

1 **Climate Change**
2 **Carbon losses in the Alps**

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4 Soil carbon stocks depend on inputs from decomposing vegetation and returns to the atmosphere as
5 CO₂. Monitoring of carbon stocks in German alpine soils has shown large losses linked to climate
6 change and a possible positive feedback loop.

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10 The response of the terrestrial carbon cycle to global change is one of the main uncertainties in current
11 climate change predictions¹. Most terrestrial carbon is held in soils as organic matter derived from the
12 decay of plants. Soil organic matter accounts for roughly three times more carbon than living
13 vegetation, and for more carbon than vegetation and the atmosphere combined. Because elevated
14 atmospheric CO₂ concentrations have a fertilizing effect on plant growth, anthropogenic CO₂
15 emissions have triggered increases in the land carbon sink². However, models predict that other
16 factors – such as water and nutrients – will eventually become limiting to plant growth, and hence to
17 the land carbon sink. In contrast, the turnover of soil organic matter producing CO₂ is expected to
18 increase as the Earth warms. As a result, simulations using coupled carbon-climate models predict
19 that the land surface will become a net source of CO₂ before the end of the century, leading to a
20 feedback loop between climate and soil carbon losses: increased emissions of CO₂ from soil organic
21 matter will lead to enhanced warming, which may then feedback to further soil organic matter losses.
22 Prietzel and colleagues³, writing in *Nature Geoscience*, provide evidence that warming has already
23 caused a decline in soil organic matter in the German Alps.

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25 The umbrella term “soil carbon” covers a diverse array of molecules, which are stabilised to varying
26 extents by binding to soil minerals and by physical protection within soil aggregates⁴. Its turnover is
27 mediated by soil microbes, with half-times ranging from weeks to millennia. Physical protection
28 within aggregates can render soil carbon inaccessible to microbes and the enzymes they produce to
29 cleave complex carbon molecules into easily digestible compounds. Like other metabolic and
30 enzymatic processes, rates of turnover are sensitive to temperature and moisture. Increasing
31 temperatures associated with climate change are expected to increase soil carbon turnover rates¹, but
32 direct evidence that this is currently taking place is limited. Since high elevation ecosystems are
33 expected to warm more quickly than other parts of the planet, with associated changes in snow cover
34 and freeze-thaw cycles, they are a good place to determine whether warming is already causing soil
35 carbon losses.

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37 Prietzel and colleagues³ measured losses of carbon from forest soils in the German Alps over the past
38 30 years, which they link to higher summer temperatures. They did this with repeated sampling of
39 soils at 35 sites across both forests and pastures. They found no change in soil carbon in the pasture
40 areas, but large losses in absolute and percentage terms in soils with high carbon stocks in lower
41 elevation forests (< 1100 m). Changes in management weren't responsible for the carbon losses,
42 because forests across the German Alps have been under constant, low intensity management for
43 more than 50 years. Instead, the losses matched changes in mean summer temperatures at the low
44 elevation sites: temperatures at these elevations increased by 0.5 °C per decade over the survey period,
45 even though mean winter temperatures at these elevations decreased by 0.3 °C per decade.

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47 Measuring climate-induced changes in soil carbon is difficult. Measurable changes occur on decadal
48 time scales, and it can be challenging to detect the changes against large background concentrations
49 and the tremendous spatial variability inherent in soils. Further, the effects of climate must be
50 disentangled from the effects of past changes in land use or management, which may persist for many
51 decades. It is therefore crucial to have long-term soil monitoring schemes that are properly designed,
52 managed and resourced to account for these factors, such as the scheme used by Prietzel et al.

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54 Various repeated soil inventories have been made in different parts of the world over the past two or
55 three decades, and some have shown losses of carbon but others gains. In most cases the changes

56 could be attributed to changes in land use and management. For example, large losses of carbon from
57 soils across England and Wales during the 1980s and 90s⁵ were largely due to land use changes, but
58 up to 10 % could have been due to climate change⁶. The losses of the order of 100 g C m⁻² yr⁻¹
59 reported by Prietzel and colleagues are somewhat greater than those found in England and Wales⁵ for
60 forest soils with similar carbon contents but at mostly lower elevations.

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62 To understand how the sources and sinks of greenhouse gases will change with the climate, it is
63 essential to have reliable mathematical models. But simulating soil carbon processes is a particularly
64 thorny challenge. In addition to the inherent complexity of soil carbon and its interactions with soil
65 physical and chemical conditions, a number of other factors complicate the picture. The availability of
66 readily decomposed substrates, such as root secretions, may fuel the turnover of otherwise more-
67 stable components in so-called priming effects. Soil microbes may adapt to warmer temperatures, and
68 thereby reduce or in some cases increase the magnitude of soil carbon responses to climate change⁷.
69 Further, the carbon cycle is inextricably linked to other nutrient cycles, and changes in these other
70 cycles, such as changes in atmospheric nitrogen deposition, can have cascading effects on plant
71 productivity and soil carbon dynamics⁸. Lastly, extreme weather events, such as drought or storms,
72 can alter the turnover rates of terrestrial carbon pools leading to prolonged release of CO₂ to the
73 atmosphere⁹.

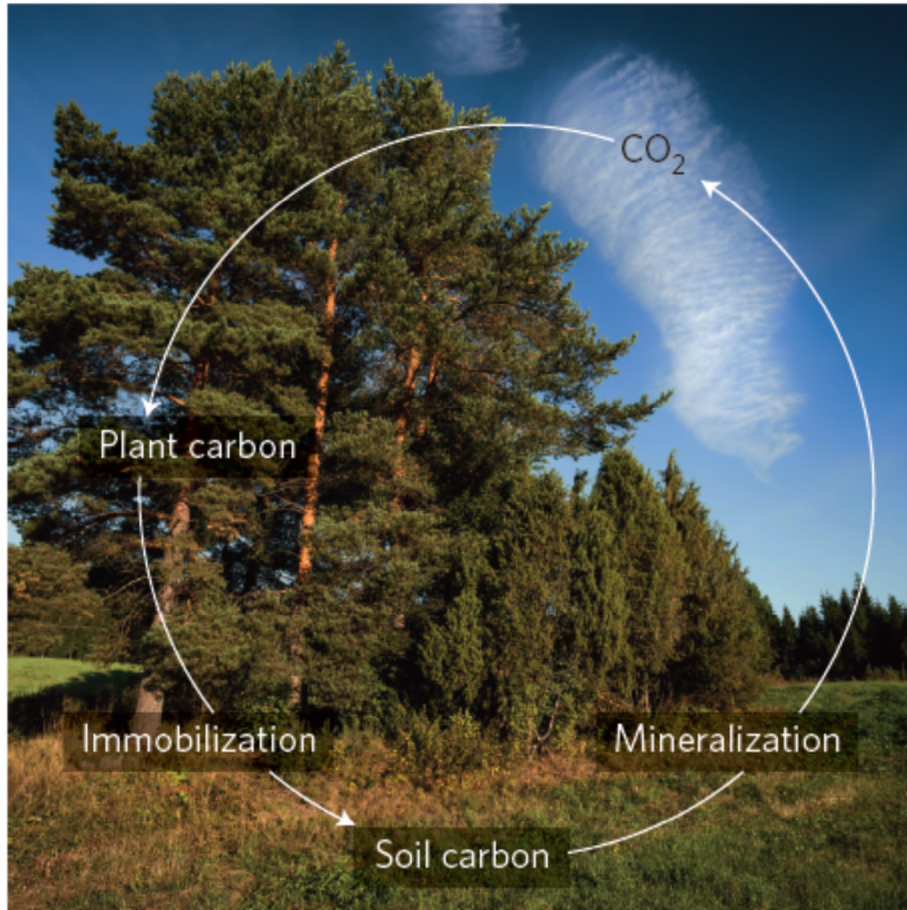
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75 Models must be under-pinned by field studies, and ultimately by long-term soil monitoring at regional
76 and national scales, of which the study by Prietzel and colleagues³ is exemplary. Their evidence that
77 climate change has already started depleting soil carbon in the German Alps raises the possibility that
78 a positive feedback between climate and ecosystems is beginning. Combined with the expected
79 decline in the fertilization effect from elevated atmospheric CO₂ concentrations, soils could become
80 important contributors to accelerating climate change.

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85 86 References

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Figure 1 | Soil carbon dynamics. Plant productivity—and plant carbon stocks—can be stimulated by increased atmospheric CO₂ concentrations. That plant carbon is then decomposed and converted to soil carbon, where it can remain immobilized for weeks to thousands of years before being mineralized to CO₂ and released back to the atmosphere. However, warming can stimulate the decomposition and mineralization of soil carbon, leading to increased emissions of CO₂ to the atmosphere. Prietzel et al.³ used repeated soil measurements in the German Alps over the last 30 years to show that soil carbon has decreased in managed forests concomitantly with an increase in temperatures.