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Analysis

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Large CO_2 removal potential of woody debris preservation in managed forests

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Limiting climate warming to 1.5 °C requires reductions in greenhouse gas emissions and CO_2 removal. While various CO_2 removal strategies have been explored to achieve global net-zero greenhouse gas emissions and account for legacy emissions, additional exploration is warranted to examine more durable, scalable and sustainable approaches to achieve climate targets. Here we show that preserving woody debris in managed forests can remove gigatonnes of CO_2 from the atmosphere sustainably based on a carbon cycle analysis using three Earth system models. Woody debris is produced from logging, sawmill wastes and abandoned woody products, and can be preserved in deep soil to lengthen its residence time (a measure of durability) by thousands of years. Preserving annual woody debris production in managed forests has the capacity to remove 769–937 $GtCO_2$ from the atmosphere cumulatively (10.1–12.4 $GtCO_2\,yr^{-1}$ on average) from 2025 to 2100, if its residence time is lengthened for 100–2,000 years and after 5% CO_2 removal is discounted to account for CO_2 emission due to machine operation for wood debris preservation. This translates to a reduction in global temperatures of 0.35–0.42 °C. Given the large potential, relatively low cost and long durability, future efforts should be focused on establishing large-scale demonstration projects for this technology in a variety of contexts, with rigorous monitoring of CO_2 removal, its co-benefits and side-effects.

The Paris Climate Agreement has spurred research and development of climate solutions to help hold global mean temperature rise to 2.0 °C or preferably 1.5 °C (refs. 1–3). Among such solutions, carbon dioxide (CO_2) removal (CDR) strategies can accelerate the pace of decarbonization, compensate for emissions from hard-to-abate sectors (for example, agriculture and heavy industry) and enable net-negative global emissions (for example, to enable a return to the agreed warming limits after overshoot, remove legacy emissions and address intergenerational justice)[4,5]. Modelled pathways of global emissions to limit global warming to 1.5 or 2 °C entail the removal of 3–18 $GtCO_2\,yr^{-1}$ from the atmosphere[2]. As carbon budgets consistent with <1.5 °C of global warming dwindle, it is thus urgent to identify and implement large-scale CDR methods using our known principles of carbon cycle science.

From the perspective of carbon cycle science, CDR approaches effectively transfer carbon from the atmosphere to storage in land, ocean and geological reservoirs[6]. The amount of land carbon storage is determined together by two processes: the carbon influx from the atmosphere and the residence time of the stored carbon[7]. To remove CO_2 from the atmosphere at the gigatonne scale, we can either increase the carbon influx into pools with long residence times (that is, durability

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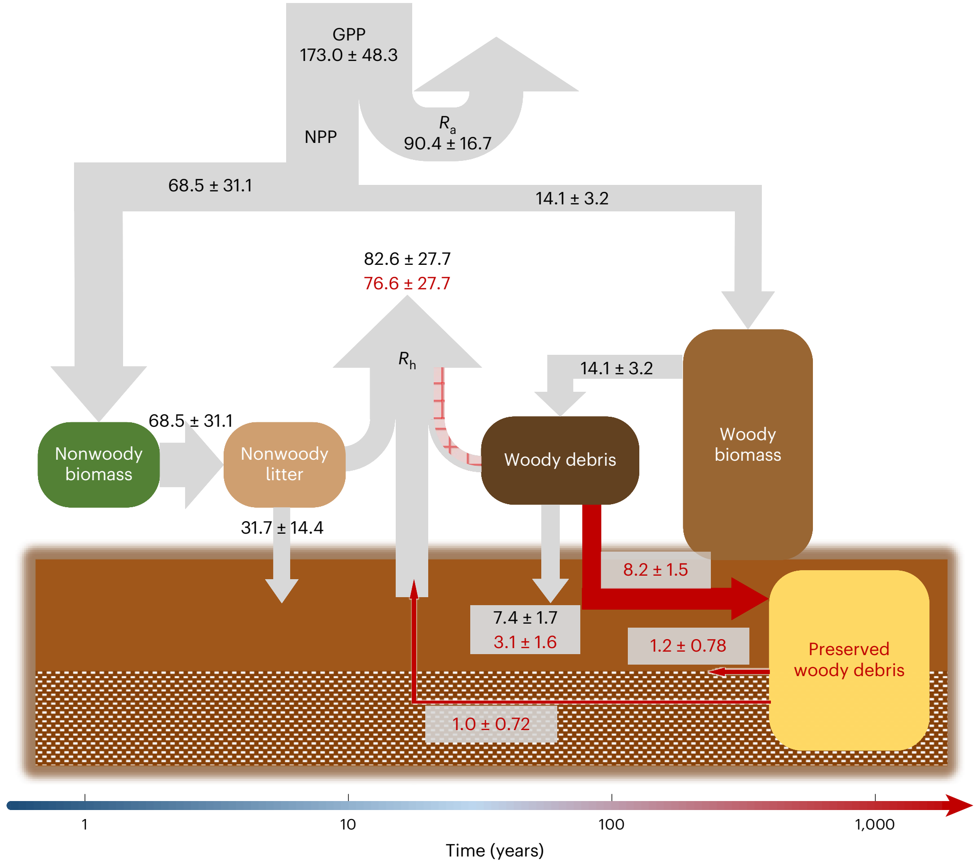

Fig. 1 | A schematic illustration of CDR via preserving woody debris in managed forests. The managed forests take up approximately 173.0 ± 48.3 $GtCO_2\,yr^{-1}$ from the atmosphere by photosynthesis. Autotrophic respiration (R_a) releases 90.4 ± 16.7 $GtCO_2\,yr^{-1}$ back to the atmosphere, while the remaining carbon uptake is used to grow plant biomass, mostly for fine roots and foliage. Approximately 14.1 ± 3.2 $GtCO_2\,yr^{-1}$ is used to grow woody biomass in managed forests. The woody biomass is harvested to produce woody products for construction, furniture and other uses, while woody debris is generated from logging and sawmill wastes. Wood products, once abandoned after they are used for a period, are usually landfilled. Averaged over time, the managed forests generate approximately 14.1 ± 3.2 $GtCO_2\,yr^{-1}$ of woody debris, ignoring minor disequilibrium (that is, carbon sink) during the period, while the global forests produce approximately 40.4 $GtCO_2\,yr^{-1}$ of woody debris[11,44]. The woody debris is decomposed or burned to release CO_2 back to the atmosphere at a similar rate to wood production. If the woody debris is preserved in deep soil to depress heterotrophic respiration (R_h) and prevent burning of, for example, 6 $GtCO_2\,yr^{-1}$, R_h from both woody debris and nonwoody litter would decrease from 82.6 ± 27.7 $GtCO_2\,yr^{-1}$ as marked in dark colour to 76.6 ± 27.7 $GtCO_2\,yr^{-1}$ as marked in red colour. The gross primary production (GPP), net primary production (NPP), R_a, nonwoody biomass production and woody biomass production in managed forests are derived from the model ensemble mean of CLM5, CoLM and CABLE over the 2004–2013 period.

or permanence), lengthen the residence times of high-influx pools, or both. For example, bioenergy with carbon capture and storage aims to store CO_2 in long-residence-time pools (geologic reservoirs) after using the biomass to generate energy[8], whereas enhanced rock weathering approaches seek to increase influxes of CO_2 into long-term carbon pools in oceans and deep soil[9].

Here we present a case study in which we used scientific knowledge gained from basic carbon cycle research to guide development and evaluation of CDR technology. Specifically, we analysed whether lengthening the residence time of woody debris via preservation in deep soils could result in a scalable and traceable CDR technology. Our analysis is built upon past studies with detailed methods of implementation, cost estimates and life-cycle analysis[10–13]. This Analysis describes how woody debris preservation in deep soil leads to negative carbon emission by depressing carbon emission from wood debris decomposition or burning, and how this technology is scaled up to sustainably remove gigatonnes of CO_2 from the atmosphere.

CDR via lengthening residence time

Preserving woody debris in deep soil removes CO_2 from the atmosphere by depressing carbon emission from its decomposition or burning, leading to negative carbon emissions in reference to that with its default uses. Woody debris generated from logging, sawmill wastes and abandoned wood products is usually decomposed or burned to release CO_2 back to the atmosphere at a similar rate to wood production (Fig. 1). When it is preserved in deep soil to lengthen its residence time, the CO_2 emission is delayed for a period determined by the lengthened residence time[13].

This mechanism underlying CDR though preserving woody debris resembles those underlying afforestation and reforestation, which mainly lengthen biomass carbon residence time in comparison with their reference ecosystems. For example, afforestation removes CO_2 from the atmosphere by converting a grassland or cropland into a forested area. While a newly established forest may have similar carbon input to the previous grassland or cropland[14], input carbon is partially allocated to woody biomass, which has a longer residence time by decades or centuries than biomass in either a grassland or a cropland, which turns over annually (Fig. 2). Similarly, restoration of a peatland results in CDR mainly by allocating carbon to soil carbon pools with long residence time (Fig. 2). By comparison, preservation of woody debris in deep soil diverts carbon from being released via microbial respiration or burning and, thus, effectively transfers carbon from the fast live biospheric cycle into a slow storage pool. While some forms of ecosystem restoration, for example, reforestation, may no

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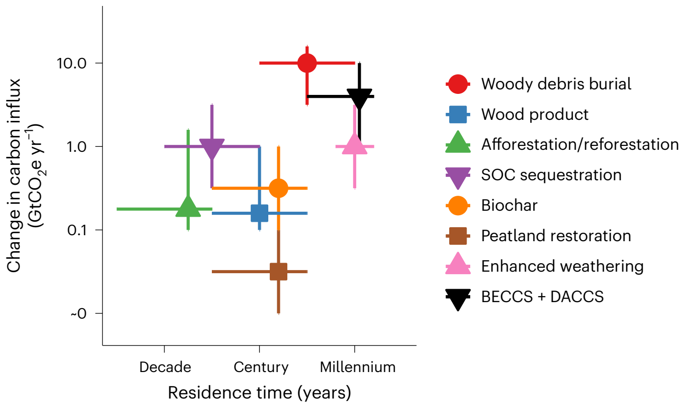

Fig. 2 | Carbon influxes and residence times of newly created pools under various CDR strategies at the global scale. The axes only indicate carbon influxes and residence time induced by each CDR method in the order of magnitude in reference to ref. 2 and ref. 45, as neither of them is well quantified. SOC, soil organic carbon; BECCS, bioenergy with carbon capture and storage; DACCS, direct air carbon capture and storage.

longer be effective once the past disturbed ecosystems have mostly been restored to saturation in carbon sink, preserving woody debris can keep removing CO_2 from the atmosphere, as woody debris can be sustainably delivered year after year.

Preserving woody debris takes advantage of large annual production rates. Woody biomass is produced at a rate of approximately 14.1 ± 3.2 (mean ± s.d.) $GtCO_2\,yr^{-1}$ in managed forests (Fig. 1, Methods and Extended Data Fig. 1). Woody biomass eventually becomes debris in various forms, such as logging debris during harvest, sawmill wastes, and abandoned furniture and other wood products. Logging debris is commonly piled up in the field for natural decomposition or burned on site, leading to rapid CO_2 release to the atmosphere. Sawmill wastes are mostly used in ways, such as woodchips and pellets, which be rapidly decomposed. Wood products, such as furniture and lumber, may lengthen the residence time of woody carbon but are eventually abandoned before being burned or landfilled for decomposition. These kinds of woody debris can all be preserved to remove CO_2 from the atmosphere.

In addition, preserving woody debris is much less energy intensive and can be implemented with lower cost than some of the current CDR techniques, such as direct air carbon capture and storage (DACCS)[12,13]. While woody debris is readily available for CDR, DACCS requires engineering of the carbon influxes into storage pools of long residence time through chemical adsorption, absorption or mineralization[9,15] (Fig. 2).

Preserving woody debris sustainably at the gigatonne scale

Woody debris can be preserved with many methods to lengthen its residence time, mostly involving extremely dry, cold and/or anoxic conditions[16]. For example, deep soil provides anoxic conditions to preserve woody debris for hundreds or thousands of years[10–13], primarily because soil is a very effective medium to deplete O_2 concentration to slow decomposition. O_2 concentration decreases from 21% in air to about 1% at a soil depth of 1 m and <0.1% at a soil depth of 2 m (ref. 17). Although decomposition of buried woody debris in deep soil may still occur, its rate is expected to decrease by orders of magnitude in comparison with debris left aboveground[18]. Additional treatments (for example, with smoke and salt) could further lengthen the residence time of deeply buried debris. Inhibiting microbial respiration via microbial biotechnology may be another way to further lengthen residence time[19].

Woody debris can be collected and buried nearby in areas where it is produced with minimal transportation. Logging debris can be collected and buried in the forests where tree harvests take place, whereas sawmill wastes and abandoned wood products can be entombed in nearby land. If an average of 4 tCO_2 equivalent (CO_2e) woody debris is available per hectare for preservation, 0.1 $MtCO_2$ will be removed from the atmosphere via collecting woody debris from 2,500 km^2 to be buried in a soil vault of 100 m long, 100 m wide and 10 m deep, assuming an average of 571 kg dry woody biomass per cubic metre and 1.75 kg CO_2 per kilogram of dry woody biomass (Methods)[12]. In this case, the land area used for the soil vault accounts for 1 over 2.5 million the area of woody debris collection. The volume of the excavation of one soil vault of this size is equivalent to that needed for constructing a mid-sized commercial building. Preserving 1 $GtCO_2$e woody mass requires 10,000 soil vaults of this size, with the total soil excavation being comparable to that needed for constructing the Burj Khalifa in Dubai[20]. Woody debris can be also preserved in existing quarries or abandoned mines to reduce soil excavation. The excavated underground vaults are capped with soil layers so that their land surface can be reused for growing trees, grasses or crops. Soil respiration may be slightly stimulated by excavation of soil vaults[21]. Yet capping the vaults probably results in more carbon storage as the carbon-rich topsoil is mixed in deep soil layers[22]. Life-cycle analyses indicated that CO_2 emissions due to energy use for the whole process of preserving woody debris are equivalent to 2–5% of buried woody debris carbon (Methods)[12,13].

Many countries generate woody debris in managed forests that can offset a substantial fraction of carbon emissions. The USA and China are among the top countries with the largest managed forest lands of nearly 300 million hectares and generate woody debris of 1.33 ± 1.07 and 1.24 ± 0.35 $GtCO_2\,yr^{-1}$, respectively (Fig. 3). If the rate of woody debris production in managed forests holds, it requires a fraction of the produced woody debris to be preserved to generate 0.88 $GtCO_2\,yr^{-1}$ for net-zero emission for the USA in 2050. In comparison, China could offset a small fraction of the required 5.6 $GtCO_2\,yr^{-1}$ in 2050 by preserving woody debris produced from its managed forests. On the other hand, Colombia produces woody debris of 0.51 ± 0.14 $GtCO_2\,yr^{-1}$, more than the required offset. These envelope estimates of the preservation potentials need to be verified with ground measurements in the future.

Accuracy of measurement and reporting

CDR via woody debris preservation can be accurately measured, monitored, reported and verified (MMRV) to facilitate trading on the voluntary carbon market. The amount of carbon in the to-be-preserved woody debris can be reliably quantified by weighing woody biomass and measuring carbon concentration. How well the woody debris is preserved can be monitored by measuring changes in gaseous CO_2 and CH_4 concentrations in the wood vaults and their release rates at the soil surface above the wood vaults reliably with instruments, such as a gas chromograph or infrared gas analyser. As a consequence, reporting and verification can be reliably done with high creditability without sophisticated modelling. In comparison, some of the nature-based solutions to climate change, such as soil carbon sequestration[23], suffer from uncertainties in MMRV despite evidence for large-scale CDR capacity. Owing to its high accuracy in MMRV, trading of preserving woody debris has started on voluntary carbon markets[24].

Climate benefits of preserving woody debris

To predict CDR and resultant climate benefits through annual preservation of woody debris in managed forests, we conducted 24 experiments each with three models—the Community Land Model version 5 (CLM5), the Common Land Model (CoLM) and the Australian Community Atmosphere Biosphere Land Exchange (CABLE) model version 2 (Methods). The three models are used to simulate woody debris production in managed forests at 16.0 ± 3.4 $GtCO_2\,yr^{-1}$ on average from 2025 to 2100 under the Shared Socioeconomic Pathway (SSP)1-2.6 climate change scenario. Meanwhile, we created one additional pool

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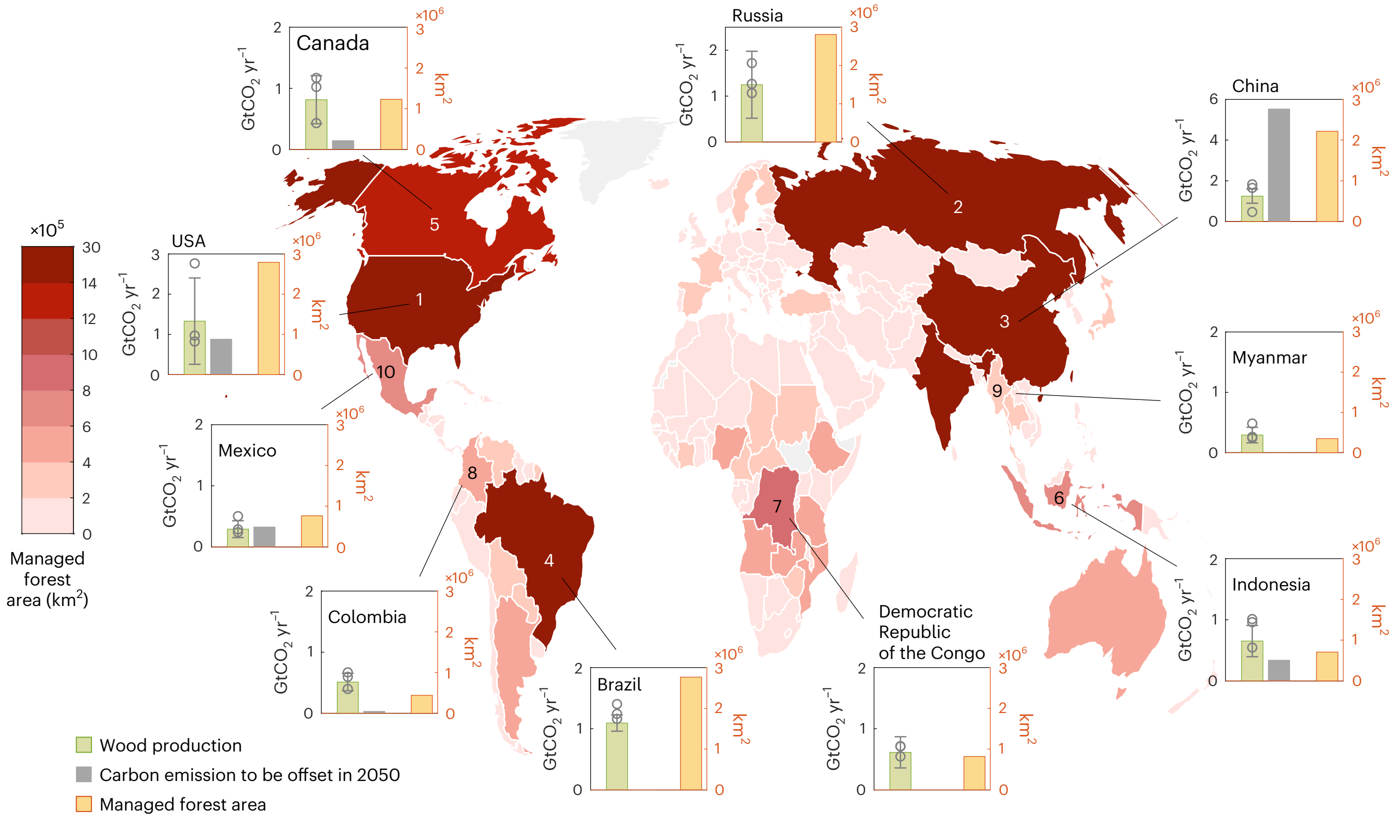

Fig. 3 | Top ten countries with the highest wood production in managed forests. The ranking of wood production is indicated by numerical values. The wood production rate is estimated as a mean over the period 2025–2050 predicted by CLM5, CoLM and CABLE models under the SSP1-2.6 scenario. The managed forest map used in the analysis is from Lesiv et al.[46] and cross-validated with the UN FAO Global Forest Resources Assessment 2020[47] (Methods) despite their differences in areas of managed forests for individual countries. The bar plot presents country-level estimates of wood production rate (mean ± s.d., $n = 3$), projected carbon emissions to be offset in 2050 and managed forest area. Emission estimates are from ref. 1, except for Russia, Brazil and Democratic Republic of the Congo (no data; see Methods).

for preserved woody debris in each of the models (Extended Data Fig. 2 for CABLE). Woody debris is preserved at four fractions—25, 50, 75 and 100%—each with six levels of lengthened residence time—0, 20, 50, 100, 200 and 2,000 years (Fig. 4 and Methods). If all the produced woody debris in managed forests is fully preserved to lengthen residence time for 100, 200 and 2,000 years, 10.6 ± 4.6, 11.7 ± 4.2 and 13.0 ± 3.5 $GtCO_2$ yr^{-1} are removed from the atmosphere, respectively. CDR steeply increases with lengthening residence time in the low range from 0 to 50 years, but slightly in the high range from 100 to 2,000 years. After the 5% CO_2 cost is reduced for the energy use of the implementation, the net CDR is 10.1, 11.1 and 12.4 $GtCO_2$ yr^{-1}, respectively, for lengthened residence time by 100, 200 and 2,000 years.

An extra 3.0 $GtCO_2$ yr^{-1} of woody debris is required for preservation to compensate largely for reduced soil carbon storage with a lengthened residence time of 2,000 years. When woody debris is preserved to depress decomposition and reduce CO_2 release, carbon input to various soil pools decreases. Thus, the modelled soil carbon storage under the scenario of woody debris preservation is less than that under the control, assuming that wood debris in default uses is all returned to the soil (see Extended Data Fig. 3 for CABLE results). The amount of extra woody debris for the compensation becomes larger due to faster backflow from the increased stocks in the preservation pool if the residence time of the preserved woody debris is lengthened less. Preserving the total sum of woody debris produced from 2025 to 2100 with a net increase of residence time by 2,000 years and the 5% CO_2 cost subtracted for the operation has a capacity to remove 936.2 $GtCO_2$ from the atmosphere, leading to a reduction of temperature rise by 0.42 °C according to the transient climate sensitivity value of 0.45 °C per 1,000 $GtCO_2$ to cumulative CO_2 emissions (median from Earth system models)[25]. Lengthening the mean residence time by 100 years removes 768.7 $GtCO_2$ and reduces temperature rise by 0.35 °C.

It is unlikely that all the woody biomass produced in managed forests can become debris to be preserved. For example, woody biomass belowground in forest ecosystems, paper pulp wastes and abandoned wood products are difficult to collect for preservation. On the other hand, urban and orchard woody wastes can be preserved for CDR. Besides woody debris, other biomass and materials, such as crop residues and landfill organic wastes of more than 100 Gt (refs. 26,27), can be preserved in deep soil to decrease their decomposition, contributing to CDR from the atmosphere. In addition to preservation, woody debris can be used in other alternative ways, such as biochar as a soil supplement and wood fuel for energy, for climate mitigation[28]. While the relative benefits of different wood usages for climate mitigation are yet to be evaluated[29], woody debris preservation probably offers one of the most effective climate solutions because its lengthened residence time can be up to thousands of years.

Co-benefits and side-effects to be evaluated in the future

A major co-benefit of burying dead wood salvaged from forestry is the potential reduction of wildfire risks in fire-prone regions. Globally, wildfire burning releases 7.7 ± 0.7 $GtCO_2$ yr^{-1}, and other greenhouse gases, for example, methane (18 Mt CH_4 yr^{-1}), and unhealthy particles (44 Mt $PM_{2.5}$ yr^{-1})[30–33], to the atmosphere. As one of the most fire-prone regions on Earth, the USA has invested about US$25.7 billion for fire suppression since 2010[34], but still releases more than 180 Tg CO_2 yr^{-1}

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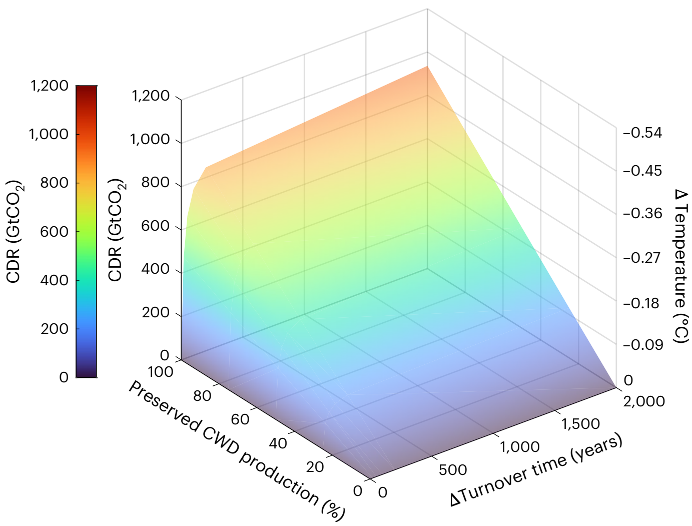

Fig. 4 | The potential for CDR and climate benefits from preserving woody debris in the global managed forests over the period 2025–2100 under the SSP1-2.6 scenario. The amount of carbon removal (left vertical axis) and its resultant climate benefit (right vertical axis) depend on residence time lengthened and the fraction of CWD to be preserved. The response surface is the average of outputs from three models, CLM5, CoLM and CABLE, with 5% discount for the cost of operation estimated from life-cycle analysis[13] (see Extended Data Figs. 4–6 for outputs of individual models in two-dimensional figures). The climate benefit (that is, the temperature reduction) is calculated approximately according to the transient climate sensitivity value[25].

due to fires[30] and induces annual property damage of US$10.8 billion[35]. Removing woody debris reduces surface fuel availability and decreases combustion-induced carbon emissions. Forest thinning in fire-prone regions for woody debris preservation to prevent wildfire will result in additional CDR from the atmosphere.

Another co-benefit is to offer new options to manage woody wastes from various sources, such as fruit tree pruning and urban management, while achieving negative carbon emissions. Urban woody waste is produced every year from pruned branches, stumps and whole trees from street and public areas. But its production rate has not been well quantified, varying from 58 $MtCO_2\,yr^{-1}$ in the USA[36] to 66.5 $MtCO_2\,yr^{-1}$ in California[37]. The amount of woody material from fruit tree pruning can be substantial[38] enough to contribute to carbon neutrality in orchards if buried. Moreover, this strategy can be implemented together with afforestation, reforestation and agroforestry to enhance their effectiveness for climate mitigation.

One major concern of preserving woody debris under anaerobic conditions is the production of methane, a highly potent greenhouse gas. Previous studies suggest that methanotrophic microorganisms ubiquitously exist in various environments[39,40] and probably oxidize most of the methane along soil profiles before it reaches the atmosphere, therefore we assumed that these methane emissions are negligible in this study, whereas wood debris on ground surface emits methane[41]. Nevertheless, it is still essential to measure methane production from buried woody debris, its transport and oxidization along the soil profiles, and methane fluxes at the soil surface. Other possible side-effects to be quantified include carbon release from soil excavation and impacts of woody debris removal from the forest floor on soil health; diversity of microorganisms, animals and plants; and tree regeneration[42].

While the residence time of buried woody debris in deep soil is likely to be substantially lengthened, new research is needed to quantify very slow processes of decomposition under anaerobic conditions. Although methods to bury woody debris underground are readily available, techniques to deprive O_2 more effectively from buried woody debris for CDR at the gigatonne scale need to be explored and further developed. Moreover, the relative impacts on nutrient availability are yet to be evaluated for woody debris preservation versus other uses, although woody debris has low nutrient concentrations[43].

Many aspects of this CDR strategy need to be evaluated before it can avoid unintended ecosystem degradation and achieve true climate benefits. It is critical to identify situations under which this approach could provide benefits and/or where it could have negative impacts. Although wood wastes from urban management and forest thinning in fire-prone regions were not accounted for in the estimates of CDR and subsequent reduction in temperature rise in this Analysis, future research may be focused on these sectors as they probably offer high societal benefits in addition to climate mitigation. Practices to be avoided for this CDR strategy are harvesting woods from intact forests, especially the primary tropical forests, and prohibiting other long-lived uses of the material for the sake of burying the woods. Careful research is needed to elucidate opportunities for possible misapplications of this CDR strategy.

Future research towards implementation

Here we present a novel analysis based on the principles of carbon cycle science to suggest that woody debris preservation offers a scalable, durable and sustainable technology of CDR from the atmosphere. Preserving woody debris in managed forests has the potential to remove 769–936 $GtCO_2$ from the atmosphere by 2100 and reduce temperature rise by 0.35–0.42 °C if woody residence time is lengthened by 100–2,000 years and 5% of buried carbon is discounted for CO_2 emissions due to preservation operation. Because the amount of carbon preserved can be MMRV with high accuracy, this technology can facilitate trading on and potentially be promoted by voluntary carbon markets. Biomass preservation in deep soil reduces wildfire risks, whereas its impacts on soil health, methane emission, nutrient dynamics and biodiversity are yet to be investigated. While preserving woody debris has large potential for climate mitigation due to relatively easy implementation and long durability, it is important to establish large-scale demonstration projects for this technology in a variety of contexts, with rigorous monitoring of CDR, co-benefits and side-effects. Through such demonstrations, strengths and weaknesses of preserving wood debris relative to other CDR options can be assessed, while implementation can be optimized and operational costs and CO_2 emissions minimized.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-025-01731-2.

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Methods

Definition of managed forests

We derived a mask of managed forests from a global wall-to-wall map of forest management at a 100 m resolution for the year 2015[46]. This global map was generated by a machine learning algorithm based on PROBA-V satellite imagery and a reference dataset of 226,322 unique locations through a series of expert and crowdsourcing campaigns using Geo-Wiki (https://www.geo-wiki.org/). We included five categories from the global map as managed forests, which are naturally regenerating forest with signs of management (for example, logging and clear cuts), planted forests, plantation forests (rotation time up to 15 years), oil palm plantations and agroforestry, covering a total area of 3.1×10^7 km^2. The areas of mapped forest management classes under the definition by Lesiv et al.[46] were cross-checked and generally consistent with the United Nations (UN) Food and Agriculture Organization (FAO) Global Forest Resources Assessment 2020[47].

Woody biomass and debris expressed in units of CO_2e

Woody biomass is expressed here in units of CO_2e to be consistent with the units commonly used for CDR research and practice. The unit is defined by biomass × carbon (C) concentration × CO_2/C ratio of 3.67 (that is, 44/12). Wood carbon concentrations range widely from 28 to 65%, with a global average of 47.6 ± 4.0 (s.d., 95% confidence limits = 45.7, 49.4%)[48]. One unit of dry matter of wood equals 1.75 units of CO_2 (= 3.67 × 0.476). This unit measures the amount of CO_2 released from mineralization of one unit of woody biomass.

We assume that woody debris contains the same amount of carbon as woody biomass in the managed forests. One cubic metre of space stores approximately one metric tonne of CO_2-eqivalent woody debris if we assume the specific weight of wood is 0.571 tonnes of biomass per cubic metre[11]. The specific weight of wood ranges from 0.2 to 0.9 tonnes[49–51].

Model description and experimental design

Three models—CABLE, CLM5 and CoLM—were used in this study to estimate the woody debris production over global managed forests and predict potential carbon sequestration by preserving woody debris annually. The CABLE model is a comprehensive land surface model that incorporates fully coupled carbon (C), nitrogen (N) and phosphorus (P) cycles[52]. In this model, the representation of plant, litter and soil C stocks includes nine distinct pools, namely leaf, root, wood, metabolic litter, structural litter, coarse woody debris (CWD), fast soil organic matter (SOM), slow SOM and passive SOM.

The CLM5 is the default land component for the Community Earth System Model version 2 (CESM2)[53]. CLM5 describes the energy, water and mass balance of the land surface and the interaction with the atmosphere. The CLM5 biogeochemical module describes the C and N mass balance of terrestrial ecosystem processes. Carbon stocks in CLM5 are represented by 18 vegetation pools and 140 soil organic pools (7 pools × 20 layers). Vegetation pools include six nutritive organ tissue pools: leaf, fine root, live stem, dead stem, live coarse root and dead coarse root. Every tissue pool is accompanied by a storage and a transfer pool. Seven soil organic pools include metabolic litter, cellulose litter, lignin litter, CWD, fast SOM, slow SOM and passive SOM.

The CoLM adopts all the C stock representation from CLM5 but with ten soil layers. The major differences between CoLM and CLM5 are from biophysical processes, which influence the biogeochemical processes. The CoLM employs a three-dimensional canopy representation[54], reflecting a more realistic energy redistribution within canopy and radiation competition among plant functional types. CoLM developed a variably saturated flow scheme to numerically solve the soil wetting front and water table. The variably saturated flow scheme has considerably improved the soil moisture simulation[55], which has been identified as the largest uncertainty source of the permafrost soil carbon dynamics in land models[56].

Meteorological data, including temperature, precipitation, downward shortwave radiation, downward longwave radiation, specific humidity, pressure and wind speed, to drive models were obtained from Climatic Research Unit gridded Time Series (CRU TS) and National Centers for Environmental Prediction (NCEP) reanalysis (CRUNCEP)[57,58] (for CABLE) and the Global Soil Wetness Project (GSWP)[59] (for CLM5 and CoLM). These data, along with observed atmospheric CO_2 concentration data, were used for spin-up of the CABLE, CLM5 and CoLM models in 1901, followed by transient simulations from 1902 to 2013. The spatial resolutions for these models were 0.5° × 0.5° (CABLE), 1.875° × 2.5° (CLM5) and 1.875° × 2.5° (CoLM). Note that the two forcing datasets, CRUNCEP and GSWP, use different algorithms for spatial upscaling from similar observational datasets, resulting in similar spatial patterns of temperature, precipitation, downward shortwave and longwave radiation, specific humidity, pressure and wind speed (Extended Data Figs. 7 and 8). The CRUNCEP dataset in this study mainly results from interpolation of the NCEP reanalysis, with 2.5° × 2.5° 6-hourly data from 1948 to 2013[60] with the CRU TS3.2, providing 0.5° × 0.5° monthly data from 1901 to 2002, used to apply monthly adjustments for improved accuracy[61]. Similarly, GSWPv3 builds upon the 20th Century Reanalysis (20CR) dataset, a global 2° resolution[62]. Using a spectral nudging technique within a global spectral model, it is dynamically downscaled to a finer ~0.5° grid. The CRU TS data were also used in correcting biases in the downscaled 20CR data[62], making the GSWPv3 and CRUNCEP similar (Extended Data Figs. 9 and 10). Using these simulations from the models and a managed forest mask[46], we estimated a woody debris production rate of 14.1 $GtCO_2$ yr^{-1} in the global managed forests on average from 2004 to 2013 (Extended Data Fig. 1).

To examine additional carbon storage created for CDR through the preservation of woody debris we established a new pool for preserved woody debris in each of the CABLE, CLM5 and CoLM models. The new pool receives carbon from woody biomass pool(s) with different fractions for preservation and different lengthened residence times (Extended Data Fig. 2). The latter determines the rate of decomposition of preserved woody debris, which partially releases CO_2 to the atmospheric and partially transfers to soil carbon pools.

Then, we extended the historical simulation from 2013 to the year 2100 under SSP1 with a radiative forcing at the 2.6 W m^{-2} level (SSP1-2.6) climate change scenario[63]. From 2025 onwards, woody debris was annually redirected to the preserved pool as described below (Extended Data Fig. 2). To investigate the impacts of the amount of annually preserved woody debris and varying degrees of lengthening residence time on ecosystem C storage, we conducted 24 experiments with four levels of burying woody debris (that is, transferring 25, 50, 75 and 100% of the annual woody production to the preserved pool) and six levels of lengthened residence time of preserved woody debris (that is, 0, 20, 50, 100, 200 and 2,000 years). By comparing the ecosystem C storages under different levels of woody debris burial and varied residence time, we evaluated the potential of CDR from the atmosphere in managed forests (Extended Data Figs. 4–6).

We estimated CDR for each of the countries in Fig. 3 consistently using averaged woody debris production from the three models. One caveat is that none of the three global models has specific plant functional types for managed forests and all the three models use forests with existing plant functional types to estimate woody production of managed forests.

Life-cycle analysis for discounting CDR

Here we used an estimate of 5% to discount CDR from wood debris preservation according to the life-cycle analysis of two wood vault projects presented in ref. 13. The estimated emission ratio of machine operation, including wood harvest and transportation, soil vault excavation, and recapping, to the carbon entombed in the wood vault is 2% for the Montreal project in 2013 but 5% for the Potomac project.

The higher emission ratio in the Potomac project than the Montreal project is due to much longer transportation distance, which accounts for 83% of the total emissions, with the remaining 17% of the total emissions from wood vault construction. Here we used 5% as the emission ratio to reduce the total amount of CDR by burying wood debris.

Data availability

The data used to produce Figs. 1–4 and Extended Data Figs. 1–10 are available via Figshare at https://doi.org/10.6084/m9.figshare.28824182.v1 (ref. 64).

Code availability

The code used to produce Figs. 1–4 and Extended Data Figs. 1–10 is available via Figshare at https://doi.org/10.6084/m9.figshare.28824182.v1 (ref. 64). Code for the three woody debris preservation models is available at https://ecolab.cals.cornell.edu/download/Luo_et_al_Preserving_wood_debris_for_CDR_data_code.php. These materials are freely accessible to researchers for the purpose of reproducing or extending the analysis presented in the study.

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Author contributions

Y.L. conceived the study. N.W and X.L. did the modelling analysis. Y.Z., F.T., Q.Q. and C.L. collected relevant information from the literature. Y.L. wrote the first draft. All authors contributed to major revisions of the paper and approved the final version.

Competing interests

N.Z. is the inventor of a US patent 12198146B2 and cofounder of Carbon Lockdown. The other authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41561-025-01731-2.

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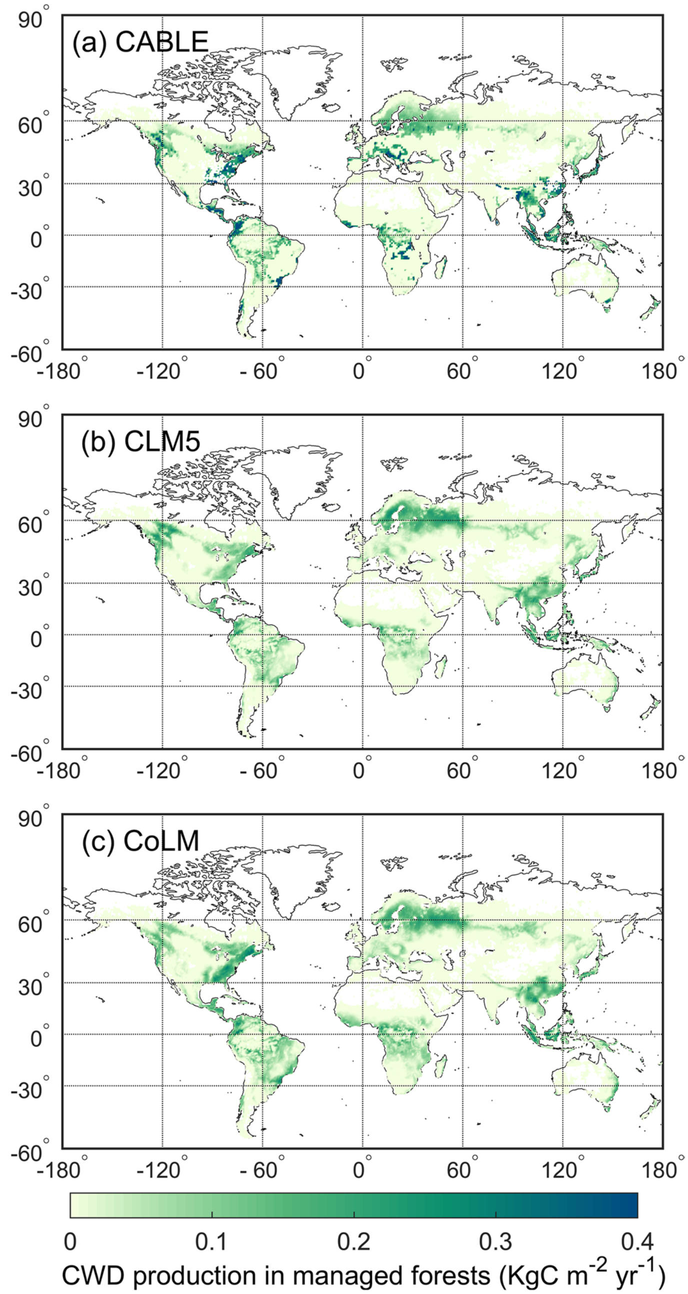

Extended Data Fig. 1 | Spatial patterns of coarse woody debris (CWD) production. Simulated with (**a**) CABLE, (**b**) CLM5 and (**c**) CoLM in managed forests, averaged over the 2004-2013 period.

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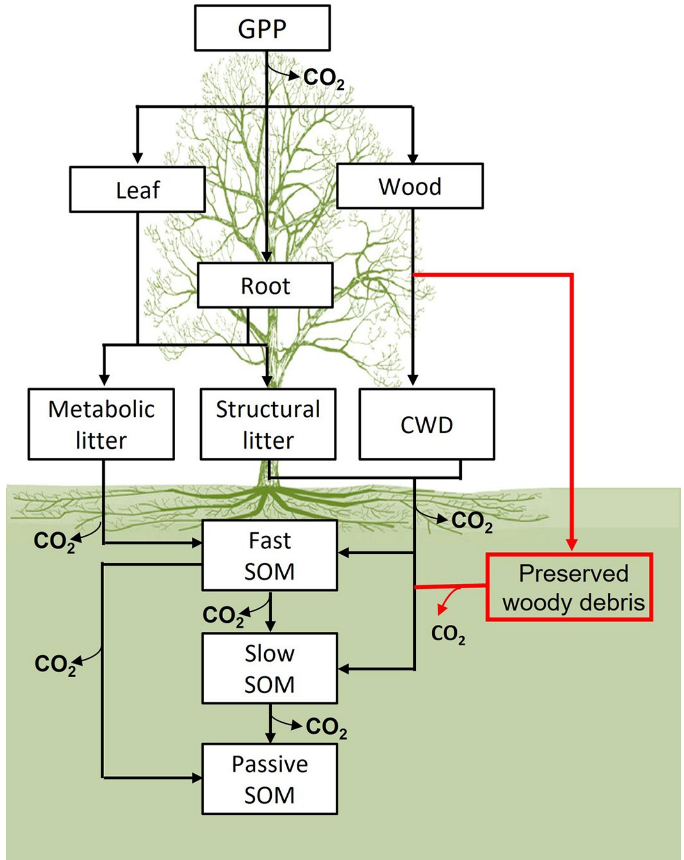

Extended Data Fig. 2 | Schematic diagram of a new pool for preserved woody debris added to the CABLE model. GPP stands for Gross Primary Production, CWD for coarse woody debris, SOM for soil organic matter. Adapted from Xia et al.[65].

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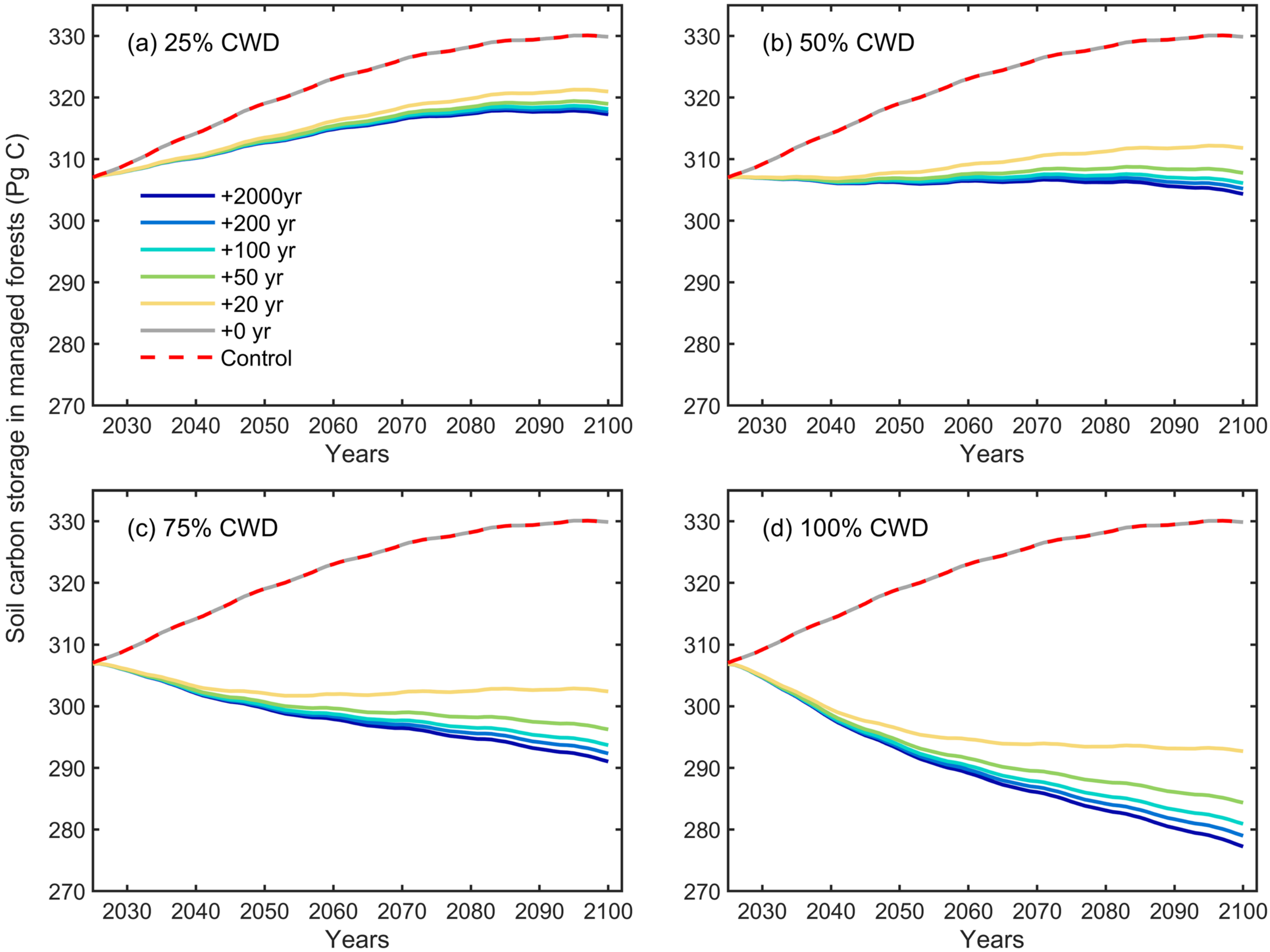

Extended Data Fig. 3 | Soil carbon storage in managed forests from 2025 to 2100. Under the 24 scenarios of woody debris preservation and the control run simulated by the CABLE model. Shown in panels are soil carbon storage with preservation of (**a**) 25% wood debris, (**b**) 50% wood debris, (**c**) 75% wood debris and (**d**) 100% wood debris.

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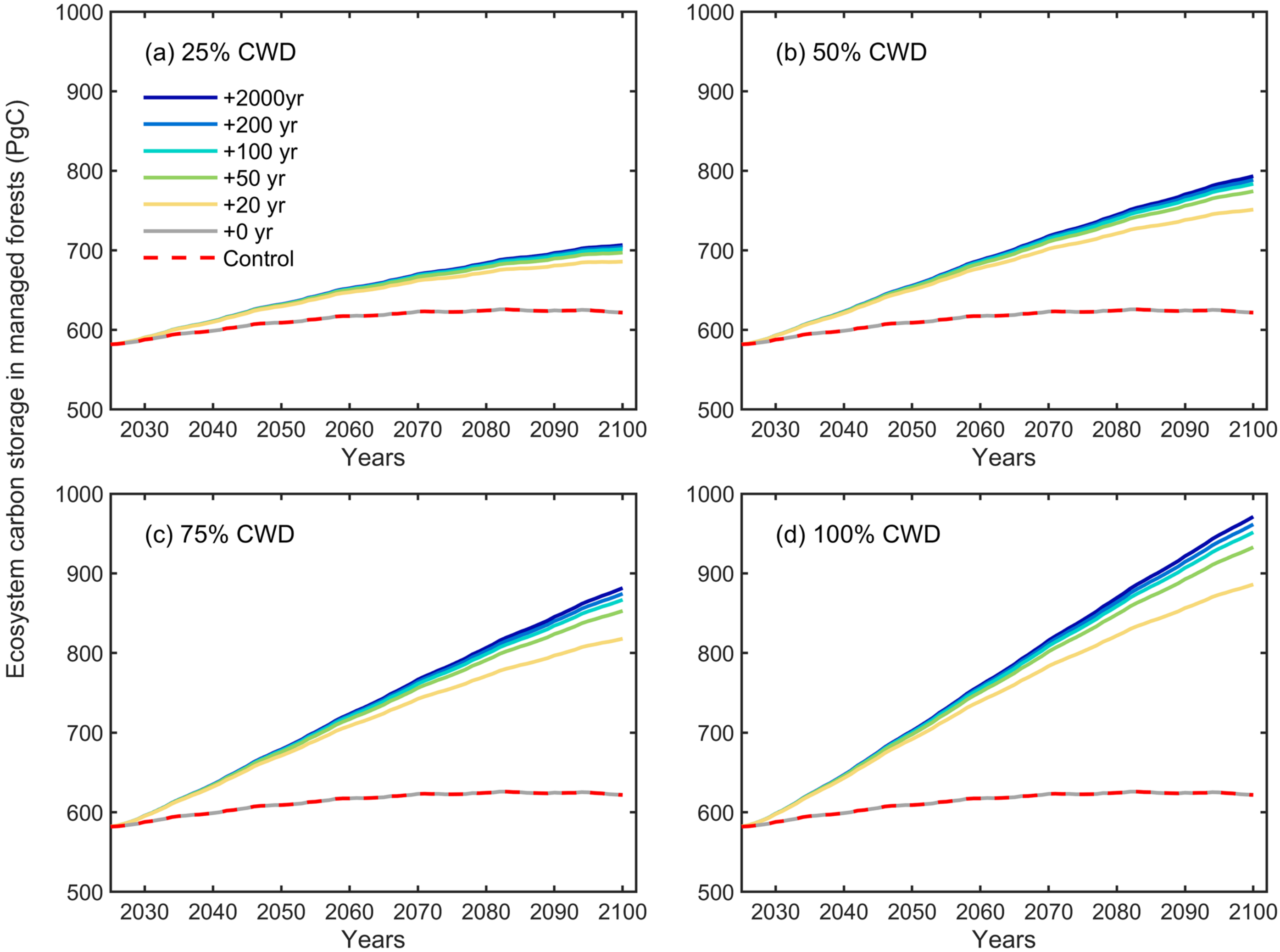

Extended Data Fig. 4 | Ecosystem carbon storage in managed forests from 2025 to 2100. Under the 24 scenarios of woody debris preservation and the control run simulated by the CABLE model. Shown in panels are ecosystem carbon storage with preservation of (**a**) 25% wood debris, (**b**) 50% wood debris, (**c**) 75% wood debris and (**d**) 100% wood debris.

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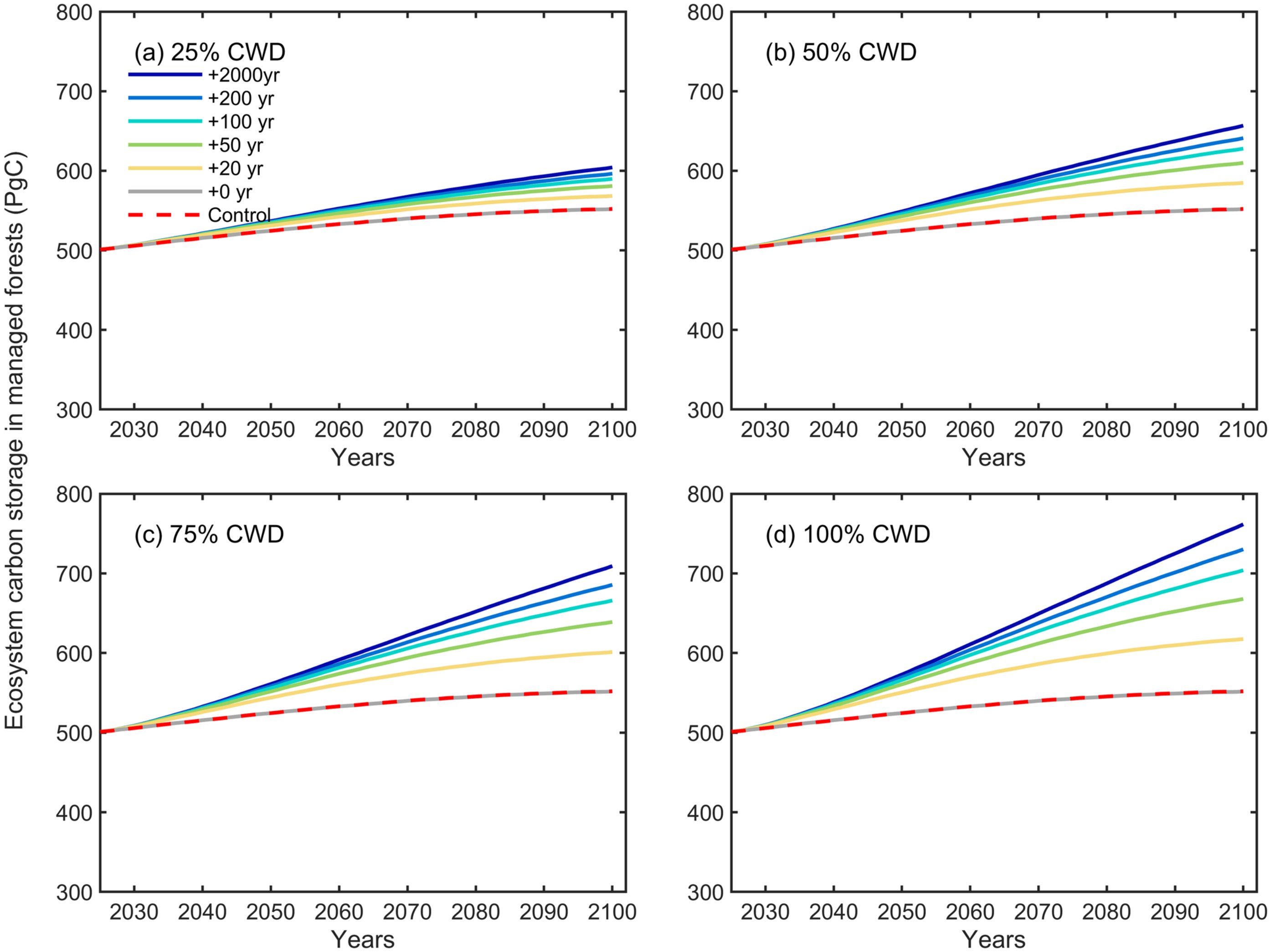

Extended Data Fig. 5 | Ecosystem carbon storage in managed forests from 2025 to 2100. Under the 24 scenarios of woody debris preservation and the control run simulated by the CLM5 model. Shown in panels are ecosystem carbon storage with preservation of (**a**) 25% wood debris, (**b**) 50% wood debris, (**c**) 75% wood debris and (**d**) 100% wood debris.

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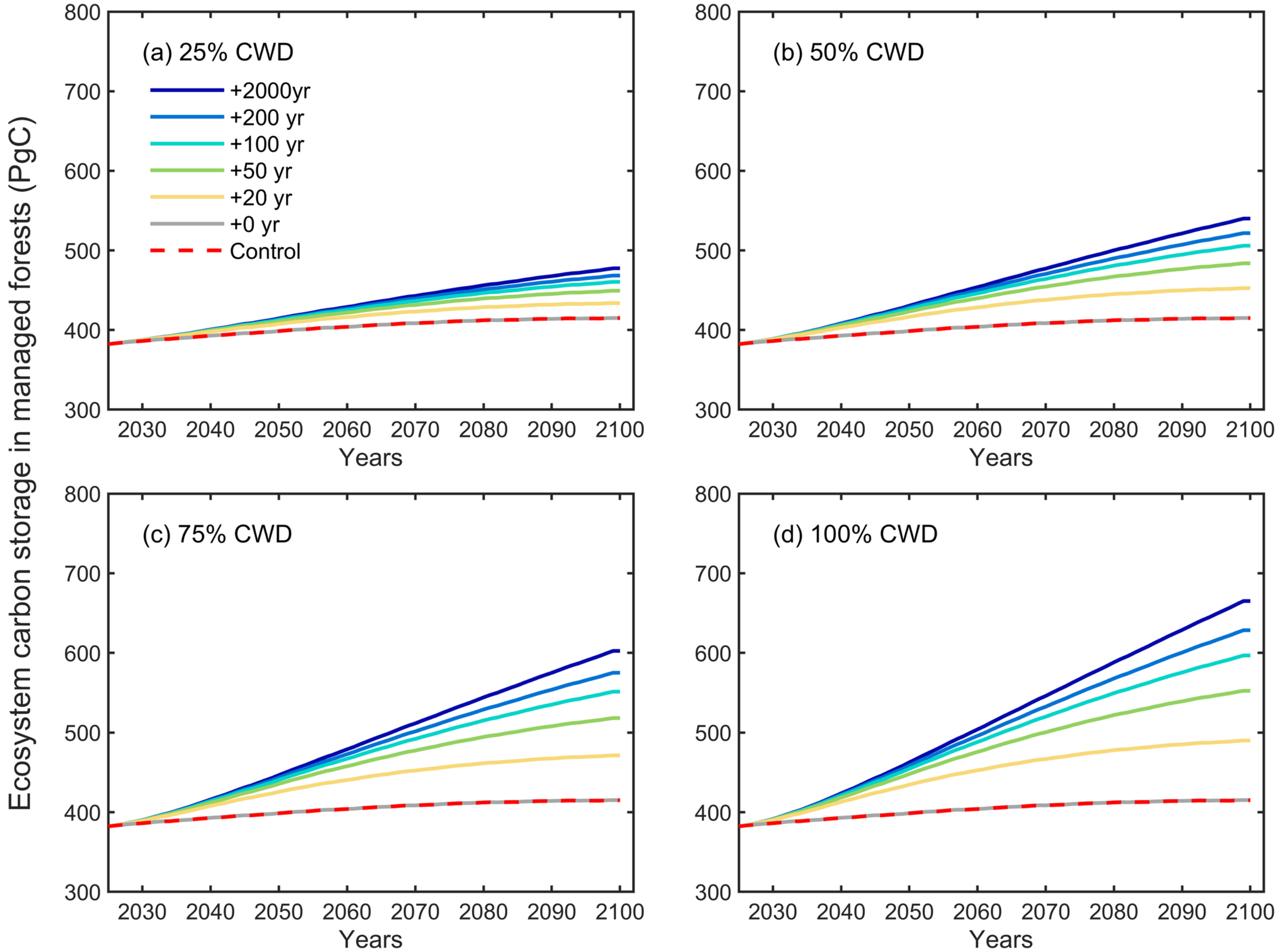

Extended Data Fig. 6 | Ecosystem carbon storage in managed forests from 2025 to 2100. Under the 24 scenarios of woody debris preservation and the control run simulated by the CoLM model. Shown in panels are ecosystem carbon storage with preservation of (**a**) 25% wood debris, (**b**) 50% wood debris, (**c**) 75% wood debris and (**d**) 100% wood debris.

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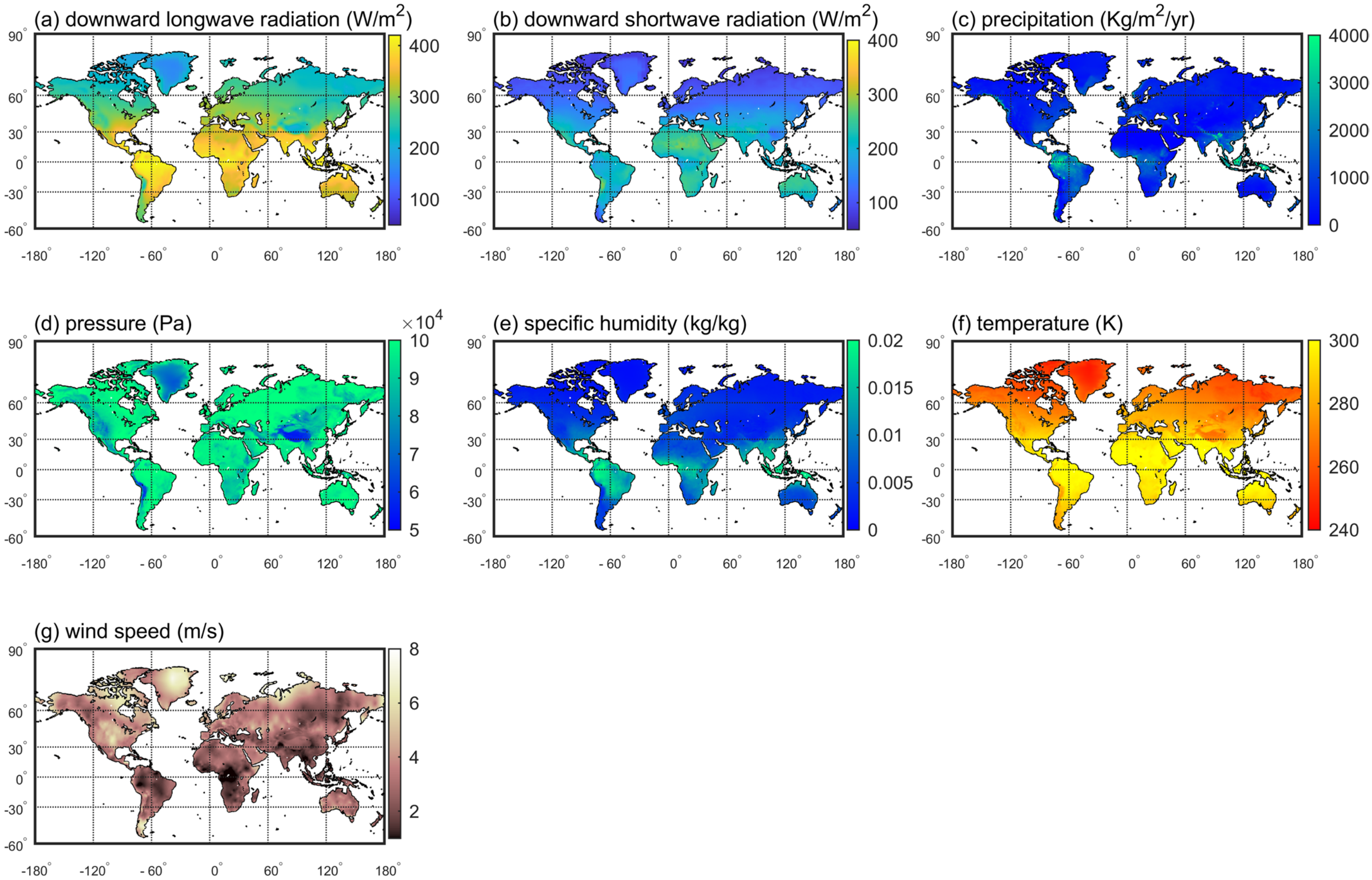

Extended Data Fig. 7 | Spatial patterns of atmospheric variables from GSWPv3 forcing data averaged over the period 1901–2013. (**a**) Downward longwave radiation, (**b**) downward shortwave radiation, (**c**) precipitation, (**d**) pressure, (**e**) specific humidity, (**f**) temperature, and (**g**) wind speed.

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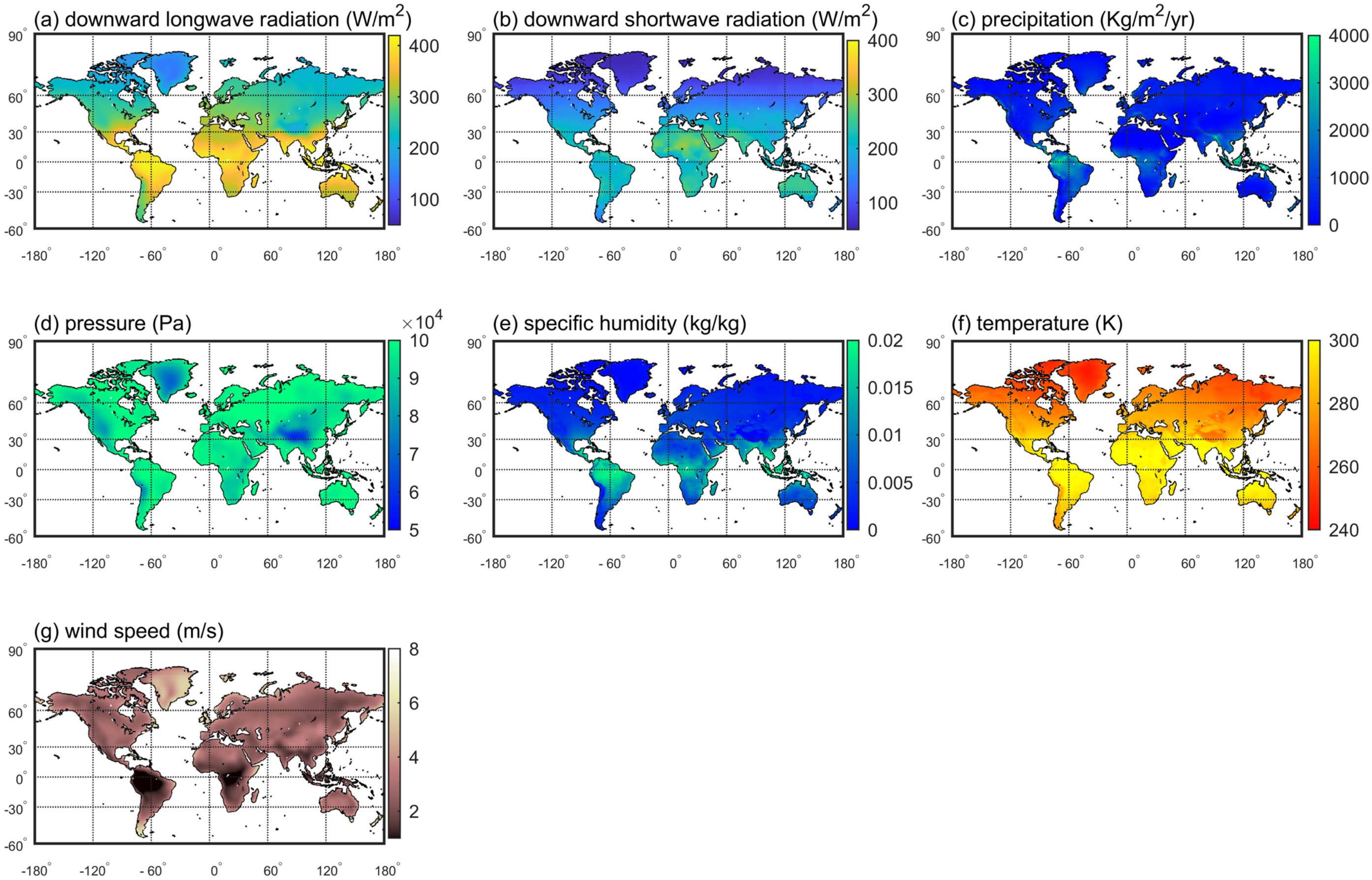

Extended Data Fig. 8 | Spatial patterns of atmospheric variables from CRUNCEP forcing data averaged over the period 1901–2013. The same as Extended Data Fig. 7 but for the CRUNCEP forcing data. (**a**) Downward longwave radiation, (**b**) downward shortwave radiation, (**c**) precipitation, (**d**) pressure, (**e**) specific humidity, (**f**) temperature and (**g**) wind speed.

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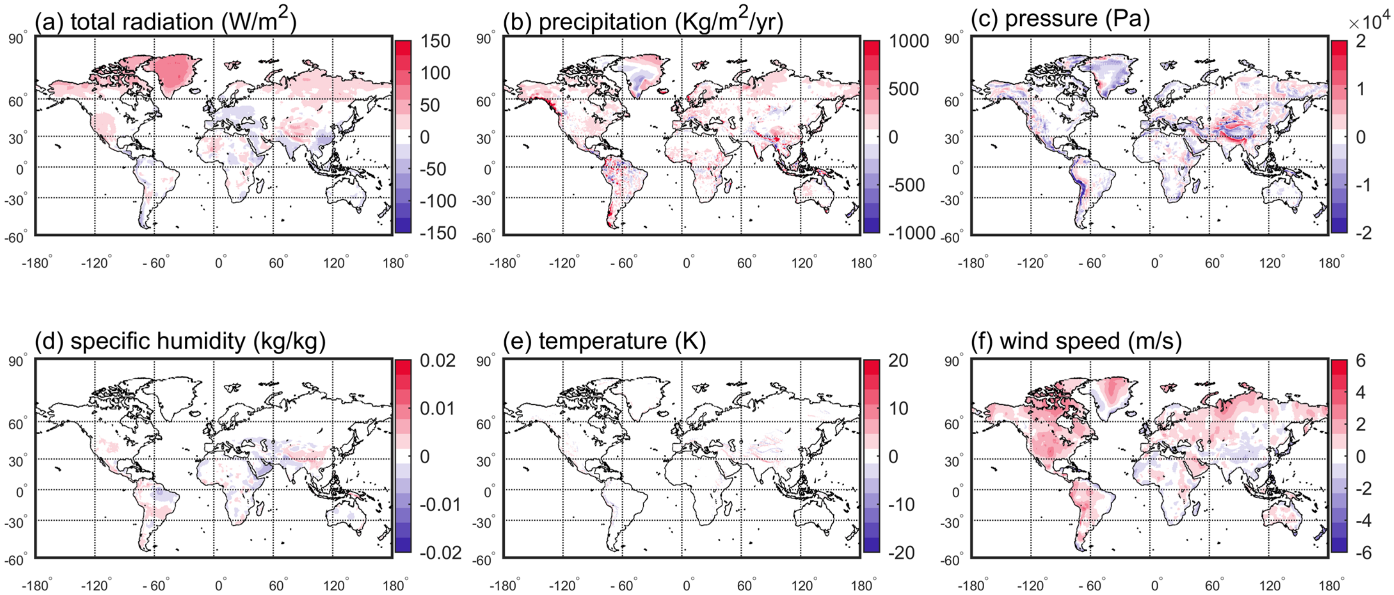

Extended Data Fig. 9 | Spatial patterns of the differences between GSWPv3 and CRUNCEP averaged over the period 1901–2013. Shown are for (**a**) total radiation (sum of downward longwave and shortwave radiation), (**b**) precipitation, (**c**) pressure, (**d**) specific humidity, (**e**) temperature and (**f**) wind speed.

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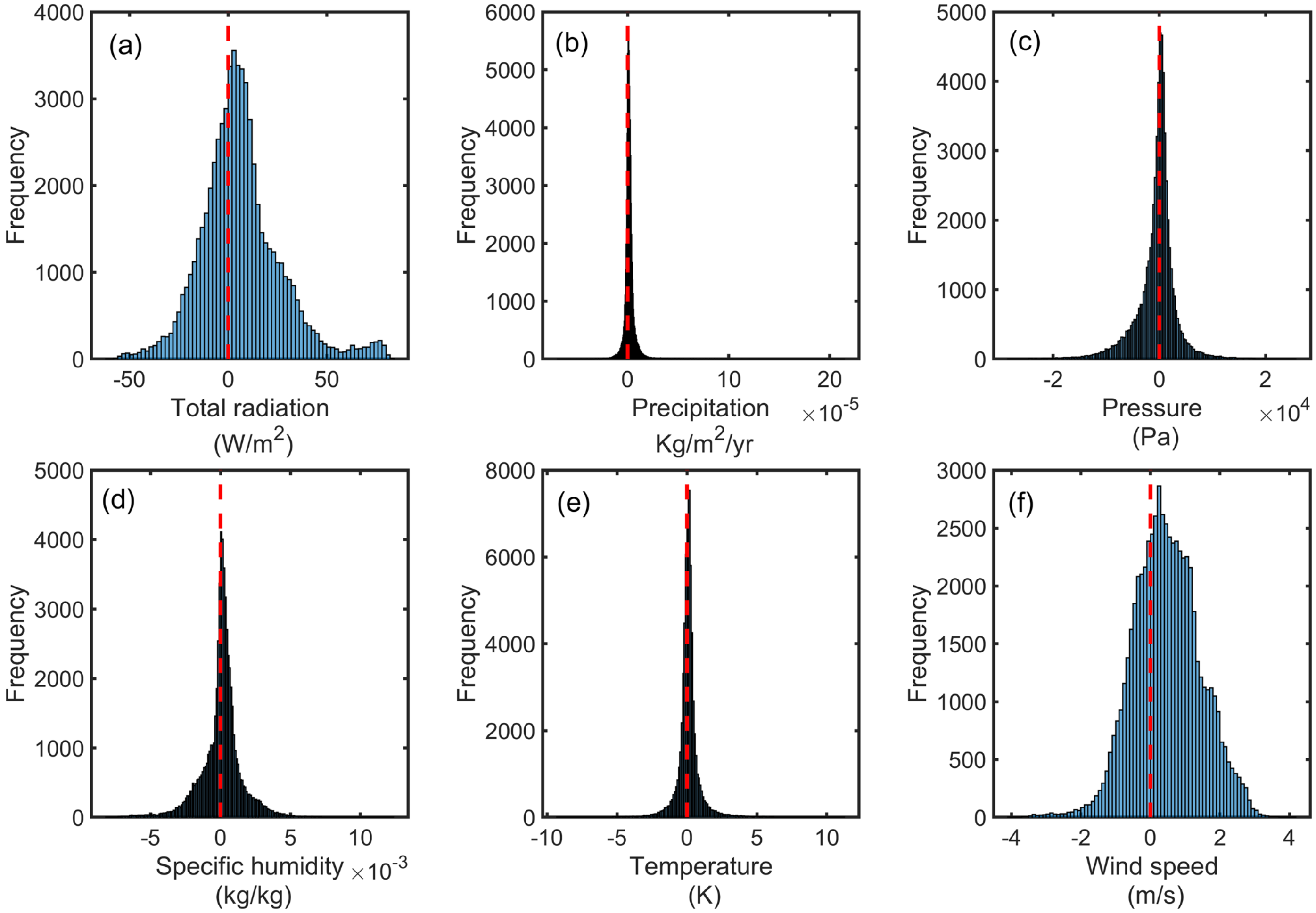

Extended Data Fig. 10 | Frequency distribution of the differences between GSWPv3 and CRUNCEP across all global grid cells as in Extended Data Figs. 8 and 9. (**a**) Total radiation, (**b**) precipitation, (**c**) pressure, (**d**) specific humidity, (**e**) temperature and (**f**) wind speed.