humification is dependent on how long the plant material that makes up the peat is exposed to the influence of oxygen in the acrotelm. The boundary between the drier acrotelm and wetter catotelm is the **water table**, the position of which changes over time [seasonal] and over longer time scales under the influence of natural climate change. [In more recent times, human induced climate change is a factor too.]

High water tables caused by wetter and/or cooler [low evaporation] climatic conditions, result in less decomposed peats.

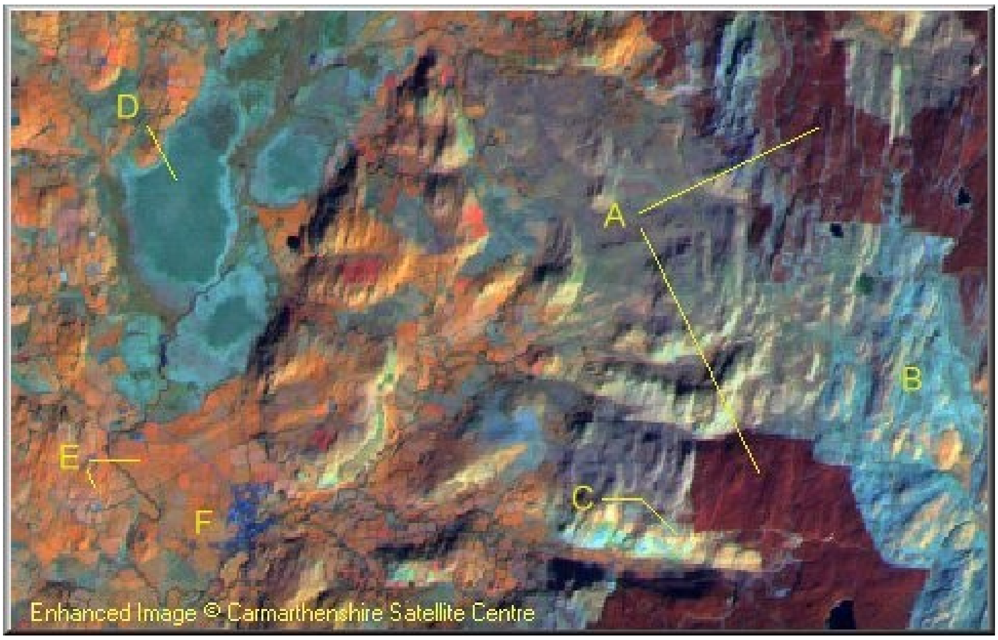
Lower water tables occurring in warmer and/or drier climates cause the peat to break down more as it sits in the acrotelm for longer.

The decomposition of the peat can be measured by its humic acids content. These acids are dark brown, so by extracting them from the peat and measuring the colour it is possible to work out the level of humification. This method has been criticised in more recent years, but peat humification analysis remains a central technique to help understand what is going on in a bog over time.

6. The Development of Raised Bogs in the Teifi Valley – Gors Goch, Tregaron

Location: 1 mile north of Tregaron on the Teifi flood plain. NGR: SN685622

Covering an area of 792ha, Tregaron bogs represent 11% of the near natural raised mire/bog resource of England and Wales. There are three active raised mire domes and two others in the northern and south western sectors of the system that have been destroyed by the extraction of fuel [ceased 1960s] and agricultural reclamation. Significant quantities of peat survive under some fringing fields.



1984 Landsat image – A Conifer Plantations, B Upland Blanket Bog, C Enhanced colour on steep slope exposed to sunlight, D Raised Bog, E Improved grazing, F Tregaron. Source TDW

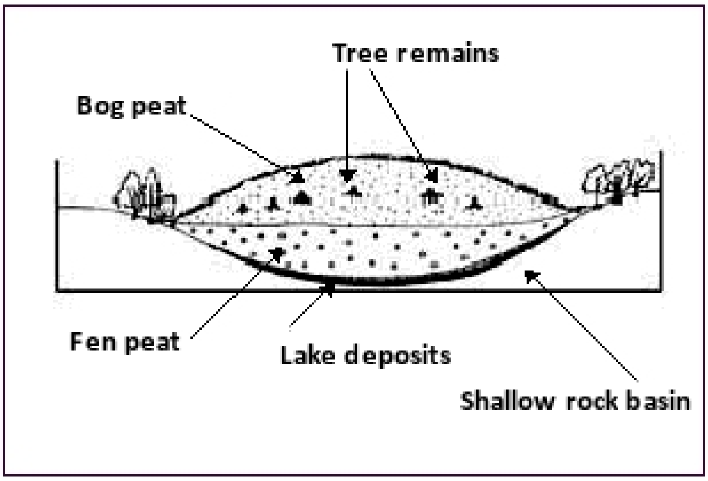
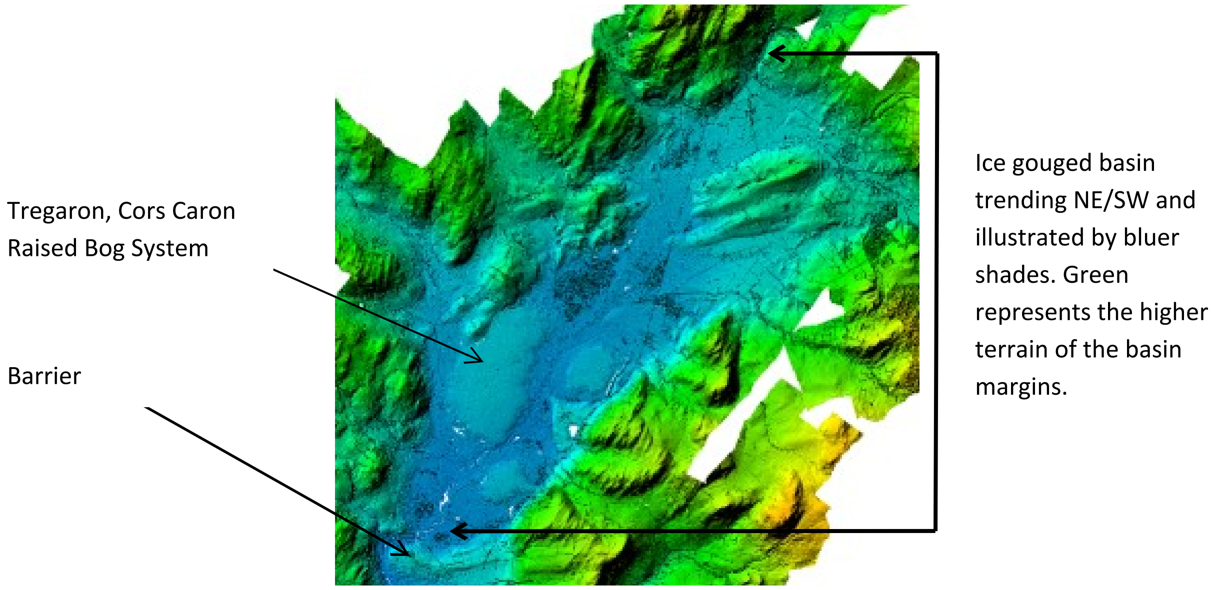


Diagram to show a section through a raised bog. Source: Prof' Mike Walker, UCW Lampeter

Raised bogs are so called because of the domed profile of the peat - highest towards the centre of the bog and gently sloping away towards the edges rather like an inverted saucer.

6.1 Raised bog formation in Mid Wales started at the end of the Younger Dryas[1] just over 11,000 years ago. The ice front had retreated northward in the main leaving large areas of ice to waste away in situ. At this time the evidence suggests that some areas within the Teifi valley were covered by small lakes formed from the melt water. These lakes tended to form where glacial ridges, such as moraines and kames, impeded free drainage and trapped the water. Just north of Tregaron it appears that two glacial features combined to provide a suitable location for such a lake to form :-

1. Late Pleistocene ice gouged out a shallow 10m trough in the valley bedrock.
2. A depositional feature, deposited as the ice thawed, formed a barrier across the valley.



2002, 2m DSM Lidar Data of the Tregaron Raised Bog System – Source TDW

Consequently, in the depression to the north of the barrier a meltwater lake formed. Given enough time, lakes silt up and where the right climatic conditions exist, mires form. In this case Cors Goch Glan Teifi was produced, one of only two large remnants of active raised bog left in Wales.

Welsh Raised Bog Systems JNCC	
Sites of Primary Importance	**Qualifying feature only**
Cors Caron	Afon Eden - Cors Goch Trawsfynydd
Cors Fochno	Afonydd Cleddau/ Cleddau Rivers
Fenn`s, Whixall, Bettisfield, Wem and Cadney Mosses	Cernydd Carmel
Rhos Goch	**Follow these links for brief descriptions. Cors Fochno good alternative, but limited compared to Cors Caron**

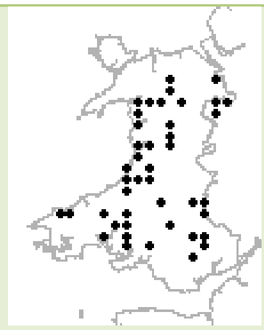
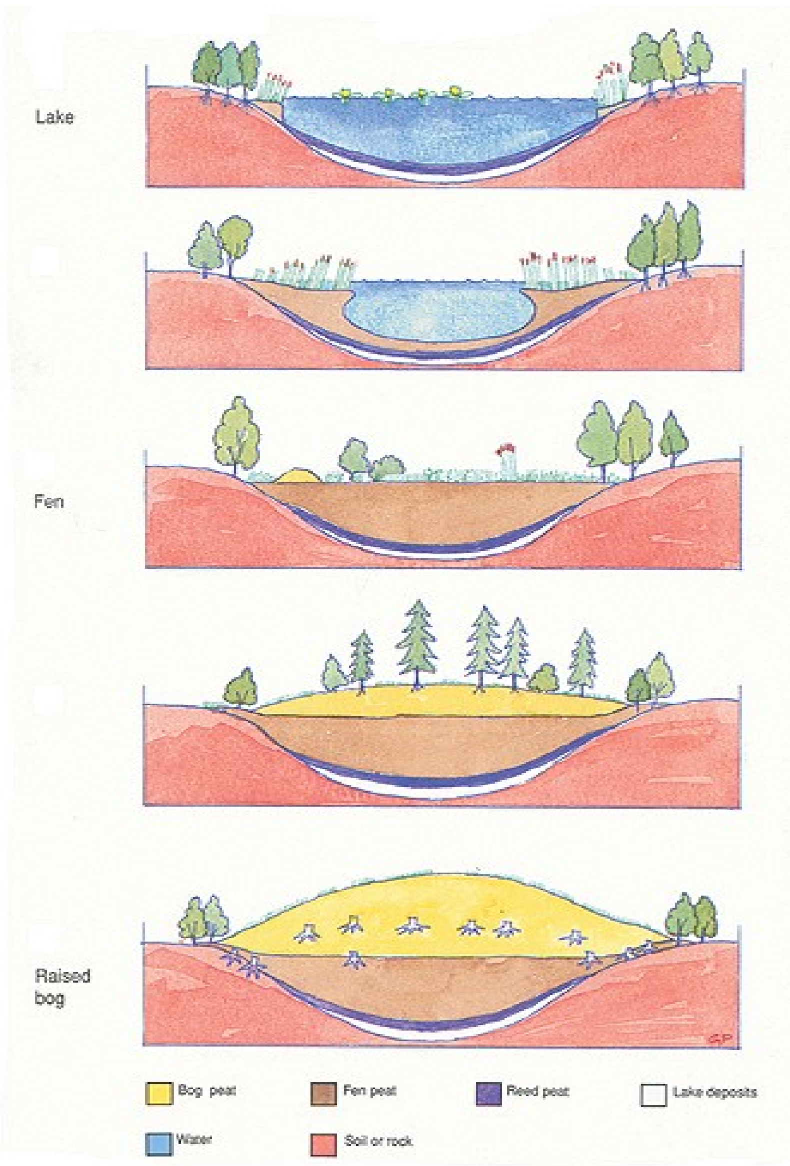


Table 2. Welsh Raised Bog Systems Source: JNCC – Joint Nature Conservation Council - a statutory adviser to UK Government and devolved administrations

1This was a return to glacial conditions after the last glacial maximum, which temporarily reversed the gradual climatic warming

Raised bog formation diagram. Source: Irish Peatlands Conservation Fact Sheet from an original diagram by Cross 1990.

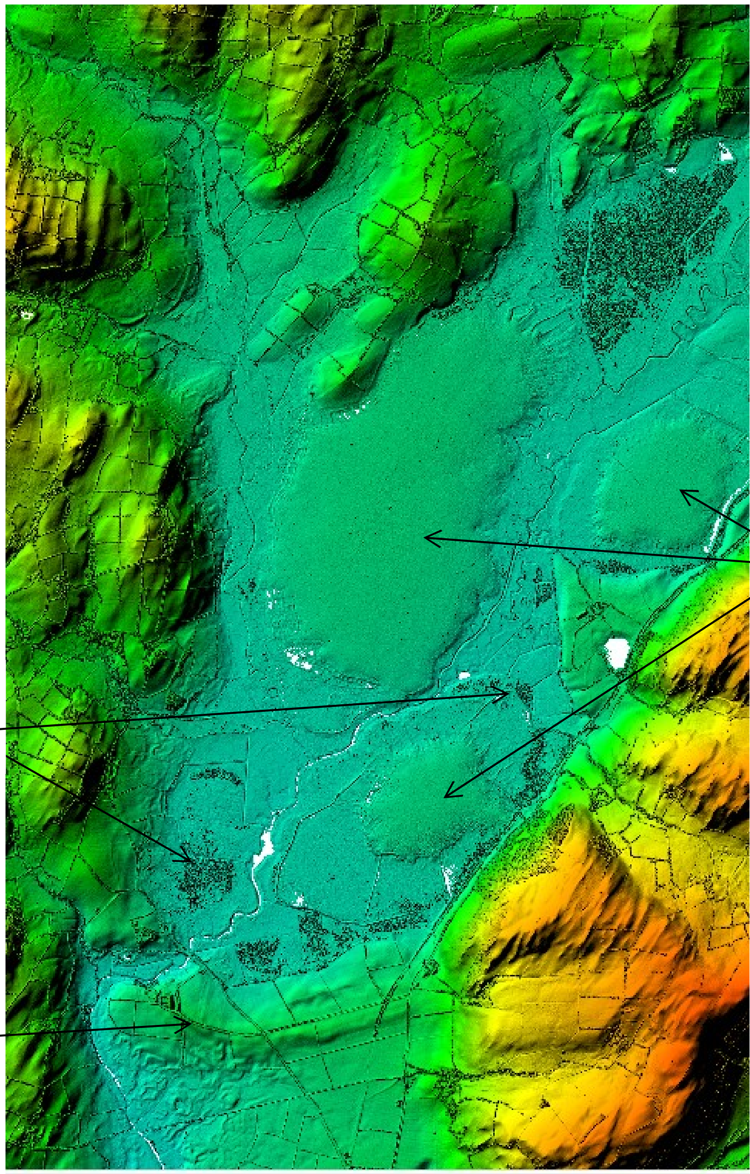


The lake, out of which the bog formed was originally fed by mineral-rich waters and supported floating plant communities. These sometimes produced thin peat layers just above the lake bed.

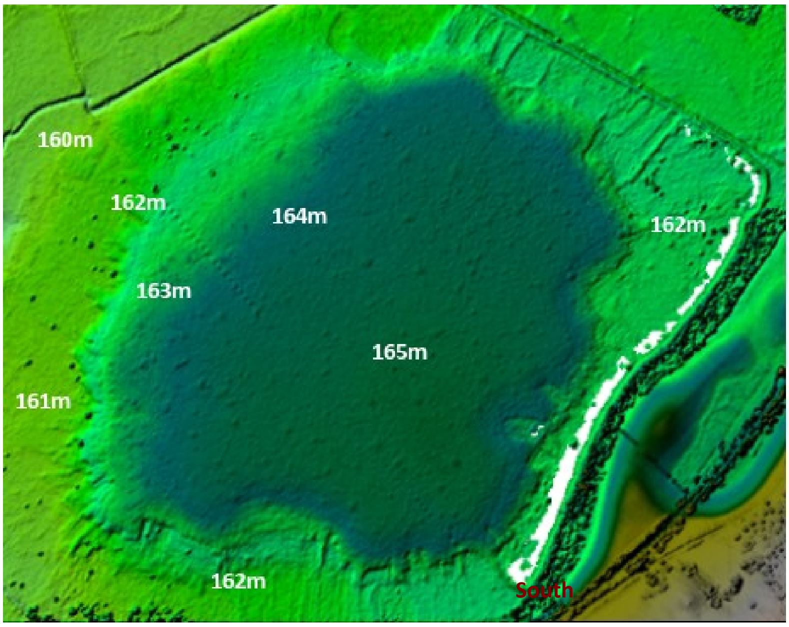
The lake edges were dominated by tall reed and sedge beds. As these plants died, their remains fell into the water and were only partly decomposed. They collected as peat on the lake bed. With time, this process formed a thick layer of reed peat that rose towards the water surface. As the peat surface approached the upper water level, sedges expanded, and their remains added to the accumulating peat.

Eventually, the peat layer in these shallow lakes became so thick that the roots of plants growing on the surface were no longer in contact with the mineral and nutrient rich waters below. When this happened the only source of minerals and nutrients for the plants came from rainwater. This is a very poor source of the essential minerals needed for plant growth. As a result, plants invaded that were able to grow in the mineral-poor habitats on the surface of the peat.

The best indicator of the changing conditions was the invasion of Sphagnum moss. This moss became common and made the ground even more acidic. Plants typical of raised bogs, such as heather [*Erica tetralix*], cotton grass, sundews, sedge and bog rosemary invaded. Where the water table has been lowered, such as the tops of the Sphagnum hummocks, heather, rush and deer grass predominates, producing today's familiar habitat. In some of the peripheral areas adjacent to the raised bog and alongside pools of open water, alder, birch and willow have invaded. Purple moor-grass is particularly prominent on the more modified bog margins. This variation in the vegetation cover stands out well on the satellite and Lidar images.

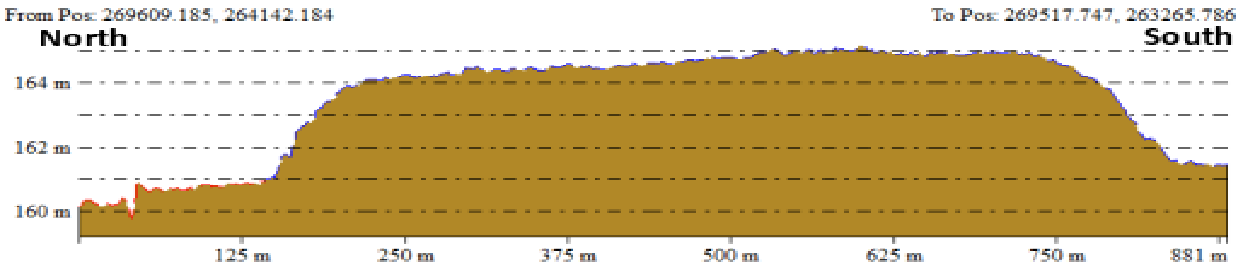


2002, 2m DSM Lidar Data of the Tregaron Raised Bog System - TDW



2015, 1m Lidar Data of part of the East Bog, Tregaron Raised Bog System – TDW

The mottled nature of this image reflects the bog's hummocky surface. The colour shader applied to this Lidar image is based upon elevation and reveals the domed nature of the raised bog. Heights in metres above ODN.



North to south cross-section through the East Bog . The raised bog stands around 5m above the surrounding area and is a little over 650m in length. Some of the larger surface hummocks are up to 11m across.

The Sphagnum is important as it acts like a sponge, drawing up water and keeping the surface of the bog wet and waterlogged, even in the dry periods. So, although the bog continues to grow upwards, away from the water table, the moss ensures that the water table rises in tandem with the rising peat level.

In some traditional ecosystem models, the succession from open water to mire and bog is known as a hydrosere. The raised bog was seen as its final stage. This is not a view that the evidence supports however as there appears to be repeated wetting and drying of the area.

7. Subdivisions of the Holocene Epoch

7.1 The Peat Archive – The plant and pollen species preserved in the peat reveal how the climate and environment of the area has changed over time. During Cors Caron's long history of bog growth, there have been changes in the overall climate of Wales for example. About 7,300 years ago the annual rainfall decreased. This caused bog surfaces to dry, and allowed the invasion and establishment of Eriophorum vaginatum [cotton grass] on the surface of the bog. The presence of charcoal indicates wild fire events. Wetter phases punctuated the record until about 4,500 years BP. At this point the surface of the bog dried out again, this time significantly and a pine wood developed. This woodland persisted for some 500 years, until the climate reverted to a wetter form. Rapid bog growth recommenced as the surface became waterlogged, and the trees died. There is some debate as to the role of early settlers in this process clearing the woodland to improve hunting and grazing.

The Tregaron bog system provides the principle pollen reference source for West and South Wales and helps in our understanding of climate change and the landscape and ecosystems' response.

Subdivisions of the Holocene Epoch

Period	Epoch	Stage	Age BP	Climate	Evidence
Quaternary	Holocene	Subatlantic	2,500 to present	Climatic deterioration – cool & wet	Poorly humified Sphagnum peat
		Subboreal	5,000 to 2,500	Climatic optimum – warm & dry	Pine stumps in humified peat
		Atlantic	7,000 to 5,000	Climatic optimum – warm & wet	Poorly humified Sphagnum peat
		Boreal	9,500 to 7,000	Rapid amelioration – warm & dry	Pine stumps in humified peat
		Preboreal	11,500 to 9,500	Rapid amelioration - subarctic	Macrofossils of subarctic plants in peat
		Younger Dryas	12,800 to 11,500	Near return to glacial conditions. - drastic cooling and drought	Organic component in lake sediments disappears
	Pleistocene	Bolling-Allerod	14,700 to 12,700	Rapid amelioration - warm and moist climate. Transition from Pleistocene to Holocene	Temperate forests expanded, followed by the expansion of evergreen and deciduous forests – Pollen & macrofossils

Figure. Subdivisions of the Holocene. Source:

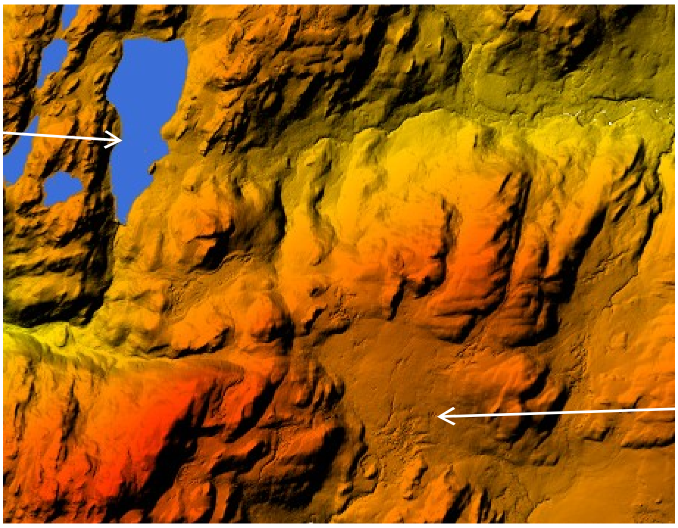
8. The Development of Blanket Bog on the Watershed of the Upper Teifi Valley – Bryniau Pica

Location: On the watershed between the Teifi Pools and Claerwen Reservoir. NGR: SN802659

1997, Aerial photograph of the Teifi Pools/Claerwen watershed looking north. The eroded surface of Bryniau Pica [part] appears in the lower right hand corner.

Altitude: ~455m   Peat depth: 4.6m

In the Elenydd/Cambrian Mountains there are distinct rocky outcrops that trend NNE by SSW. They reflect the highly folded local bedding of the underlying Silurian sediments. However, in places these features are masked by the overlying peatlands.



2002, 2m DSM Lidar Data of the Bryniau Pica Upland Blanket Bog System - TDW

Blanket bogs are typical of the upland areas of Wales, and their shape reflects the contours of the landscape, consequently overlaying them like a blanket! They are ombrotrophic, water-shedding features and are therefore significant sources of water for the water industry. [70% per cent of the UK's drinking water comes from the peat uplands.]

Welsh Blanket Bog Systems JNCC		
Sites of Primary Importance	**Qualifying feature only**	
Berwyn a Mynyddoedd de Clwyd/ Berwyn and South Clwyd Mountains	Cadair Idris	
Elenydd **– Bryniau Pica**	Eryri/ Snowdonia	
Migneint-Arenig-Dduallt	Gweunydd Blaencleddau	
	Rhinog	
Follow these links for brief descriptions. Berwyn or Migneint good alternatives to Bryniau Pica.	Usk Bat Sites/ Safleoedd Ystlumod Wysg	

Table 3. Welsh Blanket Bog Systems Source: JNCC – Joint Nature Conservation Council

Bryniau Pica is a small part of the Elenydd which comprises the largest extent of blanket bog within the uplands of central Wales. Areas of good quality mire are fragmented. In between, large areas have been modified by human activity leaving a vegetation cover dominated by grasses [purple moor-grass *Molinia caerulea], some* dwarf shrubs and widespread *Sphagnum* mosses. Where the habitat is healthy, the wetter mires are comprised of *Erica tetralix* , *Sphagnum papillosum* with locally abundant bog-rosemary. 'Drier' mires see a switch to the heather *Calluna vulgaris* and hare's-tail cotton grass. Areas of pool, hummock and lawn pattern the surface locally, but elsewhere the mire surface is heavily eroded.

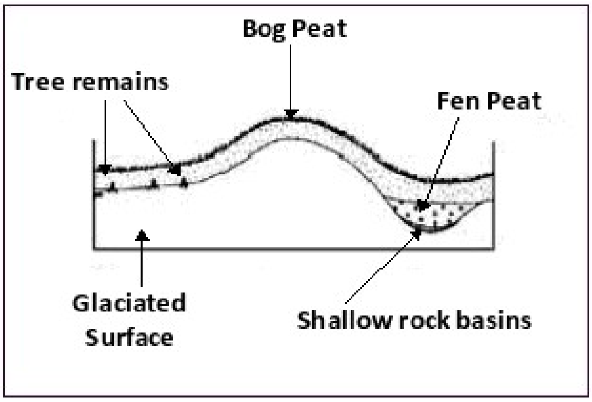


Diagram to show a section through a blanket bog. Source: Prof' Mike Walker, UCW Lampeter

8.1 Blanket bog formation on the glaciated plateau around Teifi Pools also started at the end of the Younger Dryas, however there was a time lag due to the elevation of some 500 plus years, putting the age of the base deposits at about 10,500 years BP. Initially, peat formation was confined to shallow lakes and wet hollows, which had formed in depressions gouged out by the ice. An infilling sequence from open water to telmatic peats[2] and terrestrial peats has been recorded in these areas. Later, peat spread out to form a blanket covering a huge area. It is thought that the initial spread may have taken place as early as

2 Telematic peats, sometimes termed reed peats are developed in very shallow water and consist mainly of reeds.

7,000 years ago, although many areas were not engulfed until 4,000 years ago when the climate became wetter.

Heavy rainfall caused minerals such as iron to be leached from the surface layers of the soil. These were deposited lower down where they formed an impermeable layer known as an iron pan. Water cannot move down through such a layer and the soil surface became waterlogged as a result. Under these conditions the accumulation and spread of peat was made possible.

8.2 What can the Bryniau Pica peat tell us? – It is not all about sphagnum moss accumulation.

At Bryniau Pica there is a 4.6m peat deposit which has accumulated over the last 9,500 years. As you walk across the present eroded surface of the peat you can see the well preserved remains of birch trees that grew in this area some 4,000 years ago! Extract some core data and you find evidence for climatic change as the region swung between wetter and drier conditions.

At some levels it is clear from the wood fragments preserved in the peat that these now open uplands were once extensively covered with oak, hazel and elm. By going deeper, birch and sedge remains point to a wet mire type of environment.

Colour change represents a change in vegetation as the area experienced dryer conditions [lighter brown]. Wet conditions darker colouring.
Not clear in this image but dark black lines are charcoal from dry times when fires occurred. Some of which may reflect early human activities of using fire to clear the area.

Core profile from Bryniau Pica Source: Walker & Wright

Apart from macro-plant fragments –like root, leaf, branch, seed, nuts etc, microfossils also give information.

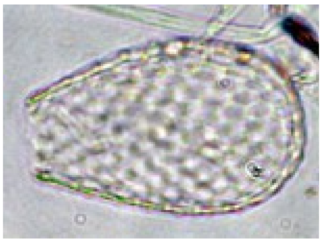
Micrgrphs of birch and oak pollen grains extracted from a peat core.

Microscopic animals also reveal changing conditions and are particularly helpful as climate change indicators over the last 10,000 years. Testate amoebae [Protozoa: Rhizopoda] are unicellular shelled animals which are common in the surface pools of most peat bogs. The tests/shells are also preserved in peat layers as microfossils.

They are sensitive to changes in the hydrological conditions of the peat bogs and good indicators of the depth of the water table. Where a peat bog has a hydrological regime controlled by precipitation, the fossil testate amoebae preserved in a peat core sample can be used to explain past climatic conditions. However, problems can arise as some species are difficult to identify, others are poorly preserved, and we do not have enough current ecological information for some species.

Key markers include:-


A wet indicator - Amphitrema flavum


An indicator of intermediate conditions. - Euglypha tuberculata


Dry conditions. Assulina muscorum

8.3 Where have all the trees gone? - The peat record gives one or two clues to the answer. As the trees die away in the record, heathers and grasses start to appear. Evidence for this comes from the pollen record trapped within the peat deposits along with minute traces of charcoal. This indicates an opening up of the woodlands which is an unusual natural development. The fact that it first occurs some 8,500 BP and then again at around 7,500 BP might suggest that Mesolithic hunters were occasionally migrating into the area. Burning woodland increases variety in the vegetation cover as it recovers, which in turn expands the type of habitat and encourages a broader assortment of prey animals.

More extensive evidence shows up about 5,000 BP and at 3,000 BP which coincides with the expansion of early human settlements in West Wales in the Neolithic.

Why should they wish to clear these areas? – On this occasion it appears that the intention was to extend grazing grounds, possibly in response to a greater number of people sharing the available resources. It might also reflect the human response to climate change. At this point Wales's climate was becoming wetter and cooler. This would have an impact upon the yields produced from the arable farming practices of the time. Expanding the pastoral part of farming perhaps guaranteed a food resource.

8.4 How was such a clearance achieved? - Surely an early axe cannot be equated to the destructive power of a chainsaw? - Returning to the peat record the evidence takes an interesting turn. At the same time that the heathers and grasses start to appear and increase, so to, does the presence of charcoal. The area appears to be managed at this time by a variation of the "slash and burn" method of cultivation employed in tropical rainforests by indigenous people today. If, as it appears most likely, that it was done to extend grazing grounds, then the sheep or cattle moving across this area would ensure that the regeneration of the timber was severely inhibited. The repeated trace of charcoal through the upper part of the peat record suggests that the burning was carried out on a regular cycle. This is very similar to what happens on the Welsh uplands even now, when local hill farmers wish to encourage new growth in the heathers and grasses.

This early human interference has greatly influenced the manner in which this part of the Teifi's upland catchment now works. Being an area of high precipitation, it is a water shedding environment. It is fair to say that more water enters the system from an open upland than an equivalent area which is wooded. More water running off high ground leads to more erosion. Those peats that are now revealing so much about our early history are also disappearing downslope, washed away with the water.

This landscape demonstrates quite clearly the changes brought about by human demands. What the peat archive is revealing - is just how long we have been making those demands, - and how great the ecological and hydrological changes have been.

9. Degradation of Bogs

9.1 Introduction - After 5,500 years, little has changed! Human activities are still having a great impact on the health of Welsh bogs. The following are examples of typical impact sources associated with Welsh bogs:

- Atmospheric pollution
- Grazing [mainly sheep]
- Agricultural improvement schemes
- Drainage, Reseeding and fertiliser applications
- Over-planting with coniferous plantations
- Water storage reservoirs
- Road and rail links
- Quarry stone from uplands slopes
- Walkers, mountain bikers, off-road vehicles use the area recreationally.

When a bog is damaged it is usually the upper acrotelm that is lost. This exposes the catotelm peat to the effects of oxygen, sun, wind, frost and rain and so it begins to weather and erode. Carbon is released into the atmosphere and watercourses at an increasing rate as the exposed surface area increases. A peat bog in this state is termed a ***haplotelmic*** bog [a single-layered bog].

The impact of degradation can easily be misinterpreted leading to an underestimate of the damage. This is especially the case when the invading vegetation looks healthy as is often the case when heathland vegetation invades. Not being a wetland vegetation, heathland vegetation does not add fresh peat. Further, it causes more degradation of the peat through the aerating and drying action of its root systems. In this situation the hummock, pool and lawn topography first reduces in extent and is then lost. It is replaced by a tussock-dominated landscape. By the time the impact becomes more evident, the level of underlying damage has increased dramatically.

Young Molinia [Purple moor grass] –
Developing a healthy looking tussock dominated landscape.

In other instances, the surface can degrade into a full-blown erosion complex dominated by haggs and gullies. Inevitably, these physical changes produce a change in the associated species assemblages.

Comparing the damage transition model [below] with the earlier 'natural states' model [p16], it is possible to see that human induced degradation, drainage for example, can induce changes similar to those occurring under changing climatic conditions.

Peat haggs and erosion gullies.

Threat to Biodiversity - Damage to a peatland ironically often increases the number of species locally by introducing a heath habitat. The invading heathland species out-compete those species more characteristic of peat-forming conditions. As a consequence, some of the peat-forming species are now nationally rare, while others are in steep decline. Loss of such species and their associated habitat thereby threatens biodiversity at a national scale.

Of note: **the majority of UK peat bogs are currently in a state of degradation or recovery. Very little is in a state which can be regarded as 'near-pristine'**.

Stages of degradation can be summarised in diagrammatic form.

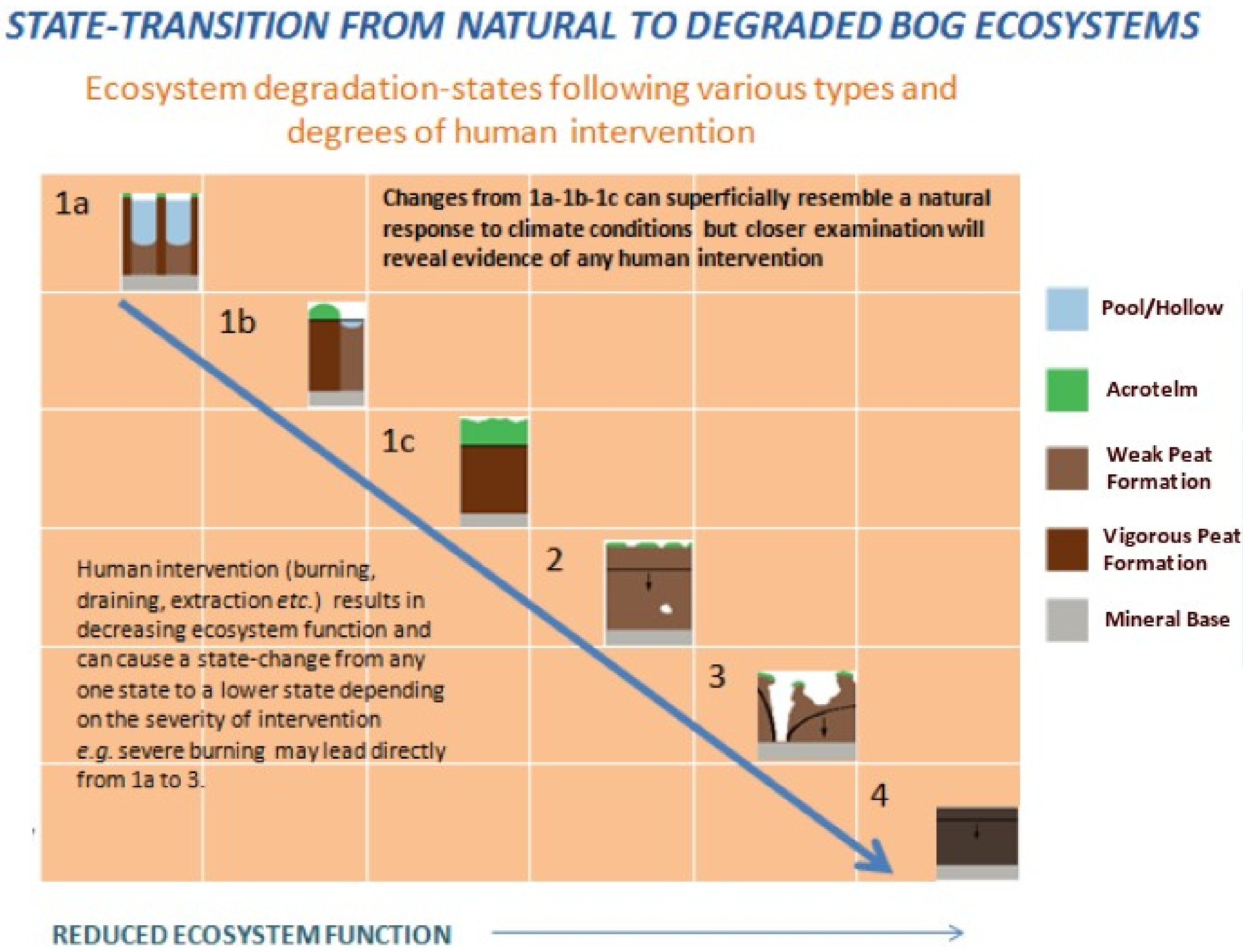


Diagram Source: Linsay, Birnie & Clough IUCN UK Committee Peatland Programme Briefing Note No. 2, 2014

In the Damage Transition Model above the starting points for 1a, 1b & 1c are determined by climate and surface gradient.

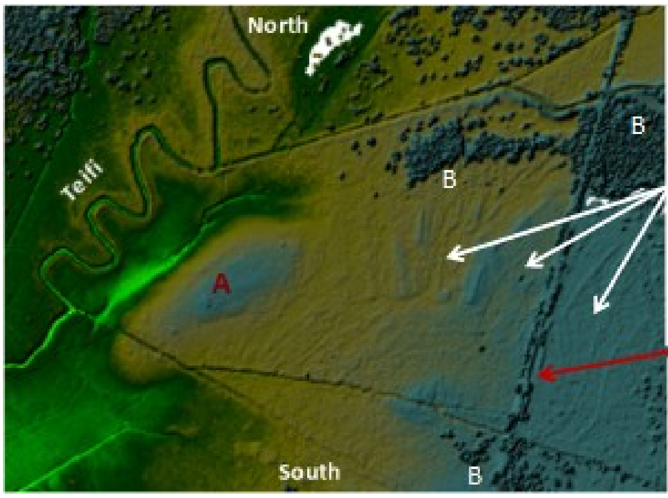
> ***1b & 1c – Drying or drained bog displaying a loss of aquatic zones.***
>
> ***2 - Further drying, or burning – some areas of active bog remain***
>
> ***3 – Hagg and gully eroding bog – fragmentary areas of active bog – losing much catotelm carbon***
>
> ***4 – Haplotelmic bog – all functions associated with an active bog are lost***

***For Cors Goch and Bryniau Pica there is no evidence of exploitation for forestry or economic peat extraction. Therefore, these topics, although important elements of peat bog degradation elsewhere in the UK, are not covered here.**

Bog Degradation - Cors Goch Tregaron.

9.2 Domestic Peat Extraction

Peat has been used as a fuel for thousands of years in the UK. Archaeological evidence exists for its use from Neolithic, Bronze Age and Iron Age sites. On Cors Goch it appears that the historical cutting of peat contributed to the loss of the southern and north eastern units.



*The north eastern part of the bog system was **destroyed long ago through peat digging for domestic use**. [West of Dolyrychain farm] Area around **A** is a remnant section of degraded bog. A similar loss has occurred in the south near Tregaron.*

*The **linear scars** of the old peat workings are still visible on this Lidar image*

***B indicates** areas where alder, birch and willow have invaded*

The Carmarthen to Aberystwyth railway line also crosses the area. The track bed was laid down on a thick bed of withies to stop it sinking into the underlying peat.

In terms of the damage transition model stages 1b, 1c and 2 are represented here.

2012 Lidar image of the North Eastern section of Gors Goch, Tregaon.

Historic setting - Residents of Tregaron, Ystrad Meurig and Pontrhydyfendigiad as well as neighbouring farms cut peat on the bog. Records from 1907 suggests that a family would require six loads a year. An earlier reference from the 19th century indicates 'that as much as one man can cut in one day, supplies a cottage hearth for a whole year. If the cottager has children, they may need to cut peat for two or three days.'
Domestic peat cutting on Cors Caron ended in the 1960s. It is the historic extraction that makes it necessary to include a discussion on the nature of the impact of peat extraction on peat bogs.

Ystrad Meurig family cutting peat on Cors Caron. Note the stack of peat turves in the background.

The domestic cutting of peat is traditionally carried out on individual peat 'banks' which take the form of a cut peat face, often no more than 10 or 20m long, but sometimes extending up to 180m across the bog. The peat is cut using a special spade. Each year the face retreats further across the peat bog. The turves are allowed to air-dry, heaped up for collection and then gathered to form a peat stack which represents the annual fuel supply. Such stacks are therefore normally located close to the dwelling. There are often rights or social agreements about the location of individual peat banks within a community. However, on Cors Goch the cutters paid 5 old pence a day to the landowner and by 1907 a load cost six shillings.

Peat cutting needs to make use of a slope. Any attempt to cut a peat face into the flatter, central parts of the raised bog would produce a trench that is unable to drain.

Around a raised bog system like Cors Caron, you would expect to find a wet lagg fen, which represents the natural transition zone between the deep-peat habitat and the mineral soil/deposits of the valley sides. As at other locations in the UK, the lagg fen zone is fragmentary. In the majority of cases this loss has been caused by domestic peat cutting. Extraction is started on the lower margins and slowly advances upslope towards the centre of the raised bog. The cut peat face acts like a one-sided drain with the result that the water table falls in the area of the bog immediately upslope. This results in a loss of function in the acrotelm, along with a general drying out, shrinkage and collapse of the adjacent peat.

Image showing traditional peat cutting with the exposed retreating peat face. 2012, Falkland Islands

The rate of peat extraction outstrips the rate at which peat is deposited. Peat typically accumulates at about 0.5 - 1mm per year, which means a 1 metre depth of peat can take 1,000 years to form. Individual domestic peat banks may appear to have a relatively low impact on the peatland ecosystem, but the **collective impacts over an extended time period** are devastating. Domestic cutting at Cors Caron is implicated in the removal of two domes within the raised bog system. On other bogs JCBs and 'sausage' ploughs have been used to mechanise the process.

In **blanket bog** landscapes, extensive areas of peat have been dug for domestic use for centuries. Remote upland blanket bogs a long way from human habitation were visited using 'peat tracks' and the turves were transported home using ponies, cattle or carried in baskets. Peat gathering was often a community activity, with neighbours coming together to help each other. There are no records of peat digging at Bryniau Pica. There are however, suspicious scars in the landscape, which might be attributed to historic peat cutting.

Need to Know Impacts associated with domestic peat extraction include:

- ***Cutting removes the acrotelm with its actively growing vegetation.***
- ***The cut peat face acts like a drain with the result that the water table falls***
- ***The acrotelm dries and ceases to function and peat formation is inhibited or stops.***
- ***Heather increases in abundance as the bog dries out. Heather is not a significant peat-forming species. Alder, birch, willow and pine also invade the 'dryer' peat.***
- ***Extensive drying creates cracks in the peat that allows rainfall to penetrate and lubricate the base of the peat just above the mineral sub-soil or rock, provoking mobilisation.***
- ***Where peat banks cut into the edge of deep, wet peat systems it can also initiate massmovement [bog slides], and erosion, which then often spreads across the bog.***

Specific Carbon store impacts relating to domestic peat extraction:

- ***Bulk removal and burning – CO_2 lost to atmosphere***
- ***Oxidation of exposed drying peat - CO_2 lost to atmosphere***
- ***Carbon losses from DOC and POC [lesser extent].***
- ***Reduction in future peat production***

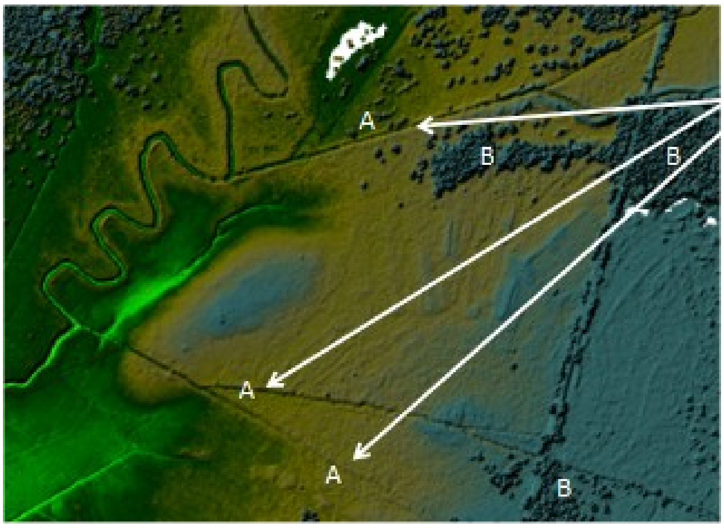
Landscape degradation: ***Not only is the impact clear in bog areas close to settlements like Tregaron, it is also found on isolated upland peat deposits too. Where mechanisation of domestic peat cutting occurs, more dramatic damage to a bog system follows. Such impacts have until now gone largely unnoticed and unrecorded as the heathland ecosystem that invades gives the observer the impression of a healthy ecosystem.***

Bog Degradation - Cors Goch Tregaron.

9.3 Impacts of Drainage

A major impact of drainage is the re-shaping of the bog system

Peat bogs have a **moisture content greater than 95%** in an undisturbed state. Bog surfaces also have areas of standing surface water depending on precipitation/evaporation rates. This water-logging is what creates a peatland and allows it to function. Consequently when humans decide to change the use of the bog area, drainage is generally the first phase. The developer is often disappointed by the lack of apparent impact of the drainage because the anticipated drying effects are limited in extent. Peat within a metre of the drain will still retain more than 80% moisture content by weight. Although disappointing for the developer, this change is sufficient to degrade the bog habitat. In the past, local farmers used Cors Goch in dry periods for grazing and concentrated their attention on improving the margins. However, this changed after World War Two with a general drive towards improving national productivity. Livestock subsidies and improvement grants for marginal areas, promoted by the then Ministry of Agriculture, also helped fuel the drive to improve marginal land.



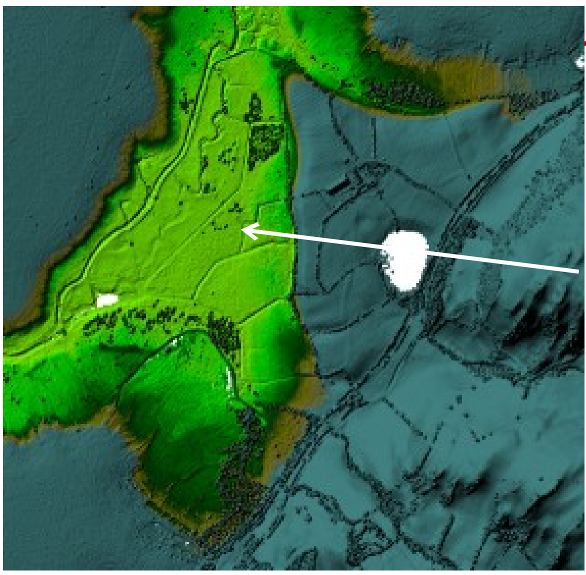
Cors Goch Tregaron - north eastern part of the bog system. [West of Dolyrychain farm]

Drainage channels [A] to improve grazing have resulted in further degradation and in some areas alder, birch and willow have colonised the surface [B].

Although this is a wet area with some peat retained at depth, active peat formation is limited and isolated to small areas.

In terms of the damage transition model stages 1b, 1c and 2 are represented here.

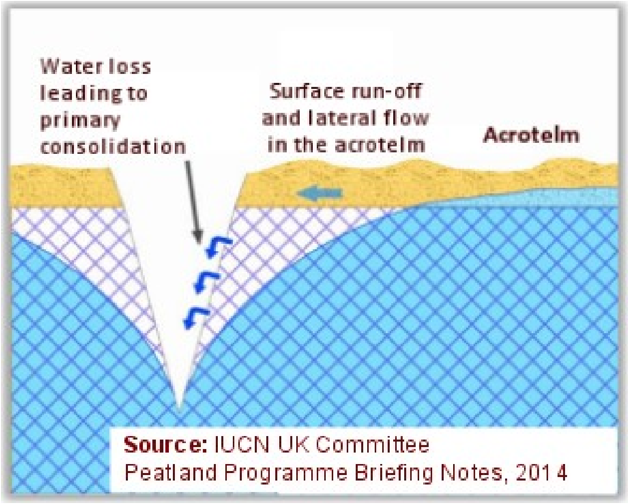
The main long-term effect of drainage is to deflate and re-shape the bog, with major implications for water, carbon and biodiversity. As the rate of change is slow, deflation and change of shape are difficult to record or monitor.



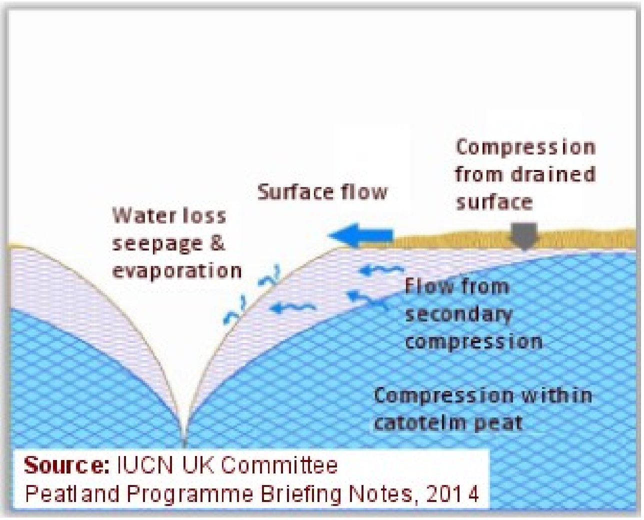
At Maesllyn, ~3km north of Tregaron, the farm has been located on a debris flow and kame terrace at the mouth of a tributary valley. The western fringes of the farm are located on improved bog.

Drainage ditches and hedges/fences are clearly visible on the Lidar image alongside. Peat is preserved at depth, but there is no active peat formation.

Most of the development undertaken on bogs is for agricultural purposes or the extension of upland grouse/deer moors. Therefore, drainage is undertaken to lower the water table to help create a deeper, better aerated soil for exploitation. What makes this so difficult to achieve in a peat bog is that it is only the thin surface acrotelm which can be drained.



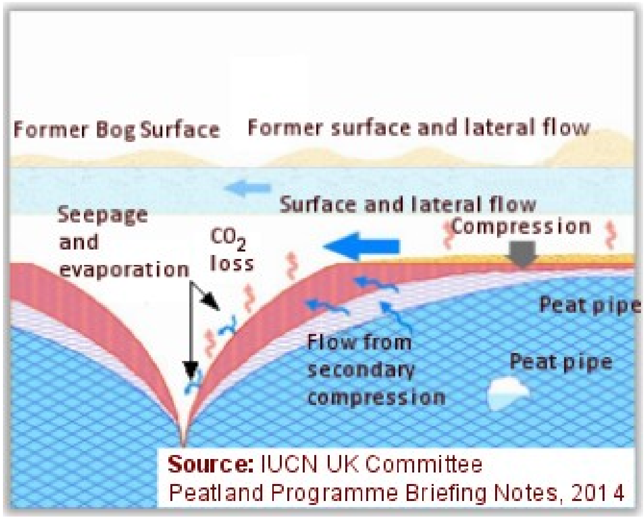
The relatively thin acrotelm layer [10-20 cm] of a bog can lose water vertically and laterally. Consequently, drainage tends to empty the acrotelm of water, sometimes over several hundred metres. From the perspective of the bog ecosystem, however, such effects represent a significant impact. The high and relatively stable water table in the acrotelm maintains the waterlogged environment necessary to support peat-forming conditions. It also allows bog species to resist competition from other plant species which are not normally peat forming.



The impact of drying out the bog - With the drying of the acrotelm and the progressive loss of peat-forming conditions, the acrotelm is no longer capable of providing material to the catotelm. In addition, many of the plant species which invade the dry acrotelm surface have root systems which further dry out the acrotelm and the upper layers of the catotelm.

The catotelm resists drying, but responds instead to water loss by collapse and shrinkage. Water movement in the catotelm is extremely slow, and the lower catotelm layer is particularly resistant to the lowering of the water-table. Drainage tends to promote gravitational loss of water in the catotelm adjacent to the drain only. Consequently, the water table is only lowered adjacent to the drain too. Interestingly, drainage ditches widen over time. This occurs because prior to drainage; water occupied ~ 50% of the catotelm peat volume. It is the loss of this water that results in shrinkage and the collapse of the peat adjacent to the drain. This process is called **primary consolidation**.

Once water has been lost from the peat, the drier catotelm peat adjacent to the drain becomes a heavy load on the peat beneath. The drained layer no longer 'floats' buoyantly within the bog water table. **This load compresses the peat beneath it and squeezes more water from the peat into the drain and allowing the bog surface to deflate further.** This downward pressure can even force water upwards into the drain from the peat below. As a result the entire catotelm peat experiences further subsidence, which is called ***secondary compression***. Secondary compression acts across a steadily widening area beyond the drain and continues as long as drainage is present.

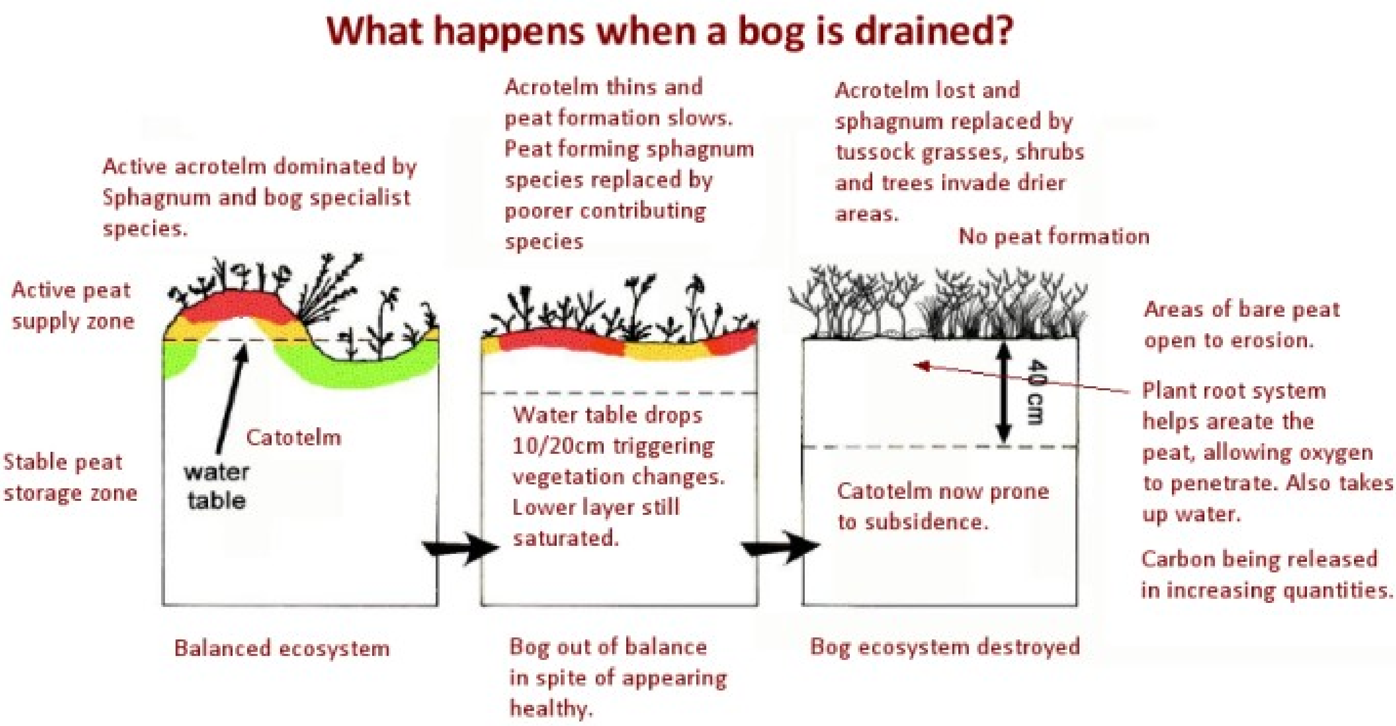


The normal water-logged conditions in the catotelm prevent oxygen-fuelled decomposition. However, once drained, oxygen penetrates the catotelm peat and relatively rapid decomposition takes place. The breakdown produces CO_2, which is lost to the atmosphere and promotes further subsidence. This process is called **oxidative wastage**.

Shrinkage of the peat mass also causes the formation of sub-surface 'peat pipes'. These can work to drain the peat further.

In the fenlands of Lincolnshire and Cambridgeshire, the surface of the fens has deflated by nearly 3m in the last 150 years as a result of large scale drainage programmes. Unfortunately, no reliable data exists for Cors Caron. However, as mentioned above [Domestic Peat Extraction section], a lagg fen peat surrounds raised bog systems like Cors Caron. Observations from other sites reveal that when these areas are drained or removal, over the long-term they cause subsidence across the adjacent raised bog dome. The overall subsidence after the initial rapid effects of primary consolidation indicate that the bog surface subsides by about 1-2 cm per year. Measurements of CO_2 emissions suggest that up to 0.5 cm per year of this may be due to oxidative loss

Impacts on micro-topography and bog vegetation - Bog vegetation is adapted to very stable water table levels. Small-scale groups of species occupy particular zones above or below the water table. Such zones may be no more than 10-20 cm in vertical range. Therefore, a 15 cm fall in the average water table may represent the entire zonal range for a group of species; forcing them to take up new positions within the microtopography, or disappear entirely.



Source: Modified from O'Riley, Trot & Bonn – Field Studies Council & Lindsay, Birnie & Clough IUCN UK Peatland Programme 2014 [Uni East London] The bog surface also loses its **characteristic surface pattern of low ridges and hollows after drainage.**

Where trees colonise raised bogs after drainage, there is evidence that their roots remove water from the system. Water is taken up by roots from the peat and the canopy prevents rainfall reaching the bog surface. In time, the increasing weight of the trees helps to compress the peat, resulting in further subsidence.

Need to Know Impacts associated with draining peat bogs include:

- **Thinning and destruction of the acrotelm with its actively growing vegetation.**
- **Drainage results in the lowering of the water table**
- **Peat formation is inhibited or stops.**
- **Extensive drying creates cracks causing collapse and shrinkage.**
- **Peat surface is lowered.**
- **Heather increases in abundance as the bog dries out. Heather is not a significant peat-forming species. Alder, birch, willow and pine also invade the 'dryer' peat.**

Quantifying the effect of drainage on the bog carbon balance is difficult because:-

- **There are a number of potential pathways for the loss.**
- **Calculating the changing methane to carbon dioxide emissions ratio is difficult**
- **The extent of drainage impacts are not always evident, so identifying the area impacted becomes problematic.**
- **Determining the time frame that applies is similarly problematic.**

Specific Carbon store impacts relating to draining peat bogs:

- **Loss of a functioning acrotelm means loss of carbon-sequestering capacity.**
- **Oxidation of exposed drying peat - CO_2 lost to atmosphere. Greatest alongside drains**
- **Particulate organic carbon [POC] is washed from the face of the drain into water courses. POC losses tend to be greatest when the drains are first dug and during periods of heavy rain.**
- **Dissolved organic carbon [DOC] is released directly into the water forced from the peat by secondary compression. DOC release appears to be most intense during heavy rain following a dry period**
- **If shrinkage pipes are also formed, this provides another route by which POC and DOC can be lost.**
- **The drier nature of the peat reduces methane [CH_4] emissions. Some methane is emitted from the drain bottoms.**
- **Reduction in future peat production**

Landscape degradation: Such impacts have until now gone largely un-noticed and un-recorded as the heathland ecosystem that invades gives the observer the impression of a healthy ecosystem.

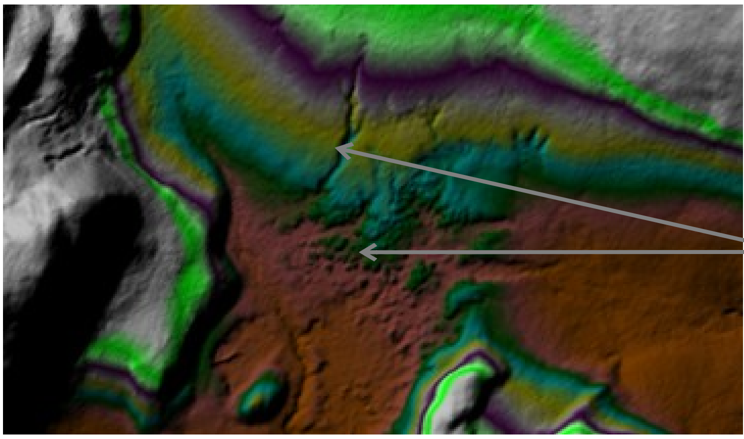
Bog Degradation – Bryniau Pica.

9.4 Impacts of Weathering and Erosion

Bryniau Pica serves as a good example of a blanket bog that is being depleted through weathering and erosion. In fact, this probably began in the Neolithic with early tree clearance. Undisturbed blanket bog peat can have a water content of around 90% to 98% by weight and yet it is draped across slopes of 35˚ or more. Such factors would appear to set up an environment where high rates of weathering, erosion and massmovements are common. In the past, the fact that blanket bog erosion is so widespread in the UK, led observers to the conclusion that collapse and erosion was an integral part of the systems' natural process. However, no convincing evidence has been collected to support this concept. In contrast, research has revealed evidence that links blanket bog weathering and erosion to a variety of human-induced impacts including fire damage, atmospheric pollution, drainage, trampling and overgrazing.

Bryniau Pica - *1997, Aerial photograph of Llyn Egnant and Bryniau Pica.*

The eroded peat surface of Bryniau Pica clearly stands out in this oblique aerial photograph.



Refined contour shading applied to the 2m Lidar data reveals the surface erosion of upland blanket bogs.

Hagg and gully formation. Note the upstream extension.

2002, 2m DSM Lidar Data of the Bryniau Pica Blanket Bog System

Weathering incorporates the processes of physical breakdown and chemical decomposition of material at or near the earth's surface. Freeze thaw, differential heating and chemical attack reduce particle size and create products that are soluble in water. These particles can then be transported away by massmovement and through the process of ***erosion*** by agents such as water and wind. Uplands usually suffer from higher rates of weathering and erosion because:-

- The climate is more extreme

- Slopes are steeper
- Soils are thin
- Rock is readily exposed at the surface.
- Past processes [e.g. glaciation] have attacked the rock surface and removed surface cover.

High precipitation, more frequent frosts, and greater wind speeds assist weathering and erosion. Steeper slopes provide greater potential gravitational energy aiding massmovements and erosion.

Drying peat haggs, crack and collapse. Dry peat is more susceptible to wind erosion.

In some places the acrotelm has been removed and catotelm peat is weathering and eroding also.

Carbon is being released into the atmosphere and watercourses from this site.

Extensive erosion, visible here, equates to stages 2, 3 & 4 on the degradation transition model.

Vegetation in part, acts as a protective layer, insulating bare rock and soils from these processes**.** Some weathering continues beneath a vegetation cover, permitting soils to stabilise and build up, but erosion tends to diminish. Plant roots biologically weather by splitting rock as roots invade cracks. They also release chemicals [living and dead] which breakdown the parent rock or soil.

Blanket mire landscapes in upland regions like Bryniau Pica **should** serve as good examples of these processes. In such inhospitable landscapes the formation of peat results in the stabilisation of the fragile mineral ground surface and the amelioration of processes associated with weathering and erosion.

Where a gully and hagg system forms, weathering and erosion is exacerbated by:-

- Increasing the surface area available to weathering and erosional processes
- The gaps between the haggs act as conduits by which water drains from one pool to another.
- Over time, further drying and collapse extends the gulley system into a quasi-channel system and encourages headward/upstream erosion.
- On the haggs and dryer hummocks heather, bilberry moss and tussock forming grass [*Molinia caerulea]* invade.

Weathering and erosion together can remove peat at rates of **more than 3 cm per year, or ~3 m per 100 years** where rates are maintained. Losses are closely linked to individual weather events. A single heavy storm, particularly after a long dry spell removes more material in a few hours than sustained periods of moderate precipitation. Over recent years Wales has experienced an increasing frequency of intense precipitation events.

Of note: - Given the widespread nature of blanket bog erosion and its ancient origins, **it is surprising how little ground in the uplands has been completely denuded**. Individual gullies may expose underlying glacial till or bare rock, but it is rarely widespread. The answer appears to lie in the natural blocking up of gullies with peat and sphagnum moss debris. This 'seeds' shallow ponds that allow sphagnum to re-assert its presence via a natural re-wetting of the bog.

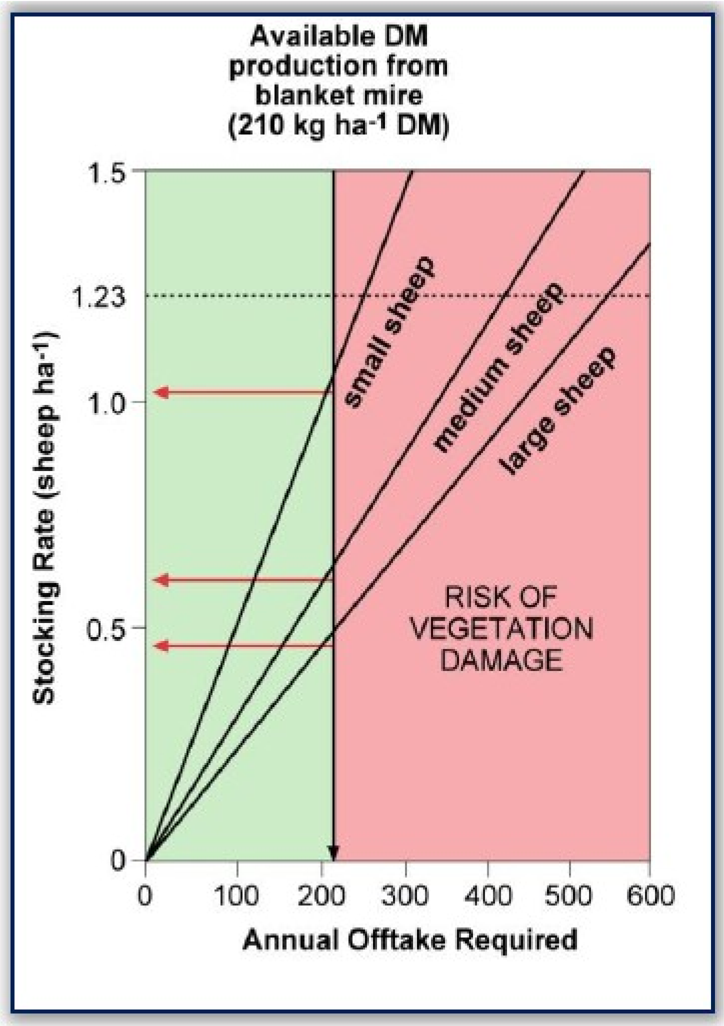
In some areas extensive damage has occurred along the routes of footpaths and tracks as a result of recreational use. This is limited in the Bryniau Pica area.

9.5 Bog Surface trampling and grazing impact [Bryniau Pica] **Watch -** Wind farm Bog Slide

This is the result of long term exploitation of the uplands for grazing. Grazing, browsing and trampling by native wild animals are **components of a natural bog ecosystem.** However, unsustainable levels of grazing and trampling from grazing livestock [sheep, cattle and deer*] have adverse effects on the peatland ecosystem.
*Not a notable issue at Bryniau Pica.

Research evidence suggests that **blanket bog vegetation can sustain wild and/or domestic herbivores at relatively low stocking rates [equivalent to around 0.4 sheep per ha or 1 sheep to the acre].** Higher densities are not sustainable because the total available dry matter produced from a blanket bog ecosystem is low relative to the food requirements of large herbivores. Trampling pressure also becomes significant as it destroys part of this meagre resource. Therefore, even before taking wild herbivore numbers into account, the risk of vegetation damage at low stocking rates, particularly with larger animals is unsustainable.

The graph [right] shows the relationship between sheep stocking rate and annual animal dietary requirements. This issue has now become much more important post-Brexit. In an attempt to make lamb produced on Welsh hill farms more competitive and attractive to foreign markets, hill farmers are being encouraged to produce larger lambs. This means a move away from the traditional hill breeds [Welsh mountain, Ceri & Clun] in favour of bigger, and therefore heavier, breeds. This will increase the grazing and trampling impact on upland areas such as Bryniau Pica.



Source: Lindsay, Birnie & Clough IUCN UK Peatland Programme Briefing Note No. 7. 2014 [Uni East London]

Immediate ecosystem impacts associated with physical damage to the vegetation and bog surface through trampling, grazing and urine/faecal returns.

Livestock often create tracks and small areas of bare peat surface that then become enlarged through erosion. Over many years a **reduction in the annual biomass that is retained in the living surface layer occurs**. This leads to a decline in the thickness of the acrotelm, which makes the site more susceptible to other damaging events.

Keystone Sphagnum species are particularly sensitive to trampling so even the typical small hill sheep breeds cause damage. Evidence suggests that sphagnum cannot withstand more than 1 or 2 trampling events in a year. [Remember, all growth takes place in the head of the plant.] However, in the Welsh uplands the damage caused by grazing has taken place over generations, with a distinct increase in stocking densities post World War Two due to subsidies. A breakdown of the seasonal mixed grazing system of sheep and cattle to a year-round system of sheep only also contributed to the decline**.** Areas where the **level and quality of stock management is low** are also more at risk. For example, much of the blanket bog in Mid-Wales is found on common land and managed under common grazing regulations. In real terms management inputs and investment are poor. Ultimately, it results in a loss of peat forming vegetation and the drying out of the bog surface. In sensitive locations the end-result of persistent high stocking levels is that the acrotelm is lost completely, the drier surface is colonised by non-peat-forming species with expanding patches of bare peat. **The impact on the bog ecosystem is lost because the replacement heather and tussock grasses are healthy.**

In the past, livestock grazing [including deer] has also been intimately associated with burning and drainage of peat bog systems, the former to encourage fresh growth and an 'early bite', the latter to encourage heather or grass growth at the expense of peat-forming vegetation and to minimise the hazard to stock [sheep in particular] posed by very wet ground. Of note, is the input of animal urine/faecal returns, which add additional nutrients to the bog ecosystem. This hits sphagnum particularly and it is unable to compete against those plants that can process higher nutrient levels.

Bog vegetation is sensitive to trampling by humans too. Whether for recreation or scientific research, open country roaming and repeated visits to monitoring points, even if only once a year, can kill the *Sphagnum* in the space of two or three visits.

Summary - Grazing, with its associated trampling, is rarely the only factor involved in the degradation of a bog. Management strategies, such as burning and draining are serious impacts in their own right. It is essential that a reduction in stocking rates to below 0.4 sheep per hectare or the removal of grazing activities altogether must occur to allow the recovery of the vegetation to begin. Heavily-grazed areas which have been largely free from grazing for 10-20 years have been found to show clear signs of recovery in the absence of other pressures.

Sites with a harsher climate, extensive bare peat and high levels of erosion will take longest to recover and may require greater levels of stock reduction and/or wild herbivore control. In all cases, controlled grazing measures should be carried out in concert with other land management measures such as reducing burning and encouraging drain blocking. Any continuation will actively hamper any restoration efforts.

There are no active restoration activities at Bryniau Pica.

9.6 Burning [Cors Goch & Bryniau Pica]

Across the UK, the evidence stored in the peat archive reveals that over the last few centuries burning has been frequent, even in the remotest parts of the country. Usually, this burning has been associated with grazing management for sheep or sporting management for grouse. Both Cors Goch and Bryniau Pica have experienced phased burning as a strategy to improve grazing, primarily for sheep.

Natural fires on bogs are not very common. They are started by lightning strike after a long period of dry weather that has evaporated the surface water and dried out the vegetation cover in places. Natural fires on wet peat bog tend to only burn the surface vegetation and drier features such as hummocks, leaving the wet surface relatively intact. The burning vegetation may, however, cause the peat beneath to catch fire if the peat is unusually dry.

The peat archive reveals that the **time interval** between lightning-induced **natural fires** on an area of peat bog is in the **order of once every 200 – 300 years**. This provides sufficient time for the bog surface and vegetation to recover. If the surface has been burnt to the point where all living *Sphagnum* has been lost, it may take between 80 and 100 years for *Sphagnum* to return on bare burnt peat surface. Full recovery of the ecosystem and its characteristic features is thus a slow process, longer than a single human lifetime.

Human-induced fires on peat bogs, whether as wildfires or as part of a managed burning regime, generally occur 10 times more frequently than natural fires, - roughly every 15-30 years. Over time, such high frequencies lead to a reduction in the Sphagnum cover through increased competition from other species.

Short term studies often focus on the immediate recovery of the vegetation and report a short term carbon gain due to rapid heather growth. This can lead to the mistaken view that burning is beneficial for both the ecology and the carbon store of a bog. However, the damage to the acrotelm leads to the loss of the microtopography. This impacts on the catotelm as it is no longer being supplied with new peat. Further, it is being undermined and dried out through root penetration and water uptake. Aeration increases oxygen and increases carbon loss both to the atmosphere and water courses. In the wetter areas, often dominated by cotton grass methane emissions increase.

Human-induced fires tend to encourage fire-tolerant species at the expense of other peatland species. At fire intervals of around 25-30 years, heather [*Calluna vulgaris*] and a moss carpet develop, which are poor peat formers. At shorter 10-15 year intervals, fire-resistant tussock growth forming species such as cotton grass [*Eriophorum vaginatum*], or purple moor grass [*Molinia caerulea*] prosper. [In Scotland Deer grass tends to be the dominant invader]. Although cotton grass is an important peat-forming species, the tussock growth form appears to be particularly associated with initial stages of peat formation only.
Once peat formation is not possible and the bog becomes 'non active', drying out and surface erosion predominates. A non-active bog means that the bog has lost much of its capacity to respond to external pressures such as climate change and carbon is lost from the store.

10. Restoration

Cors Caron – Raised Bog is currently being restored as an active bog. The main work involves the damming of ditches and the digging of a series of pools to help higher the water table. Monitoring points to register elevational changes and gas emission have also been located across the bog system. To offset trampling damage [details in blanket bog section] livestock is excluded from some areas, while in others; numbers and the duration of the grazing period have been reduced. Raised boardwalks have been built to permit human access for scientific and leisure activities.

Cors Goch bog system at the start of the rehydration programme late 1990s

10.1 Reversing Drainage

Effects - Where drains are not maintained, choking with slumped peat and vegetation occurs. Slowly water levels rise and bog vegetation re-establishes its presence. **Conservation management programmes** actively block drains **to speed up this process**. The open ponded water in the drains is infilled by aquatic plant species. However, these species are poor peat formers. Nevertheless, they do perform an essential function in stabilising a high water table across the adjacent bog surface. The wetter bog surface is then capable of supporting more vigorous peat-forming sphagnum species. Bog vegetation starts to lay down fresh peat relatively quickly as recovery takes place. However, it takes a much longer time to offset the subsidence and restore the bog's former elevation and shape.

Using local spoil to block drains is very cost effective at around £6/£20 per dam. Where undertaken correctly, a drain will infill with sphagnum and disappear in about 30 years.

Damming also reduces flow rates, which in turn slows erosion, reduces bank collapse and peat solids being washed into the local water course.

Invading tree species are also being felled and new growth suppressed.

February 2012 with an expanded pool network.
Source: RCAHMW colour oblique photograph of Tregaron Bog. Taken by Toby Driver

10.2 Re-introduction of new plants is an integral element of restoration at some locations. This is usually achieved by transplanting sphagnum plugs from a healthy donor site. **Cors Goch retains large areas of healthy sphagnum and did not require transplants.**

A novel fast-growing Gel Mix - for restoration of lowland bogs, BeadaGel™ has been used to encourage faster establishment and denser coverage than using the traditional sphagnum plugs obtained from a donor site.

However, the water table needs to be consistently maintained within 10-15cm of surface and to be well controlled to prevent both drought and inundation. BeadaGel™ also requires a mulch cover for establishment. It is:

- Available in 11 species
- Produced from tiny amount of parent source material – No damage to donor sites
- The application of gel mix is quick and easy
- Gel mix contains special protectant to assist water holding
- Requires mulch cover - further protection from desiccation e.g. brash, straw

Have no knowledge of BeadaGel™ being used on Cors Goch.

Greenhouse trials showed that water level in the peat column greatly influences the recolonization success of the *Sphagnum*. Most species reacted positively to wetter conditions. When the water level was close to the peat surface [5 cm below] a density of 450 *Sphagnum* plants/m² resulted in some species covering up to 50% of the peat surface in 3 months and 100% in 6 months. *Sphagnum* cover reached 5-10% after 3 months in the drier areas and was generally comparable to results obtained in the field after one season of growth under shade cloth.

Results from this trial, suggest that *S.fallax* should be favoured above *S.fuscum and S.magellanicum* as a pioneer in bog restoration to stimulate rapid colonization and recovery. Other *Sphagnum* species characteristic of ombrotrophic bogs can then re-establish more slowly.

A Canadian model based on the redevelopment of extractive sites takes 10 years to go from bare peat to healthy growth. Here a staged moss transfer technique has been developed:

1. Cotton grass is used as a first stage cover.
2. Followed by sphagnum plugs.

A sphagnum dominated plant cover is re-established over 3-5 years following restoration and biodiversity and hydrology returns to near pre-harvest conditions.

Although peat starts to form relatively quickly, bog surfaces in a state of restoration are net emitters of CO_2 and methane. Methane emissions are particularly high in the first 5/6 years of the programme especially where cotton grass dominates. Carbon sequestration may start after this 5/6 year period, but takes between 20-30 years to optimise.

10.3 Other benefits of re-wetting - The re-establishment of a functioning ecosystem helps to offset flood peaks. Hydrologists consider the Teifi to be a very well behaved system, flood wise, as it suffers from fewer destructive flood events compared to the Dyfi for example. In addition, POC and DOC release into catchment waters is reduced, which in turn lowers water-treatment costs and reduces threat of trihalomethane production.

In Canada beavers have been introduced with mixed results. In some areas the beaver dams naturally help to flood and maintain water levels. Elsewhere, results have been less favourable with beaver excavations being responsible for the lowering of the water table. There is some evidence to suggest that the beavers help to reduce tree numbers, particularly adjacent to the channels and water bodies. There are plans in the UK to release beavers into the wild following a successful captive programme in S W England.

Alternative local case study - Carmarthenshire Bog Programme

10.4 Restoration of Upland Blanket Bogs

Restored areas on former bare peat surfaces can present tough challenges. In some cases these areas are restored to grassland to prevent erosion of the exposed peat. This has sometimes prompted calls for grazing on the new grassland. The grassland phase, however, is but one step in the restoration process and careful management of grazing levels is needed to aid the transition from grassland to active bog.

Restoration after burning - Where one-off burning has been used on degraded peat bogs as part of the restoration programme to remove the invader plants; evidence shows that it also poses a serious risk of damage to species associated with the re-establishment of a functioning acrotelm.

Evidence suggests that it takes between 80 -100 years for a fully-functioning and biodiverse acrotelm to re-establish itself through natural processes. In order to increase the speed of acrotelm development, re-wetting is generally the most effective strategy. Although some mowing of heather and other invasive species may assist.

Re-wetting – damming drains to raise the water table and slow discharge rates within the channel. Slowing discharge rates reduces bank and upstream erosion. Further, it reduces the peat content in the exiting water and helps alleviate flooding downstream.

Other benefits from bog restoration include:-

- The recovery of bog species and bog ecosystem functions.
- Increased carbon uptake and carbon storage.
- Improvements in water quality.
- There may also, depending on catchment context, be benefits in terms of flood mitigation.

Re-introduction of new plants is an integral element of restoration. This is usually achieved by transplanting sphagnum plugs from a healthy donor site.

A novel fast-growing Gel Mix - for restoration of bogs, BeadaGel™, has been used to encourage faster establishment and denser coverage than using the traditional sphagnum plugs obtained from a donor site.

However, the water table needs to be consistently maintained within 10-15cm of the surface; and to be well controlled to prevent both drought and inundation. BeadaGel™ also requires a mulch cover for establishment. At present it is:-

- Available in 11 species
- Produced from tiny amount of parent source material – No damage to donor sites
- The application of gel mix is quick and easy
- Gel mix contains special protectant to assist water holding
- Requires mulch cover - further protection from desiccation e.g. brash, straw

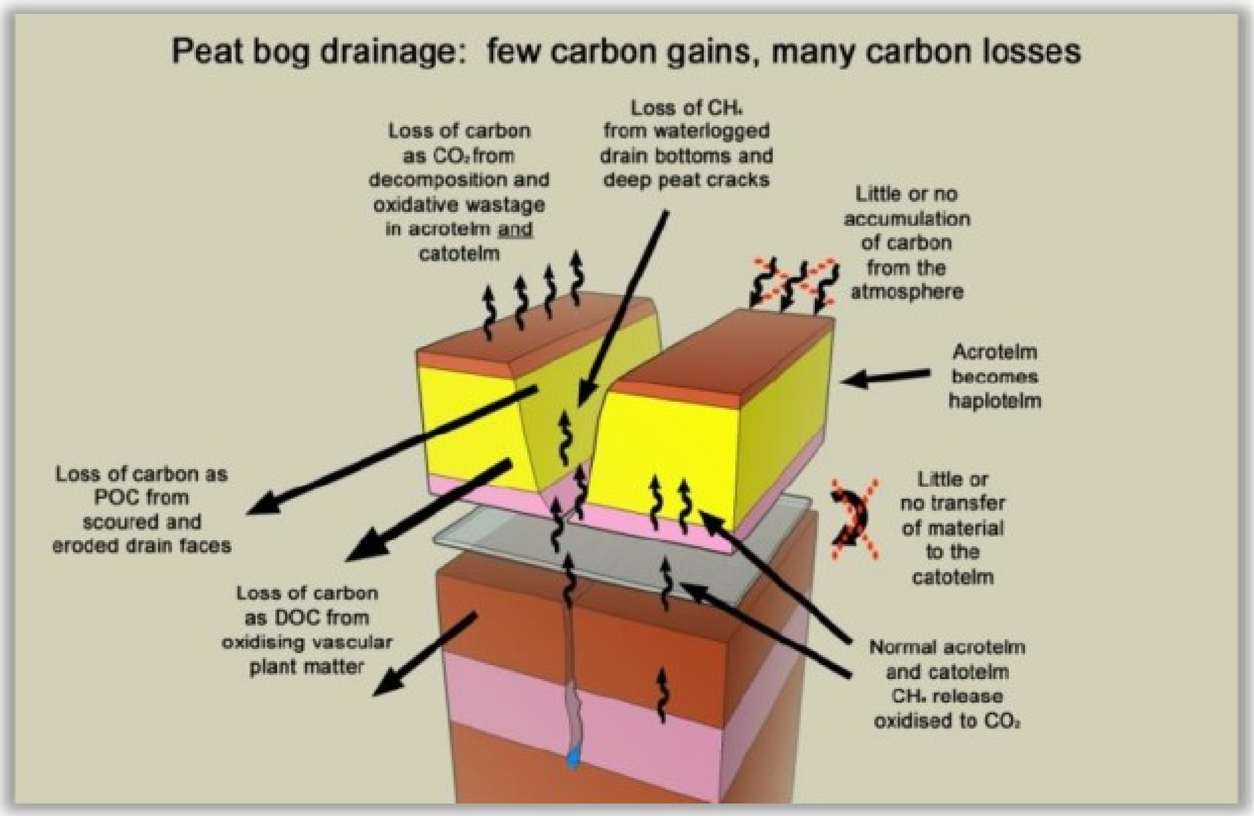
Where this has been trialled in upland areas some reports suggest low survival rates. Also transporting the mulch material to an isolated site can be expensive and requires specialist machines. Consequently, re-seeding large areas is difficult.

Sphagnum plugs - 50,000 plugs of sphagnum moss have been transplanted from an upland Ceredigion donor site, to Dove Stone in the Peak District as part of a bog restoration programme.

Sterling moss Welsh moss gives new hope to degraded Peak District bog

Reseeding of a blanket bog often requires a mini-bund to be dug around the area to retain water and the new sphagnum plugs are protected by mulch. This can be straw transported in from the lowlands, or heather brashings from the uplands. If the sphagnum plugs are being transported in from a distant donor site too, this all adds to the cost of restoration. Given that the location of upland blanket bogs are often isolated, moving people and machinery onto the site on a daily basis is expensive in terms of time and cost. The duration of the projects can also be lengthened by frequent poor weather conditions.

11. Carbon Release From Degrading Peat Formations



Particulate organic carbon [POC]   Dissolved organic carbon [DOC]   Methane [CH_4]   Carbon dioxide [CO_2]
Source: Lindsay, Birnie & Clough IUCN UK Peatland Programme 2014 No. 3 [Uni East London]

As mentioned elsewhere, blanket bogs represents the **largest accumulated terrestrial carbon store** in the UK. Unfortunately, they are now **actively losing carbon at the rate of around 3.7 Mt of CO_2e** [equivalent] **each year,** which is similar to the annual emissions from 700,000 households.

This reflects the fact that the majority of UK's blanket bogs are now degraded. Over 50% are without peat forming vegetation and only about 18% can be described as being in a "near-natural" condition. The remainder are in varying states of damage and collapse.

When blanket bog erodes it can **produce over 30 tonnes of CO_2e per hectare per year**. [See the above diagram for more detail.] Some is directly lost to the atmosphere through oxidation of the peat. High levels of particulate [POC] and dissolved organic carbon [DOC] are carried away by water. **This** significantly reduces water quality and substantially increases water-treatment costs. Downstream fisheries and flooding patterns may also be affected by increased peat sediment.

11.1 Conwy Carbon Catchment: Prof Chris Evans

Data collected so far at the Conwy watershed site suggests that the peat is a large source of both dissolved organic carbon [DOC] and methane [CH_4] emissions.

- DOC ~22g C m^{-2} yr^{-1}
- CH_4 emissions ~6 to 8g C m^{-2} yr^{-1}.

These values could be representative of upland blanket bogs across Wales.

Source: Carbon losses from all soils across England and Wales 1978–2003 - Pat H. Bellamy, Peter J. Loveland, R. Ian Bradley, R. Murray Lark & Guy J. D. Kirk

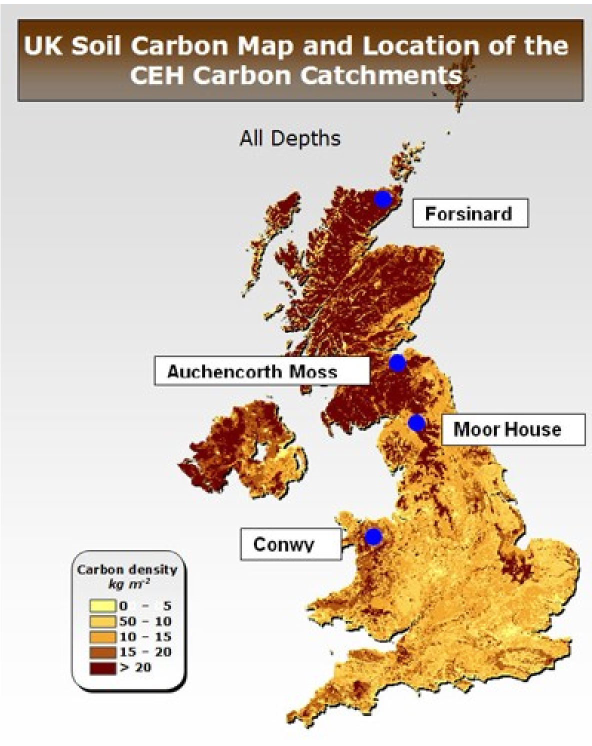
Carbon was lost from soils across England and Wales over the survey period at a mean rate of 0.6% yr^{-1} [relative to the existing soil carbon content]. Findings reveal that the relative rate of carbon loss increased with soil carbon content and was more than 2% yr^{-1} in soils with carbon contents greater than 100 g/ kg^{-1}. The relationship between rate of carbon loss and carbon content is irrespective of land use, suggesting a link to climate change. Further, these findings indicate that losses of soil carbon in England and Wales—and by inference in other temperate regions—are likely to have been offsetting absorption of carbon by terrestrial sinks.

Interestingly, methane emissions are known to increase as re-wetting of bogs occurs at a greater rate than carbon dioxide uptake. Apart from the physical conditions that support its release, research has now revealed that cotton grass actively encourages methane production. Current research suggests that this equals out after 5/6 years and from then on carbon sequestration predominates, albeit at minimal values to start.

A healthy bog systems sequester carbon at 15g C /m^2/y

Of note: Bogs are also a sink of nitrogen, which as released is available to react in various ways too. Atmosphere & water courses. European bogs are subject to greatest nitrogen deposition as a result of atmospheric pollution and wind-blown dust carrying agricultural fertiliser. Increased nitrogen in the bog ecosystem is associated with shrub invasion.

Cover	Blanket bogs	Acid Peaty Upland soils
Wales	3.3%	9%
England	2.1%	1.6%

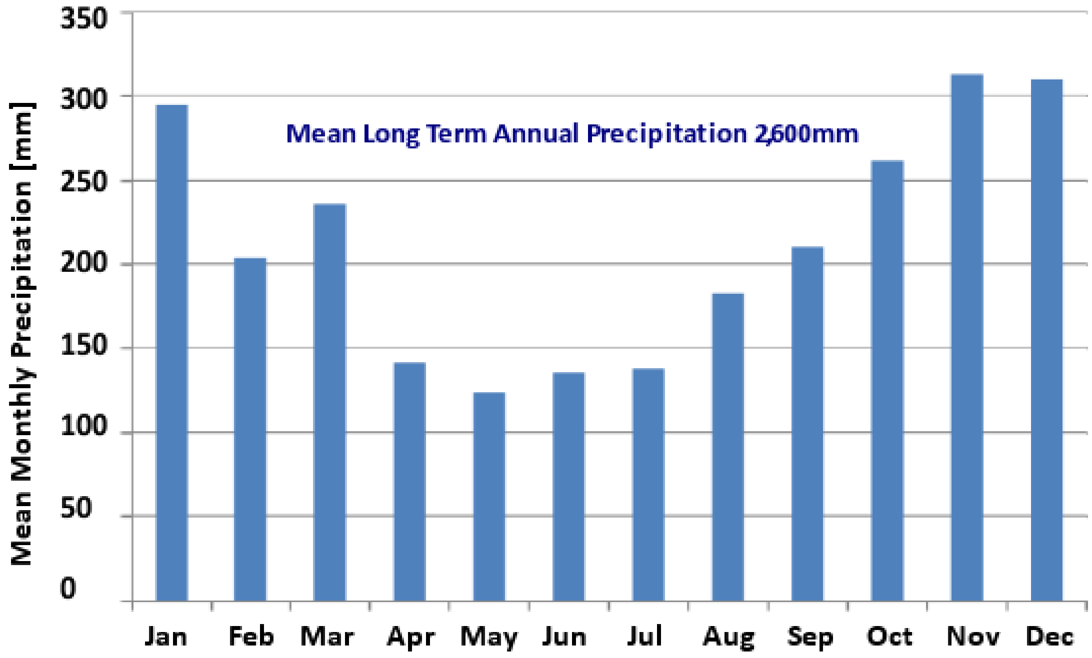


Centre for Ecology & Hydrology [CEH]

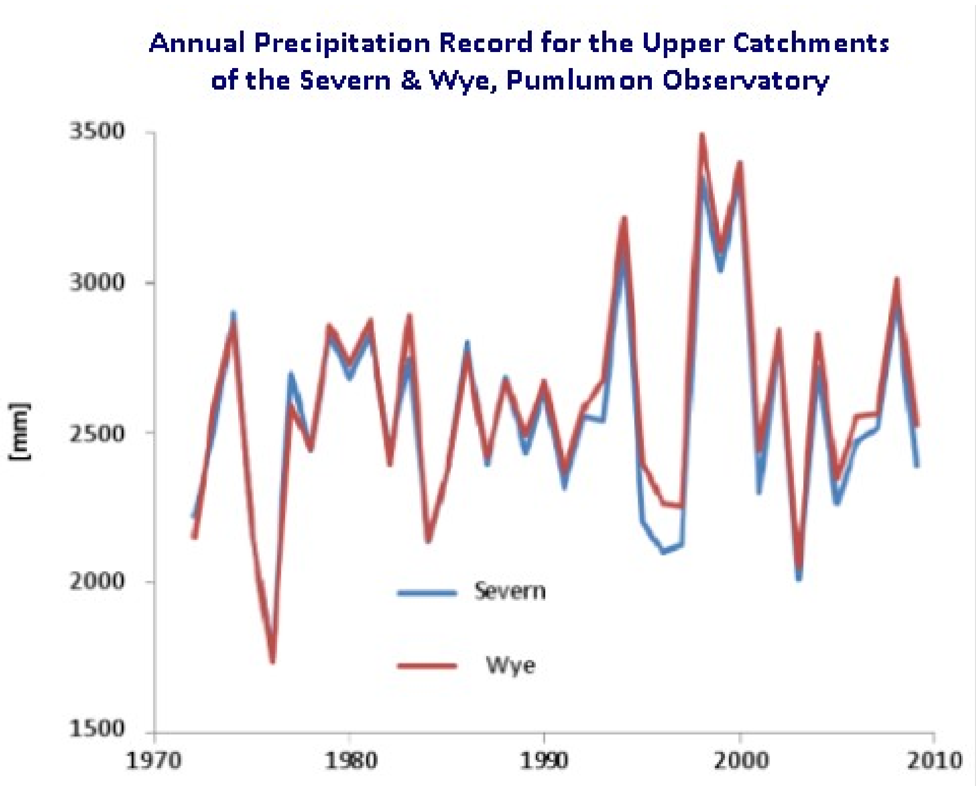
In the UK peatlands cover ~15% of the land area and store >1400 Mt of carbon

12. Additional Resources

12.1 Climate Data for Upland Blanket Bogs. [Based on Pumlumon Observatory ~26km north of Bryniau Pica]

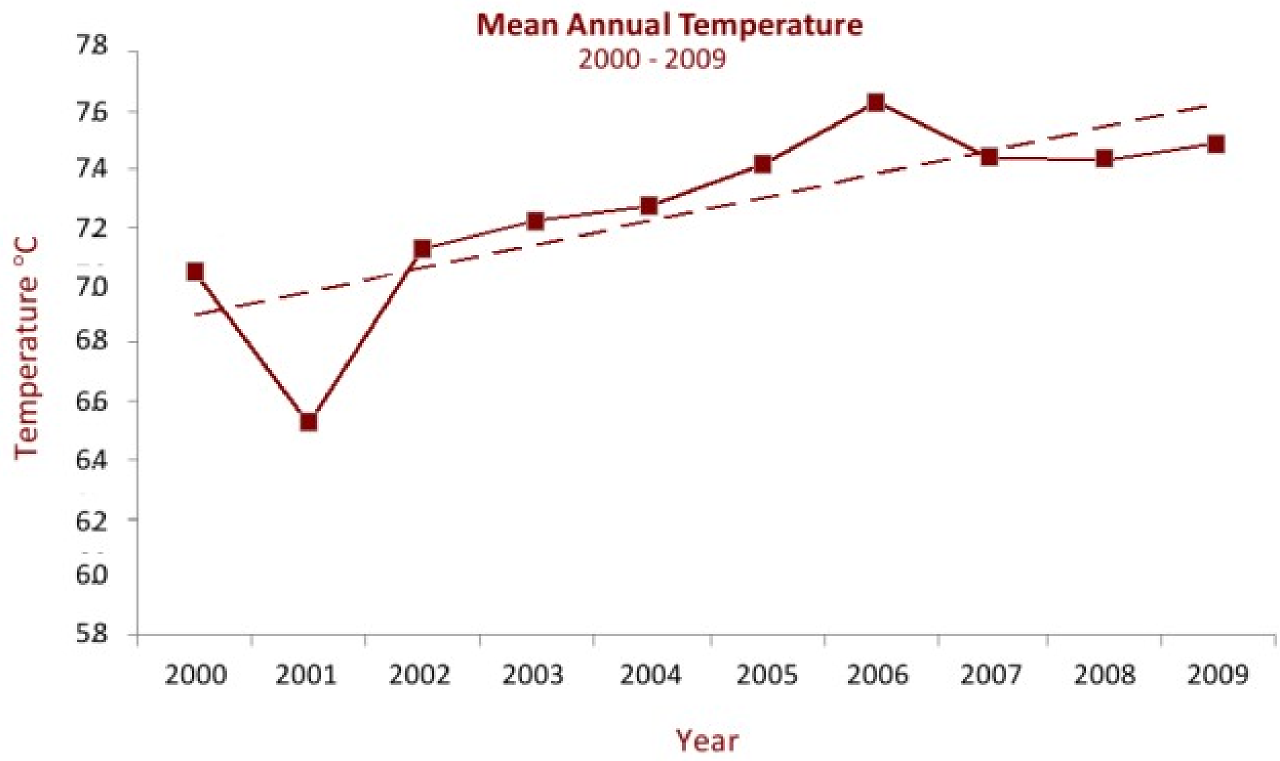


The upland study site of the Pumlumon observatory has mountainous topography with altitudes ranging from 320m to 740m, and slopes typically of 5 to 15 degrees. Bryniau Pica is around 455m an Cors Goch 165m.



Records began in 1972. Of note, rainfall delivered in more intense events is increasing. October to January are the wettest months, with April to July being the driest months of the year.

Evaporation for the upper catchment is about 500mm per year.



Slight increase in mean annual temperature over the decade, in spite of experiencing two unusually cold winters.

Elevation [m]	575	530	380
Mean wind speeds*	4.35m/s	4.41m/s	2.96m/s
Mean Temperature [°C] 1979 - 2009	6.94	6.13	
2000 - 2009	7.77	7.31	7.88

*Impact of forestry shelter in these areas.

12.2. Peat bogs and Climate Change

Over the past 10,000 years peat bogs have been a cooling influence upon climate through their sustained sequestration of carbon. [0.4/0.5°C]

General climatic constraints - Peat bog water supply comes exclusively from precipitation. To function effectively and remain waterlogged they are highly dependent upon the frequency and amount of precipitation they receive. Saturated air ensures that the precipitation inputs cannot be lost back to the atmosphere through evaporation or transpiration. *Sphagnum* mosses take water up easily because they do not have a waterproof cuticle. Consequently, even the low cloud/hill fog as is frequently found on Welsh uplands, make an important contribution along with dew. Air temperature is also important because as air becomes warmer it can take up more moisture before becoming saturated, but equally release more when it cools. Therefore, the prevailing westerly and south westerly air streams originating over a warm Atlantic deliver high moisture content to western Britain.

The diagram alongside illustrates the importance of the UK's location with respect to the prevailing winds at these latitudes. As the mild/warm winds are forced to rise and cool, condensation occurs. This ensures copious amounts of precipitation.

Climate Change - Precipitation patterns and air temperature are widely regarded to be key factors in climate change. Consequently, concern has been growing about the possible impact of climate change on peat bog ecosystems. Current **climate models** based on greenhouse gas emissions scenarios for the UK **project higher temperatures, generally drier summers and wetter winters.** The degree of change will be influenced by the level of emissions achieved. Rainfall is also expected to fall in heavier rain events.

A number of studies suggest that UK peat bogs will experience lower water tables during the summer, which will have a negative impact on their ecosystems. Furthermore, future-climate models are at their weakest when predicting cloud cover, air humidity and events such as hill fog and dew-fall. - All important factors in terms of bog preservation. Evidence from the peat archive however, indicates that drier conditions, and thus lower water tables, have occurred in the past and yet the peat has often continued to accumulate even during these periods.

This resilience in the face of climate change has been linked with the surface of active bogs whereby, in dry conditions, pattern structures such as pools become overgrown as ridges and hummocks expand. Individual Sphagnum species typical of wetter conditions are replaced by Sphagnum species more suited to drier conditions. Not only are these 'dry climate' Sphagnum species adapted to lower water table levels predicted in current climate models, but they are more resistant to decomposition than species which dominate during wetter climate phases. This suggests that during drier phases the rate of peat accumulation might actually have increased.
Furthermore, the Sphagnum carpet may remain extremely damp just a few centimetres below the drought-bleached surface layer.

This **resilience in the face of past climate change** has resulted in almost continuous peat formation for, ~10,000 years in the UK. Such **adaptive capacity however, relies on the presence of an 'active' living peat bog surface**. Human impact is therefore the key to future survival. Recent surveys indicate that more than 80% of UK peat bogs now lack an active living surface as a result of human activity. Under these conditions, bogs have little or no capacity for resilience in the face of climate change. Restoration of UK peat bogs to an active state is therefore essential.

Unprotected peat eroded by heavy rainfall

Other key climate change factors - Increased temperatures may lead to increased decomposition of peat-forming material in active, healthy bogs, although this is still an issue of debate. However, in peat bogs which lack a healthy acrotelm they are already losing their long-term carbon store and will do so at an increasing rate under predicted changes to the UK climate. As well as carbon loss directly to the atmosphere through **oxidation** of the peat, unprotected peat will be **eroded** from the un-vegetated surface by heavier rainfall events leading to **further carbon loss and reduced water quality**.

Bogs most at risk are those **degraded haplotelmic bogs**, [no acrotelm with peat-forming species] which are dominated by areas of bare peat and species that are poor at peat forming. Without an acrotelm with its peat bog flora, these **haplotelmic bogs are unable to respond to climate change with any stabilising feedback mechanism**. The most likely response is increased decomposition and degradation of the peat stored in the unprotected catotelm, which will lead to high rates of carbon loss. Even where restoration programmes are in place on degraded bogs, the reduced complement of peat forming species and/or poor *Sphagnum* cover, may not be sufficient to provide the necessary resilience for climate change.

Benefits of addressing the issue
The benefits of a bog restoration programme are:

- Improved carbon capture
- Improved carbon storage.
- An active bog capable of a biotic response.
- Increased peat bog biodiversity.
- Improved water quality.

Practical Actions

- Restore 'non-active' bogs to an 'active' peat-forming state.
- Restore partially-damaged active bogs to increase adaptive resilience to climate change.
- Investigate detailed record of climate-change responses contained within the UK peat archive.
- Adapt existing climatic models or create new models for UK peat bogs, incorporating the species/patterning biotic response.
- Measure and model potential inputs from occult precipitation (fog, mist, dew) under differing climate scenarios.
- Monitor the effects of climate change on peat-forming species such as growth rate and cover and assess the contribution of restoration work to this.

12.3. Managing Nature to Aid Carbon Capture

The Earth's carbon resides in four broad sinks:

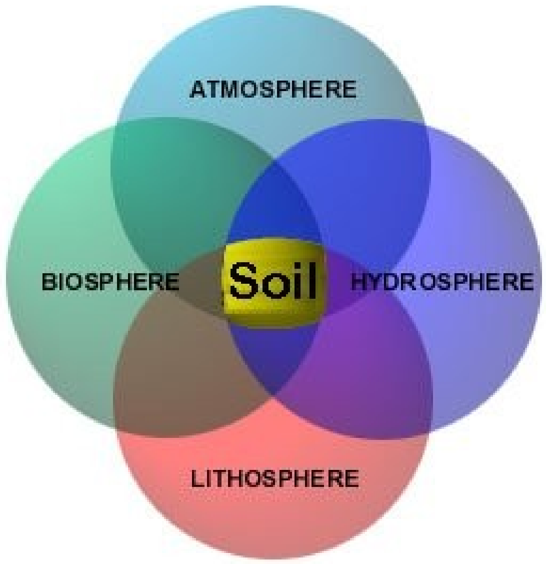
- The crust,
- The oceans,
- Terrestrial ecosystems
- The atmosphere.

The terrestrial carbon sink can be subdivided into:

- The biotic [the carbon in living organic matter]
- The soil sink.

Total carbon in the soil sink, down to 2m depth, has been estimated to be ~ 3000 Gt, mostly as soil organic carbon [SOC] ~ 2400 Gt. This is over twice the combined atmospheric [760 Gt] and above-ground terrestrial biotic sinks [560 Gt] and underlines the importance of soils in the global carbon cycle.

Soil



Juma and Nickel

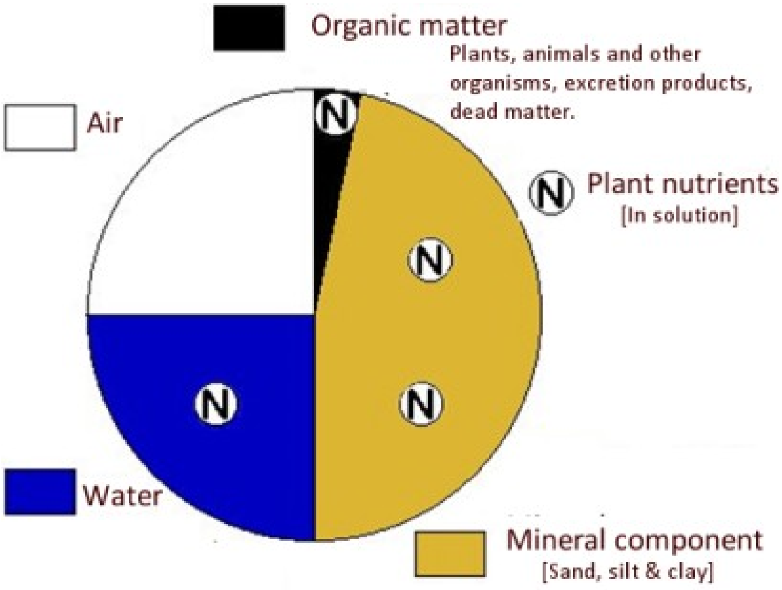
Definitions

- **The stuff in which plants grow!**
- **Soil is the biologically active, structured porous medium that has developed below the continental land surface.**

  All soils are composed of the same basic materials. However, proportions vary greatly from one soil type to another.

Individual soils are made up of four main constituents: *water, air, mineral components and organic matter* [humus].

The diagram below shows the average composition of a British agricultural soil. Generally, the *soil air and soil water occupy about 50% of the volume*, the *organic matter* consisting of living organisms and their products or by-products accounts for *5%* and the remainder is occupied by the mineral component**.**



Soils contain **o**rganic **m**atter [SOM]. Soil organic matter is the fraction of the soil that consists of plant or animal tissue in various stages of breakdown. It includes:

1. Plant residues and living microbial biomass.
2. Active soil organic matter also referred to as detritus.
3. Stable soil organic matter, often referred to as humus.

Soil organic carbon (SOC) is the carbon fraction of soil organic matter (SOM). This is any material in soils originating from biota, but excluding living plant roots.

For more information on soils see accompanying PowerPoint.

Soil and Carbon - The main exchange to and from the soil sink is with the atmosphere.

Plants provide the primary input into soils.

The primary losses are due to biological oxidation of soil organic matter.

Consequently, because the soil sink is so much larger than the atmospheric sink, any small percentage net losses or gains of carbon can lead to much larger corresponding increases or reductions in atmospheric CO_2.

SOC is the primary constituent of organic matter in soils. On average 58% of organic matter by weight in soils is carbon, although this can vary depending on the:

- Composition of the source material
- The physical nature of the soil
- The chemical nature of the soil.

As well as being a sink for carbon, soil organic matter is also an important driver for fertility as it reduces nutrient losses through leaching and promotes the formation of aggregates that improve the soil's physical properties, including resistance to erosion.

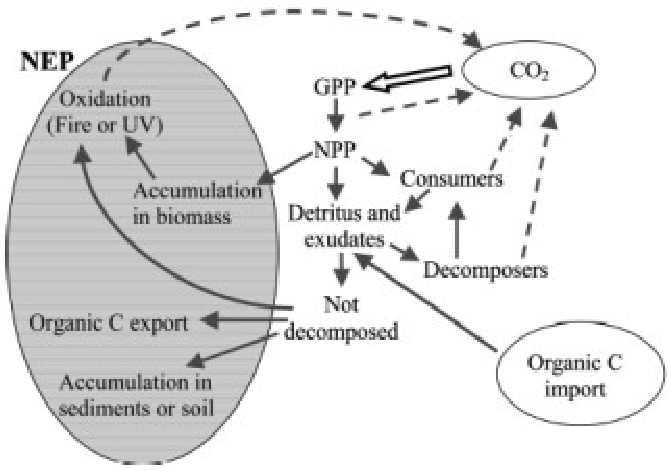
In the top 1m of UK soils, total SOC is estimated to be ~4500 Mt. This is likely to be an underestimate of total soil C stocks as peatland soils can be more than 2m deep. On the other hand, the amount of carbon stored in vegetation has been estimated to be approximately 114 Mt for mainland Britain and 4 Mt in Northern Ireland. This indicates that **in the UK, the carbon stored in vegetation is less than 4% of the soil store**. **This emphasises the role of soils in sequestering carbon.**

The majority of below ground carbon in the UK is found in Scottish soils. [Over 3000Mt with 60% stored in deep peatland soils.] This is a function of climate as high rainfall and lower temperatures combine to reduce the decomposition rate of SOC. **A 2005 estimate for Welsh soil carbon stock was 340 Mt, a large proportion of which is sequestered in upland peatland soils. A more recent estimate for the Welsh**

Assembly Government [WAG, 2010] gave the total soil carbon stock in Wales as 409 Mt. The difference between the two is mainly due to a variation in estimates of carbon below 15cm depth in upland organic soils.

Environmental factors control soil carbon stocks and whether carbon can be sequestered. - An ecosystem's ability to accumulate or lose carbon depends upon the balance between inputs and outputs. One way to look at sequestered carbon is to define it as the difference between gross primary productivity [GPP] and ecosystem respiration. Gross primary production is the rate at which an ecosystem's producers capture and store a given amount of chemical energy as biomass in a given length of time. Some fraction of this fixed energy is used by primary producers for cellular respiration and maintenance of existing tissues. The remaining fixed energy is referred to as net primary production [NPP]. Simply, this is the amount of energy made available by plants that can be passed on to other consumers. Ecosystem respiration [ER] is the sum of plant respiration and heterotrophic respiration of non-photosynthetic organisms [e.g. herbivores].

The difference between gross primary productivity [GPP] and ecosystem respiration is termed the net ecosystem productivity [NEP]. However, the final rate of accumulation or loss of carbon in a particular ecosystem depends on external deposition of carbon [such as inputs of organic manures and dissolved carbon in rain water] and losses through erosion, removal [harvesting] and non-biological oxidation through fire or ultraviolet radiation.



Source: Lovett 2006
Fates of organic carbon (C) fixed in or imported into an ecosystem.
The shaded area contains the components of the NEP of the system. ''Accumulation in biomass'' represents all biomass (plant, animal, or microbial)

Input material composition - The rate of decomposition on the soil surface depends on the resistance of plant material to microbial attack [recalcitrance]. Woody tissue provides the greatest challenge to soil organisms, but most leaf and stem tissue decompose at the surface. What happens below ground is more complex, but most of the carbon inputs to soil are from root tissues and exudates [40%]. Surface organic matter is incorporated into the soil via the action of soil animals and fungi. Fungi play an important part in carbon sequestration because they stimulate root exudates and also produce protein secretion that stimulates soil aggregation. When soil particles clump together it increases the protection of soil organic matter. Earthworms play an important role in moving litter from above ground to below ground. They also consume soil particles, mix it with the mineral content of the soil which enhances adsorption.

Soil carbon turns over more slowly than carbon above ground. This leads to a build up until the optimum level is reached specific to prevailing conditions. In soils, organic carbon is to some degree protected from oxidation. The soil properties that influence the protection are therefore important in determining the potential level of soil carbon.

Land use changes - The SOC content of a soil is a function of net inputs of organic carbon to the soil and net outputs due to respiration and physical factors such as erosion. Changes in land use can alter either inputs or output of carbon, or both. When forest or permanent grassland is changed to arable cropland then above ground inputs to the soil are significantly reduced as crops are removed when harvested and in addition any residues are more easily changed. Tillage breaks up soil aggregates and exposes protected soil carbon to the oxidising atmosphere. This results in increased outputs of carbon from the pool and potentially increases erosion. Although erosion may be viewed as a loss of SOC at a local level it has been suggested that the majority of the eroded carbon is deposited at other sites.

Studies show that when forestry or permanent grassland is converted to arable land, there are marked losses of soil carbon. However, where the process has been reversed there are clear gains of carbon. The losses/gains are less clear cut where land use changes from permanent grassland to forestry or vice versa.

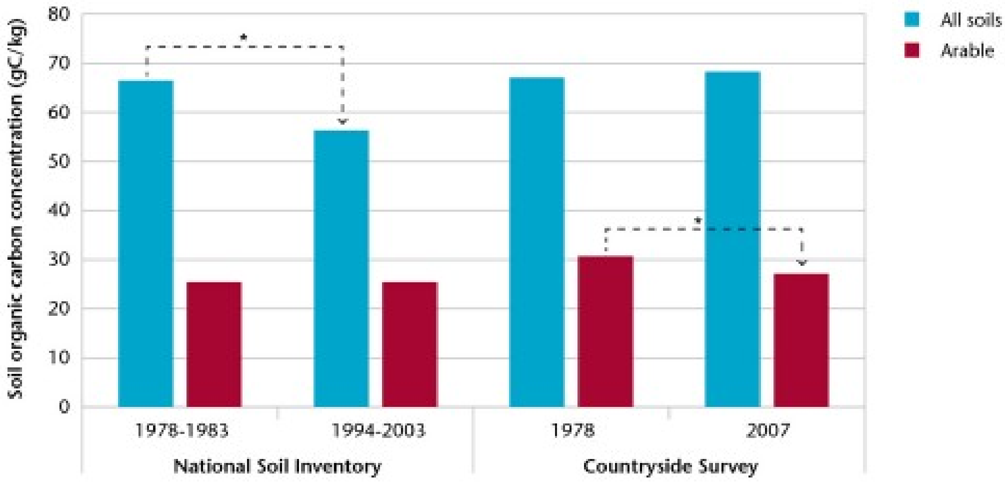
A general misconception is that above ground vegetation is a good indicator of sequestered carbon, but there are several examples where afforestation of permanent grassland leads to a loss of soil carbon.

Of note: carbon density is characterised as kg C per m^2 and national stocks are given in Mt C per land use type.

Semi-natural vegetation (but not woodland) - The highest density and largest stock of soil carbon was found under semi-natural vegetation where there is little or no management. This includes organic soils such as peats, most of which is in Scotland.

Woodlands and permanent managed grasslands have similar overall carbon density in the first 0-30cm, but under woodland, the carbon density at depth is higher than under grasslands. Although the total C inputs for woodlands and grasslands are similar their input patterns differ. Woodlands are deeper rooted and surface leaf litter input is seasonal [applies more to broadleaved than coniferous woodlands]. Some of the litter C is incorporated in the soil profile through earthworm activity, although a lot is broken down at the surface by fungi. The main difference in terms of ecosystem [as opposed to soil] carbon sequestration between permanent grasslands and woodlands is that more carbon is situated in the standing biomass of woodlands. For the UK, the above ground carbon stock in woodlands is estimated at ~90 Mt, which is about 80% of the total UK vegetation carbon stock. However, woodland accounts for only ~11% of the land area. The carbon stock in UK woodland soils is estimated to be ~400 Mt. Consequently, the standing biomass of woodland contains approximately 18% of the total carbon stock. Looking at the combined carbon stock of all types of UK vegetation cover in relation to soil carbon stock, the figure is less than 4%.

UK arable soils – Estimates suggest that arable land has lost 17% of its carbon in last 30 years. This is across 15 million acres. If this loss translated to carbon dioxide emissions, then that would represent a contribution of about 1% of the UK's global warming potential. Suggestions to increase soil carbon by 20% would mean that UK agriculture adopts different techniques [less ploughing] and divorces itself from intensive production and high yields.



Concentration of soil organic carbon [SOC] across all soils and arable soils in England 1978 – 2007 Source: National Soil Inventory & Countryside Survey Cranfield Uni [2013] & Carey et al [2008].It is important to note that there is a high degree of uncertainty around this data.

Mine and quarry spoil sites are virtually carbon free as they have a depleted soil structure and lack a well-developed vegetation cover.

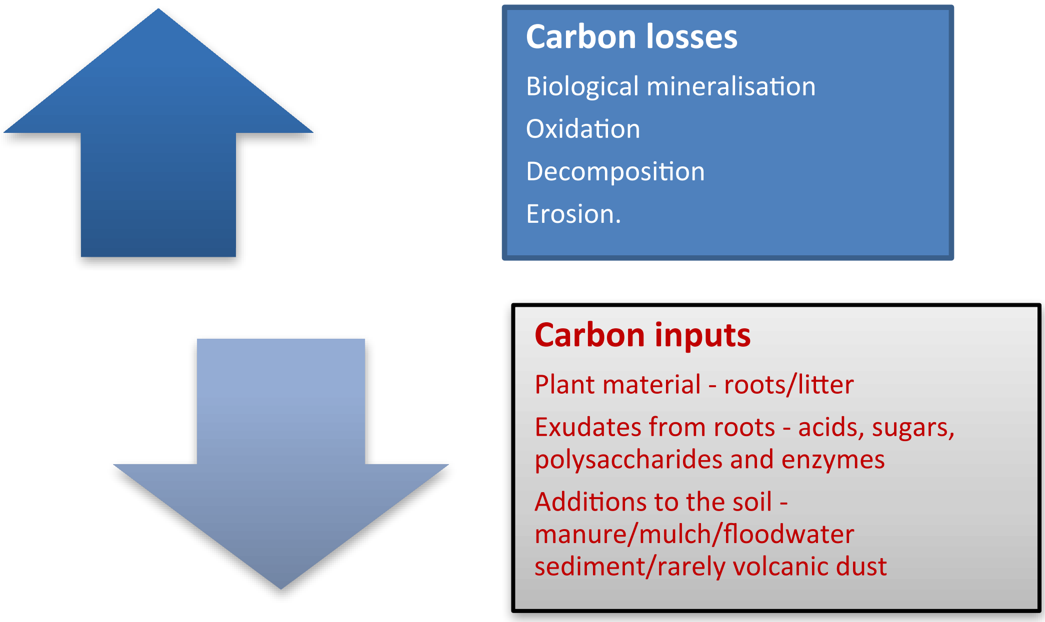
Climate - Climate plays a significant role in determining soil carbon content. High moisture content can slow decomposition leading to high carbon content. Cold conditions not only slow plant growth but also rates of decomposition and over time carbon can accumulate. In addition to climatic influence on carbon content, changes in climate also drive changes in fluxes of carbon from soils. When rainfall reduces, organic soils that have accumulated during the wet conditions dry and the carbon begins to oxidise. Drying peat rich soils are also more prone to erosion. Alternatively, soils that have accumulated little carbon due to unfavourable climatic conditions for plant growth [e.g. deserts] begin to accumulate carbon if the climate becomes more conducive to growth.

Carbon loss due to climate warming contested - Across England and Wales it has been suggested that losses in soil carbon between 1978 and 2003, based on the National Soil Inventory data, were mainly due to a change in climate. This was particularly the case for organic peat soils which suffered high losses. Researchers drew this conclusion as carbon losses occurred in the absence of land use change. Consequently, they attributed the loss to the average 0.5 °C rise in temperature across England and Wales over the study period. These results are inconsistent with a comprehensive study of British Woodlands [Countryside Survey – see graph above], which concluded that there were no losses of soil carbon between 1971 and 2003. Critics pointed out that the National Soil Inventory data used to derive the carbon losses, did not include bulk density measurements and few field samples had been taken.

What soil factors and processes limit soil Carbon stocks and sequestration rates?

There are several theoretical models that help our understanding of what happens to the total carbon stocks under different cropping and management regimes. This section introduces some of the key ideas.

In the simplest model of carbon sequestration the change in carbon over time depends on an input and output of carbon approach.



The linear model of carbon sequestration - In a soil with low carbon levels and with enhanced inputs, the carbon stock increases over time. As the stock of carbon increases the outputs also increase. Once they match the level of inputs no further net carbon storage occurs. At this point the soil carbon stock is said to have reached equilibrium. If the level of input is then raised further via a regular application of manure say, then the soil will sequester more carbon until a new equilibrium is reached. This is termed the linear model of carbon sequestration and is used in many soil modelling applications.

The linear model of carbon sequestration implies that soil has an infinite capacity to sequester carbon. So when the level of inputs is increased this will lead to a new higher equilibrium level of carbon stock. This model has been criticised for overstating a soil's capacity to store carbon, especially when soil carbon stocks are already high, or when inputs are increasing. In addition, it does not accurately describe the variation in residence times of many of the different plant materials.

The physiochemical capacity model - An alternative model of carbon sequestration focuses on the chemical stabilisation and physical protection of carbon. In this model the conditions existing within the soil limits the carbon that can be stored. At some point all additional inputs are mineralised or lost through erosion and this is referred to as the saturation capacity of the soil. In this model turnover rates are not just limited by the recalcitrance of the input material but also by the ability of the soil to protect organic matter from decay. Some forms of carbon that are naturally labile may have long residence times in the soil if physically protected, whereas other more recalcitrant materials such as lignin may be more susceptible to decomposition if not protected. Simply, there is a limit to the carbon storage capacity of any soil.

Carbon sequestration rates are not only about input availability but also soil clay content and the extent to which soil biota facilitates the formation of micro aggregates. Incorporated within these soil micro-aggregates the carbon is protected from further breakdown. This implies that the carbon saturation level of a soil/ecosystem depends upon both litter quality and the physiochemical properties of the soil. Current management practices such as crop removal, tillage, drainage will all impact upon carbon saturation because disturbance reduces protection.

Temporal scale - Differences in time scales over which carbon is measured can lead to different conclusions as to which planting and management regime may be the most effective for sequestering carbon. For example; the same soil type is planted with birch or oak and carbon levels measured every 5 years. In the first 30 years soil carbon levels under birch rise more rapidly due to faster growth rates and higher inputs. [More leaves to photosynthesise and form litter etc.] However, birch litter is more labile than that of oak and so as the carbon stock increases, outputs due to decomposition increase more rapidly than under oak. The continued growth of oak would then lead to higher rates of carbon sequestration than in the soil planted with birch until in the longer term [100 years] the oak soils achieve a higher equilibrium carbon stock. This illustrates the importance of time frames when discussing policies aimed at increasing C stocks. In the short term the level of inputs are likely to have an important impact, but if the saturation model is correct then edaphic conditions and decomposition rates will play a more significant role in the longer term.

Non-mineral soils such as peats are different in that the organic matter does not decompose because of waterlogging, low pH and low temperature slows the rate of decomposition. **Peatland soils are the most important for carbon sequestration in the UK accounting for 50 – 60% of the total carbon stock. However, creating new wetland will not significantly alter the carbon budget in the short term due to the slow rate of accumulation.**

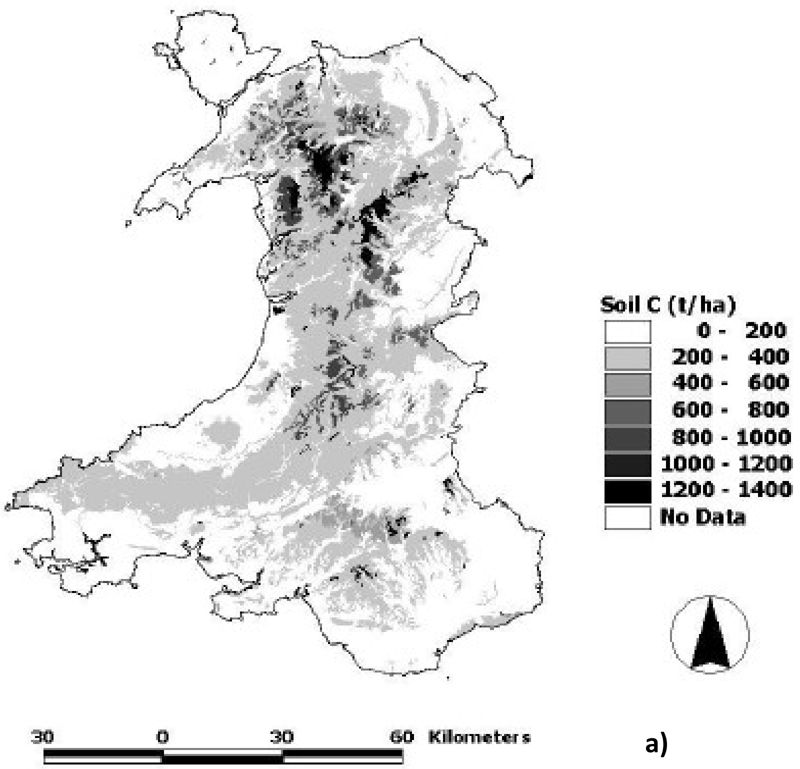
In summary - when estimating the potential of a soil to sequester carbon there are two main factors that need to be considered:-

1. **If carbon stocks are well below the saturation potential of the soil there is larger scope for increasing carbon levels in the soil. <u>If stocks are close to saturation there is little scope</u> for increasing carbon stock and sequestration rates are likely to be low too.**
2. **Disturbed soils have a carbon stock well below their potential. Mine spoil, may be considered as having a zero carbon stock and so offer great potential for carbon sequestration.**
3. **Changes in the nature and amount of C inputs to soils also have the potential to promote C sequestration and increase soil stocks. Plant and crop varieties with:**
    a. **Greater allocation of C to belowground structures**
    b. **Deeper rooting traits**
    c. **Greater root turnover**
    d. **Higher content of more recalcitrant compounds compared to current equivalents may lead to higher C sequestration and accumulation.**

12.4 How are soil C stocks distributed in Wales and what is the potential for further sequestration?

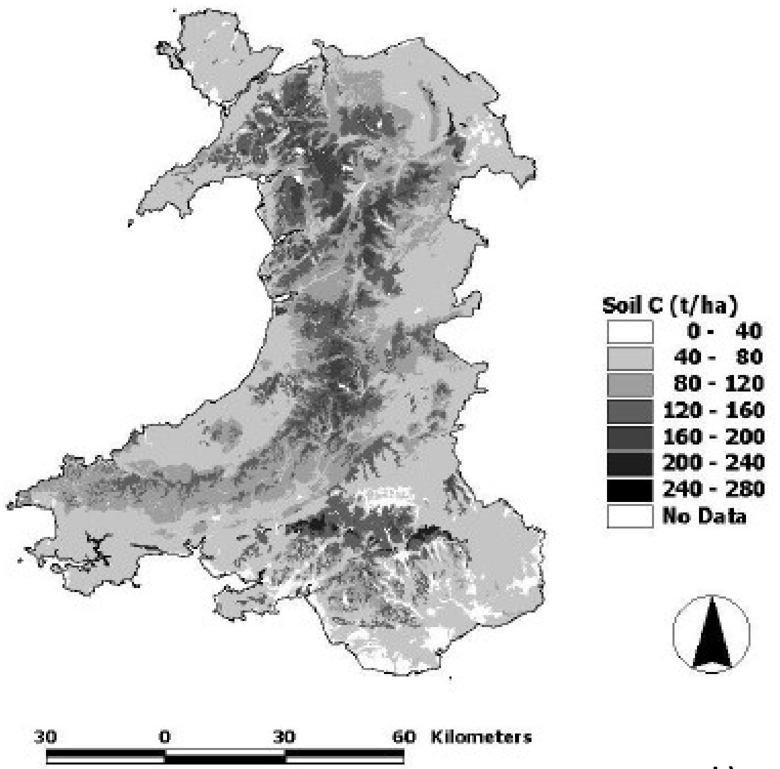
Approximately half of the Welsh soil carbon stock is found in the 23.4% of land surface classed as uplands, emphasising the importance of these organic soils as a carbon store. The link between the carbon store and Welsh uplands is clearly visible on the Map a) alongside and Map b) below. The highest densities of C (>1000 t/ha) are restricted in the main to the upland peat bogs. [The lowland raised bog systems are the exception.]

Of note: On comparing the two maps, it is evident that the major contribution to overall soil C stocks comes from soil layers below 15 cms depth.



Distribution of soil C stocks in Wales.
Map a) 100 cm and Map b) 15 cm depths
Source: Ibn Malik [2006]

a)



b)

Soil carbon sequestration and habitat in Wales. - The potential for a particular vegetation cover or crop to sequester or lose soil carbon on a landscape scale depends on the surface area of that particular habitat. The table below gives the area of land in Wales under a particular habitat and is taken from the Countryside Council for Wales' habitat survey.

Habitat Type	Area ha	% Cover
Woodland and Scrub	289,216	13.9%
Improved Grassland	1,002,236	48.2%
Semi or Unimproved Grassland	270,006	13.0%
Bracken	64,805	3.1%
Heathland	106,447	5.1%
Mire & bog	63,701	3.1%
Open Water	15,713	0.8%
Coastal edge	56,452	2.7%
Quarry/Spoil/Mine	10,264	0.5%
Other	199,060	9.6%

Areas of land in Wales for broad habitat types. Source: [Howe *et al.*, 2005]

Over 60% of the land area of Wales consists of the two grassland habitat types. Therefore a change in land use or species composition of these grasslands may have a significant impact on overall soil C stocks in Wales. However, it is important to note that grassland soils, especially those in the semi or unimproved class and land classified as bracken/heathland, are often associated with the uplands. These soils have high C stocks already [see Maps above] so their capacity for further C sequestration may be limited, particularly in the topsoil. Only the C deficient subsoil layers may offer the capacity for significant additions to soil C stocks.

Mire and bog habitats cover a relatively small area but make a disproportionate contribution to total soil C stocks due to the very high densities of C because of their great depths. Of the categories listed above Quarry and Mine spoil has the greatest potential for C accumulation on an area basis in that these 'soils' are deficient in C and therefore will act as a C sink on restoration. Unfortunately, this habitat represents a relatively small proportion of land cover in Wales. Woodland and scrub represents ~ 14% of land cover and a significant area within this is given over to commercial plantations, which are disturbed land uses. Conversion to other less disturbed land uses might also have a marked effect on a national scale.

Accelerating the rate of carbon sequestration to offset the impacts of climate change.

Targets in natural systems for increasing the amount of captured carbon include:

- soils
- vegetation
- deep geological reservoirs

Carbon capture at source and storage in geological reservoirs is a long term solution dependent on future technological innovations. Soil and vegetation capture are immediate solutions because they only require a change in how we use the land.

Improving our understanding of carbon resilience, and how we can manage the land to retain carbon in vegetation, soil and seabed sediments is essential to mitigate effects of climate change. However, it is clear that the soil is not an easy retainer to work with. Peat bogs offer a self-sustaining partial solution. It requires long term funding and a willingness of different interest groups to cooperate. Inevitably, the outcome of restoring the peat bogs is a question that will take 30 years to evaluate. Unfortunately, to do nothing and allow the world's peat bogs to degrade further will accelerate the emission of GHGs CO_2 and CH_4 at ever increasing rates as global temperature rises. The melting of the permafrost in northern latitudes adds to the equation as increased water table presence will permit more methane to be emitted along with CO_2.

12.5 Summary of 'Between a bog and a hard place' - *Prof. Chris Evans writes about his work with* peat bogs and leaky carbon.

Focus on ***reducing levels of organic matter in order to prevent production of trihalomethanes***

Original article submitted by Prof. Chris Evans Fri, 09/10/2015
The Centre for Ecology & Hydrology

1. Much of the water we drink in the UK comes from our uplands.

2. A lot of this water is naturally brown because it contains dissolved organic compounds leached from the soil, especially where that soil is peat.

3. Water companies invest large amounts of money and energy in removing these compounds during the water treatment process.

However, upland waters are getting browner. In the UK, the Upland Waters Monitoring Network have been monitoring the quality of water in lakes and streams for the past 25 years. **Of particular note is that concentrations of dissolved organic carbon [DOC] have roughly doubled.**

This is significant because:-

1. It increases treatment costs for water companies.

2. It also increases the risks of toxic by-products, created by reactions between DOC and the chlorine compounds used in water treatment, entering water supplies.

One solution to this problem is to invest in new water treatment processes, but another – which is being trialled by a number of water companies – is to try to reduce the amount of DOC leaching from the soils in the first place.

The UK's uplands have been historically degraded by human activities such as:

- **Drainage**
- **Over-grazing**
- **Burning**

Restoration to a more **natural state** aims to reduce:

- **DOC losses**
- **Need for expensive water treatment technology.**
- **Reduce energy consumption in the process**

More natural solutions are appealing because of the additional benefits they deliver:

- Restoring the UK's peat bog ecosystem

- Enhance bog biodiversity
- Reduce bog greenhouse gas emissions
- Reduce flood risk in the rivers which drain bogs.

Will it work? Unfortunately, the answer isn't clear-cut. The brown elephant in the room is that DOC concentrations have been going up not only in reservoirs draining degraded peat bogs, but in lakes and rivers all over the UK's uplands, in Scandinavia, in Central Europe and in parts of North America.

Current thinking implicates **acid rain**. Back in the 1970s and 80s, sulphur pollution from coal- burning power stations affected vast areas of Northern Europe. As well as killing fish and damaging forests, this pollution also changed the chemistry of the soil, making it more acidic. In effect, the soil got stickier – so more of the organic matter produced by plants and soils stayed in the soil, and less made it out into lakes and streams.

Over the last 30 years, Europe has succeeded in reducing acid rain by well over 90%, to the immense benefit of our sensitive natural ecosystems. Unfortunately for the water companies, one of the consequences of this remarkable achievement has been increasing water colour. We can even see, using new techniques to reconstruct historical conditions, that lake sediment DOC concentrations are returning to levels last seen in the 19th century, before the onset of acid rain.

Does this mean that the efforts of the water companies to reduce water colour by managing their catchments are doomed to fail? Again the answer appears to be yes, and no. Whatever anyone does, we are never going to go back to the clear [acidified] lakes and streams of the 1970s – we now live in a browner world. On the other hand, it seems very likely that poor management of our peatlands in the past has made matters worse, and that better management of them in the future could make things better.

The Centre for Ecology & Hydrology is trying to understand these processes, and to develop models to predict how DOC may change in the future. They are also investigating whether other nature-based measures, such as reducing nutrient inputs to reservoirs, might reduce the problems that water companies face in treating water colour. If they can, then it would reduce the need for more concrete, chemicals and energy for water treatment, which in turn would mean lower costs for the water industry and lower costs for customers. If this also happened to help restore and protect uplands that store carbon, support biodiversity and reduce flood risk, then it's hard to argue that this would be anything other than a good thing.

12.6 Wales – Resources & Potential Case Study Sources

Web Sites

Peatland Restoration in Snowdonia

'Preserve peat bogs' for climate

Videos

Peat Bog Restoration North Wales - Hiraethog and Migneint areas of north Wales, land adjoining the Berwyn Mountains, Arthog bog near Dolgellau

Prosiect Gronfa Ecosystem Wydn. Film adfer mawndir

Montgomeryshire Wildlife Trust hosts The Pumlumon Project, a pioneering, science-based project to revive the ecology and economy of the Welsh uplands. Launched in 2007, it's a long-term vision for the countryside, a pioneering experiment in an area of Mid Wales which contains 250 farms, 15,000 inhabitants and catchments for five rivers, including the Severn and Wye, which supply water to four million people.

The aim is to find new solutions to current and future land use problems. It's philosophy centres on restoring or building ecosystems and economies relevant to today's conditions. In other words, to change the way 40,000 hectares of Mid Wales is managed for products and services. That can only happen with a landscape-scale strategy that forges new partnerships between conservation, farming, forestry and tourism. So while Pumlumon is hosted by Montgomeryshire Wildlife Trust on behalf of Wildlife Trusts Wales, it has the full support of the Welsh Assembly Government, the Countryside Council for Wales, Environment Agency, Forestry Commission and many other stakeholders.

12.7 UK – Resources & Potential Case Study Sources

Restoring the UK's peatlands – Work on English Bogs – Potential comparison studies [Material from organisations web pages.]

Dartmoor Restoration

Moors for the future

Wildlife Trusts - The Wildlife Trusts are involved in an ambitious plan to restore 4% of the UK's landmass to improve water quality, alleviate flooding, aid carbon storage and help wildlife.

A million hectare challenge map is being prepared to set an ambitious target for restoring peatlands. It has huge implications for people and for business.

Peatlands cover 12% of the UK and their restoration has never been a more pressing issue - unfortunately, 80% are in a poor condition because they've been drained of water or damaged by extraction.

Peatlands are amazingly wild places, teeming with birds, insects and unusual plants.

The Wildlife Trusts are helping to protect and restore these special places around the UK. We are one of several partners involved in the exciting 2020 Million Hectare Challenge map to encourage the restoration of a million hectares of peatland over the next seven years.

The Peatland Code will encourage the private sector/businesses to invest in restoring this precious resource. Restoration is vital because peatlands:

- store carbon – over three billion tonnes of carbon already stored and if repaired, they could remove an additional three Mt of carbon dioxide every year from the atmosphere
- both store and clean water as well as help reduce flooding – there's huge economic value in improved water quality and flood alleviation
- are fantastic landscapes for wildlife - rich habitats that are home to subtle and unique wild plants and animals, and fabulous wild places for people to enjoy

Investment by businesses is key to progress. The call for private sector involvement comes at a time when water companies are being encouraged to improve water quality using upstream solutions. Restoring peatlands can play a key part in tackling water quality issues at source.

Read more about the Million Hectare Challenge here.

Peatland restoration projects being carried out around the UK by The Wildlife Trusts

***Upland peatland restoration can have a direct affect on water quality and flood alleviation as well as being vital carbon stores and wildlife havens. Upland restoration examples*:**

Yorkshire Wildlife Trust

Yorkshire Wildlife Trust is an integral part of the Yorkshire Peat Partnership (YPP). The YPP is an umbrella organisation working to restore and conserve upland peat resources in order to ensure the long-term future these unique and valuable habitats.

The potential project area is vast, encompassing the uplands of the Yorkshire Dales National Park, Nidderdale Area of Outstanding Natural Beauty, North York Moors National Park and areas of the South Pennines, North of the river Calder.

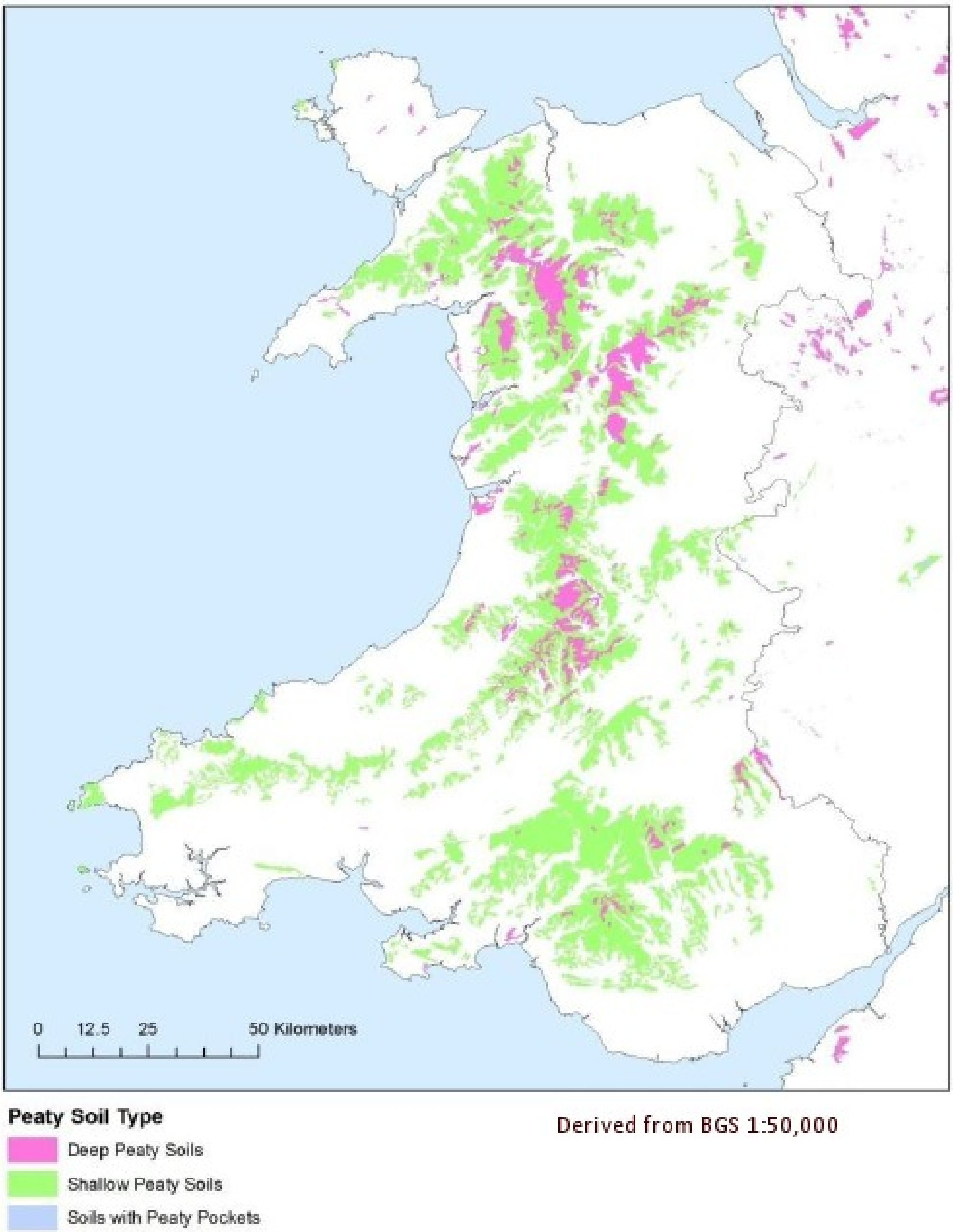
Within the Yorkshire region alone there is nearly 70,000 ha of upland peat soil, upon which a staggering 4,350,000 m of grips (drainage channels) have been incised. There is a real and pressing need to undertake restoration in the Yorkshire region in order to protect these precious carbon sinks. The partnership aims to substantially increase the amount of peatland restoration activity.

In May 2013, Yorkshire Peat Partnership announced that it has restored more than a quarter of Yorkshire's peatlands in a multi-million pound project that aims to preserve vital habitats and help cut global warming. Around 100 square miles of Yorkshire's precious peatlands have been restored in a multi-million pound project that aims to preserve vital habitats and help cut global warming by reducing the amount of carbon escaping from them into the atmosphere.

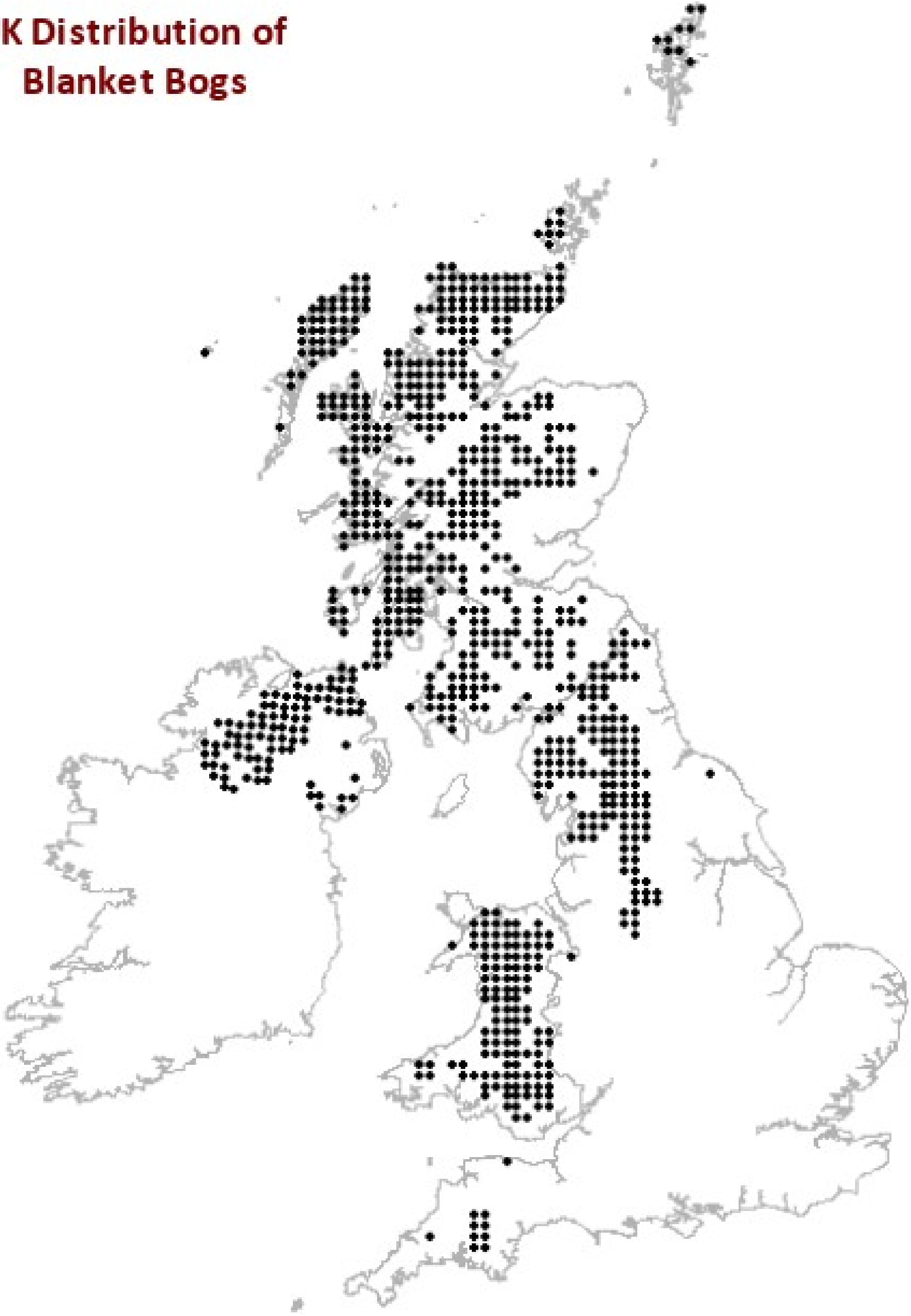
The achievement is a significant milestone for the Yorkshire Peat Partnership (YPP) because it means nearly a quarter of Yorkshire's damaged peatlands have been restored and an estimated 29,500 tonnes of the damaging greenhouse gas CO_2 prevented from being emitted, a major cause of global warming. This is equivalent to the amount of carbon produced annually by 62,000 UK households.

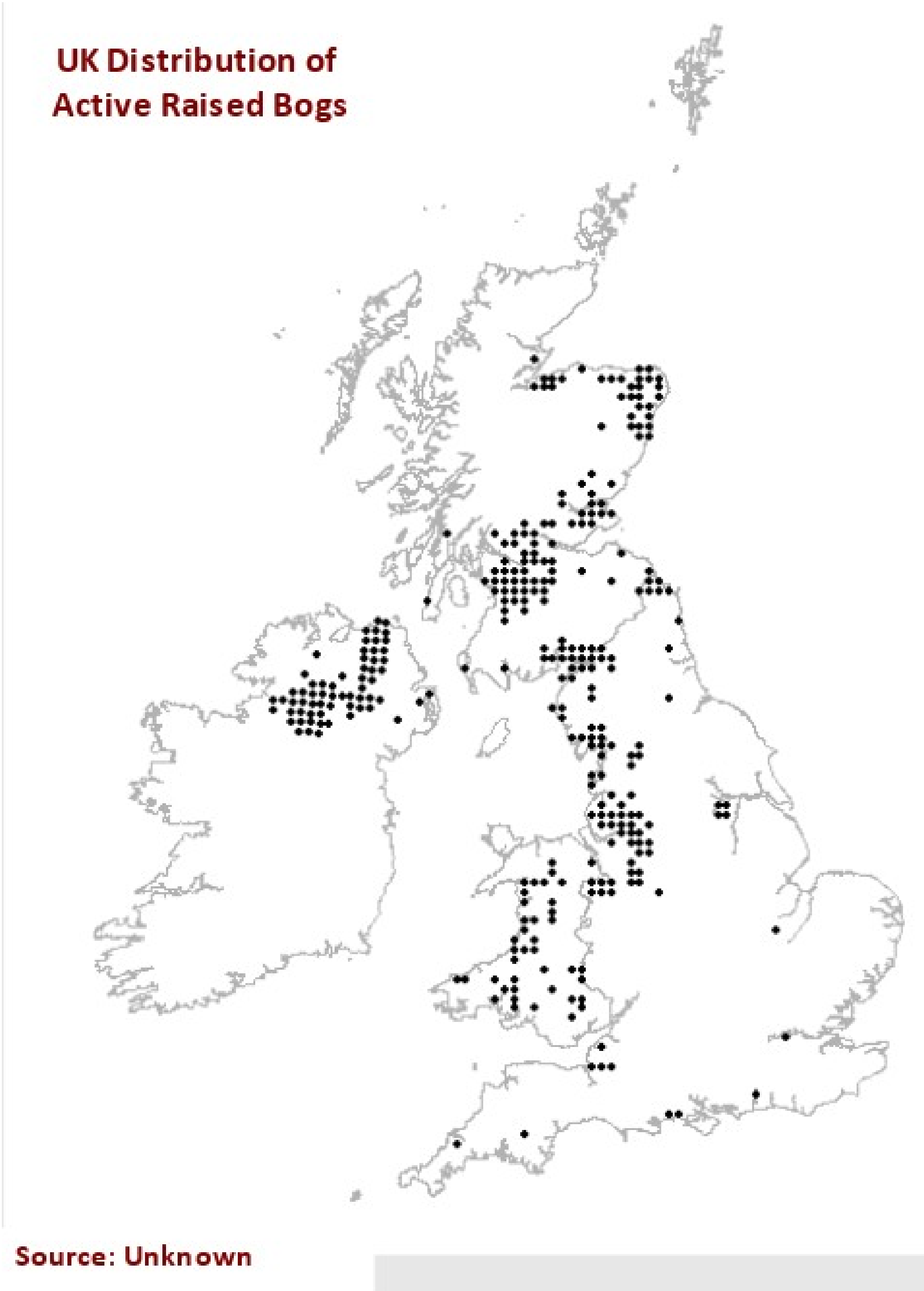
12.8 Assorted Distribution Maps

Wales



UK Distribution of Blanket Bogs





Most likely Joint Nature Conservation Committee – Special Areas of Conservation

12.9 Key Peat Facts

Global Peatlands cover ~3% but contain nearly a third of all organic carbon on earth. Their collective carbon sequestration is responsible for suppressing global temperature by 0.5°/0.4°C.

Global total carbon in the **soil sink** [2m depth], ~ 3000 Gt,

- Soil organic carbon [SOC] ~ 2400 Gt.
- Combined atmospheric carbon ~760 Gt
- Above-ground terrestrial biotic sinks ~560 Gt

In their natural state, peat bogs function as carbon 'sinks'. Term '**sink**' is applied when a natural process absorbs and stores more carbon than it releases. Have seen – "World's peatbogs store ~455Gt of carbon equivalent to the total annual CO_2 output of 438,038 coal-fired power stations. [Currently 2,300 coal-fired power stations in the world - 620 in China]." Not sure about this, but it appears reqularly.

Peatland area, Carbon storage and long term Carbon accumulation rate			
	Area [km^2]	C Pool [GtC] (Range)	Holocene C Rate [g C m^{-2} yr^{-1}]
Northern Peatland	4,000,000	547 (473 - 621)	18.6
Tropical Peatlands	368,500	50 (44 - 55)	12.8
Southern Peatlands [Patagonia]	45,000	15 (13 - 18}	22

Of note: 3,000 Mt/y CO_2 is released into the atmosphere from bogs damaged by human activity. Equivalent to ~10% of all the world's fossil fuel emissions.

May 2013, atmospheric CO_2 concentration of 400 parts per million achieved [Now 404.7ppm].

In the UK

	Soil Data		**UK Biodiversity Action Plan – Mire Areas***	
	Shallow Peaty or Organo-mineral soils [km^2]	**Deep Peaty or Organic Soils [km^2]**	**Peat-forming Mires [km^2]**	**Peat-forming Fens [km^2]**
England	7,386	6,799	2,727	80
Wales	3,592 [7.64%]	706 [2.63%]	718 [3.15%]	62 [24%]
Northern Ireland	1,417	2,064	1,069	30
Scotland	34,612	17,269	17,720	86
Total Area	**47,007**	**26,838**	**22,775**	**258**
UK Cover [%]	**19.3%**	**11%**	**9.35%**	**0.11%**

Source: Lindsay, Birnie & Clough IUCN UK Peatland Programme 2014 [Uni East London]

UK soils [1m depth] total SOC ~4500 Mt. *Underestimate of soil C stocks as peatland soils 2m +.

Carbon stored in vegetation ~114 Mt for UK mainland and 4 Mt in N Ireland. [less 4% of the soil store].

UK Woodland accounts for ~90 Mt or 80% of the total carbon stock of UK vegetation. Woodland occupies 11% of the land area. Woodland soils carbon stock ~400 Mt. Therefore, timber is about 18% of the combined carbon stock. Standing biomass for the UK as a whole is less than 4%.

UK peatlands cover between 15/20% of the land area and store >1400 Mt of carbon

Scottish soils store 3000Mt+ - **60% stored in deep peatland soils**.

Welsh soil carbon stock is at least 409 Mt. **Approximately half [~200Mt] of which is sequestered in the uplands** [23.4% of land surface]. The **highest densities of C (>1000 t ha-1)** are found in a small area of upland deep peat soils. [Peat bogs] This is between 3.3% and 5% of the area of Wales, but contains 33% of Welsh soil carbon. **In Wales, 50% of upland blanket bogs [~35,000ha] are untouched**.**[?As peat bogs are poorly understood, -not sure how accurate this is.?]**

Snowdonia National Park publication - Other estimate of the extent of deep peat soils [depth ≥0.5m] in Wales is 90,995ha, some 4% of the' total land area. **They provide Wales' largest terrestrial ecosystem store of carbon, estimated at around 157mt.** There source is NRW Doc - **A Snapshot of the State of Wales' Natural Resources 2015**

Sequestration rates - **Healthy bog systems sequester carbon at 15g C /m²/y**

Rates of up to 25g C/m²/y are quoted elsewhere. At this higher rate it is broadly equivalent to around 10% of the amount of carbon accumulated over the duration of a forest crop 35/40 years.

UK peatlands have the potential to sequester 3 Mt of carbon dioxide every year!
Interestingly, agricultural soils could take up an additional 115 Mt of carbon, which is equivalent to 22 % of total carbon dioxide emissions from the energy sector.

The **Carbon credit value** of the world's 400 million hectares of peatland, is valued between US$400,000 million and US$18 billion per year.

Degradation - UK's upland blanket bogs [13% of global blanket bogs] are degraded.

- 50%+ are without peat forming vegetation.
- 18% are in a "near-natural" condition.
- The remainder are in varying states of damage and collapse.

Sphagnum carpet degraded in the last 200 years:

- Firstly by acid rain & air pollution from the industrial revolution
- Government incentivised programmes to drain and manage moorland for grazing and game management.

In Wales ~50% [35,000ha] are degraded in some form.

Weathering and erosion together remove peat from the catotelm at rates of **more than 3 cm per year, or ~3 m per 100 years.** They are now **actively losing carbon at the rate of around 3.7 Mt of CO_2e** [equivalent] **each year,** similar to the annual emissions from 700,000 households.
When a blanket bog erodes it can **produce over 30 tonnes of CO_2e per hectare per year some to the atmosphere and some into water courses.**

Wales - Data collected on the Conwy watershed site suggests that peat is a large source of both dissolved organic carbon [DOC] and methane [CH_4] emissions.

- DOC ~22g C m^{-2} yr^{-1}
- CH_4 emissions ~6 to 8g C m^{-2} yr^{-1}.

Restoration - UK Biodiversity Action Plan for 1 million hectares of bog to be restored. Estimates that 1.5 Mt of carbon dioxide emissions will be saved by 2015 as a result. **Wales** – Cors Goch, Berwyn Mountains, Ogwen Valley, Migneint, Mynydd Hiraethog, and Arthog bog - Welsh Government's Ecosystems Resilience and Diversity Fund. **Initially, methane emissions increase with re-wetting at a greater rate than carbon dioxide is taken up.** Takes 5/6 years to even up.

Evidence suggests that the 80 -100 years natural recovery period can be shortened to 30 years with re-wetting. Water levels within 5cm of the peat surface resulted in some species covering up to 50% of the peat surface in 3 months and 100% in 6 months.

Basic Peat Facts – Sphagnum mosses can hold up to 20 times their own weight in water. Up to 50,000 individual plants per square metre. The common peat forming varieties …*Sphagnum capillifolium*   *Sphagnum fuscum*   *Sphagnum fallax Sphagnum papillosum*   *Sphagnum magellanicum*. *Sphagnum* colonies annual radial growth rates of between 0.5 cm and 13 cms, - mean of 3.6 cms. Peat typically accumulates at 0.5 - 1mm per year [1 metre per 1,000 years]

70 per cent of the UK's drinking water comes from the peat uplands.

The Peatland 'Wealth' of Nations					
Nation	Area [10^6 km^2]	Peatland Area [km^2]	Peatland Cover [%]	Population million [2005]	Peatland area [m^2] per capitat
Canada	9.97	1.13 x 10^6	12	32	35312
U.S.A.	9.63	0.63 x 10^6	6	296	2128
Russia	17.8	1.41 x 10^6	8	143	9860
Finland	0.34	85000	25	5.2	16346
Sweden	0.41	66000	16	9	7333
UK	0.24	17500	7	60	292
Netherlands	0.04	2350	6	16	147

Global coverage: Peatlands 4 to 5 million km^2
Wetlands [incl. Peatlands] 5 to 10 million km^2

Source: - Tim Moore from McGill University, Department of Geography, speaking at the UW 2014 World Wetlands Day Symposium. Organised by the CERC Ecohydrology Research Group on January 31st 2014.

***Not covered – Forestry and commercial peat extraction.**

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