Siberian tundra and changes to the carbon store

Global carbon stores and changes in magnitude 3.1.1.3

Case study: The Siberian tundra

One of the key carbon stores of the earth that is undergoing the most dynamic change is the cryosphere: the frozen surface of the earth that is subject to rapid climate change at present. One of the largest regions experiencing this is the Siberian tundra extending from eastern Europe to eastern Asia across the largest landmass on earth.

The region within the Arctic circle is showing the most rapid response to climate change. As summer and winter temperatures rise the extent of both permanent and seasonal ice and snow cover reduces. The reflective surface of ice retreats, exposing a darker surface of rock, mosses and lichens with a lower albedo rate. Solar radiation is more readily absorbed by the ground and sea surfaces, warming the air above and providing a positive feedback response to further atmospheric warming.

The visible signs of this in the Siberian tundra includes the release of frozen woolly mammoth remains that lived (and died) between 11 500 and 45 000 years ago. Whilst fascinating, of more concern is the invisible consequence of permafrost melting in the release of potentially vast amounts of stored carbon in the form of methane (CH4) as well as carbon dioxide (CO2). Not only is methane a greenhouse gas, it has far more potency than CO2 to absorb and trap atmospheric heat, contributing to yet further global temperature increase.

The source of this carbon lies in the thick layers of permafrost containing organic matter that have accumulated in the Siberian Arctic during the eight or more ice advances and retreats of the last 2.5m years (Quaternary period). Ice sheets ground up and pulverised exposed rock into fine particles that, during interglacials were blown by wind to form thick loess deposits downwind. Vegetation grew readily on each new accumulation deposited on top of permafrost that contained plant remains from the previous interglacial. With the next advance of ice the most recent topsoil and vegetation became frozen, part of the permafrost – and remained so when the next interglacial brought a new deposit of loess and vegetation on top. Over time these deposits have accumulated into layers of organic-rich permafrost many tens of metres thick.

The buried organic remains of mosses, lichens and tundra vegetation represents a huge carbon store. The current high global temperatures, particularly in high northern latitudes, is leading to more rapid melting of surface layers of permafrost and the release of this matter into active layers that are subject to micro-organism activity. Where decomposition takes place with oxygen present, the bacterial digestion of thawed vegetation releases carbon dioxide; in the swampy saturated surface layer of much thawed tundra oxygen is absent, and in anaerobic conditions methane is produced instead.

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The quantities of carbon-rich gases contained in the Siberian tundra vary, but the Yedoma deposits are particularly rich – composed of 50-90% ice and 2% carbon. The Yedoma region covers over a million square km. from north-east Siberia eastwards to Alaska and much of that is tens of metres thick. It is thought to contain between 210 and 450 Gt (Gigatonnes) of carbon that may be released into the atmosphere as CO_2 or CH_4. The entire global permafrost is estimated to contain over 1 400 Gt of carbon; that is almost twice the entire atmospheric carbon content of around 850 Gt.

The atmospheric exchange of carbon is not one-way, however. As conditions warm over the Siberian tundra the growing season for plants is extending and growing conditions are becoming more conducive in warmer temperatures and higher atmospheric CO_2 levels. The growth of tundra vegetation is stimulated and draws down a significant quantity of atmospheric carbon, storing it as organic plant material. In fact, currently, more carbon is absorbed by active vegetation than melting permafrost releases. So the net balance is one of the tundra acting as a carbon sink.

The concern, however, is that if atmospheric temperatures rise much higher and significantly more permafrost thaws, then the exchange will become reversed with greater output of carbon to the atmosphere from CO_2 and CH_4 than plant growth absorbs. The significance of methane is that it is a far more efficient greenhouse gas than carbon dioxide at trapping heat; over 20 times more potent. It is, however, much shorter-lived in the atmosphere: about 12 years compared to the 50 to 100 of CO_2 molecules.

Continued temperature rise could see a 'tipping point' reached in which the negative feedback cycle of enhanced vegetative growth occurring because it is fertilised by increasing amounts of atmospheric CO_2, is replaced by a positive feedback cycle of net release of CO_2 an CH_4 resulting in accelerated further global warming. That is the 'runaway' global warming scenario that international conferences, such as COP21 in Paris in December 2015, are attempting to address by seeking agreement to implement measures so that global temperature rise does not exceed 2 centigrade degrees by the end of the century.

Exam style questions

1. **Explain what you understand by the terms 'carbon sink' and 'carbon store'. (6 marks)**

2. **Assess the extent to which changes to carbon stores are a result of human action or natural systems. (20 marks)**

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1. Explain what you understand by the terms 'carbon sink' and 'carbon store'. (6 marks)

Some students may use the terms carbon 'sink' and 'store' interchangeably, but they have different features despite some of the natural spheres of the earth being both carbon stores and sinks. They involve overlapping elements of a systems approach.

- A carbon sink involves a net absorption of carbon by a component in the system even though it may release some carbon at the same time. The flux is active and on-going at present with processes enabling the absorption to take place. The fact that a smaller volume is released also means the sink becomes a store of carbon. An example is the fast carbon cycle involving biomass in natural tropical forests. Carbon dioxide is absorbed by plants as part of photosynthesis. Carbon dioxide may be released in the decomposition of annual leaf litter but the net balance is one of absorption making the forest a carbon sink and the biomass a carbon store.
- A carbon store may be active but may also be removed from fast carbon cycles and be locked beyond current fluxes. Hydrocarbons locked in sedimentary rocks from fossilised remains of tens of millions of years ago represent a carbon store, but they are no longer being added to so they cannot be considered a carbon sink any more.

Level 1 (1-3) for some concept of either sink or store but not clarifying a difference.
Level 2 (4-6) for a clear understanding of the difference between a sink and store. Top end for similarities and differences.

2. Assess the extent to which changes to carbon stores are a result of human action or natural systems. (20 marks)

This answer encourages students to consider both fast and slow carbon cycles and the changes that take place within them as a result of both natural systems and anthropogenic interventions. The answer should also consider scale of change and rate of change.

The key natural carbon stores that should be discussed include:

- The lithosphere – being the largest store of carbon by far. Carbon is stored in sedimentary rocks composed of fossilised and lithified marine deposits (limestone and chalk), marine sediments and hydrocarbon reservoirs. There is very little change to these stores while they are below the surface and it takes hundreds of millions of years for them to be transferred to the surface as mountain-building uplift at continental collision margins (where they are then subject to loss via weathering), or subducted at destructive margins for the carbon to be emitted in volcanic eruptions. This is the largest, but slowest change to stores.
- The oceans – the second largest store of carbon is in the oceans. It is largely in two forms: dissolved carbon dioxide from the ocean/atmosphere gas exchange and dissolved bicarbonate ions introduced by rivers from weathered terrestrial carbonate rock. The ocean/atmosphere exchange does change the store of ocean carbon slightly but it can go in either direction depending on the respective gas pressures of CO_2, relative temperatures and circulation of currents. Phytoplankton in the upper ocean surfaces absorb dissolved CO_2 and put it into the fast carbon cycle of marine biota before eventually becoming part of the slow carbon cycle as their remains contribute to marine carbon deposits on the sea bed. Incoming carbon from weathering may be introduced into the fast carbon cycle as the basis for calcium carbonate skeletons for marine creatures, which also gets transferred into the slow carbon cycle as creatures die and skeletons fall to the sea bed.
- The terrestrial carbon cycle of biomass and soils – the growth and extension of vegetative zones and active soils has largely been a feature of natural climate change. Where and when

conditions are conducive to biomass, a key carbon store of the fast carbon cycle develops and helps develop a soil chemistry that also acts as a carbon sink.

- The atmosphere – the store of carbon in the atmosphere has varied throughout earth's history as a result of inputs from volcanic eruptions, outputs to vegetation due to temperature, and in the ocean/atmosphere with two-way exchanges with the ocean. Colder seas can absorb more CO_2 so at times when vegetation has been less able to absorb the gas, oceans have taken in more, regulating the overall atmospheric store.
- The cryosphere – in periods when the earth is in an ice age (there have been several, the current one commencing around 2.5m years ago) the cryosphere becomes a key carbon store. But during interglacials, it is likely to release its store of carbon to the atmosphere which enhances the naturally occurring warming effect.

Human intervention:

- Destroying natural vegetation for urbanisation and clearing it for agriculture leads to a net loss of biomass and its capacity to store carbon. This is one of the major impacts humans have had on the planet over the last 10 000 years, with an associated reduction in soil carbon storage.
- Removing hydrocarbons from their long-term underground store in the last 200 yrs. to use as fossil fuels; namely coal, gas and oil, has released significant quantities of carbon sufficient to raise atmospheric CO_2 from 350 ppm in the nineteenth century to 405 ppm today. This is a significant and very rapid change.
- The positive feedback response that hydrocarbon use may have on the cryosphere may be the largest change of carbon stores yet to be witnessed by the planet. If a tipping point is passed of global temperature increase that melts vast areas of sub-Arctic permafrost, then the amount of potential CO_2 and CH_4 that may be released might instigate a phase of unstoppable global temperature increase. This could take place within the next century and be the most significant human-induced change in two carbon stores yet experienced – from cryosphere to atmosphere.

A conclusion is required which address the 'assess the extent to which' element. By far the largest changes to carbon stores have, until the last hundred years, been natural systems. Human intervention in hydrocarbon stores has been small in terms of relative volumes released from those stores, but very significant in where it has gone (the atmosphere) and the positive feedback cycle it could potentially give rise to.

