The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change

Supplementary Material

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Table S1. Emission pathway details

| Experiment Name | Simulation Name | Cumulative Emissions | Cumulative Negative Emissions | Peak Fossil Fuel Emission Rate GtC/year | Year of Peak Emission Rate | Maximum Rate of Emission Reduction % |
|-----------------|-----------------|----------------------|-------------------------------|----------------------------------------|-----------------------------|-------------------------------------|
| CCE             | CCEp10          | 551                  | 0                             | 10                                     | 2017                        | -3.6                                |
|                 | CCEp11          | 551                  | -66                           | 11                                     | 2022                        | -4.0                                |
|                 | CCEp12          | 551                  | -151                          | 12                                     | 2025                        | -3.9                                |
|                 | CCEp13          | 551                  | -224                          | 13                                     | 2027                        | -4.0                                |
|                 | CCEp14          | 551                  | -305                          | 14                                     | 2029                        | -4.0                                |
| VCE             | VCE 200         | 208                  | -456                          | 12                                     | 2025                        | -4.3                                |
|                 | VCE 250         | 258                  | -410                          | 12                                     | 2025                        | -4.2                                |
|                 | VCE 300         | 308                  | -364                          | 12                                     | 2025                        | -4.2                                |
|                 | VCE 350         | 358                  | -318                          | 12                                     | 2025                        | -4.1                                |
|                 | VCE 400         | 408                  | -273                          | 12                                     | 2025                        | -4.1                                |
|                 | VCE 450         | 458                  | -229                          | 12                                     | 2025                        | -4.0                                |
|                 | VCE 500         | 508                  | -186                          | 12                                     | 2025                        | -4.0                                |
|                 | VCE 550         | 551                  | -151                          | 12                                     | 2025                        | -3.9                                |
|                 | VCE 700         | 703                  | 0                             | 12                                     | 2025                        | -4.1                                |

Table columns explanation: Column 1: Experiment name; Column 2: Simulation name; Column 3: Total (fossil fuel and LUC) cumulative emissions over the period 2001-2500; Column 4: Total (fossil fuel and LUC) negative emissions; Column 5: Peak emissions rate (fossil fuel emissions only); Column 6: Year of peak emission rate (fossil fuel emissions only); Column 7: maximum rate of emission reduction calculated with respect to year 2000-level (fossil fuel emissions only).
Table S2. Efficiency of Carbon Dioxide Removal

The change in atmospheric carbon in year 2200 (shown in column 4) is calculated relative to pathway VCE 700 for VCE simulations.

Column 5 shows the ratio of column 4 and column 3.

| Experiment Name | Simulation Name | Cumulative Negative Emissions [GtC] | Change in atmospheric carbon in year 2200 [GtC] | Ratio of change in atmospheric carbon to cumulative negative emissions |
|-----------------|----------------|------------------------------------|-----------------------------------------------|---------------------------------------------------------------------|
| VCE             | VCE 200        | -456                               | -238                                          | 0.522                                                               |
|                 | VCE 250        | -410                               | -217                                          | 0.529                                                               |
|                 | VCE 300        | -364                               | -195                                          | 0.537                                                               |
|                 | VCE 350        | -318                               | -173                                          | 0.544                                                               |
|                 | VCE 400        | -273                               | -150                                          | 0.549                                                               |
|                 | VCE 450        | -229                               | -127                                          | 0.552                                                               |
|                 | VCE 500        | -186                               | -102                                          | 0.549                                                               |
|                 | VCE 550        | -151                               | -81                                           | 0.538                                                               |
|                 | VCE 700        | 0                                  | 0                                             | N/A                                                                |
Supplementary Figure S1. Rate of thermosteric sea level rise for CCE simulations (panel a) and VCE simulations (panel b). The rate is calculated as a differential of the annual global mean sea level rise over time. No smoothing is applied.
Supplementary Figure S2. Time series of global variables for Variable Cumulative Emissions (VCE) with extreme amounts of negative emissions implemented.

a) \( \text{CO}_2 \) emission rate (fossil fuel and land use change) b) atmospheric \( \text{CO}_2 \) concentration; c) global mean temperature change relative to 1801; d) thermosteric sea level rise relative to 1801. Scenario names in the legend indicate total cumulative (fossil fuel and land use change) \( \text{CO}_2 \) emissions since 2001 (in GtC).
Supplementary Figure S3. Time series of global average ocean heat flux (panel a); integrated net top-of-atmosphere (TOA) radiation (panel b); total radiative forcing (panel c) and thermosteric sea level rise relative to year 1801 (panel d) for Variable Cumulative Emissions (VCE) scenarios with extreme amounts of negative emissions implemented. Total radiative forcing aggregates forcing from CO₂, sulphate aerosols, non-CO₂ greenhouse gases, volcanoes and solar variability.
Supplementary Figure S4. Time series of global variables for Variable Cumulative Emissions (bold lines) for simulations with different non-CO₂ radiative forcing.

a) Radiative forcing from non-CO₂ greenhouse gases and sulphate aerosols (aerosol forcing was multiplied by -1 to facilitate comparison between the two forcings); b) atmospheric CO₂ concentration; c) global mean temperature change relative to 1801; d) thermosteric sea level change relative to 1801. v1 indicates original simulations described in the article (solid lines), while v2 refers to additional simulations carried out with radiative forcing from non-CO₂ greenhouse gases and sulphate aerosols following RCP 2.6 (dashed lines).
Supplementary Figure S5. Time series of global variables for Variable Cumulative Emissions with different climate sensitivity (cs) values.

a) atmospheric CO₂ concentration; b) global mean temperature change; c) thermosteric sea level rise change. Note: Changes are relative to 1801. Scenario names in the legend indicate cumulative total (fossil fuel and land use change) CO₂ emissions since 2001 (in GtC). Solid lines represent simulations run with the default climate sensitivity of the UVic ESM (3.6°C), dashed lines represent simulations with climate sensitivity of 2.0°C, while dotted lines are for the simulations with climate sensitivity of 4.5°C.
Supplementary Figure S6. Boreal forest coverage change for Variable Cumulative Emissions (VCE) simulations.
Fractional boreal forest coverage change for simulations VCE200 (left) and VCE550 (right) between years 2100 and 1810 (a,b), between 2200 and 2100 (c,d), and between 2500 and 2200 (e,f).
Supplementary Figure S7. Time series of changes in total land carbon (panel a) and ocean carbon (panel b) for the CCE simulations (changes relative to 1801).