Meeting the 1.5 °C target may require removing up to 1,000 Gtonne CO₂ by 2100 with Negative Emissions Technologies (NETs). We evaluate the impacts of Direct Air Capture and Bioenergy with Carbon Capture and Storage (DACCS and BECCS), finding that removing 5.9 Gtonne/year CO₂ can prevent <9·10² disability-adjusted life years per million people annually, relative to a baseline without NETs. Avoiding this health burden—similar to that of Parkinson’s—can save substantial externalities (<148 US$/tonne CO₂), comparable to the NETs levelized costs. The health co-benefits of BECCS, dependent on the biomass source, can exceed those of DACCS. Although both NETs can help to operate within the climate change and ocean acidification planetary boundaries, they may lead to trade-offs between Earth-system processes. Only DACCS can avert damage to the biosphere integrity without challenging other biophysical limits (impacts ≤2% of the safe operating space). The quantified NETs co-benefits can incentivize their adoption.
limiting global warming to 1.5 °C above pre-industrial levels with or without overshoot will require removing up to ~1000 Gtonne CO₂ from the atmosphere by 2100 (median estimate: 584 Gtonne)\(^1\). Nonetheless, it is still unclear whether the benefits of deploying Negative Emissions Technologies (NETs) at large scale would offset their potential damaging effects on humans and the planet.

Prior studies on Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS)—two of the most prominent NETs—\(^2-3\), primarily focused on analyzing their costs\(^4-6\) and CO₂ removal (CDR) potentials.\(^7-14\). In contrast, their side-effects and co-benefits beyond global warming have often been overlooked. Some studies have quantified the environmental impacts of DACCS and BECCS, but their results are hard to interpret from an absolute sustainability viewpoint.\(^15-19\). Only recently, the impacts of BECCS were assessed against the Earth’s biophysical limits\(^20,21\), i.e., the Planetary Boundaries (PBs) within which humanity could safely operate.\(^22\).

Notwithstanding these scarce global studies, a comprehensive analysis of the implications of DACCS and BECCS embracing simultaneously human and planetary health is lacking. Filling this knowledge gap is critical to uncover the co-benefits of CDR and minimize the potential collateral damage of combating climate change—especially considering that environmental trade-offs frequently arise in the energy sector\(^23,24\), which is deeply intertwined with NETs.\(^25\).

Here we quantify the human health impacts of DACCS and BECCS in terms of Disability-Adjusted Life Years (DALYs), alongside their planetary footprint on seven Earth-system processes key to maintaining the Earth’s stability. We found that DACCS and BECCS could preserve a substantial number of years of healthy life—on the order of the healthy life years lost annually due to Parkinson’s disease—, with Africa and Asia benefiting the most from CDR because of the avoided risk of undernutrition and malaria. Nevertheless, these NETs could also generate detrimental health impacts associated with pollutant emissions and water consumption, chiefly at the regional level. Both NETs could avert the future climate change and ocean acidification impacts of past carbon emissions. However, the large-scale deployment of BECCS could exert substantial pressure on the terrestrial biosphere, nitrogen biogeochemical flows and freshwater use Earth-system processes. In contrast, DACCS emerges as environmentally superior due to its lower planetary impact and its ability to prevent adverse side-effects on the terrestrial biosphere.

The long-term global co-benefits of CDR on human and planetary health, quantified here for the first time, could act as solid incentives to promote NETs, helping to accelerate the climate change mitigation agenda.

**Results**

**Scenario definition.** We studied 16 scenarios removing 5.9 net Gtonne/year CO₂ between 2030 and 2100. This corresponds to the average annual CDR rate in climate change mitigation scenario SSP2-1.9 (marker scenario, model MESSAGE-GLOBIOM)\(^26\), excluding CDR in the agriculture, forestry and other land-use sector. Hence, the underlying assumptions of our scenarios are those adopted in the SSP2-1.9 marker scenario\(^27,28\), which limits the temperature increase to 1.3 °C above pre-industrial levels by 2100 and is based on Shared Socioeconomic Pathway 2 (SSP2). The middle-of-the-road narrative of SSP2 is consistent with development trends following historical patterns, persistent income inequality and moderate global population growth. This pathway presents slow progress toward achieving the Sustainable Development Goals (SDGs) and overall reductions in resource and energy use, which are not sufficient to halt environmental degradation.\(^29\).

The 16 modeled scenarios differ in the deployed NET, the energy and biomass sources, and the CO₂ storage configurations. We modeled ten DACCS scenarios, four BECCS scenarios, and two hybrid scenarios combining DACCS and BECCS (Fig. 1). We compare these scenarios to a baseline without NETs—otherwise identical to the SSP2-1.9 marker scenario—, which would lead to a mean rise in global temperatures of 1.5 °C with respect to pre-industrial levels (see Temperature in the baseline, in Methods). To facilitate the assessment of our scenarios against the baseline, we define scenario 0, where 5.9 Gtonne/year CO₂—the difference in net CO₂ emissions between the baseline and the SSP2-1.9 marker scenario—are emitted.

Concerning the DACCS scenarios, we evaluate High-Temperature Liquid Sorbent (HTLS-DACCS) and Low-Temperature Solid Sorbent (LTSS-DACCS) technologies powered by various energy sources: geothermal (GEO), onshore wind, solar photovoltaic (PV), nuclear, natural gas with carbon capture and storage (NG + CCS), or the global electricity mix deployed between 2030 and 2100, consistent with the SSP2-1.9 marker scenario. Heat is supplied by NG+CCS in the HTLS-DACCS scenarios, whereas either the excess heat from geothermal facilities or heat pumps are used in the LTSS-DACCS scenarios.

The BECCS scenarios generate electricity from biomass combustion—displacing the global electricity mix of the SSP2-1.9 marker scenario in the period 2030–2100—and, use monoethanolamine to separate CO₂ from the flue gases.\(^31\). Unlike hydrogen-BECCS, the assessed BECCS systems rely on existing infrastructure for energy distribution and use\(^32\), and show greater sequestration potential than biofuel-BECCS.\(^33\) In scenario BECCS0-MISC, the boiler is fed with Miscanthus grown without irrigation in areas previously classified as grasslands. Scenario BECCS0-POP considers the cultivation of poplar, which requires irrigation. We assume that the land-use change (LUC) from grassland to poplar plantation leads to soil carbon emissions, whereas introducing Miscanthus in natural grasslands contributes to soil carbon sequestration.\(^33\)

In the two hybrid scenarios (BEDACCS-MISC and BEDACCS-POP, based on BECCS0-MISC and BECCS0-POP, respectively), a fraction of the low-pressure steam generated in the bioenergy process supplies the heat required to regenerate the monoethanolamine solution, as in the BECCS scenarios (Supplementary Fig. 9). The remaining low-pressure steam alongside the electricity generated with high-pressure steam cover the energy needs of the coupled LTSS-DACCS, capturing 66–70% of the sequestered CO₂ via BECCS, and the rest, through DACCS.

We study four CO₂ storage options, namely (1) sequestration at high pressures in geological formations, in situ mineral carbonation\(^34\) using (2) freshwater or (3) seawater, and (4) ex situ mineral carbonation.\(^35,36\) The latter configuration does not apply to the DACCS scenarios because heat pumps cannot supply the required high-temperature heat.\(^37\) Unless otherwise indicated, the results reported for HTLS-DACCS, LTSS-DACCS, BECCS0 and BEDACCS consider the average impacts of storage options 1, 2, and 3, as labeled above. In scenarios BECCS-EXSITU-MISC and BECCS-EXSITU-POP (based on BECCS0-MISC and BECCS0-POP, respectively), electricity and high-pressure steam diverted from the bioenergy processes cover the energy needed for the ex situ mineralization.

**Human health impacts.** We start by analyzing the long-term health effects of scenario 0, where NETs are not deployed. Emitting 5.9 Gtonne/year CO₂ during the considered period would lead to a rise in the global surface temperature of 0.19 °C
[0.11–0.26 °C], causing 9·10^2 DALYs per million people per year, a health burden similar to that of prostate cancer. The long-term health co-benefits of CDR offset the adverse life-cycle health effects associated with freshwater use and pollutant emissions in all the NETs scenarios but one, leading to net health gains between 2·10^2 and 9·10^2 DALYs per million people per year with respect to the baseline (health damage pathways of NETs in Fig. 2, scenarios 1–16 ranked according to their health impacts in Fig. 3). Notably, the health impacts prevented in scenario BECCS0-MISC (ranked first) are slightly lower than the global burden of prostate cancer in 2019, while the health savings in the BEDACCS and DACCS scenarios that follow (7·10^2–8·10^2 DALYs per million people per year) are comparable to the annual burden of Parkinson’s disease and higher than that of ovarian cancer.

In the BECCS scenarios, replacing electricity from the global mix with the generated bioelectricity averts additional harmful health effects. The performance of BECCS slightly worsens when integrating with DACCS—because less electricity is exported to the grid—, and it substantially drops when poplar is the biomass source, mostly due to the water used for irrigation. The health benefits of displacing the grid electricity play an important role in the BECCS scenarios; without the electricity credits, the health impacts that BECCS0-MISC and BECCS0-POP avoid with respect to the baseline would drop by 9% and 26%, respectively (Supplementary Fig. 1).

HTLS-DACCS tends to outperform LTSS-DACCS due to its lower electricity demand, with HTLS-DACCS powered by wind and nuclear energy—both of which attain the lowest emissions of fine particulate matter—ranked third and fourth. The utilization of excess geothermal heat endows LTSS-DACCS with an advantage over the other LTSS-DACCS configurations, while the worst-performing DACCS scenario is LTSS-DACCS deploying PV energy, mainly because of the formation of fine particulate matter associated with the energy required to produce the PV panels. Regarding the sequestration processes, ex situ mineralization is the most damaging storage option in terms of human health, whereas in situ mineralization with seawater minimizes health impacts because of its lower electricity and freshwater requirements (Supplementary Fig. 3).

Focusing on the impact contributors, fine particulate matter formation is the main driver (>44%) of regional health effects—i.e., those affecting the regions where NETs operate, which we did not specify in this analysis—in all scenarios except for BECCS0-POP and BEDACCS-POP. In these two scenarios, the freshwater used for biomass irrigation is the most significant contributor (50% and 47%, respectively) to the regional health impacts (breakdown in Supplementary Fig. 5). Particulate matter is

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**Fig. 1 Overview of the assessed NETs scenarios.** High-Temperature Liquid Sorbent (HTLS) and Low-Temperature Solid Sorbent (LTSS) Direct Air Carbon Capture and Storage (DACCS)—powered by natural gas with carbon capture and storage (NG+CCS), wind, solar photovoltaic (PV), nuclear, geothermal (GEO), or the global electricity mix—, the basic Bioenergy with Carbon Capture and storage (BECCS) scenarios (BECCS0) deploying Miscanthus or poplar, the hybrid BEDACCS configurations integrating BECCS0 and LTSS-DACCS, and the BECCS scenarios where CO₂ is mineralized ex situ (BECCS-EXSITU). The CO₂ in situ sequestration options include geological sequestration at high pressure and mineral carbonation with freshwater or seawater. The set of scenarios generating bioenergy include BECCS0, BEDACCS and BECCS-EXSITU, all referred to as BECCS.
mainly linked to the energy input in the DACCS scenarios, excluding LTSS-DACCS powered by wind and nuclear, where most of the fine particulate matter is associated with the energy consumed in the production of the polyethylenimine that composes the adsorbent. Particulate matter is primarily generated in the biomass combustion in the BECCS0-MISC and BEDACCS-MISC configurations, and in the mining operations related to the ex situ mineralization in the BECCS-EXSITU scenarios. These results suggest that the NETs location could be key to minimizing their detrimental health effects. Notably, DACCS should be prioritized in regions with high renewables or nuclear energy availability. In contrast, BECCS based on irrigated energy crops should be avoided in areas suffering from water scarcity.

Concerning the regional toxicity impacts, HTLS-DACCS outperforms LTSS-DACCS owing to its lower energy consumption. In the BECCS scenarios relying on poplar, the leaching of heavy metals—which mainly occurs in the biomass plantation and the landfill where the fly ashes are disposed of—is responsible for most of the toxicity impacts. Conversely, the BECCS scenarios deploying Miscanthus avoid toxicity impacts due to the ability of biomass to retain metals from the soil. Finally, the regional health effects of ozone formation and the global exposure to the ozone-depleting substances and radionuclides embodied in the NETs supply chains are negligible in all the scenarios.

To further contextualize the impacts of NETs, we quantify their health externalities—i.e., their health impacts expressed in monetary terms—in Fig. 3b, where externalities are expressed per gross tonne CO₂ captured (scenarios 1–16) or emitted (scenario 0). Fifteen scenarios would incur monetized health benefits relative to the baseline, ranging from 35 to 148 US $/tonne CO₂ (health externalities for the in situ sequestration configurations and additional externalities in Supplementary Figs. 7, 8). The substantial hidden benefits of NETs, often omitted in their economic evaluation and comparable to the leveled CO₂ costs of scaled-up combustion-BECCS (134–188 US$/tonne)34 and HTLS-DACCS (121–249 US$/tonne)4, would make these technologies more affordable than initially thought.

We next study the regional and causal distribution of the climate-sensitive health impacts averted in a representative DACCS scenario (HTLS-DACCS deploying wind energy and CO₂ mineralization with seawater, ranked third in Fig. 3a) with respect to the baseline. This analysis reveals significant disparities across regions, with 98% of the health benefits realized in Africa and Asia, and over half of them in Sub-Saharan Africa (Fig. 4a).

The breakdown of the avoided climate-sensitive DALYs (Fig. 4b) shows that 70% of the human health co-benefits of NETs arise from preventing the climate change impacts on crop productivity, which lead to undernutrition39 in Africa, Asia and Latin America. The expected decrease in the incidence of malaria, exacerbated by warm temperatures and rainfall39, follows next, representing 15% of the global health savings and mostly benefiting Sub-Saharan Africa. The prevention of coastal floods accounts for 9% of the avoided health impacts. It is noteworthy in Asia (particularly in the East, where 77% of the population lives within 100 km from the coast)40 and Oceania. Around 5% of the prevented health impacts stem from the avoided risk of diarrhea, which increases with rising temperatures and little precipitation39, and mainly affects Africa and South Asia. The averted impacts of heat stress—more prominent in North America, Europe and Russia—represent 2% of the co-benefits.

In relative terms (considering the population size), Sub-Saharan Africa is the most favored region, with the annual climate-sensitive health impacts averted per million inhabitants almost doubling those in South Asia, which follows next (Fig. 4b). By contrast, North America, Europe, and Russia benefit the least from NETs because they are less sensitive to the health risks intensified by climate change. The health effects prevented in the Caribbean are low in absolute terms but much higher than in the northern areas with respect to their population size, further evidencing the uneven distribution of the health co-benefits across regions. Our life-cycle assessment models preclude a regionalized analysis of the non-climate health impacts. However, the asymmetrical spatial distribution of the prevented climate-related health impacts suggests that the regional health effects of NETs could offset the avoided climate-sensitive health impacts in some locations.

Fig. 2 Streamlined human health damage pathways of Negative Emissions Technologies (NETs). These pathways are consistent with the cause-and-effect chains considered by the ReCiPe 2016 method67 and Tang et al.71. Dashed and solid arrows lead to prevented and additional health risks, respectively, relative to the baseline.
Impacts on the Earth system. To quantify the planetary implications of deploying NETs, we assess their impacts on seven critical Earth-system processes relative to the size of the Safe Operating Space (SOS) delimited by the PBs (Fig. 5a, scenarios sorted according to maximum impact across Earth-system processes).

The climate change impacts associated with the CO₂ emissions of scenario 0—which lead to an increase of 0.19 °C in the global mean temperature by 2100—represent more than twice the climate change SOS. Moreover, the ocean acidification impacts of scenario 0 correspond to 70% of the SOS. Although these impacts are substantial, they are estimated over a 300-year timescale, i.e., they do not occur immediately after the CO₂ is emitted. Scenario 0 also affects the integrity of the terrestrial biosphere, generating impacts equivalent to 12% of the SOS.

Regarding the NETs scenarios, LTSS-DACCS powered by renewable energy performs best, closely followed by HTLS-DACCS, while the BECCS scenarios show the highest impacts. The studied NETs could avoid impacts equivalent to 204–229% and 70–73% of the climate change and ocean acidification SOSs with respect to the baseline, respectively. The averted impacts are greater in the BECCS scenarios, where bioenergy replaces electricity from the grid, and in the BECCS-EXSITU scenarios, given the avoided impacts related to the byproducts of the ex situ mineralization (see disaggregated contributions in Supplementary Fig. 6).

By contrast, the impacts of BECCS on the terrestrial biosphere exceed those of the baseline by up to 16% of the SOS, whereas DACCS averts impacts equivalent to 8–12% of the biosphere integrity SOS with respect to the baseline. In the BECCS scenarios, the land-use impacts on the terrestrial biosphere outweigh the avoided impacts linked to the removed CO₂, resulting in net damage to this Earth-system process. The opposite happens in the DACCS scenarios due to their lower land-use requirements.

![Figure 3 Health impacts. a Contribution of environmental mechanisms to the total health impacts, expressed in Disability-Adjusted Life Years (DALYs) per million people per year. Scenarios 1–16 comprise High-Temperature Liquid Sorbent (HTLS) and Low-Temperature Solid Sorbent (LTSS) Direct Air Carbon Capture and Storage (DACCS)—powered by natural gas with carbon capture and storage (NG+CCS), wind, solar photovoltaic (PV), nuclear, geothermal (GEO), or the global electricity mix deployed in the SSP2-1.9 marker scenario without NETs (which limits the increase in radiative forcing to 1.9 W/m² by 2100 and is based on Shared Socioeconomic Pathway 2) —, the basic Bioenergy with Carbon Capture and Storage (BECCS) scenarios (BECCS0) deploying Miscanthus (MISC) or poplar (POP) 2100 and is based on Shared Socioeconomic Pathway 2)—, the hybrid BEDACCS configurations integrating BECCS0 and LTSS-DACCS, and the BECCS scenarios where CO₂ is mineralized ex situ (BECCS-EXSITU). Scenarios 1–16 are ranked by the total health impacts, scenario 1 is the best. We show the global burden of certain diseases in 2019 38 for reference. The black bars indicate the health impact range of the scenarios based on the in situ sequestration options, i.e., geological sequestration at high pressure and mineral carbonation with freshwater (upper bound) or seawater (lower bound). b Health externalities, expressed in US$2020 per gross tonne CO₂ captured (scenarios 1–16) or emitted (scenario 0).](https://doi.org/10.1038/s41467-022-30136-7)
The use of industrial fertilizers in the BECCS scenarios contributes to further transgressing the biogeochemical flows PBs. While the impacts on the phosphorus flows do not surpass 1% of the SOS in any of the assessed scenarios, the impacts on the BECCS scenarios deploying Miscanthus and poplar represent ≤22% and ≤54% of the nitrogen biogeochemical flow SOS, respectively. Conversely, the impacts of DACCS on the biogeochemical flows are low (≤0.5% of the SOS).

The main unintended impact of the DACCS scenarios stems from their freshwater use, which corresponds to 1–2% of the SOS, with the total freshwater use strongly linked to the sequestration method (Supplementary Fig. 4). The freshwater consumption in the BECCS scenarios based on Miscanthus is low (≤1%), whereas those deploying irrigated poplar show a significant freshwater use (i.e., 40% of the SOS in BECCS-EXSITU-POP). We note that the deployment of NETs in water-stressed areas could have detrimental impacts at the regional level, even in the scenarios where freshwater consumption is low relative to the global PB.

BECCS and DACCS lead to low stratospheric ozone depletion (≤1% of the SOS) and land-system change (≤0.002% of the SOS). The land-system change impacts of BECCS are negligible—despite its high land-use requirements—because the LUC modeled in our scenarios does not involve the transformation of forested land, which is the only land type that the control mode modeled in our scenarios does not involve the transformation.

Fig. 4 Climate-related health effects avoided with respect to the baseline in the High-Temperature Liquid Sorbent Direct Air Carbon Capture and Storage (HTLS-DACCS) scenario based on wind energy and CO₂ mineralization with seawater. a Geographical distribution of the prevented climate-related health impacts, expressed in Disability-Adjusted Life Years (DALYs) per year. b Prevented climate-related health impacts relative to the size of the regional population (DALYs per million people per year) and distribution of the avoided health impacts by cause (DALYs per year). The distribution of the averted climate-related health impacts by region and cause remains constant across the studied scenarios despite the change in the impact magnitude.

Discussion

Our analysis provides new insights into a much-debated question: are the risks and costs associated with the large-scale deployment of NETs worth their potential benefits? We found that DACCS and BECCS could—provided they overcome the current scale-up barriers—preserve a substantial number of years of healthy life that would otherwise be lost due to climate change. Notably, removing 5.9 net GtGonne/year CO₂ could lead to net health improvements of a similar magnitude to the annual burden of common diseases. However, NETs would simultaneously generate some adverse health effects, mainly due to fine particulate matter formation. These unintended health impacts are negligible compared to the global effects of ambient air pollution, which currently reduce life expectancy by 3 years on average42. On the other hand, quantifying the NETs’ payback in terms of health externalities could incentivize their deployment, as the hidden monetized health benefits—often omitted in the economic analyses—are substantial (e.g., 142 US$/tonne CO₂ captured for HTLS-DACCS powered with wind, which represents 81–117% of its estimated cost)4.}

Focusing on the planetary health implications of the assessed NETs, only DACCS can avert the future climate change and ocean acidification impacts of past emissions without critically exacerbating the pressure on other Earth-system processes and concurrently preventing damage to the terrestrial biosphere integrity. In contrast, the biosphere integrity, nitrogen flow, and freshwater use would act as ecological bottlenecks for BECCS. Assessing the environmental impacts of NETs against regional PBs and the ecological limits to novel entities and aerosol loading —yet to be defined—could uncover other potential obstacles to their deployment. Nevertheless, DACCS will likely remain appealing given its positive effects on the two core planetary boundaries through which the others operate, i.e., climate change and biosphere integrity42. Moreover, future improvements in the energy efficiencies of DACCS systems could lower their health and environmental impacts; the long-term energy requirements of LTSS-DACCS could decrease by 38% (electricity) and 20% (heat) with respect to the values considered here43, whereas the energy demand of HTLS-DACCS could be reduced by optimizing the process parameters4. Furthermore, coupling HTLS-DACCS with electric furnaces could eliminate its dependence on natural gas.

NETs can prevent a temperature increase of 0.19 °C in our scenarios, but the combination of multiple climate change mitigation strategies might also allow us to meet the 1.5 °C target without resorting to NETs. It is challenging to evaluate whether
Fig. 5 Impacts on the Earth-system processes and ranking of scenarios by impacts on human health and the Earth system. a Impacts on Earth-system processes expressed as a percentage of the size of the Safe Operating Space (SOS). The impacts on the following Earth-system processes were assessed: climate change—considering atmospheric CO₂ concentration (CC-CO₂) and energy imbalance (CC-EI) as control variables—, ocean acidification (OA), terrestrial biosphere integrity (TBI), global biogeochemical flows—considering the application rate of intentionally fixed reactive N to the agricultural system (BGC-N) and phosphorus flows from freshwater into the ocean (BGC-P) as control variables—, global freshwater use (FWU), stratospheric ozone depletion (SOD), and global land-system change (LSC). Scenarios 1–16 comprise High-Temperature Liquid Sorbent (HTLS) and Low-Temperature Solid Sorbent (LTSS) Direct Air Carbon Capture and Storage (DACCS)—powered by natural gas with carbon capture and storage (NG+CCS), wind, solar photovoltaic (PV), nuclear, geothermal (GEO), or the global electricity mix deployed in the SSP2-1.9 marker scenario (which limits the increase in radiative forcing to 1.9 W/m² by 2100 and is based on Shared Socioeconomic Pathway 2) without NETs—, the basic Bioenergy with Carbon Capture and Storage (BECCS) scenarios (BECCS0) deploying Miscanthus (MISC) or poplar (POP)—assuming either Soil Carbon Sequestration (SCS) or land-use change (LUC)—, the hybrid BEDACCS configurations integrating BECC50 and LTSS-DACCS, and the BECCS scenarios where CO₂ is mineralized ex situ (BECCS-EXSITU). The values of empty cells range between 0 and 0.05%. We show qualitatively the current level of the control variables for the Planetary Boundaries (PBs) of the studied Earth-system processes below, according to the PB framework. Current status of the control variables: ▶ Below PB, □ PB exceeded. Uncertainty zone. □ PB exceeded. High-risk zone.

b Ranking of scenarios by health impacts and maximum impacts across Earth-system processes relative to the SOS size, scenario 1 is the best.

the benefits of DACCS would outweigh its risks in such optimistic scenarios where emissions are significantly reduced. However, we are currently headed toward 2.7 °C, and the full implementation of pledges and binding targets would be conducive to 2.1 °C. Therefore, unless efforts to reduce emissions are considerably intensified worldwide, NETs might become instrumental in meeting the Paris goals. While it is imperative to prioritize emissions reductions, the co-benefits and limited side-effects of DACCS might position this NET as an attractive option to counteract the historical responsibility of the most polluting countries and compensate for hard-to-abate emissions. Setting separate CDR and emissions reductions targets could prevent the
potential mitigation deterrence effect of NETs, which might discourage emissions reductions and allow a temporal temperature overshoot.

From a broader perspective, our work provides a scientific basis to underpin current initiatives that complement the IPCC’s efforts by enlarging its scope beyond climate change. These include the ones led by the Earth Commission, aiming to establish scientific guardrails for the Earth’s life-support systems, and the Global Commons Alliance, focused on strengthening development policies.

Furthermore, our results provide quantitative information about the implications of deploying NETs for several SDGs, besides SDG3 on climate action. Our human health analysis showcases how DACCS and BECCS could benefit SDG3 (good health and well-being) and SDG2 on zero hunger through their impacts on the freshwater use and biosphere integrity, respectively. To assess the characteristics of NETs for SDG7 (affordable and clean energy) and SDG14 (life below water), a broader set of indicators should be analyzed.

The performance of NETs will ultimately depend on their location; thus, a portfolio of negative emissions technologies and practices will probably be needed. Finding the optimal CDR portfolio will require regional assessments and cooperation among countries to design sustainable supply chains for NETs, minimizing their collateral damage and costs by exploiting regional advantages. In this context, analyses like ours could bolster negotiations between international stakeholders, and guide climate change mitigation strategies aligned with sustainable development policies.

**Methods**

**Life-cycle modeling**. We applied the Life-Cycle Assessment (LCA) methodology to quantify the impacts of the studied NETs on human health and the Earth system throughout their entire life cycle. The functional unit—the net removal of 5.9 Gt CO2/year CO2—corresponds to the average CDR rate in the SSP2-1.9 marker scenario during the period 2030–2100. Excluding CDR in the agriculture, forestry, and other land-use sector. Based on previous assessments, we identified the demand for energy and land of DACCS and BECCS as the main factors constraining their deployment and verified that their global availability is sufficient to fulfill the functional unit (Supplementary Table 12). The impacts related to the functional unit were calculated by dividing the impacts of capturing 5.9 Gt CO2/year CO2 by the CDR efficiency, ηCDR (Supplementary Table 1), i.e., the ratio between the net amount of CO2 that is permanently sequestered—calculated as the total captured CO2 (MCO2)—minus the overall CO2 emissions (MECO2)—and the amount captured, MCO2, (Eq. 1).

\[
\eta_{CDR} = \frac{M_{CO2} - M_{ECO2}}{M_{CO2}} \quad \text{(Eq. 1)}
\]

We followed an attributional modeling approach where the background processes reflect the average market consumption mix. Consequently, the results of our models change linearly with the net amount of CO2 removed. To address the multi-functionality of BECCS systems, which concurrently remove CO2 and generate electricity, we applied the system boundary expansion method. Thus, we consider that the produced electricity replaces electricity from the global mix projected for the SSP2-1.9 marker scenario in the period 2030–2100 (Supplementary Table 1), and the byproducts of the ex situ mineralization process substitute beneficiated iron ore and sand used as an inert filler. We also generated results for the BECCS scenarios disregarding the health and environmental credits (Supplementary Figs. 1, 2).

We assume that the impacts prevented by removing CO2 from the atmosphere are equal in magnitude to the impacts generated by emitting the same amount of CO2. However, several studies point out that global net emissions could weaken the natural carbon sink and reducing the NETs efficiency. Moreover, our LCA omits the impacts related to the infrastructure of NETs due to the lack of data. Nonetheless, previous studies suggest that the contribution of infrastructure to the total impacts of NETs might be minor. Notably, the impacts of constructing and decommissioning biomass power plants are negligible, whereas the impacts related to the infrastructure of LTSS-DACCS are small relative to other climate-change impacts.

Our models were implemented in SimaPro 9.2 and are based on generic—i.e., not geographically differentiated—data extracted from the Ecoinvent 3.5 database (the classification allocation method). Supplementary Section 4 (Supplementary Tables 17, 18) provide further details on these LCA models and the assumptions made.

**Health impact assessment.** Human health impacts are expressed in DALYs, which represent the years of healthy life lost due to either premature mortality or disability caused by prevalent disease or health conditions. The estimate of the health impacts in proportion to the global population, we considered the population prospects for SSP27,66.

The non-climate health impacts were quantified following the Hierarchist cultural perspective of the ReCiPe 2016 endpoint method, which integrates impacts over a 100-year time horizon to align with the scientific consensus. The environmental mechanisms leading to human health damage can be classified as global or regional depending on the scope of the health impacts. The health effects of climate change, stratospheric ozone depletion and ionizing radiation are global, whereas tropospheric ozone formation, water consumption and fine particulate matter formation cause regional health impacts. Stressors leading to human carcinogenic and non-carcinogenic toxicity impacts can affect human health at the global and regional levels, depending on their impact pathways. The methods compiled in Supplementary Table 2 contribute to at least 95% of the toxicity impacts across the studied scenarios. The USES-LCA 2.0 model—on which the characterization factors of the toxicity stressors provided by ReCiPe are based—identifies human exposure via water consumption at the regional level as the main impact pathway for these metals within a 100-year time horizon. Therefore, we classified carcinogenic and non-carcinogenic toxicity as regional impacts.

The ReCiPe method does not provide spatially differentiated characterization factors for the stressors contributing to stratospheric ozone depletion and ionizing radiation, which precludes the analysis of the geographical distribution of the associated global health impacts. To keep the analysis general, our models do not consider the NETs location; hence, we applied generic characterization factors, set S of stressors to contribute to the non-climate health impacts of scenario i to environmental mechanisms (Hi_i,eq) with Eq. 2, where EF_i,eq represents the elementary flows (kg/year), and CF_i,eq, the characterization factors (DALY/kg). This equation applies to all the environmental mechanisms contributing to human health impacts except for climate change (cc).

\[
H_{i,eq} = \sum_{i} EF_{i,eq} CF_{i,eq} \quad \text{with Eq. 2}
\]

Tang et al. derived spatially differentiated health damage factors from the models developed by the WHO25 for a subset of climate-related health risks—undernutrition, malaria, coastal floods, diarrhoea, heat stress, and dengue—under different adaptation measures. Other potential health impact pathways that are hard to predict, such as the effects of economic damage, or major heatwaves, are excluded from these models. Tang et al. estimated the aforementioned damage factors over the period 2000–2100; i.e., they do not refer to any specific year but to the whole period. These damage factors contribute an update of the factors used by the method to link global warming impacts to human health damage, which were derived from a previous WHO report by De Schyver et al. Thus, we calculated the impacts of climate change on human health with damage factors provided by Tang et al. for SSP2 (Supplementary Table 13). We determined the climate-related health impacts of scenario i associated with health risk k in region r (HI,eq, and related premature deaths in one year (2019). To quantify the health externalities of CDR, we applied the conversion factor proposed by Weidema (DALY/kg CO2). To quantify the characteristics of the toxicity stressors considered by Tang et al. (DALY/kg CO2-equ), and GWPs, the Global Warming Potential provided by the Hierarchist perspective of the ReCiPe method (kg CO2-equ/kg).

\[
H_{i,eq,cc} = DF_{i,eq} \sum_{i} EF_{i,eq} \cdot \text{GWPs}_{i,eq} \quad \text{with Eq. 3}
\]

Neither the characterization factors used to quantify the climate and non-climate health impacts, nor the global burden of disease estimates of the WHO consider age-weighting or time discounting; therefore, they are comparable. Nevertheless, the health impacts of the functional unit are aggregated over a 100-year time horizon, i.e., the impacts are associated with the net CO2 removed in 1 year, but they occur over a 100-year period. In contrast, the WHO’s global burden of disease estimates refer to the health loss due to the prevalence of diseases and related premature deaths in one year (2019). To quantify the health externalities of CDR, we applied the conversion factor proposed by Weidema (1 DALY = 74,000 €2010), which reflects the typical monetary value that society is willing to pay to preserve one DALY. Supplementary Section 3.2 provides further details about the monetization method.

**Earth-system impact assessment.** We evaluated the impacts of our scenarios on the Earth-system processes identified by Steffen et al. as critical to preserving the Earth’s stability, excluding atmospheric aerosol loading and novel entities, for which global PBs are yet to be defined. We used the impact assessment method developed by Ryberg et al. complemented with the characterization factors
The data supporting the findings of this study are available in the Supplementary Information document.

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