Water and carbon cycling

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New A Level Subject Content Overview

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1. Water and Carbon Cycles

Cycling of carbon and water are central to supporting life on earth and an understanding of these cycles underpins some of the most difficult international challenges of our times. Both these cycles are included in the core content elements of the specifications for A Level geography to be first taught from 2016[1]. Whether we consider climate change, water security or flood risk hazard an understanding of physical process is central to analysis of the geographical consequences of environmental change. Both cycles are typically understood within the framework of a systems approach which is a central concept to much physical geographical enquiry. The concept of a global cycle integrates across scales. Systems theory allows us to conceptualise the main stores and pathways at a global scale. The systems framework also allows for more detailed (process detail) and local knowledge to be nested within the wider conceptual framework. Local studies on aspects of hydrology or carbon cycling can be understood as part of a broader attempt to understand in detail the nature of water and carbon cycling. Global environmental challenges frequently excite student interest in physical geography but it can be difficult for students to see how they can conduct relevant investigations of fieldwork given the large scale and complexity of the issues. By embedding their knowledge within systems framework students can understand how measurements and understanding derived from their own fieldwork and local studies contribute to the wider project of elucidating the cycling of water and carbon at the global scale.

This capacity to link scales means that the study of biogeochemical cycles is intrinsically geographical so that students can understand how processes operate in, and impact upon particular places and how they are distributed in space.

[1] Geography GCE AS and A Level Subject Content. Department for Education (2014)

This overview starts with a discussion of the systems approach and then considers the key processes and geographical understanding of both the water and carbon cycles. Potential fieldwork activities under this theme are discussed and finally some starting points for relevant case study material are outlined.

A Systems Approach

Water and carbon cycles are understood through a systems approach. Systems are bounded and have inputs, outputs and throughputs.

The throughputs are mediated by processes internal to the system which are often understood grouped together as sub-systems (figure 1). For example, in the case of the water cycle we might consider a drainage basin sub-system which has inputs of rainfall from the atmosphere, outputs of river discharge (to the ocean) and evaporation (to the atmosphere) and includes water storage in surface waters and as soil moisture and groundwater.

There are three concepts key to understanding biogeochemical cycling within a systems framework;

- **Stores** or stocks are the total amount of the material of interest held within a part of the system. This is effectively how much of the material there is and where it is. For example, soils are a major store of carbon within the terrestrial carbon system. Stocks are usually expressed in units of mass. e.g. total global soil carbon storage is estimated at 1500-2400 PgC (PgC is petagrams of carbon, a unit equivalent to 10^{15} grams or one gigatonne.)
- **Fluxes** are measurements of the rate of flow of material between the stores. Because fluxes are a rate the units are mass per unit time, commonly for global cycles these are expressed as Pg per year.
- **Processes** are the physical mechanisms which drive the flux of material between stores. For example one of the key processes which drive the flux of carbon from the atmosphere to the vegetation store is photosynthesis.

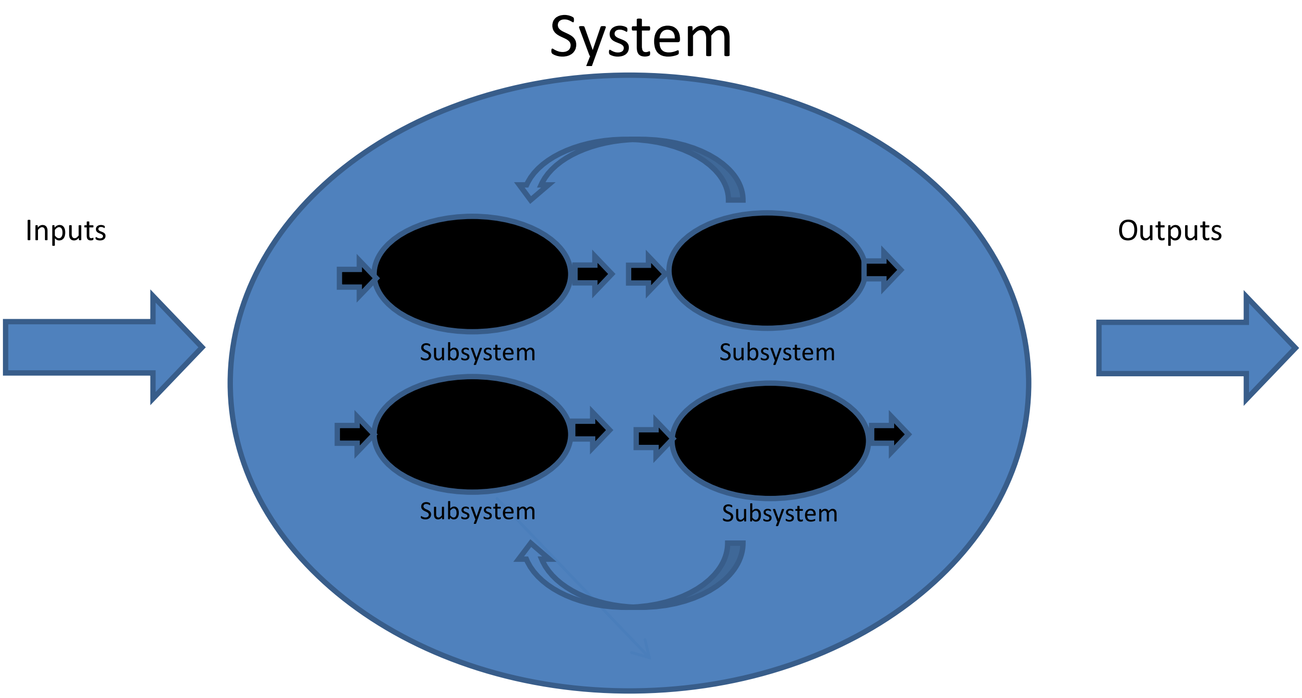

Figure 1: *A systems approach © Professor Martin Evans*

At their simplest, systems can be understood as 'black boxes' so that we simply quantify inputs and outputs to create material and energy budgets for the system. An example of this is creating a water balance for a drainage basin where we measure inputs (rainfall) and losses of water (evaporation and runoff) from the catchment. More detailed understanding of the system requires understanding of the internal processes which produce throughputs in the system by considering the functioning of sub systems. For example, to understand the runoff from our catchment we might study the role of rainfall infiltration into the soil and the way in which it partitions rainfall between soil water storage and runoff.

This ability to understand systems at different scales at different levels of abstractions is key to the success of the approach. Abstracting the complexity of systems in this way is central to creating models of their operation such as the Global Climate Models which are used to predict potential impacts of changes in atmospheric CO_2 levels. The systems approach is central to modern environmental science. 'Earth System Science' (which spans geography, geology/earth sciences, meteorology and oceanography), has been promoted as an interdisciplinary approach to understanding the physical basis of global environmental challenges
(See for example: http://serc.carleton.edu/introgeo/earthsystem/nutshell/index2.html)

Through the study of water and carbon cycles students will develop understanding of physical processes which control some of the most significant environmental changes occurring on the earth and the geography of their impacts.

2. The Water Cycle

Water is present in three phases on earth, as liquid water, as ice and as atmospheric moisture. At the global scale there are stores of water in all three phases. Liquid water dominates with about 98% of water in liquid form, predominantly in the oceans (table 1)

Water is cycled between these stores by a range of key processes as identified in figure 2. The mean residence times for various stores vary both with the size of the store (larger stores take longer to turn over) and with the rate of the processes which move water between stores (for example surface runoff is relatively rapid but groundwater flows are much slower so that groundwater residence times can be high). Brief introductions to key processes are given below.

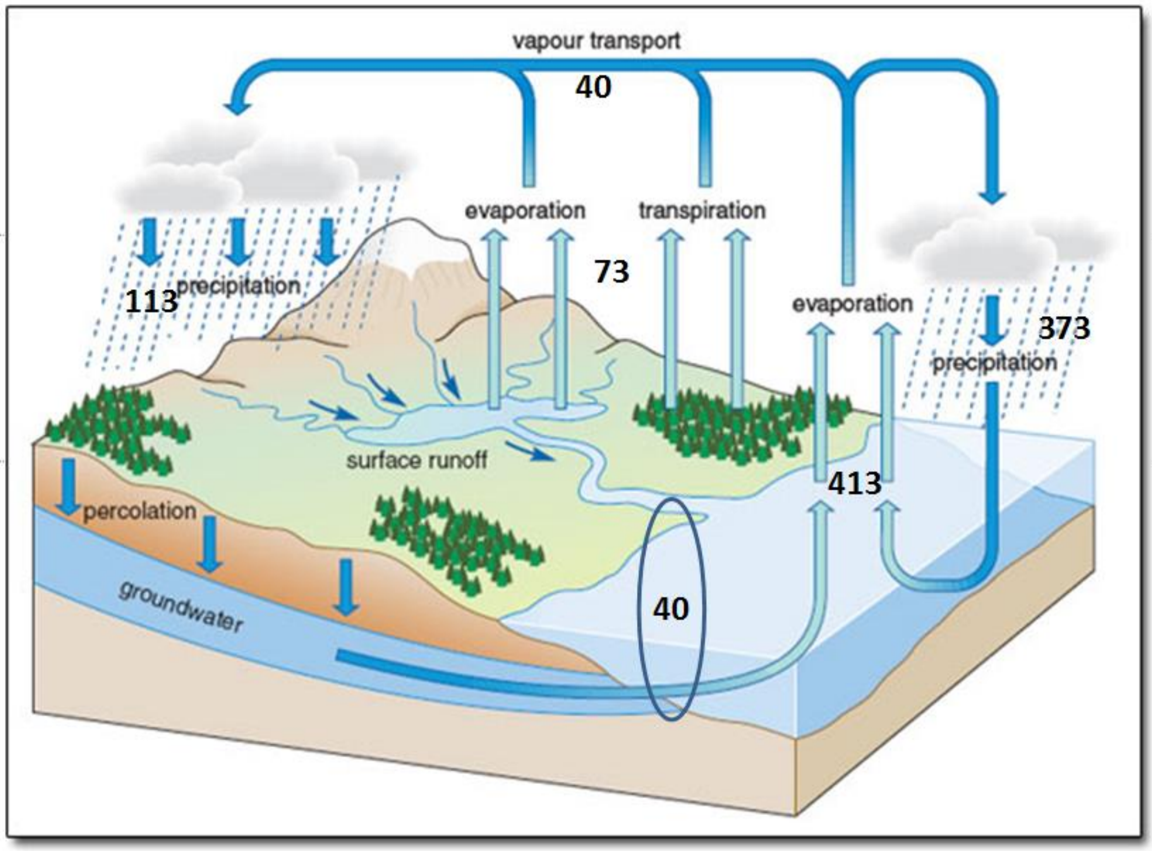

Figure 2: *The global water cycle. Fluxes of moisture indicated in units of 10^3 km^3 yr^{-1}*
Original Figure © Open University Modified with data from Trenberth et al. 2007.

Store	Volume $10^3 km^3$	%	Residence time
Oceans	1335040	96.9	3600 years
Icecaps	26350	1.9	15000 years
Groundwater	15300	1.1	Up to 10000 years
Rivers and Lakes	178	0.01	2 weeks to 10 years
Soil Moisture	122	0.01	2-50 weeks
Atmospheric Moisture	13	0.001	10 days

Table 1*: Scale of stores in the global water cycle and typical residence times. (Data from Trenberth et al. 2007; and Lockwood, 2012)*

Key Water Cycle Processes

Evapo-transpiration

Evaporation can occur from open water or from wet surfaces. Total evaporative losses also include water vapour transpired by vegetation, taken up by root systems and released through the stomata of the leaves. Taken together these processes are often referred to as **evapotranspiration.**

Rates of evaporation are controlled by the surface energy balance, temperature, relative humidity and wind speed. Rates of transpiration are also affected by plant type and growth condition. Both evaporation and transpiration are maximised when water is not limited, this is known as **Potential Evapotranspiration**, and values (**Actual Evapotranspiration**) may fall below this level due to reduced soil moisture or due to closure of plant stomata under moisture stress.

Rates of evaporation over the ocean exceed terrestrial rates because over the land actual evapotranspiration is less than potential. This result in a net transfer of atmospheric moisture to the continents as moist air moves across the continents driven by global air mass circulation.

Precipitation

Atmospheric moisture is returned to the terrestrial system through precipitation. Vertical motion of air masses in the atmosphere controlled by global circulation of air masses, local radiation balance and by interactions with topography cause cooling and condensation of atmospheric moisture. These processes generate frontal, convective and orographic rainfall respectively. For an excellent summary of processes controlling precipitation see chapter one, in Shaw *et al*. (2010).

Runoff generation

The atmospheric moisture which is transferred to the continents is returned to the oceans as runoff either surface runoff or as groundwater flow. Overland flow and river flow is relatively rapid whereas transit times to the ocean for deep groundwater can be thousands of years. Infiltration is a key process partitioning precipitation between runoff and water which either enters the soil as soil water storage/soil throughflow or percolates to bedrock and becomes groundwater flow. Surface flow is generated when rainfall intensity exceeds infiltration capacity (Infiltration excess overland flow) or when rain falls on soils where the soil water store is full and water table is at the surface (saturation excess overland flow). Understanding of runoff and the partitioning of moisture at the surface is central to terrestrial water management since both water resources and flood hazard are intimately associated with our ability to manage and respond to these flows.

Cryospheric processes

After oceanic water, the largest stores of water on earth are in the frozen form. Ice sheets covering Greenland and Antarctica make up 95% of cryospheric water. Snow falling on icecaps is compressed to form ice and this water enters long term storage. During the annual cycle water is removed from the icecap by melting and runoff during the summer months and accumulates during the winter. At longer timescales the balance of accumulation and melting is controlled by temperature and by polar snowfall. On glaciers and ice sheets the elevation on the glacier where annual accumulation equals annual melting is the equilibrium line altitude (ELA). Reduced snowfall or higher temperatures lead to higher ELA and net conversion of ice into liquid water. *Total* melting of the polar ice sheets could lead to 60 metres of sea level rise (an increase in the size of the oceanic water store). Because of the importance of these regions for the water cycle they are the focus of considerable monitoring effort (see National Ice Snow and Data Centre: http://nsidc.org/greenland-today/). Rising sea levels are a positive feedback on the rate of removal of glacial ice since they can destabilise glaciers and ice streams which end in the sea leading to accelerated rates of iceberg calving.

The Geography of the Water Cycle

The water cycle can be studied at scales from global to a small-scale hillslope plot. For any unit we can measure or estimate a water budget by quantifying the key stores and fluxes. The spatial variation of these local budgets and their aggregation to larger spatial units produces understanding of spatial variability in hydroclimate, water availability, and flood hazard. Water is essential for human populations and yet also poses significant risks. Understanding local, regional, and global transfers of water and the way in which these interact with and control physical and biological processes, are key parts of physical geography.

3. The Carbon Cycle

Cycling of the element carbon is intimately associated with life on earth. Carbon is present in carbon based molecules that are integral to all living creatures, as carbon dioxide and methane in the atmosphere, in carbonate rocks in the lithosphere and as organic molecules in soils and sediments which are derived from formerly living material. Major carbon stores include the ocean, ocean sediments, soils, bedrock, vegetation and the atmosphere. Atmospheric carbon has become a major policy focus because of the role of carbon dioxide and methane as greenhouse gasses. The magnitude of the major stores and the way in which they are connected by key processes is illustrated in figure 3 which is taken from the Inter-governmental Panel on Climate Change (IPCC). This diagram indicates significant anthropogenic perturbations of the carbon cycle since 1750AD.

About 90% of anthropogenic carbon release comes from combustion of fossil fuels with the remainder driven by land use change. Of the anthropogenic CO_2 released to the atmosphere about 24% is absorbed by the oceans and 26% is taken up by plants. Global CO2 concentrations have increased from less than 320 ppm in 1960 to around 400 ppm at present (see Earth System Research Laboratory website: http://www.esrl.noaa.gov/gmd/ccgg/trends/index.html)

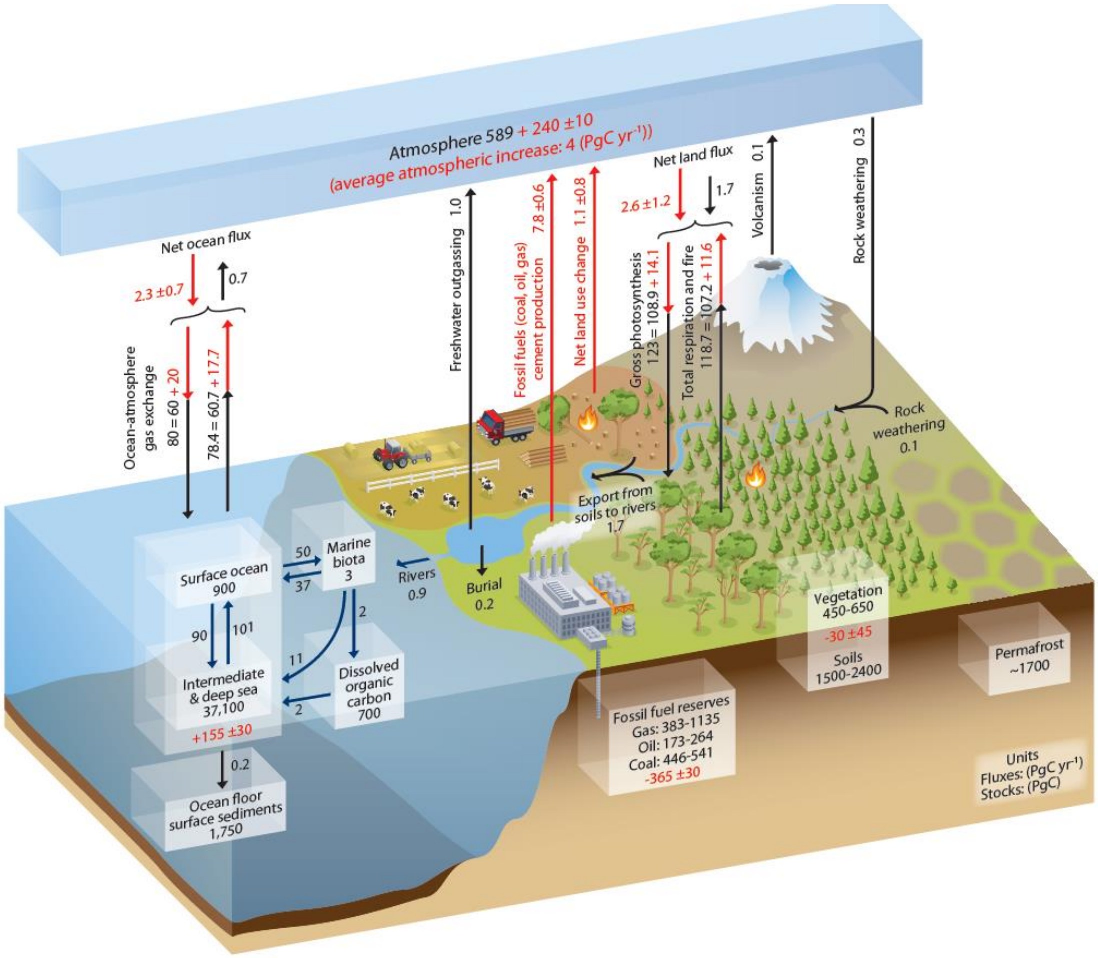

Figure 3: *The global carbon cycle © IPCC. The boxes are stores of carbon and the arrows indicate fluxes and the processes which drive those fluxes. Figures in black are estimates of the natural stores and fluxes and figures in red indicate anthropogenic impacts on the carbon cycle in the period after 1750 AD. For full details of the estimates underlying this figure see: https://www.ipcc.ch/report/ar5/wg1/*

The terrestrial carbon cycle

The terrestrial carbon cycle is dominated by uptake of CO_2 from the atmosphere by plant photosynthesis. CO_2 is released back to the atmosphere due to respiration of plants and animals and CO_2 and methane are released due to decomposition of dead organic matter. Carbon is cycled relatively rapidly between soil and vegetation and the atmosphere. This cycling of carbon through living systems is sometimes called the fast carbon cycle as distinct from the slow carbon cycle (see below). Terrestrial carbon cycling occurs within ecosystems which, in the modern world, are almost all subject to intensive human impacts. Land use change and other human impacts on ecosystems have the potential to change the balance of carbon uptake and release in the terrestrial system.

The oceanic carbon cycle

The oceans are a very significant carbon store. Carbon is held in dissolved form in the waters and in the tissues of ocean dwelling organisms. The primary inputs and outputs of carbon from the oceans are by gas exchange with the atmosphere but there is also a significant input of both organic carbon and carbonate ions from continental runoff. Carbon flux within the oceans is controlled by physical, chemical and biological processes (see below). Because of the size of the oceanic carbon store small changes in carbon cycling can have significant global impacts. Only a small proportion of this carbon is eventually buried in ocean sediments but these sediments are important long term carbon stores.

Atmospheric carbon cycle

Atmospheric carbon occurs in two main forms carbon dioxide and methane CH4. These are both greenhouse gasses but the way in which they interact in the atmosphere differs. Methane is 23 times more powerful as a greenhouse gas than CO2 but as a relatively reactive chemical it is short lived in the atmosphere (lasting about 12 years, compared to up to about 50 years for Carbon Dioxide). Carbon dioxide is relatively unreactive and is usually removed from the atmosphere through interactions with the terrestrial or oceanic carbon cycles (e.g. by photosynthesis or absorbed into surface waters)

The 'slow carbon cycle'

The phrase the slow carbon cycle is sometimes used to refer to cycling of carbon between bedrock stores and the atmosphere and ocean through processes of weathering over long timescales (millions of years). Over these long time periods weathering of rocks on the continents creates a net sink of carbon in the oceans. Chemical weathering of rocks by carbonic acid (produced by the reaction of atmospheric CO_2 with water) produces carbonate in runoff water which is transferred to the ocean. In the oceans carbonate is used by organisms to create shells. When organisms die these carbonate shells are deposited as carbonate rich sediment and eventually lithified to form limestone. Carbon from this long term store is returned to the atmosphere by volcanism where CO2 is released from melted rocks which have been subducted at plate boundaries.

Key Processes controlling carbon cycling

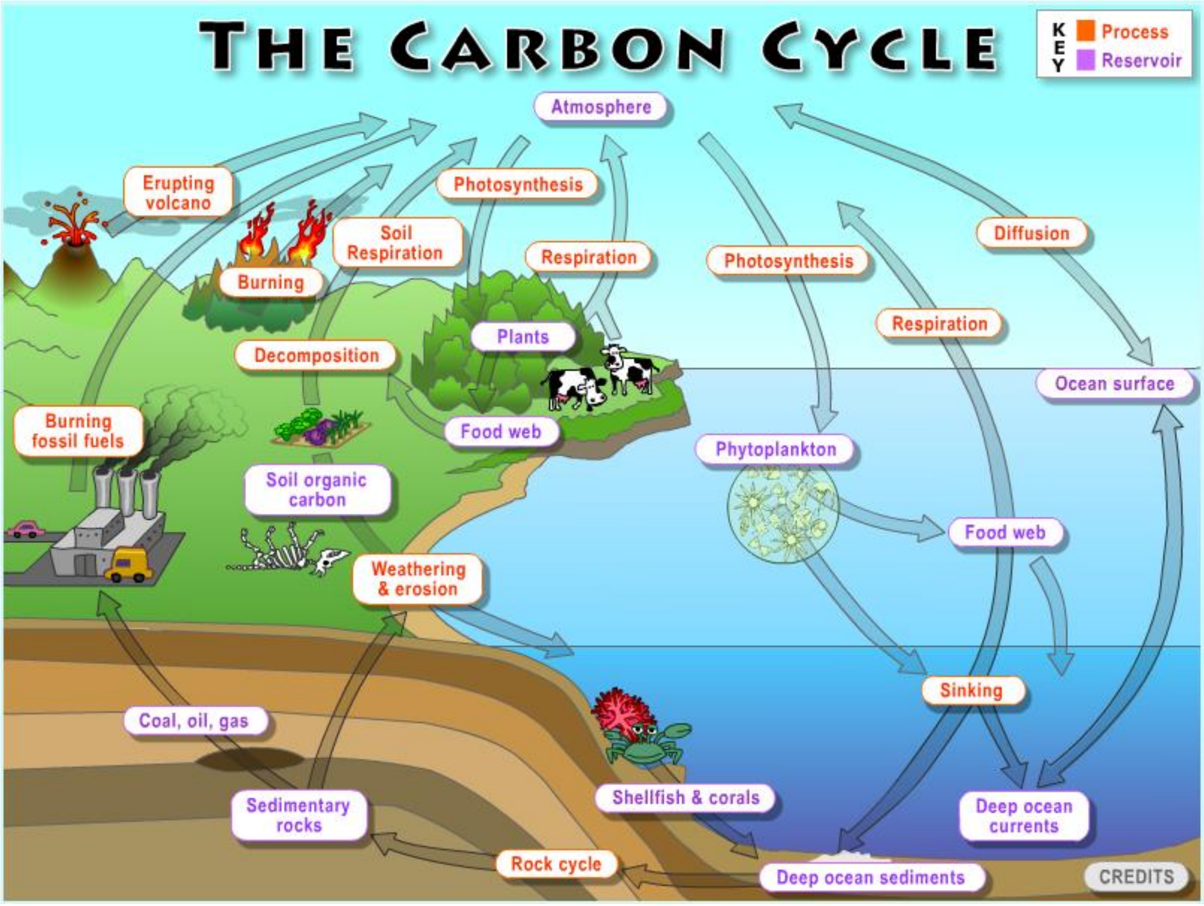

Figure 4: Some key processes which drive the flux of carbon between the main stores © Candace Dunlap. Source: http://serc.carleton.edu/eslabs/carbon/index.html

Photosynthesis and respiration

Key to terrestrial carbon cycling are the processes of photosynthesis and respiration. Photosynthesis is the process of the production of carbohydrate molecules from carbon dioxide and water using energy from light. Plants and some algae and bacteria photosynthesise and so fix gaseous carbon dioxide from the atmosphere into solid form in their tissues. CO_2 is released to the atmosphere by living things through the process of respiration. Life derives energy from the combination of sugars and oxygen and CO_2 is a by-product of this reaction.

Decomposition

CO_2 from plants and animals is also returned to the atmosphere through processes of decomposition of dead tissue. These decomposition processes occur through the action of fungi and bacteria. Carbon is released in gaseous form but decomposition may also produce soluble organic compounds so that carbon can also be mobile dissolved in runoff from the land surface.

Methanogenesis

Methane is a by-product of respiration by methanogenic bacteria which are found in anaerobic (low oxygen) environments. Methane emissions from wetland environments such as peatlands or rice paddy are significant because of the high global warming potential of methane.

Carbon sequestration in oceans

Carbon dioxide moves from the atmosphere to the ocean by diffusion. CO_2 dissolved in the surface of the ocean can be transferred to the deep ocean in areas where cold dense surface waters sink. This is a physical process sometimes called the physical pump. Phytoplankton in the ocean also fixes carbon dioxide through photosynthesis and these organisms form the bottom of the marine food web. Carbon from this source may be transferred to the deep ocean either as dead organisms sink or transported with downwelling waters. Removal of carbonate from sea water by shell building organisms is another important mechanism controlling transfer of carbon to deep ocean sediments.

Fossil fuels

Fossil fuel reserves are significant stores of fossil carbon. Coal for example is lithified peaty deposits. Burning of fossil fuels such as coal and gas releases carbon dioxide to the atmosphere. This is carbon released from long term storage deep in the earth and is a human induced acceleration of the cycling of this carbon.

The geography of the carbon cycle and carbon budgets

The carbon cycle like the water cycle can be studied at a range of spatial scales. For example, the key processes of the terrestrial carbon cycle can be considered through study of the carbon budget of a field or catchment or local ecosystem. Figure 5 shows an example of a carbon budget for an area of tropical forest showing that deforestation leads to a shift of the ecosystem from a carbon sink to a carbon source. Carbon cycling is strongly controlled by biological factors so variation in space is closely linked to biogeography and the distribution of major ecosystem types. In the modern world human activity is a major control on species distribution and ecosystem function.

There is also an important geography to human interaction with the carbon cycle through combustion of fossil fuels which is strongly linked to economic growth and development. There is a physical geography to the distribution and accessibility of fossil fuel reserves but equally important an economic geography governing the feasibility of exploitation and demand. Recently technological changes which have allowed extraction of hydrocarbons from new sources such as fracking and tar sands have increased the range and availability of reserves and changed the geography of extraction.

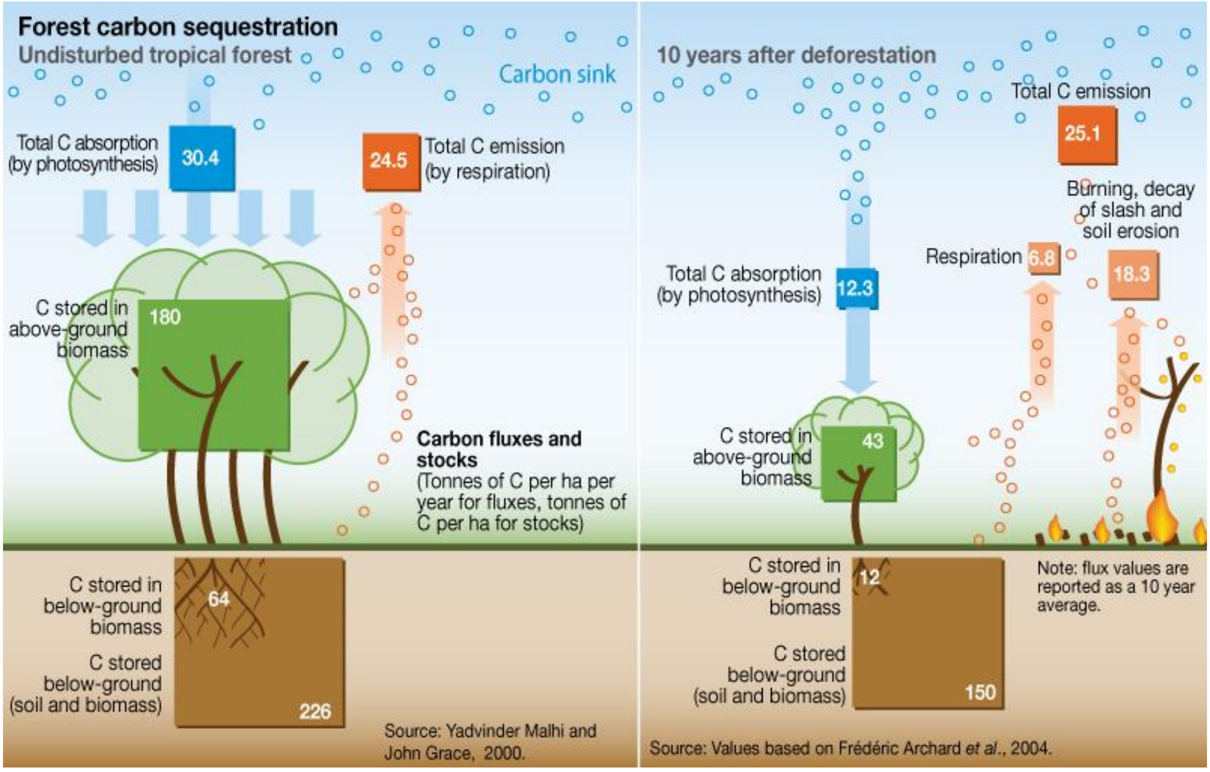

Figure 5: *Changes in carbon cycling between Tropical Forest and areas of deforestation Units are tonnes of carbon per hectare per year for fluxes and tonnes of carbon per hectare for stores.* Original diagram by Riccardo Pravettoni, UNEP/GRID-Arendal: http://www.grida.no/graphicslib/detail/forest-carbon-sequestration_06bd

Interactions of the carbon and water cycles

It is apparent from the discussion above that there are very significant interactions between water cycling and carbon cycling. The two cycles interact directly where carbon is transported dissolved or suspended in running water. Transport of weathering products and organic matter from the continents to the oceans is an important aspect of carbon cycling which is directly linked to water flux. Similarly the impact of changing atmospheric carbon concentrations on global climate has a profound effect on water cycling impacting terrestrial and oceanic evaporation and patterns of precipitation. The two cycles are also linked through the role of ecosystems in carbon cycling since moisture availability is a key control on plant distribution and plant life plays a key role in terrestrial carbon cycling. Two contexts of particular interest for exploring the linkages between the two cycles are climate change and land use change. Both climate change and land use change may lead to significant perturbations in terrestrial ecosystems which impact on both water and carbon cycling (see for example material on desertification below).

4. Fieldwork opportunities in relation to water and carbon cycling

As noted one of the characteristics of these cycles is the way in which they can be applied at a range of scales to integrate local investigations into wider understanding. Consequently the carbon and water cycling topics provide excellent opportunities for a range of local fieldwork investigations.

Potential topics include:

Investigations of rates of infiltration

Infiltration is a key process responsible for the partitioning of rainfall between overland flow (runoff) and soil storage or subsurface flow. Infiltration is easy to measure using simple infiltration rings which can be made from plastic pipe. Infiltration rates may be affected by a range of factors such as surface cover, soil moisture, soil texture, slope, and soil compaction allowing groups to conduct a range of related but distinct investigations in a constrained area.

Measurement of water balance

Catchment discharge is a fundamental parameter in the drainage basin water balance. Use of secondary rainfall and runoff data will allow students to construct simple water balance for catchments. Practice measuring stream discharge and rainfall in the field will help students to understand the potential errors associated with these estimates. Understanding errors is central to any budgeting exercise. Measurement of rainfall in multiple simple rain gauges (for example around school grounds) will allow students to examine spatial variation in rainfall and its potential impact on creating good estimates of rainfall inputs.

Estimation of carbon stocks in woodland.

The stock of carbon within woodland can be simply estimated. There are standard equations to estimate living biomass of trees from the diameter of the tree measured at 1.3m height (a simple guide from the field studies council is here: http://tinyurl.com/q5mgxru).

Tree biomass is 50% carbon so it is a simple conversion to work out how much carbon is stored in the tree. Where tree age can also be estimated, either from the girth of the tree, knowledge of the site, or from tree ring evidence on similar felled trees then the rate of carbon sequestration as mass of carbon per year can be calculated, in this case students can estimate both the stock of carbon and the flux.

Estimation of carbon stocks in peatlands

Peatland depth is easily measured by probing the peatland either with a commercially available peat probe or with sections of narrow threaded rod which can be connected to make a portable probe. Multiple probings of depth in an area can be used to estimate peat volume at a site. This is a good opportunity to introduce concepts of averaging or simple geospatial techniques such as the use of Thiessen polygons. Peat volume can be converted to organic carbon stocks by knowing typical peat densities (circa 0.1-0.2 gC cm^{-3}). Where the age of local peatlands is known for example from published radiocarbon dates on basal peats the total carbon stock can be converted to an average flux over this time period by dividing the stock by the age to give flux in units of grammes of carbon per metre squared per year (gC m^{-2} a^{-1})

Estimation of fluvial carbon flux

Estimating fluxes of materials in rivers involves measurement of discharge and of the concentration of the material of interest. Flux is calculated as the product of discharge and concentration. This is a good place to practice the use of commensurate units to produce flux estimates in sensible units. For example students might measure river discharge either from stage at a site with known stage-discharge relationships (e.g. a weir) or by measurement of velocity and river cross section. Sediment concentration could be measured by filtering water samples. The organic component of sediment can be estimated as the fraction lost after an hour in a furnace at 550 degrees C. Carbon content of sediment is typically 50% of organic content. The fluvial particulate carbon concentration (the amount of carbon being transported in the sediment) in g m^{-3} multiplied by discharge in m^3s^{-1} will give a carbon flux in grams per second (g s^{-1}). The same calculation can be applied to dissolved carbon concentrations estimated by colourimetry. This approach is particularly relevant to peatland streams where ‘brown water’ is indicative of high dissolved carbon concentrations.

5. Case studies of water and carbon cycling

Water cycle – surface water flooding in the UK

In 2007 severe weather led to significant flooding across many parts of the UK. Much of this flooding occurred in areas away from the direct influence of river flooding. This was surface water or 'pluvial' flooding caused by high intensity rainfall leading to excess runoff overwhelming drainage systems and leading to localised flood impacts (Figure 6). Under conditions of climate change there is a risk that increased frequency of high magnitude rainfall events will lead to wider pluvial flooding (see: https://www.gov.uk/government/publications/future-flooding). The drainage infrastructure of the UK much of which was built over 100 years ago is not always designed to cope with this enhanced runoff. Various approaches are being developed to mitigate these risks including Sustainable Urban Drainage Systems (SUDS) (see: http://www.bgs.ac.uk/suds/) which aim to reduce surface water flooding by designing surfaces which maximise infiltration and allow temporary surface and subsurface water storage to reduce storm runoff.

Figure 6: *Flash flooding in a village in Bedfordshire, 2004 © Malcom Campbell*. Source: http://www.geograph.org.uk/photo/657563

Water Cycling in Tropical Forests

The dense canopy of tropical forests mean that rates of interception are high and consequently rates of evapotranspiration are high. High rates of evaporation transfer latent heat to the atmosphere and together with high humidity drive local convectional rainfall. This drives high rates of precipitation so that water is effectively recycled within the Tropical forest system. Forest evaporation is also important in sustaining regional rainfall in areas marginal to the forest so that for example Amazonian rainforest supports rainfall totals over key agricultural regions of Brazil

Deforestation leads to higher albedo and higher surface temperatures lead to greater loss of sensible heat to the atmosphere but reduced biomass and lower interception means that there is less evapotranspiration. This leads to lower atmospheric humidity and reduced precipitation (Marengo, 2006).

Forest land use change and carbon cycling.

Forests are significant stores of carbon. Carbon is stored primarily in the biomass of the trees but thick litter layers on the forest floor can also be significant. Forest landscapes are important resources for human populations so that throughout human history deforestation for timber resources, or to clear land for agriculture has been a major human impact on ecosystems. Similarly in some contexts afforestation associated with timber cropping is significant. Historical and geographical changes in forest clearance and forest management have a significant impact on forest carbon storage. Forest growth leads to sequestration of carbon from the atmosphere whilst forest clearance can lead to carbon emissions to the atmosphere through burning or decomposition of biomass and through changes in soil organic carbon storage associated with forest clearances e.g. figure 5.

Figure 7 illustrates how these impacts on carbon balance have been variable in time and space. Tropical forests are an important carbon store sequestering up to 1 Pg of carbon per year. Clearance of tropical forests for settlement and agriculture has led to significant increases in carbon emissions from the tropics. In contrast in N. America (and in Europe to a lesser extent) forest regrowth due to agricultural abandonment after the great depression of the 1930’s has led to increases in carbon sequestration by forest land

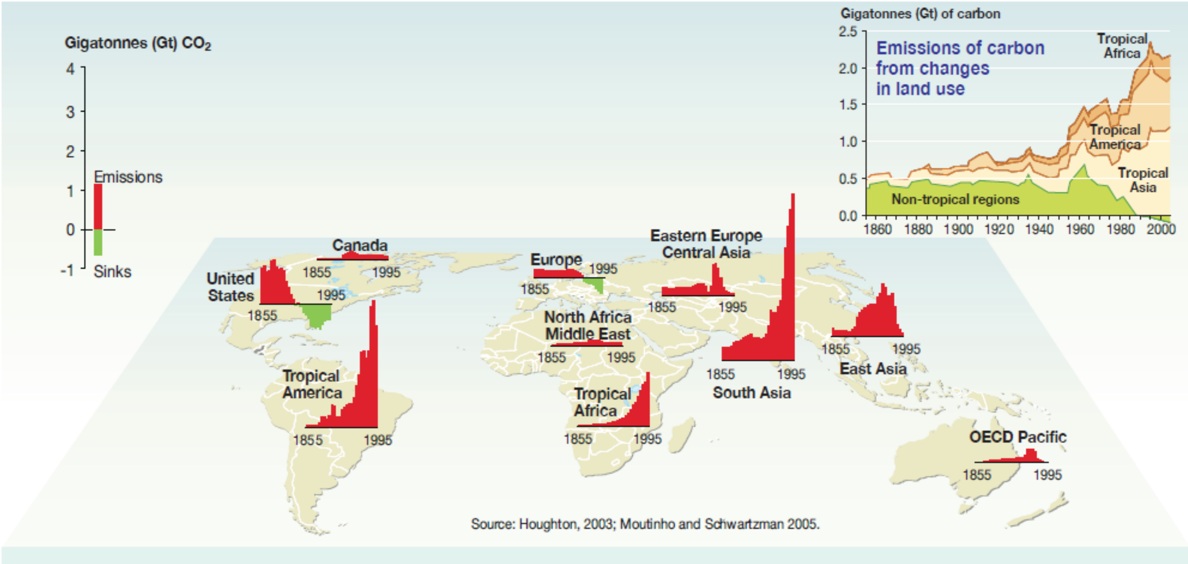

Figure 7: The geography of carbon emissions from landuse change. Reproduced from UNEP (2009) Vital Forest Graphics. Source: http://www.unep.org/vitalforest/

Carbon cycling in eroding and restored peatlands

Peatlands are thick organic soils which develop in areas where water table is high. Low oxygen conditions below water table inhibit microbial decomposition of plant litter so that thick organic layers accumulate. In the UK upland peatlands which have accumulated over approximately the last 7000 years are often 2-4 m deep. The organic matter in peat is 50% carbon so these peatlands are major soil carbon stores which lock up carbon which has been removed from the atmosphere as peatland plants photosynthesise. The northern peatlands which include the large peatlands of Siberia and the Canadian Shield as well as European peatlands store 20-30% of global soil carbon. The amount of carbon in the northern peatlands is equivalent to around 60% of the atmospheric carbon pool. Threats to the integrity of this carbon store therefore pose the risk of releasing significant amounts of carbon to the atmosphere.

Upland peatlands in the UK have been severely affected by air pollution which has caused loss of key peat forming species such as sphagnum. Historic overgrazing has further impacted some peatlands and they have been subject to climate stress during the Little Ice Age. Together these factors have led to massive erosion (Figure 8). Peatlands have also been subject to drainage during the 20th century. Only 20% of UK upland peatlands are not degraded. Organic matter eroded from peatlands may be oxidised in river systems releasing CO_2. Erosion of gullies and drainage also leads to reduced water tables in the peatland. This enhances decomposition in the upper layers of the peat and releases more dissolved carbon to waters and more CO_2 to the atmosphere. Consequently rates of carbon sequestration in degraded peatlands are reduced or the peatlands may even become carbon sources. Across the uplands of the UK there are now significant attempts being made to restore degraded peatlands by re-vegetating bare peat (http://www.moorsforthefuture.org.uk/repairing-bare-peat) and blocking drains (Figure 8). Restoration of bare eroding peat and blocking of gullies has the potential to transform eroded bogs from carbon sources to carbon sinks (http://www.iucn-uk-peatlandprogramme.org/publications/commission-inquiry/inquiry-findings).

Figure 8a: *Eroded peatlands in the Southern Pennies © Professor Martin Evans*

Figure 8b: *Restored peatlands in the southern Pennines © Professor Martin Evans*

Integrated case studies of water and carbon cycling - Desertification

Integrated case studies of water and carbon cycling are likely to focus around the impacts of land use change. An example familiar to many geographers is desertification (see http://www.unesco.org/mab/doc/ekocd/chapter11.html). Drylands cover about 40% of the earth's surface and the Millennium ecosystem assessment (http://www.millenniumassessment.org/en/index.html) estimates that 10-20% of drylands suffer from land degradation. Desertification driven partly by climate change and also by land use change leads to reductions in soil moisture. Under conditions of desertification, accelerated soil erosion and reduced vegetation cover lead to reduced carbon sequestration. This results from reduced vegetation cover (lower photosynthetic fixation of carbon) and from oxiation of soil carbon to CO_2. This leads to reduced soil carbon. Global carbon emissions from dryland degradation are estimated at 0.23-0.29 PgC a^{-1} (Lal 2001) which is around a quarter of total global emissions from land use change.

Desertification also impacts on the water cycle since reduced vegetation cover reduces infiltration and increases runoff which can lead to reductions in soil moisture. Where erosion control measures limit desertification, enhanced storage of organic matter in the soil helps to retain moisture and promote vegetation cover. Therefore, in dryland systems the water and carbon cycles are closely coupled since moisture availability is a major control on plant growth and hence on the terrestrial carbon cycle.

1. References and web resources

Earth System Science in a Nutshell:
http://serc.carleton.edu/introgeo/earthsystem/nutshell/index.html

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Visualising carbon pathways: http://serc.carleton.edu/eet/carbon/index.html
[Interesting resource which allows students to create animations of parts of the carbon cycle]