10 Changes in the carbon cycle: physical causes

In this section you will learn how changes due to physical activity take place in the stores and transfers within the carbon cycle

Why does the carbon cycle experience change?

While people are right to be concerned about recent rapid increases in carbon dioxide emissions into the atmosphere, the carbon cycle has experienced change throughout the billions of years of the Earth's history.

Carbon, like water, is subject to significant levels of change over time and space. Although carbon may be stored deep within the Earth's crust for millions of years, in other contexts it can be transferred in a matter of seconds from one store to another, say during a wildfire. Carbon within the carbon cycle is in a constant state of flux, undergoing changes in magnitudes at all scales and in all time frames.

There are many reasons, both physical and human, why these changes take place.

Physical causes of changes in the carbon cycle

Natural climate change

During the Quaternary geological period (from 2.6 million years ago to the present day) global climates fluctuated considerably between warm (interglacial) and cold periods (glacial). Look at Figure **1**. It shows temperature and atmospheric carbon dioxide levels during the last 800 000 years based on data obtained from ice cores in the Antarctic ice sheet. There are several regularly occurring cold (glacial) periods interspersed with warmer interglacial periods.

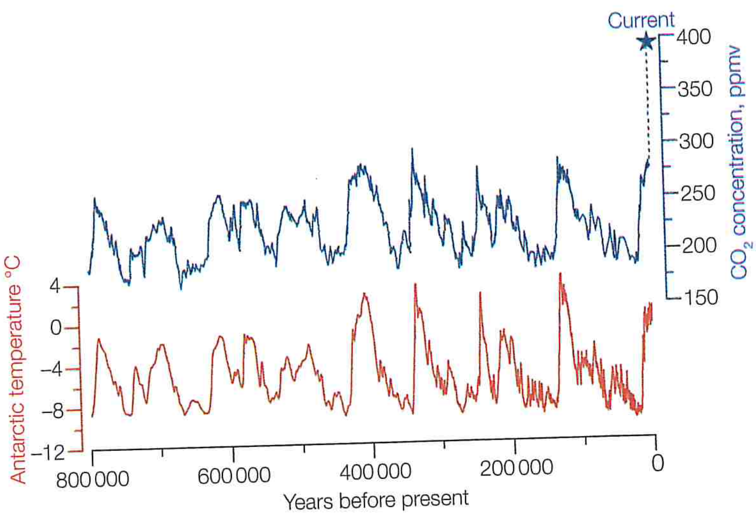


Figure 1 *Global temperature and carbon dioxide fluctuations during the last 800 000 years (ppmv = parts per million by volume)*

Notice that the trends for temperature and carbon dioxide mirror one another – higher temperatures are associated with higher levels of carbon dioxide in the air. It is interesting to see the scale of the recent rise in carbon dioxide levels, which have now surpassed 400 ppmv (parts per million by volume).

The causal relationship between temperature and carbon dioxide is an interesting one to explore. An increase in the level of carbon dioxide in the atmosphere leads to enhanced global warming and subsequent temperature increase. Lower levels of carbon dioxide reduce the effectiveness of the greenhouse effect, which leads to global cooling. So, in theory carbon dioxide levels trigger temperature change. However, temperature change also has an impact on levels of carbon dioxide.

The impacts of cold conditions on carbon stores and transfers

- Chemical weathering processes would have been more active because cold water can hold more carbon dioxide.
- Forest coverage would be very different both in total area and in geographical location. This would have affected the significance and distribution of processes such as photosynthesis and respiration.
- Decomposers would have been less effective, so carbon transfer to soils would have been reduced.
- Less water would have flowed into the oceans as it was locked up as snow and ice on land. There would be less sediment transfer along rivers and less build-up of sediments on the ocean floor.
- The soil would have been frozen over vast areas of land. This would have stopped transfers of carbon.

Wild fires

Wild fires can be started naturally by lightning strikes. However, increasingly they are started deliberately by people. Despite being restricted to tiny parts of the Earth's surface wild fires can have regional impacts. In 1997–8 and again in 2013 there were many huge fires in Indonesia (Figure **2**) that burned out of control for months. Smoke from these fires spread across parts of south-east Asia, affecting the lives of millions of people. The fires released a large quantity of carbon dioxide into the atmosphere, causing a noticeable spike in the rising trend of carbon emissions recorded since the late 1950s (see 1.16).

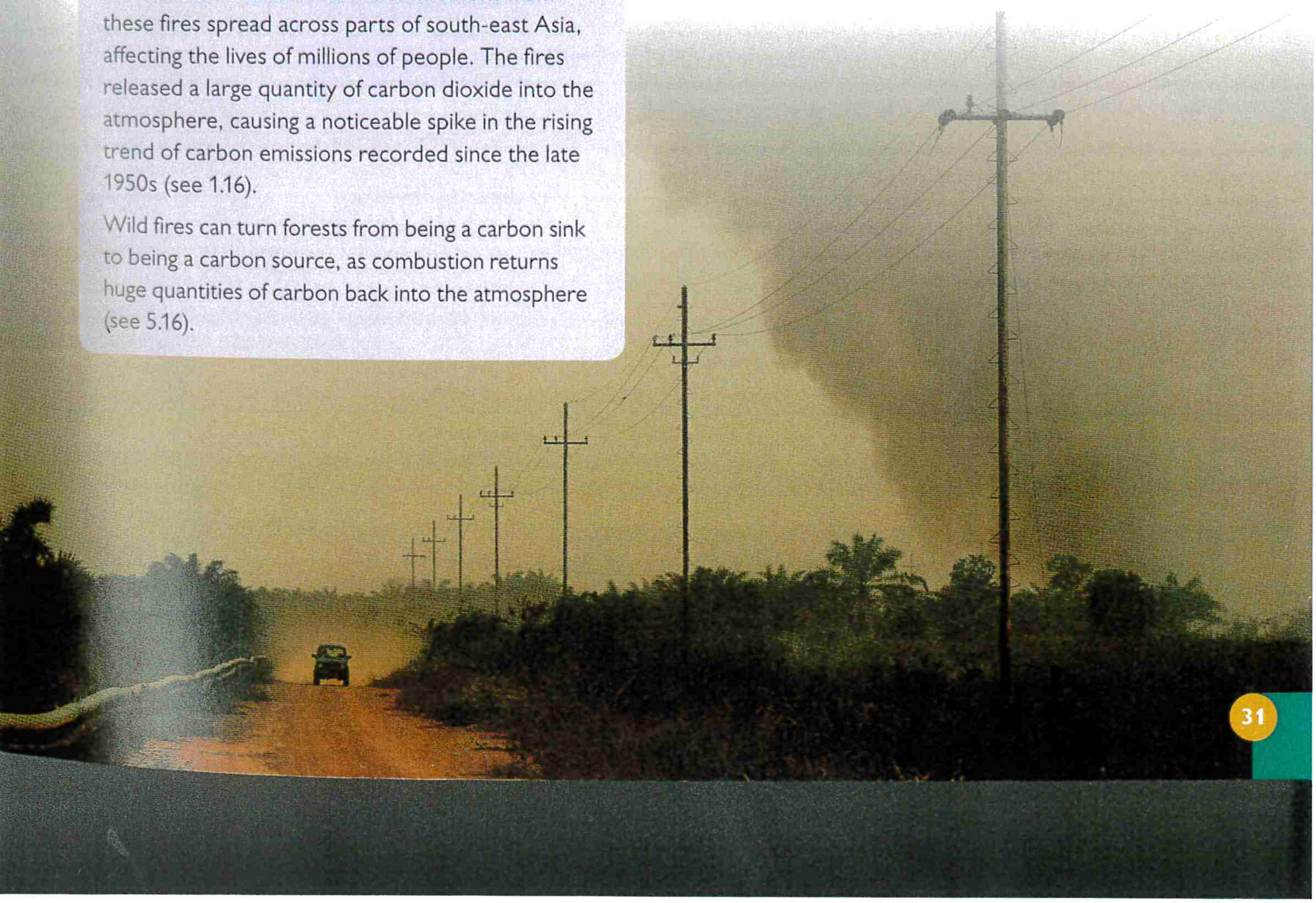
Wild fires can turn forests from being a carbon sink to being a carbon source, as combustion returns huge quantities of carbon back into the atmosphere (see 5.16).

The impacts of warm conditions on carbon stores and transfers

As indicated by Figure **1**, in recent years global temperatures have risen and this has been particularly noticeable in the high latitudes. One of the effects of this has been the melting of permafrost in tundra regions, for example Siberia in Russia.

Carbon stored within the permafrost – together with other gases such as methane – is now being released into the atmosphere where it further enhances the greenhouse effect, leading to increased warming. This is an excellent example of a positive feedback leading to further destabilisation of the system.

Figure 2 *Indonesian wild fires emitting carbon dioxide (2013)*

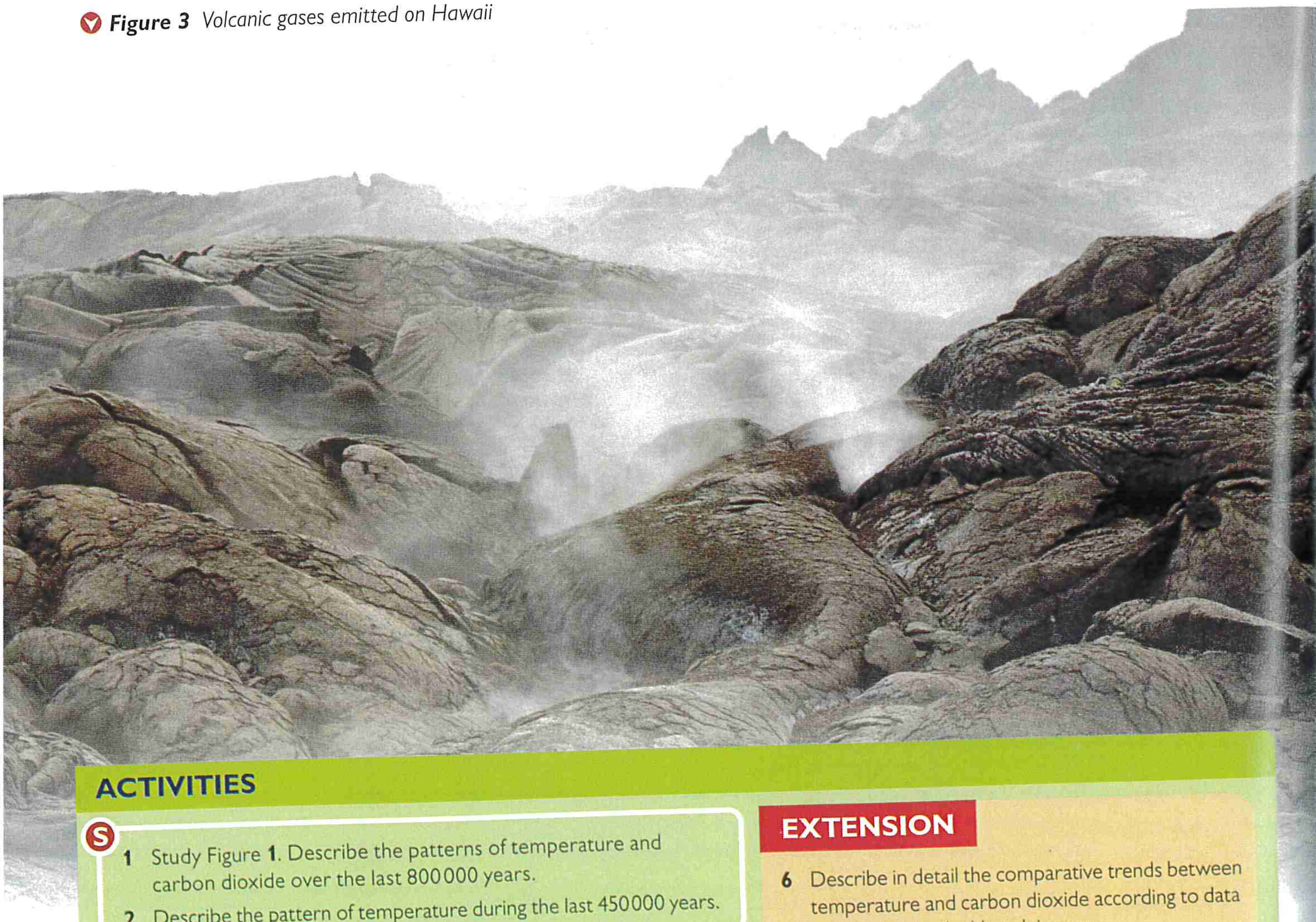


Volcanic activity

Volcanic activity returns to the atmosphere carbon that has been trapped for millions of years in rocks deep within the Earth's crust (Figure **4**). During the Palaeozoic era (542–251 million years ago) volcanoes were much more active than they are today. A vast amount of carbon dioxide was emitted into the atmosphere, where it remained for a very long time.

At present, volcanoes emit between 130 and 380 million tonnes of carbon dioxide per year. By comparison, human activities emit about 30 billion tonnes of carbon dioxide per year, mainly as a result of burning fossil fuels. Volcanoes also erupt lava, which contains silicates that will slowly weather. This converts carbon dioxide in the air to carbonates in solution. In this way carbon dioxide is absorbed very, very slowly from the atmosphere.

Figure 3 *Volcanic gases emitted on Hawaii*



ACTIVITIES

S

1. Study Figure **1**. Describe the patterns of temperature and carbon dioxide over the last 800000 years.
2. Describe the pattern of temperature during the last 450000 years.
3. Suggest how the carbon cycle was affected by cold glacial periods during the Quaternary period. How did this affect the magnitude of the stores and the operation of the transfers?
4. How do volcanic eruptions contribute to the carbon cycle?
5. How can trees be both a carbon store and a carbon sink at different times or locations?

EXTENSION

6. Describe in detail the comparative trends between temperature and carbon dioxide according to data obtained from the Vostok ice core.
7. Critically evaluate the theory that orbital cycles triggered the initial temperature rise at the end of the last glacial period but thereafter it was the increase in carbon dioxide that drove increases in temperature.

STRETCH YOURSELF

Find out about the possible impact on the carbon cycle of a future eruption of the Yellowstone supervolcano.

Explain the effects on the atmosphere and assess the possible consequences for life on Earth.

EXTENSION

Is there a causal link between carbon dioxide and temperature in explaining glacial cycles?

Look at Figure **4**. By superimposing the carbon dioxide and temperature curves for data obtained from the Vostok ice core, it can be seen that the two curves do not match perfectly. Assuming that the data are correct (this is an important assumption), there appears to be a time delay between temperature change and changes in the level of carbon dioxide.

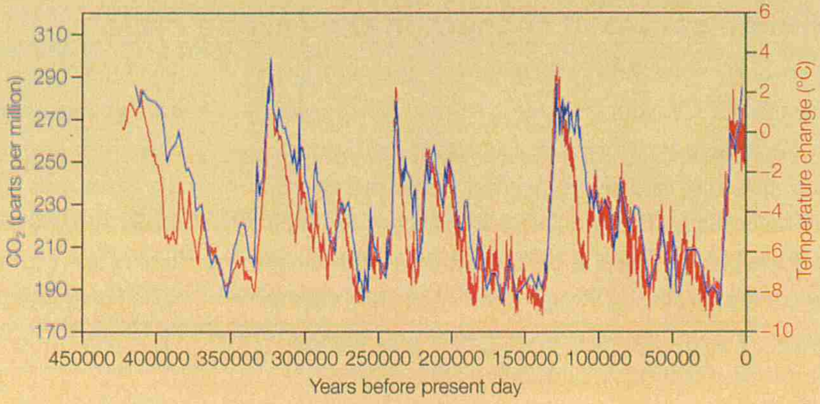


Figure 4 *Vostok ice core records for carbon dioxide concentration (blue) and temperature change (red)*

Some scientists believe that the trigger for these long-term trends in temperature and carbon dioxide is orbital change – the Milankovitch Cycles. These regular cycles of orbital eccentricity cause slight variations in the amount of the sun's radiation that warms up the Earth. So, as temperatures start to rise at the end of a glacial period (triggered by orbital change), there is a surge of carbon dioxide released into the atmosphere by the warming of the oceans and the 'unlocking' of the land surface that had previously been frozen. This surge of carbon dioxide enhances the greenhouse effect, amplifying the warming trend. This is an excellent example of a positive feedback loop.

A study in 2012 by Shakun et al. looked at temperature changes during the transition from the last glacial period to the current warmer period, about 20000 years ago. They found that:

- the Earth's orbital cycles triggered warming in the Arctic approximately 19000 years ago, causing large amounts of ice to melt, flooding the oceans with fresh water
- this influx of fresh water then disrupted ocean current circulation, in turn causing a see-sawing of heat between the hemispheres
- the southern hemisphere and its oceans warmed first, starting about 18000 years ago. As the Southern Ocean warmed, the solubility of carbon dioxide in the water fell and this causes the oceans to give up more carbon dioxide, releasing it into the atmosphere.

So, there is evidence to suggest that orbital cycles triggered the initial warming at the end of the last glacial period leading to a surge in carbon dioxide emissions, which in turn amplified the warming trend. Overall, scientists believe that more than 90 per cent of the post-glacial warming occurred after the rise in atmospheric carbon dioxide.

There is still a considerable debate about the causal connections between temperature and carbon dioxide and the role played by the Milankovitch Cycles. Issues concerning data reliability further complicate an already heated debate. Whatever the causes of climate change in the past, there is little doubt among the scientific community that the current high levels of carbon dioxide are the result of anthropogenic (human) factors and that this is causing the recent rise in global temperatures.

11 Changes in the carbon cycle: human causes

In this section you will learn how changes due to human activity take place in the stores and transfers within the carbon cycle

Human causes of changes in the carbon cycle

According to the Intergovernmental Panel on Climate Change (IPCC), about 90 per cent of anthropogenic (human related) carbon release comes from the combustion of fossil fuels, primarily coal, but also oil and natural gas. The remaining 10 per cent results from land-use change, such as deforestation, land drainage and agricultural practises. Roughly half of the anthropogenic carbon is absorbed equally by oceans and vegetation and the remainder is absorbed by the atmosphere.

Since the 1960s, global concentrations of carbon dioxide have increased dramatically from about 320 ppm to just over 400 ppm, the highest level ever recorded. In Figure **1** the boxes are stores of carbon and the arrows indicate fluxes and the processes that drive those fluxes. Black figures are estimates of the natural stores and fluxes and red figures indicate anthropogenic effects on the carbon cycle after 1750, the start of the Industrial Revolution.

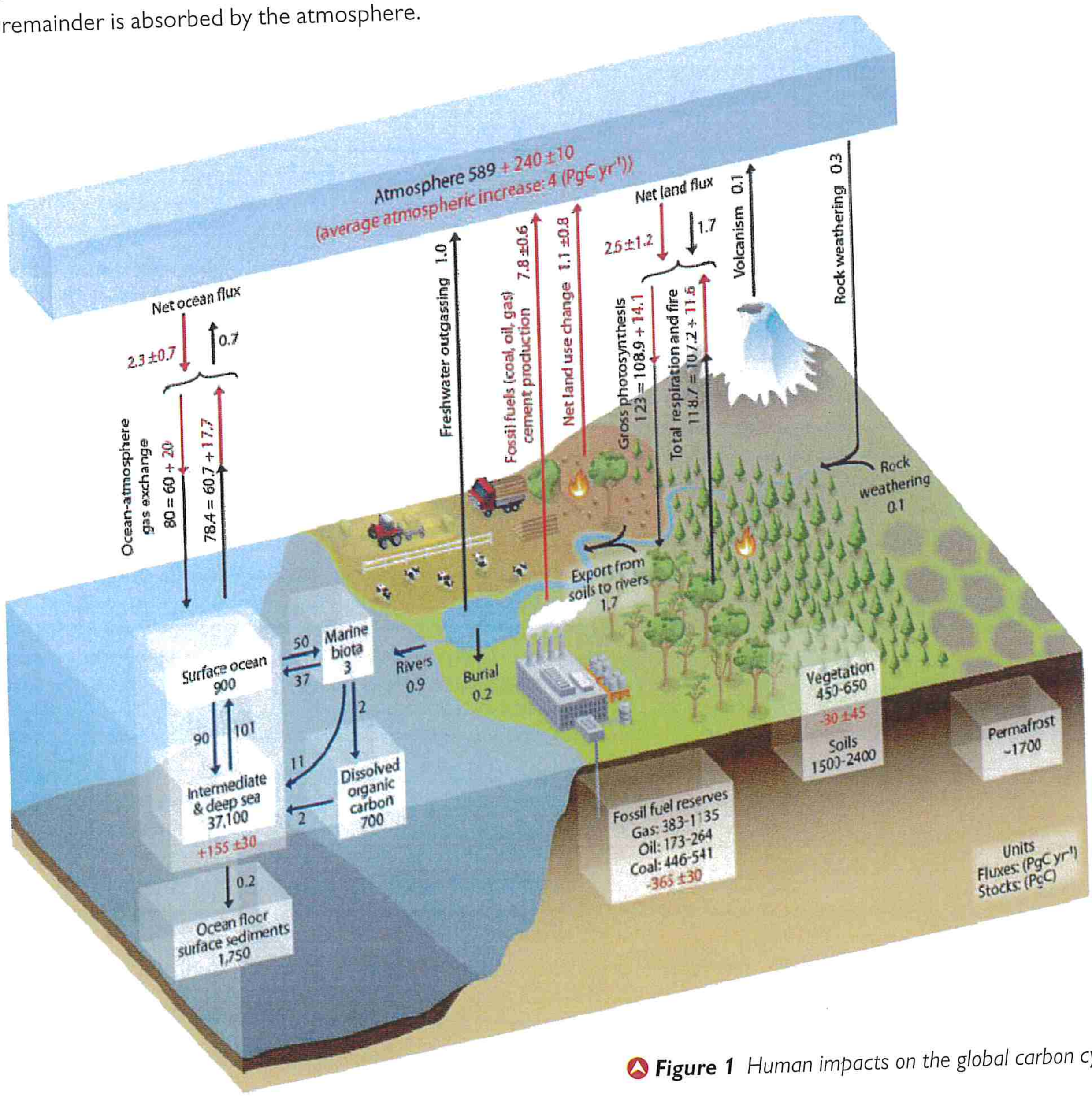


Figure 1 *Human impacts on the global carbon cycle.*

Combustion of fossil fuels

Fossil fuels are natural sources of energy formed from the remains of living organisms, primarily plants. They are extremely important long-term carbon stores comprising carbon locked away within the remains of organic matter. Today, most of the world's gas and oil is extracted from rocks that are 70–100 million years old. The carbon has remained locked up in these deposits for all that time but, when burnt to generate energy and power, the stored carbon is released, primarily as carbon dioxide into the atmosphere, accelerating the cycling of this carbon.

Fossil fuels are mainly composed of carbon and hydrogen, hence the term *hydrocarbons*. Methane, the main component of natural gas, has the chemical formula CH_4. Oil (petroleum) is a more complex compound comprising carbon, hydrogen, nitrogen and sulphur along with other impurities. When combustion takes place, reactions occur with oxygen releasing carbon dioxide and water.

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

Since the Industrial Revolution, fossil fuels have been burnt in increasing quantities, pumping carbon dioxide into the atmosphere. Once in the atmosphere it enhances the natural greenhouse effect, increasing global temperatures – so-called *global warming*. Figure **2** shows this dramatic increase since the 1950s, driven by the rapid industrialisation of developing nations (such as China) as well as the continued demand from the world's industrialised nations (such as the USA).

Since the late 1950s carbon dioxide in the atmosphere has been measured by the Hawaiian Volcanic Observatory, their research showing an alarming increase in levels of atmospheric carbon dioxide (Figure **3**). These figures have been used to support the concept of human-induced climate change and global warming.

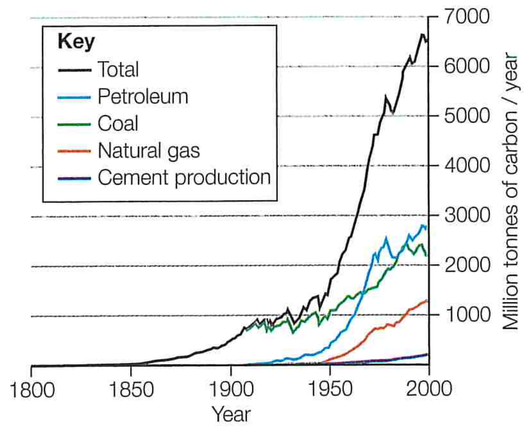


Figure 2 *Trends in global carbon emissions since 1800*

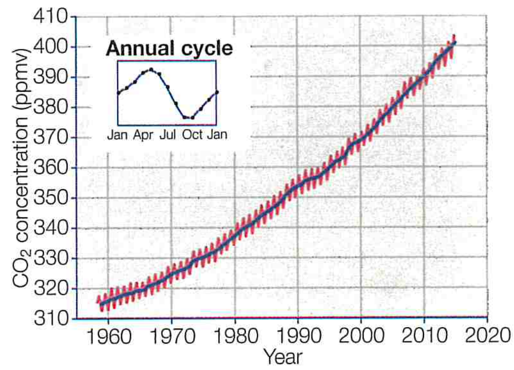


Figure 3 *Recent increases in atmospheric carbon dioxide*

Land-use change

Land-use change is responsible for about 10 per cent of carbon release globally, which impacts on relatively short-term stores and has direct links to issues of climate change and global warming. Furthermore, at the local scale, land-use changes can have a very significant impact on small-scale carbon cycles.

Farming practices

Ploughing and harvesting, rearing livestock, using machinery fuelled by fossil fuels and using fertilisers based on fossil fuels are all farming practices that release carbon. On many farms it is the use of artificial fertilisers that is the main source of carbon emission.

Methane is a potent greenhouse gas, and some farming practices result in high levels of methane emissions. Livestock, especially cattle, ruminate (regurgitate food and masticate a second time – 'chewing the cud'), which produces methane as a by-product. This has raised issues worldwide about the desirability of moving away from such a high dependence on meat and dairy products. Cattle in the USA emit around 5.5 million tonnes of methane per year into the atmosphere – around 20 per cent of the total methane emissions in the USA.

Methane is also produced from the cultivation of rice. Studies indicate that rice may contribute up to 20 per cent of global methane production. Interestingly, research in Asia and North America has found that rice yields have increased by 25 per cent due to increased levels of carbon dioxide in the air. But this in turn has resulted in a 40 per cent increase in methane emissions. Rice is the primary food source for 50 per cent of the world's population, mostly in developing regions, so this trend is likely to continue.

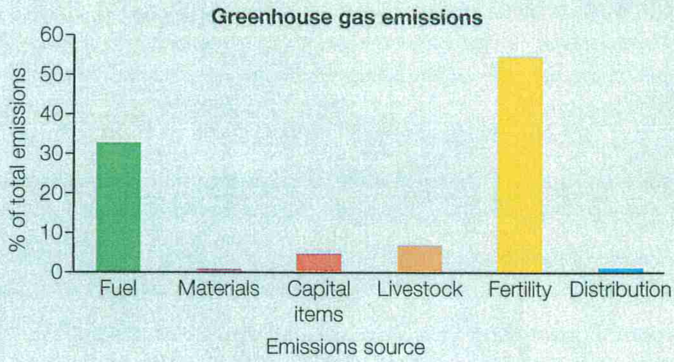
Shimpling Park Farm, Bury St Edmunds, Suffolk

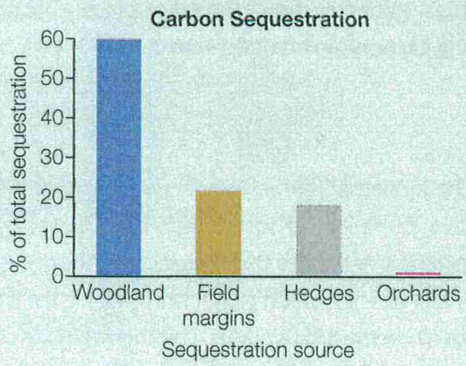
Look at Figure **4**. It shows the carbon budget for Shimpling Park Farm in Suffolk. The farm is a large (645 ha), organic arable farm specialising in wheat, barley, oats, spelt and quinoa along with some grazing for sheep.

The farm has calculated its carbon emissions as 1150 tonnes CO_2, mainly from fuel for machinery and also nitrous oxide emissions (included as carbon emissions) from crop residues and green manures. Fertilisers are usually the major source of emissions on non-organic farms. The flock of 250 sheep contribute 6.6 per cent of emissions, mostly as methane.

About 40 per cent of the carbon emissions are offset by carbon sequestration on the farm. Values for sequestration in the soil do not appear in Figure **4** but this is likely to be a significant carbon sink. In the future, the farm intends to raise the level of organic matter within the soils which will store even more carbon. An increase of just 0.1 per cent in soil organic matter over the entire farm could increase the sequestration of carbon to a level of about 4500 tonnes CO_2, four times greater than the emissions!

Figure 4 *Carbon emissions budget for Shimpling Park Farm*





Deforestation

Trees are removed, either by burning or felling, for building, ranching, mining or the growing of commercial crops such as oil palm and soya. This is *deforestation*. The timber itself is a valuable product in the production of furniture and other wood products. Forests are also harvested for firewood.

Deforestation is widespread across the world but is particularly concentrated in tropical regions, for example, in Indonesia. In total, it accounts for about 20 per cent of all global carbon dioxide emissions.

In a natural system, when a tree dies it decomposes very slowly and releases carbon over a long period of time. During that time, new vegetation starts to grow that quickly compensates for the carbon being released by the dead tree – the system is *carbon neutral*. When deforestation by burning occurs, carbon is immediately released into the atmosphere. If the land is then used for a different purpose, such as grassland for cattle ranching, the future absorption of carbon dioxide will be reduced. The system has now become a source of carbon rather than a sink (Figure **5**). This is extremely significant in terms of the carbon cycle both globally and regionally, as forest ecosystems are limited to certain regions of the world.

Urbanisation

Replacing open countryside with concrete and tarmac is known as 'urbanisation'. It is a major change in land use (see *AQA Geography for A Level & AS Human Geography*, Contemporary urban enivronments). This has a significant impact on the local carbon cycle – important stores are either replaced (vegetation) or covered up (soils) with impermeable surfaces.

Globally, urban areas occupy about 2 per cent of the total land area. However, these areas account for 97 per cent of all anthropogenic carbon dioxide emissions! The major sources of these emissions are transport, the development of industry, the conversion of land use from natural to urban, and cement production for the building sector.

Cement is an extremely important material used in construction across the world. Carbon dioxide is a byproduct of a chemical conversion process used in the production of clinker, a component of cement, in which limestone ($CaCO_3$) is converted to lime (CaO). Carbon dioxide is also emitted during cement production by the use of fossil-fuel combustion. It has been estimated that cement production contributes about 2.4 per cent of global carbon emissions (not including the use of fossil fuels), although this is highly localised close to the major cement-producing plants.