



Carbon: our flexible friend that built the natural world

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24th September 2026

Carbon used to be something that was only mentioned in school chemistry classes, but now it seems to be everywhere: on the news, in political debate, in discussions on health, and as a framework for thinking about our civilisation's future. But the carbon that's the focus of most of that debate is what's in the atmosphere, and that's only about 2% of the accessible carbon on Earth. This lecture will put that 2% in context, showing how the whole carbon cycle works, how we're affecting it, and looking at the proposed strategies for deliberately manipulating carbon reservoirs in the future.

All the Carbon in the World

Carbon atoms make up only 0.02 – 0.03% of the Earth by weight, but they have a disproportional influence on how our planet works. Most of the carbon atoms on Earth are locked up in rocks, but about 44 trillion tons of carbon atoms are distributed around the atmosphere, ocean and land (including in soils and permafrost). The vast majority of that more accessible carbon (around 84%) is held in dissolved form in the ocean. It has taken a huge scientific effort over many decades for scientists to identify where carbon is, what form it's in, and to create accurate carbon budgets. The Global Carbon Budget⁴ is now published every year, so that the latest knowledge on where Earth's carbon is and how it's moving is available to everyone.

Critical Characteristics

Two factors determine the influence that any element has on the world. The first is the chemical form that the atom is in. Very little carbon is found naturally in a pure state (for example diamond or graphite), because carbon is very reactive and so tends to be found combined with other atoms in molecules. The many different molecules that include carbon interact differently with light, have different physical properties, and are available to react chemically in very different ways. The second factor is physical location: a molecule locked in a rock that's 500 metres underground is less available to influence the world than one floating freely in the atmosphere.

There are two significant categories of carbon in the natural world: organic and inorganic. This matters because only a very small number of processes move carbon between these two types, and otherwise these pools are separate. The biological world is built from organic carbon molecules, and almost all organic carbon molecules have been built by life. Inorganic carbon is generally less reactive, but it's often far more mobile.

The process of photosynthesis creates organic carbon building blocks out of inorganic carbon dioxide, and most of that carbon is returned to an inorganic form by either respiration or combustion. It's important for the way our world works that although the speed of photosynthesis (moving carbon from inorganic carbon dioxide to organic sugars) is relatively constant, the speed at which organic carbon is either respired or burned back to an inorganic form can vary between minutes and centuries.

Wood, for example, can last for many decades without decay, and so can many of the organic molecules that make up the humus in soil. The fact that this organic matter is retained and stored, rather than being used immediately to produce energy, gives us much of the structure (forests, wooden huts, deep soil) in the world. It also creates a huge pool of stored carbon that's held away from the atmosphere.

Ocean Carbon

The deep ocean holds a huge store of carbon because of a chemical quirk. The amount of carbon dioxide from the atmosphere that can move into the ocean depends on the concentration gradient between the lower atmosphere and upper ocean. If there is a higher concentration of carbon dioxide in the atmosphere and a lower concentration in the ocean, there will be a net transfer of carbon dioxide from the air to the sea.

But when carbon dioxide dissolves in water, it quickly combines with water molecules to form carbonic acid, and this can become bicarbonate and then carbonate (which are similar ions, but with different chemical properties). There is an equilibrium between these three forms that depends on the temperature and pH of the water, and molecules will shuffle from one form to the next until equilibrium is reached. In most ocean water today, approximately 90% of the dissolved carbon exists as bicarbonate, 10% exists as carbonate and around 1% exists as carbon dioxide or carbonic acid. The significance of this is that air-sea gas transfer depends only on the concentration of dissolved carbon dioxide, and the other two forms (carbonate and bicarbonate) are effectively invisible to this process. This means that when more carbon dioxide dissolves in the ocean, most of it shuffles into bicarbonate, keeping the dissolved carbon dioxide level relatively low, and the air-sea concentration gradient high. So the ocean can keep taking in carbon from the atmosphere, and the excess is stored in this "carbonate buffer system". The details of the chemistry are complex, but the effect is very important for the ocean carbon cycle.

Influence

So once you consider the form and location of the carbon in all the "pools", and therefore the influence that those carbon atoms can have, what does the big picture look like?

The news we hear about carbon is almost all about what's in the atmosphere, because it's this carbon that affects the rate of energy that's lost from Earth. This is explained in more detail in my Gresham Lecture on the atmosphere from January 2026, titled "Atmosphere: an Ocean of Air".

We have increased the amount of carbon in our atmosphere by about 50% since the pre-industrial period, and since this is the source of carbon for land-based photosynthesis, many people have asked whether an abundance of this resource might help plants to grow faster or more quickly. In the lab, more carbon dioxide does speed up plant growth for at least some species, but the global picture is less clear. As the data shown in the lecture demonstrates, some major crop species do grow faster when atmospheric CO₂ is higher, but they also slow down when the temperature increases (which is happening now because there is more CO₂ in the atmosphere). So the overall effect depends on the plant species and broader environmental changes to temperature and water supplies.

It's important not to see the carbon "pools" just as items in a budget list. It's critical to monitor how carbon moves between these parts of the carbon cycle, but the organic carbon pools represent ecosystems and the environments that ecosystems occupy. A biodiverse world has huge benefits all by itself, without considering carbon accounting. But it's also becoming apparent that more biodiverse ecosystems (and therefore carbon pools) are more stable and resilient to change. So maintaining biodiversity is a way of keeping those carbon pools stable. We need to see them as more than carbon storage units, but it turns out that valuing them for their own sake also allows them to maintain their function as carbon storage.

Humans diverting carbon flows

We are very good at adding carbon to the atmosphere because we're good at burning things. But taking carbon out of the atmosphere (required to some extent for all the current scenarios for a liveable future on this planet) is far, far harder. There are many proposed methods, almost all in the very early stages of development, but all of them are expensive, intrusive and mostly of unknown effectiveness in the long term.

It is already clear that we cannot currently treat carbon removal methods as a way to allow us to keep burning fossil fuels. The focus must be on reducing our emissions as quickly and safely as possible: every other path is more expensive and more damaging. By the time we have reduced our emissions to a level where carbon removal could make a difference (perhaps in 10 or 20 years time) it may be that the science of carbon removal is advanced enough to deploy it seriously, and to allow us to take that decision in full view of the associated trade-offs. Then we could perhaps focus on removing past carbon emissions, reducing the damage from the way our civilization runs now.

Conclusion

Our current focus needs to be to understand how the huge natural carbon cycle works, and then design our civilization to work with it rather than against it. Carbon is woven throughout our world in a complex way, and the world needs that complexity in order to work effectively. We already have the technologies to live in a far less carbon-intensive way, and we can continue to improve them and make them accessible to more of the population. Science fiction writers have often called humanity a “carbon-based life form”, and so we are... but it's not just our anatomy that's based on carbon. It's the whole of our life support system.

References and additional reading

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