Carbon storage and dynamics in soils and ecosystems in Wales and potential for change in CO₂ sequestration

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Introduction
Levels of CO₂ in the atmosphere continue to increase and so do concerns over its potential effect on the climate. On a world scale the oceans are the main sink for CO₂ storing around twenty times more than soils and the biosphere added together. Nevertheless man’s use and management of the land can have a significant impact on the concentration of CO₂ in the air. The purpose of this article is to provide an overview of the storage and turnover of organic C in the terrestrial ecosystems in Wales, including agriculture and to explore how changes in land use might increase or decrease CO₂ sequestration.

Principles governing the organic C content of soils
Soil organic C has its origin in the above and below ground residues of plants growing on the soil. The soil biological population, mainly microorganisms, use these residues as a source of energy for growth and in so doing produce CO₂ that is released to the atmosphere. The chemical entities in plant residues differ in the ease with which they can be utilised or modified. Lignin, whose content increases with plant age and woodiness, is notably stable to breakdown. After a few years in soils the remaining C is largely in stable compounds that are either chemically altered or produced by microorganisms and are amorphous and colloidal in character. This production of more stable material is known as humification and the overall consequence is that over time the C originally in the plant residue becomes less likely to be lost as CO₂.

Looked at simplistically for every 100 atoms of C in newly added plant residue around 70 are likely to be lost as CO₂ in the first year. However for every 100 atoms of C that have become stabilised either chemically or by physical mechanisms over a several years along with the C already there, only 3 or 4 are likely to be lost as CO₂ in any one year. The overall consequences of this pattern of breakdown are twofold. Firstly the total organic matter content of a soil is very large compared with a single annual addition of plant residue, or for that matter organic manure. Secondly it takes several decades for the total organic matter content of a soil to come close to equilibrium with a change in land use that affects the level of plant residue input – say for example arable to grassland.

The pattern of organic matter turnover described so far applies to soils that are reasonably well aerated and have a pH above 5.0. These two conditions apply to most of lowland Wales in agricultural use. The main category of soils are brown earths of some kind. These category B soils
are predominantly in pastoral use but are sufficiently well drained to be used for arable cropping, at least occasionally. Between 15 and 20% of soils in the lowlands are in shallowly sloping valley sites or on flat plateaux and are liable to remain waterlogged for a few months. These category G soils are predominantly mineral gleys.

Over the last two centuries most lowland valley land has been drained, limed, fertilised and reseeded and brought into productive agricultural use as long term pasture. In the past these extensive areas of unimproved wet grassland provided habitats suited to a range of ground nesting birds including lapwing, snipe, curlew and skylark. The rushes *Juncus effusus/acutiflorus* along with *Galium palustre* and the grasses *Cynosurus cristatus* and *Holcus lanatus* are common constituents of the semi natural communities on unimproved wet grassland in Wales (Rodwell, 1991). Apart from a few peat bogs including those at Borth and Tregaron there are not many significant areas of peat in the lowlands. Soils in some of the wet valley sites have humose topsoils but organic surface horizons are rare.

In contrast to the lowlands, almost all hill and upland Wales has soils that are strongly acidic, typically below 4.5, unless improved by liming. Furthermore rainfall in these areas is at least double that in the western lowlands and in the English borderlands. Given the undulating topography, soils in hollows and valleys and on some plateaux may be saturated for much of the year and even year round in some locations. Waterlogged soils are anoxic because the diffusion of oxygen through water cannot supply the requirements of the aerobic soil microflora and roots of most plant species. As a consequence oxidative breakdown of organic residues is arrested and a peaty accumulation of organic matter develops.

The rocks that constitute directly or indirectly the parent material of most of the soils in Wales are low or very low in calcium. This is important because calcium is the main neutralising agent in soils. In addition to this, excessive rainfall causes the labile calcium in soils to be leached away. Soil acidification leads to the loss of casting earthworms and when they are absent from uncultivated soils an organic surface horizon builds on the mineral soil. This accumulation is not due to waterlogging. The organic surface horizon is not sterile in terms of its biology and if aeration is adequate, plant residues are decomposed and humified but at a somewhat slower rate than in near neutral soils. However in these circumstances fungi totally dominate the soil microbial C and bacteria feature much less than in near neutral soils. However the development of surface organic matter has two additional consequences. Firstly humification leads to the production of macro-molecular organic acids such as humic acid and if there is no input of calcium to neutralise the
acidity, the pH of the organic horizon falls to 4.0 or below which is usually somewhat lower than the mineral soil below. Secondly colloidal humus is very retentive of water so that the organic layer remains saturated for much longer periods than the subsoil. Because of this, as an organic layer increases in depth, its continued accumulation is not only a consequence of the absence of earthworms but because of the saturated conditions it promotes. The greater depth of peaty surfaces on shallowly sloping sites in the uplands compared with soils on moderate slopes is largely a consequence of the difference in slope affecting surface drainage in these high rainfall conditions.

Having explained the reason why almost all soils in the uplands have an organic surface horizon, the soils themselves differ greatly not just in the depth of the organic layer but the character of the organic and mineral profile. These differences affect C dynamics and determine actual and potential C storage. At its most simple, land and soils in the hills and uplands can be divided into three categories based on water relationships that are a consequence of topography, geomorphology and soil development processes. Topography or landform can be used as the key visual indicator of category. Category H land is where soils are on slopes more than about 7°. Category W is where soils are on slopes less than 7°. Category P land is a subset of Category W and comprises land that is in water receiving hollows, valley bottoms and on some virtually flat hill plateaux.

The soils on H land, which is the largest category, have developed in stony or gravelly colluvium which now constitutes the subsoil. This normally drains freely and has plenty of air filled porespace. The soils have an organic surface layer that is typically 7-15cm deep but may only be 1-2cm. The mineral topsoil is usually a grey, structureless silty clay loam 2-15cm deep, but may be a rusty silty loam on steep slopes. The soils are podzols in the main. The organic horizon and grey mineral topsoil are retentive of water and with the high rainfall these layers are saturated seasonally. However aerobic organic matter turnover probably takes place for more than half the year. Major species in the unimproved semi-natural vegetation on H category land include the grasses *Nardus stricta, Danthonia decumbens, Festuca ovina/rubra* and *Agrostis canina* along with the herbs and woody plants *Vaccinium myrtillus, Galium saxatile, Potentilla erecta, Calluna vulgaris, the Ericas* and on drier slopes *Ulex galii*. Bracken (*Pteridium aquilinum*) is dominant in some locations on soils of this category.

The parent material for soils on W and P land is usually fine textured although some stones are usually present. This is because, on these shallowly sloping valley and plateau sites the parent material is in the main glacial till inherited from the last ice age that has either remained on
or has moved downslope to these sites. The inherently poorly drained nature of these parent materials compounds the topographical problem of land in valley or non water-shedding locations. Therefore all of the soils on W and P land that have developed from these parent materials are wet but the degree of wetness differs and requires more detailed examination. The development of an organic horizon on these soils is a consequence of both acidity and excessive wetness. Furthermore for soil parent materials over most of Wales these conditions favour mineral weathering resulting in a more water retentive soil mineral fabric. The depth of the organic horizon ranges from around 15cm to several metres with the accumulation of peat. Travelling downslope from H land to W land towards the valley floor the vegetation typically changes from an Agrostis/Festuca/Nardus sward to one dominated by Molinia caerulea tussocks which continues to the valley bottom or close to it. At this transition the depth of the organic horizon increases and the mineral soil beneath becomes wetter and greyer. It is reasonable to conclude that the coincidental change in soil and vegetation reflects a transition from soils where the organic C status is more or less in equilibrium, to wetter sites downslope where soil organic C is probably accumulating. Molinia caerulea/Potentilla erecta mire extends over large areas of peaty (humic) gleys soils in the uplands that have organic horizons usually of around 15-40cm depth. When these soils have been improved by lime and fertiliser inputs and reseeding, soil disturbance has often led to the proliferation of rush pasture when grassland management has been inadequate. Moving to wetter sites where long periods of waterlogging are allied to high acidity, species including Scirpus cespitosus and Eriophorum vaginatum gain prominence. The wettest, perennially waterlogged locations, where peat is accumulating is category P land and here Carex echinata along with Sphagnum recurvum/auriculatum are key species of the mire community. The rate of soil organic C accumulation on W and P land is likely to depend upon the vegetation and its productivity and utilisation, together with the persistence of saturated soil conditions.

Before exploring changes in soil organic C storage that may be taking place now and how these might be modified, it is useful to assess the current position on the average amount of C stored in the soils of the categories identified and their relative importance in terms of the proportion of land area they occupy. The data in Table 1 have been arrived at through an examination of Soil Surveys and other published and unpublished analytical information on soils and their distribution in Wales but are only an estimate of current situation. The soil categories chosen attempt to separate soils that contain substantially different amounts of C but there are inevitably large differences within categories. For example the quoted C content of
lowland brown soils probably covers a range from about 100t/ha for some soils in regular arable use to over 200t/ha for some soils in permanent pasture.

One of the main difficulties in calculating total soil C from much of the relevant data is an absence of information on soil bulk density. The data on gravimetric organic matter content and soil horizon depth is extensive but a value for bulk density is needed to convert data to mass of organic matter per unit soil volume and thus per area of land. Organic matter content is the main factor responsible for differences in soil bulk density and it is particularly important to take this effect into account in peaty soils and ones with organic horizons where the bulk density may be less than one quarter of that of a mineral horizon. The relationship between organic matter content and bulk density established by Adams (1973) for some Welsh soils was used to estimate bulk density.

Table 1. Estimated storage of organic carbon (C) in the different categories of soils in Wales

<table>
<thead>
<tr>
<th>Soil description category</th>
<th>Soil category</th>
<th>Total area (x10^3) ha</th>
<th>Percent of land area</th>
<th>Organic C (t/ha)</th>
<th>Total C Mt (x10^3)</th>
<th>Percent distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland brown soils</td>
<td>B</td>
<td>1200</td>
<td>60</td>
<td>150</td>
<td>180</td>
<td>42</td>
</tr>
<tr>
<td>Mineral/humose gleys and Podzols</td>
<td>G+H</td>
<td>480</td>
<td>24</td>
<td>220</td>
<td>106</td>
<td>24</td>
</tr>
<tr>
<td>Peaty gleys</td>
<td>W</td>
<td>250</td>
<td>12.5</td>
<td>330</td>
<td>83</td>
<td>19</td>
</tr>
<tr>
<td>Peatlands</td>
<td>P</td>
<td>70</td>
<td>3.5</td>
<td>900</td>
<td>63</td>
<td>15</td>
</tr>
</tbody>
</table>

Note: Total land area 2x10^6 ha, total estimated C storage 432x10^3 Mt.

The data in Table 1 indicate that over Wales as a whole the category defined as lowland brown soils, most of which are in short or long term grassland, contain about two fifths of the soil C. Humic gleys and podzols that are essentially soils of the hills and uplands contain about one quarter of the total soil C and occupy about the same proportion of the total land.
area. Peatlands account for less than 4% of the land area but retain 15% of the total C in the soils of Wales. The estimated total C in the soils of Wales is close to the 409Mt quoted in a report for the Welsh Assembly Government (WAG, 2010).

**Current soil C storage and dynamics**

**Lowland soils**

In the case of lowland, B category soils, it is the proportion of land in arable cultivation that is the main determinant of overall soil C storage. Land over most of the country is unsuited to intensive and expansive arable cropping because of climatic limitations and either one or combinations of topography, soil particle size class, stoniness or shallowness. For these reasons it is unlikely that there will be any substantial decrease in C storage through change from grassland to arable land use. Most lowland soils are in short or long term grassland with a predominance of the latter. Cultivation and reseeding stimulates soil C oxidation but since this is typically carried out at around five year intervals or longer it is probably insignificant in terms of mean soil C storage in the long term. The use of very short term leys of one or two years is unattractive practically and economically.

Most of the lowland mineral and humose G category gley soils that used to remain waterlogged for several months of the year have been drained and the soil improved by lime and fertiliser inputs. Improved aeration may have increased organic matter oxidation but this potential decrease in soil C has probably been negated by a greater plant residue input through the greater productivity of ryegrass/clover pasture. The semi-natural unimproved rush dominated wet grassland that provided a relatively undisturbed habitat and the food sources required for ground nesting birds has diminished greatly.

Some evidence has suggested that soil C has decreased in grassland soils in Wales in recent years. If this is the case then agronomic factors decreasing plant residue returns provide the most likely explanation. The two main ones are improved efficiency in herbage utilisation in grazing and closer mowing and more efficient removal in harvesting herbage for silage. Climate change has been suggested as a causal factor but this is very speculative since any change including increased atmospheric CO\(_2\) would seem to be likely to increase productivity and thus soil C. Taking lowland Wales overall it seems likely that soil C storage is reasonably constant and in balance and furthermore that this situation will remain into the foreseeable future.

**Upland soils**

Soils of the hills and uplands range more widely in character and C storage than lowland soils but for simplicity they have been separated into three categories related substantially to topographical position. Soils
on sites where the slope is greater than about $7^\circ$ occupy the greatest area of land. The soils of this H category are mainly podzols but include other soils especially brown podzolic soils on slopes greater than about $15^\circ$. Unimproved soils in this category that support semi-natural grass dominant vegetation sustained by sheep grazing have two key chemical characteristics and one physical one. They are strongly acidic with a pH below 4.0 in the topsoil and have levels of available P that are deficient for productive herbage species. Almost invariably there is no free watertable within the profile but surface horizons are saturated for long periods because of their retentivity in high rainfall locations. The herbage productivity of these soils is low. Limited data is available but a long term experiment on H category land close to Pumlumon recorded annual herbage dry matter yields between 1000 and 1500kg/ha (Adams, 2014). This level of production is little more than one tenth of that produced by well fertilised, ryegrass dominant lowland swards. However the proportion of the dry matter returned to the soil as plant residue is greater than in lowland swards since its removal by sheep grazing is inefficient. This is because species within the grassland community including *Nardus* and *Molinia* are unpalatable. Plant residue inputs are nevertheless small and aerobic breakdown can take place especially in the summer when soil temperatures are higher. These areas have received and continue to receive virtually no deliberate nutrient inputs apart from cycling through grazing animals and land use has been reasonably consistent over a long period. If these conditions continue there is unlikely to be any material change in soil C contents for the foreseeable future. Podzols have an organic horizon and this gives the impression that their organic matter content is much greater than lowland soils. The organic C content of a typical podzol in Wales is no more than 20% greater than productive lowland soils in permanent pasture. Peaty gley soils and peats (W and P land) occupy sites that are waterlogged for much or all of the year. Anaerobic conditions in addition to strong acidity and low or deficient levels of plant nutrients limit the range of species that can survive. If anaerobic conditions persist to arrest oxidative breakdown then, provided any photosynthesising species can grow and produce a carbonaceous residue, organic C will accumulate. The rate of accumulation depends upon the productivity of the system and timescale of prevention of oxidative breakdown. Some wetland systems are productive and the key issue is their ability through a substantial base input (Ca) to maintain a near neutral or alkaline pH. This counteracts the inherent acidifying tendency of humification and greatly increases the range of species that can survive and grow. Virtually all wetland habitats in Wales are acidic and the photosynthetic species that
survive are not vigorous. Furthermore the cool upland climate is less favourable for growth than many wetlands in continental Europe. The C content of peaty gley soils is at least double that of grassland soils in the lowlands and it is probable that their storage of C is increasing albeit slowly. These soils trend into permanently waterlogged peat but, overall, areas of peat with more than 40 cm of surface organic matter occupy less than one third of the area of peaty gley soils. It is reasonable to suggest that the rate of increase in C storage in peaty gley soils is likely to be less than totally waterlogged peat even though the photosynthetic species responsible for dry matter production differ. The multi-author paper on C storage in northern hemisphere peatlands over the last millennium includes data that provides an estimate of the likely rate of net C storage in the peatlands of Wales (Charman et al. 2013) Changes in climate have affected the rate of C storage but not massively. The overall mean rate of net C accumulation has been estimated to be 250-300 kg C/ha/yr. Taking the higher value it can be predicted that it will take about 30 years for the current C storage in peat in Wales to be increased by 1% and that the amount of newly stored C would increase in the depth of peat by about 1 cm. The mean depth of peat in the Welsh peatlands is about 90 cm which on average has taken over 3000 years to accumulate. There is insufficient historical analytical data to estimate with any confidence the rate of C accumulation in peaty gleys. On mildly undulating land in the hills one can walk from peaty gley land to quite deep peat within 20 m and it is clear that a shallow depression can result in a sufficient change in hydrology for the vegetation to change and for peat to accumulate. It is reasonable to conclude given a similar time of development that the difference in organic horizon depth is a consequence of a difference in C storage and hence in a non-eroding landscape a difference in the rate of C accumulation. The average rate of C accumulation in peaty gley soils with organic horizons less than 40 cm deep is probably no more than one third of that in permanently waterlogged sites.

Natural and man induced changes to future C storage in Welsh soils and ecosystems

Land use in the lowlands is determined largely by the characteristics of the land, the climate and the economic viability of a range of practicable enterprises. There has been no substantial change in the pattern of land use in lowland Wales over the last several decades and the current mix of land uses is most likely to continue into the foreseeable future. Within the main categories of lowland soils, C storage is more or less in balance so it is most likely that this will continue to be the case. Climate change is of topical interest and there are two ways in which this could affect soil C storage. One would be a sufficient change in climate to bring about a
major change in cropping and land use. Were this to occur the timescale of change will be centuries not decades. Alternatively climate change could affect the productivity of current plant systems and therefore residue production, or increase decomposition rates or quite likely both. As of now the normal variability in weather on the timescale of weeks, months, years or decades has masked any change in overall climate that may or may not have occurred. An increase in atmospheric CO$_2$ has occurred and this has the potential to increase productivity in cool temperate climates.

Land use in the hill and uplands is influenced to a greater extent by government policy. This is because the main enterprise of sheep farming relies on subsidies for both its own economic viability and to help sustain rural communities. It is in areas in the hills and uplands where soil C storage is probably increasing. It was concluded earlier that on slopes greater than around 7°, where the soils are mainly podzols and brown podzolic soils, soil C is probably more or less in balance. However on shallowly sloping sites and in hollows where soils are either peaty gleys, with a substantial organic horizon, or which are totally waterlogged and peat has accumulated, are increasing in C storage.

Data from a variety of sources suggests that the most optimistic rate of C accumulation in peatland sites in Wales is 300kg/ha/yr. Peaty gleys occupy a much greater land area but the rate of increase in C storage is unlikely to be greater than 100kg/ha/yr. The accumulation of C in these areas of land depends upon saturation being sustained for a large part or all the year. Several conservation organisations including the Montgomeryshire Wildlife Trust are concerned about the drying out of some peatlands caused by the creation of open drainage ditches. Drainage ditches have been blocked in some areas to help restore or maintain saturated conditions (http://www.montwt.co.uk).

In addition to any perceived value in nature conservation, benefits in C storage have also been proposed. Given that rates of C sequestration by peat and peaty gleys have been estimated, together with the land areas these occupy in Wales, it is possible to get some idea of the significance of the amounts of C stabilised. Using the land areas estimated in Table 1 and the rates of C accumulation quoted above, the predicted rate of C sequestration by peaty gleys and peatland together in Wales is 46kt/yr. The contribution by the two land categories is similar. To get an idea of the significance of the C sequestration predicted it can be compared with the CO$_2$ produced by the everyday activity of motoring in Wales. There are around 1.5 million licensed cars in Wales (www.statistica.com). Average car mileage is close to 8000ml according to the National Travel Survey and the Society of Motor Manufacturers and Traders quote average values for car emissions (2014/2015) at around
150gCO₂/km. Using these values it can be calculated that the approximate amount of CO₂-C emitted per annum is 795kt. This is seventeen times more than the amount of C the peatlands and peaty gley soils of Wales are likely to sequester. Taking peatland alone, cars in Wales emit forty times more C each year than is likely to be sequestered in peatland.

A high proportion of the vegetation grown on the agricultural land of Wales is removed by grazing or cropping each year but the same does not apply to afforested land. In Wales around 80% of the land area is used in agriculture and around 14% is woodland or forest and the latter is diverse in character.

The cropped production in agriculture including grassland is used in a range of different ways. It may be eaten by man or eaten directly or as conserved fodder by animals. Cereal straw may be fed to animals or used as bedding but whatever the usage a large proportion of the C contained is returned directly or indirectly within a few years to the atmosphere as CO₂. The situation with woodland and forest is different in that whatever its management, the perennial above and below ground biomass makes a substantial contribution to the total organic C stored in the ecosystem. It is reasonable to assert that soil organic C content will come more or less into equilibrium in woodland or forest depending upon the level of input of plant residues that include leaf fall and dead and shedded twigs and branches just as it does in permanent grassland though it may take tens of decades rather than a few. One could anticipate that the quantity of plant residue input in woodland might vary widely depending on many factors but it could be that for example in closed canopy woodland the annual input of residues changes little with age of stand.

It is likely but not certain that the annual input of plant residues in woodland is not greatly different from permanent grassland and that soil organic C contents are also similar. However depending upon the character of woodland or forest and its management there is the potential for a substantial difference from permanent grassland in the sequestration of C in the ecosystem. Whilst it is not always the case, studies on the biomass storage of C in ancient unmanaged forests have shown that there is no substantial gain in stored C over the very long term because new growth is balanced by loss through the natural process of death through either age or disease or indeed fire. Much of the forested land in Wales was planted from the 1950’s onwards by the Forestry Commission with Sitka spruce as the dominant species. This is plantation forest with trees of the same age and a growth cycle of 40 to 50 years. The climate of Wales suits Sitka and growth rates can be achieved that are close to those in its native western USA. On the most favourable sites a yield class of 20 can be achieved but values of 15 (m³/ha/yr) are more widely
applicable over a 45 year growth cycle. One cubic metre of wood is equivalent to about 0.5t of dry wood and if we consider wood to contain 50% C then a yield class of 15 means a gain of around 3.75t/ha/yr in stored C. This rate of C sequestration by a forest plantation of Sitka is over twelve times greater than an optimistic estimate of the rate of C sequestration by peatland in Wales. Whilst mixed deciduous plantations are slower growing than Sitka spruce, potential C sequestration is likely to be at least six times that of peatland. Over a 45 year growth cycle a Sitka plantation will have accumulated approximately 170t/ha of C in the wood which is similar to the average total C in lowland soils. Clearly the stability of the C stored in the wood harvested at the end of a production cycle depends upon the end use of the timber.

**Conclusions**

Soils in Wales range widely in total organic C content but have been rationalised into a small number of categories within which total C contents are reasonably similar. The categories relate substantially to soil character but also reflect different ecological and land use factors. Around 80% of the land is used for agriculture but inputs and productivity vary widely. The range and pattern of distribution of agricultural enterprises has not changed markedly over the last several decades so that by and large soil C contents are close to equilibrium with soil type and land use in the Principality. Detheridge *et al.* (2014) came to a similar conclusion. Climate change could have an effect in the future if it either brought about a major change in the productivity of the current balance of cropping or was sufficient to enable a substantial change in the types of crop that could be grown profitably.

It is likely that total soil C is increasing slowly in the hills and uplands in areas of peaty gley soils and peatland. Together these account for somewhat over 15% of the total land area of Wales and it was estimated that the total gain in C could amount to around 46kt/yr. Whilst this is of some significance it is only around one seventeenth of the C emitted as CO₂ annually by vehicles licensed in Wales.

It is likely that the range in agricultural enterprises practised in Wales will not change within the foreseeable future but change to forestry would increase C storage, not necessarily in the soils themselves but in the ecosystem as a whole. It was estimated that a reasonably typical Sitka spruce plantation accumulates C in its wood at a rate around twelve times that of peatland.

Detheridge *et al.* (2014) pointed out that land affected either directly or indirectly by mineral extraction is the only habitat type in Wales that has soils that are ‘deficient’ in C and therefore capable of accumulating C depending upon the land use applied to it. Land areas involved are small and so would any contribution to C storage. Land use changes that are
practicable in Wales on a large scale are limited. Evidence indicates that afforestation of whatever type is the change in land use best able to increase C storage in ecosystems in Wales.

References

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