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Biophysical and economic limits to negative CO_2 emissions

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To have a >50% chance of limiting warming below 2 °C, most recent scenarios from integrated assessment models (IAMs) require large-scale deployment of negative emissions technologies (NETs). These are technologies that result in the net removal of greenhouse gases from the atmosphere. We quantify potential global impacts of the different NETs on various factors (such as land, greenhouse gas emissions, water, albedo, nutrients and energy) to determine the biophysical limits to, and economic costs of, their widespread application. Resource implications vary between technologies and need to be satisfactorily addressed if NETs are to have a significant role in achieving climate goals.

Despite two decades of effort to curb emissions of CO_2 and other greenhouse gases (GHGs), emissions grew faster during the 2000s than in the 1990s[1], and by 2010 had reached ~50 Gt CO_2 equivalent (CO_2eq) yr^{-1} (refs 2,3). The continuing rise in emissions is a growing challenge for meeting the international goal of limiting warming to less than 2 °C relative to the pre-industrial era, particularly without stringent climate policies to decrease emissions in the near future[2–4]. As negative emissions technologies (NETs) seem ever more necessary[3,5–10], society needs to be informed of the potential risks and opportunities afforded by all mitigation options, to be able to decide which pathways are most desirable for dealing with climate change.

There are distinct classes of NETs, such as: (1) bioenergy with carbon capture and storage (BECCS)[11,12]; (2) direct air capture of CO_2 from ambient air by engineered chemical reactions (DAC)[13,14]; (3) enhanced weathering of minerals (EW)[15], where natural weathering to remove CO_2 from the atmosphere is accelerated and the products stored in soils, or buried in land or deep ocean[16–19]; (4) afforestation and reforestation (AR) to fix atmospheric carbon in biomass and soils[20–22]; (5) manipulation of carbon uptake by the

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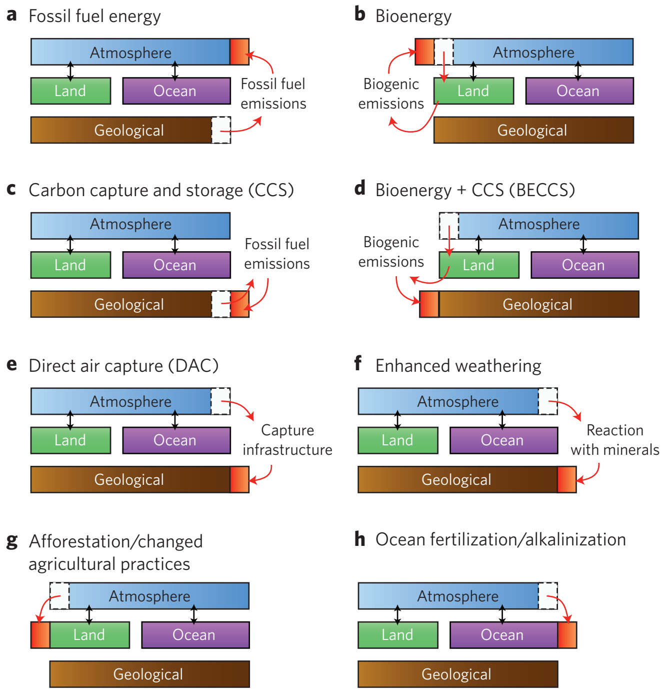

Figure 1 | Schematic representation of carbon flows among atmospheric, land, ocean and geological reservoirs. a, Climate change results from the addition of geological carbon to the atmosphere through combustion or other processing of fossil fuels for energy. Carbon is indicated in red. **b**, Bioenergy seeks to avoid the net addition of carbon to the atmosphere by instead using biomass energy at a rate that matches the uptake of carbon by re-growing bioenergy feedstocks. **c**, Carbon capture and storage (CCS) technologies intervene to capture most of the potential carbon emissions from fossil fuels, and return them to a geological (or possibly ocean) reservoir. **d**–**h**, NETs remove carbon from the atmosphere, either through biological uptake (**g**,**h**), uptake by biological or industrial processes with CCS (**d**,**e**) or enhanced weathering of minerals (**f**). Any atmospheric perturbation will lead to the redistribution of carbon between the other reservoirs (but these homeostatic processes are not shown). Note that there are significant differences in the materials and energy requirements for each process to remove (or avoid adding) a unit mass of carbon from (or to) the atmosphere.

ocean, either biologically (that is, by fertilizing nutrient-limited areas[23,24]) or chemically (that is, by enhancing alkalinity[25]); (6) altered agricultural practices, such as increased carbon storage in soils[26–28]; and (7) converting biomass to recalcitrant biochar, for use as a soil amendment[29]. In this Review, we focus on BECCS, DAC, EW and AR, because there are large uncertainties with ocean-based strategies (for example, ocean iron fertilization[30]), and other land-based approaches (for example, soil carbon and biochar storage) have been evaluated elsewhere[31–33]. Figure 1 depicts the main flows of carbon among atmospheric, land, ocean and geological reservoirs for fossil fuel combustion (Fig. 1a), bioenergy (Fig. 1b), carbon capture and storage (CCS; Fig. 1c) and the altered carbon flows entailed by each NET (Fig. 1d–h) when carbon is removed from the atmosphere.

Coupled energy–land-use analyses of NETs using IAMs have so far focused primarily on BECCS[7,34,35] and AR[36–39] strategies, and suggest that they may have considerable cost-competitive potential. Although other NET options have also been studied[13,19,40], they are not yet represented in most IAMs. The majority of IAMs allow biomass-based NETs in the production of electricity and heat in power stations as well as hydrogen generation, and sometimes for generating other transport fuels or bioplastics. The key distinguishing feature of NETs is their ability to remove CO$_2$ from the atmosphere. Depending on the development of overall emissions, this may lead to: (1) a global net removal of CO$_2$ from the atmosphere by offsetting emissions that were released either in the past or in the near future[41]; or (2) offsetting ongoing emissions from difficult-to-mitigate sources of CO$_2$, such as the transportation sector[42,43], as well as non-CO$_2$ GHGs.

The Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) database includes 116 scenarios that are consistent with a >66% probability of limiting warming below 2 °C (that is, with atmospheric concentration levels of 430–480 ppm CO$_2$eq in 2100)[41]. Of these, 101 (87%) apply global NETs in the second half of this century, as do many scenarios that allow CO$_2$ concentrations to grow between 480 and 720 ppm CO$_2$eq by 2100 (501/653 apply BECCS; with 235/653 (36%) delivering net negative emissions globally[41]; see also Fig. 2).

Results from two recent modelling exercises[10,35,44] show that median BECCS deployment of around 3.3 Gt C yr^{-1} (Supplementary Table 3) is observed for scenarios consistent with the <2 °C target (430–480 ppm CO$_2$eq); we assess other NETs for deployment levels that give the same negative emissions in 2100 (see Supplementary Methods).

A key question is whether these rates of deployment of NETs can be achieved and sustained. Most of the NETs require the use of land and water, some use fertilizer, and may also impact albedo. All NETs are expected to have considerable costs[8,10]. Earlier studies have examined a number of constraints to NETs[7,37–39,45–50], but have not assessed a range of different NET types together, or considered the range of impacts included here. We perform a 'bottom-up' implied resource use analysis rather than a 'top-down' potential efficacy analysis, using the best available data from the most recent literature. The evidence base for the values used varies greatly between NETs, with some (for example, BECCS) having been the subject of a large body of research, whereas others (for example, EW) have received less attention. The data sources and a qualitative assessment of the confidence and uncertainty in the ranges we derive are described in detail in the Supplementary Methods. We estimate the impacts of each NET per unit of negative emission, that is, per t C equivalent (Ceq), then assess the global resource implications, focussing on the limits to large-scale NET deployment and how these differ between NETs.

Impacts of NETs per unit of negative emissions

NETs vary dramatically in terms of their requirements for land, GHG emissions removed or emitted, water and nutrient use, energy produced or demanded, biophysical climate impacts (represented by surface albedo) and cost, depending on both their character and on the scale of their deployment. Figure 3 highlights the differences in these requirements expressed per t Ceq removed from the atmosphere. Geological storage capacity has recently been evaluated as a potential limit to implementation for CCS (and hence BECCS)[51,52], so is not considered further here. Indirect effects of NETs through the reduced use of other technologies in pursuit of a given goal — for example, potentially fewer nuclear reactors, wind farms and solar arrays — are not considered here. The values we have used are estimated from analyses presented in the latest peer-reviewed literature (see Supplementary Methods).

Land area and GHG emissions. The area (and type) of land required per unit of Ceq removed from the atmosphere, also termed the land use intensity, is particularly important for land-based NETs (Fig. 3a). The land use intensity of BECCS is quite high, with values ranging from ~1–1.7 ha t^{-1} Ceq yr^{-1} where forest residues are used as the BE feedstock, ~0.6 ha t^{-1} Ceq yr^{-1} for agricultural residues, and 0.1–0.4 ha t^{-1} Ceq yr^{-1} when purpose-grown energy crops are used. Supplementary Table 2 shows the carbon and GHG emissions and removals associated with a range of energy crops and forest types, and the net negative emissions delivered (see Supplementary Methods). EW and DAC have minimal land requirements, with land use intensities of <0.01 ha t^{-1} Ceq yr^{-1} (ref. 18) and <0.001 ha t^{-1} Ceq yr^{-1} (ref. 14), respectively (Fig. 3a).

Water use. This is highly variable between different BE feedstocks (including forest feedstocks) and is generally considered to be higher for short-rotation coppice and C4 grasses than for annual crops and grassland (on an area basis)[53], although when corrected for biomass productivity, the ranges are closer and overlap considerably[54] (Fig. 3b). In calculating water implications of BECCS, water use for CCS is added to the BE water use (Supplementary Methods). Where deployed, irrigation also has a dominant impact on water use. Estimates of water required per t Ceq removed by DAC and EW are an order of magnitude or more lower than for BECCS (Fig. 3b). For EW of olivine, one molecule of water is required for each molecule of CO_2 removed, so each t Ceq would require 1.5 m^3 water (Fig. 3b).

Energy input/output. This varies considerably between different NETs. BECCS has a positive net energy balance, with energy production ranges of 3–40 GJ t^{-1} Ceq for energy crops[55] (Fig. 3e). DAC and EW, on the other hand, require considerable energy input to deliver C removal; the minimum theoretical energy input requirement for the chemical reactions of DAC[14] is 1.8 GJ t^{-1} Ceq removed at atmospheric concentrations of CO_2, and for EW of olivine is 0.28–0.75 GJ t^{-1} Ceq (Fig. 3e). When also including other energy inputs for mining, processing, transport, injection and so on, the energy inputs for DAC and EW are much greater, perhaps as much as 45 GJ t^{-1} Ceq and 46 GJ t^{-1} Ceq, respectively[14,56] (Fig. 3e). The GHG implication of this additional energy use depends on the GHG intensity of the energy supply, which is likely to change over the rest of this century. Energy requirement is less important if low-carbon energy is used (for example, using large areas of solar photovoltaic panels to power DAC plants[45]), but may still have additional impacts.

Nutrients. These are depleted when biomass is removed from a field or ecosystem for use as a BE feedstock. This is therefore an issue for BECCS and for AR when biomass is removed from the site, but not for DAC or EW. Perennial energy crops typically contain around 10 kg N t^{-1} Ceq (and 0.8 kg P t^{-1} Ceq in the case of *Miscanthus*[57]), trees around 4–5 kg P t^{-1} Ceq, and annual energy crops (such as fibre sorghum) around 20 kg P t^{-1} Ceq. Nutrient removal therefore differs several-fold among biomass sources (Fig. 3c), so large-scale transition to using land for biomass production could deplete nutrients, but this will depend on the vegetation (or other land use) that is replaced. Additional nutrient requirements (that is, fertilization) are difficult to estimate on a net basis, as fertilizer may also have been used (with varying intensity) on the land before the switch to energy crops[58]. Nutrient depletion further translates into agricultural inputs and upstream GHG emissions and energy consumption.

Albedo. In addition to biogeochemical climate impacts (for example, uptake of atmospheric carbon), changes in land use affect climate by altering the physical characteristics of the Earth's surface, such as increased evapotranspiration[59] and increased cloud cover in the tropics[60]. Important among these physical changes is albedo (here we focus on surface albedo), which is the reflectance of solar energy by the Earth's surface. The albedo of lighter-coloured and less-dense vegetation (for example, food crops and grasses) is much greater than that of trees[53,61]. The situation is further complicated in areas where shorter vegetation may be persistently covered by highly reflective snow in winter, while tall coniferous trees remain exposed and therefore much less reflective[61]. This snow-mediated effect is large enough to mean that AR in northerly latitudes may have a neutral or net warming effect (larger than the carbon sink provided by the vegetation)[62–65]. Figure 3d shows the change in albedo under different NETs (focussing on the replacement of cropland or grassland with energy crops) or under AR, both with and without the effect of snow.

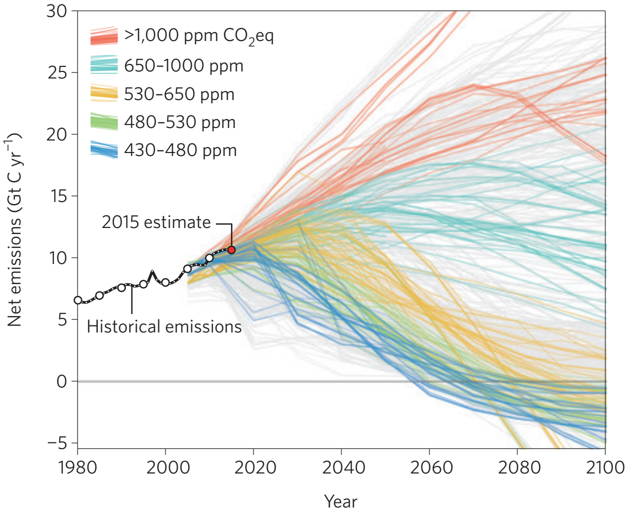

Figure 2 | Scenarios including NETs for each of the scenario categories, corresponding to the ranges and median values shown in Supplementary Table 3. Scenarios with no technology constraints (that is, including NETs) from the AMPERE[10,44] and LIMITS[35] modelling comparison exercises are shown in colours, with all other scenarios from the IPCC AR5 database shown in grey. See the caption of Supplementary Table 3 for an explanation of the representation of gross positive and gross negative emissions. Net land use change fluxes are included (note, the 1997 fluctuation is attributable to Indonesian peat fires). Sources: CDIAC[94], IPCC AR5 scenario database (https://secure.iiasa.ac.at/web-apps/ene/AR5DB/)[95] and the Global Carbon Project.

Costs. The economic costs of deploying and operating NETs will vary according to the specific technologies involved, the scale of deployment and observed learning, the amount and value of co-products, site-specific factors and the scale and cost of building and maintaining any supporting infrastructure (the costs of capturing and storing a t Ceq are from studies using approximate 2005 to 2015 US$ values). In the case of BECCS and DAC, costs can be anticipated to occur across three stages: (1) capture, (2) transport and (3) storage (including monitoring and verification). Recent estimates of the total costs of DAC technologies[40,66] are $1,600–2,080 per t Ceq, of which roughly two-thirds are capital costs and one-third operating costs (Fig. 3f). Although there are very wide ranges for costs of BECCS technologies[67], the mean price estimated across 6 IAMs for 2100[46] was $132 per t Ceq (Fig. 3f); costs of bioenergy without CCS are lower[54,55]. AR costs are estimated to be $65–108 per t Ceq for 2100, with a mean of $87 per t Ceq. Estimated costs of EW are taken from Renforth[56]: $88–2,120 per t Ceq, with a mean of around $1,104 per t Ceq; these estimates are uncertain and the relative balance between capital and operating costs has not yet been thoroughly examined.

Global resource implications of NETs deployment

We use global deployment of BECCS in the recent assessments featured in Supplementary Table 3 to derive the corresponding resource implications (Table 1), and focus on the scenario giving a 2100 atmospheric CO_2 concentration in the range of 430–480 ppm (consistent with a 2 °C target). We compare DAC resource implications at the same level of negative emission as BECCS (that is, 3.3 Gt Ceq yr^{-1} in 2100; Table 1). For other NETs, which are not able to meet the same level of emissions removal, we use values compiled from an analysis of the recent literature to give mean and maximum implementation levels (see Supplementary Methods). Mean values for carbon removals from AR are estimated to be around 1.1 Gt Ceq yr^{-1} by 2100, with a maximum value of 3.3 Gt Ceq yr^{-1} for very large-scale deployment[6,7,68] (Table 1). The potential of carbon

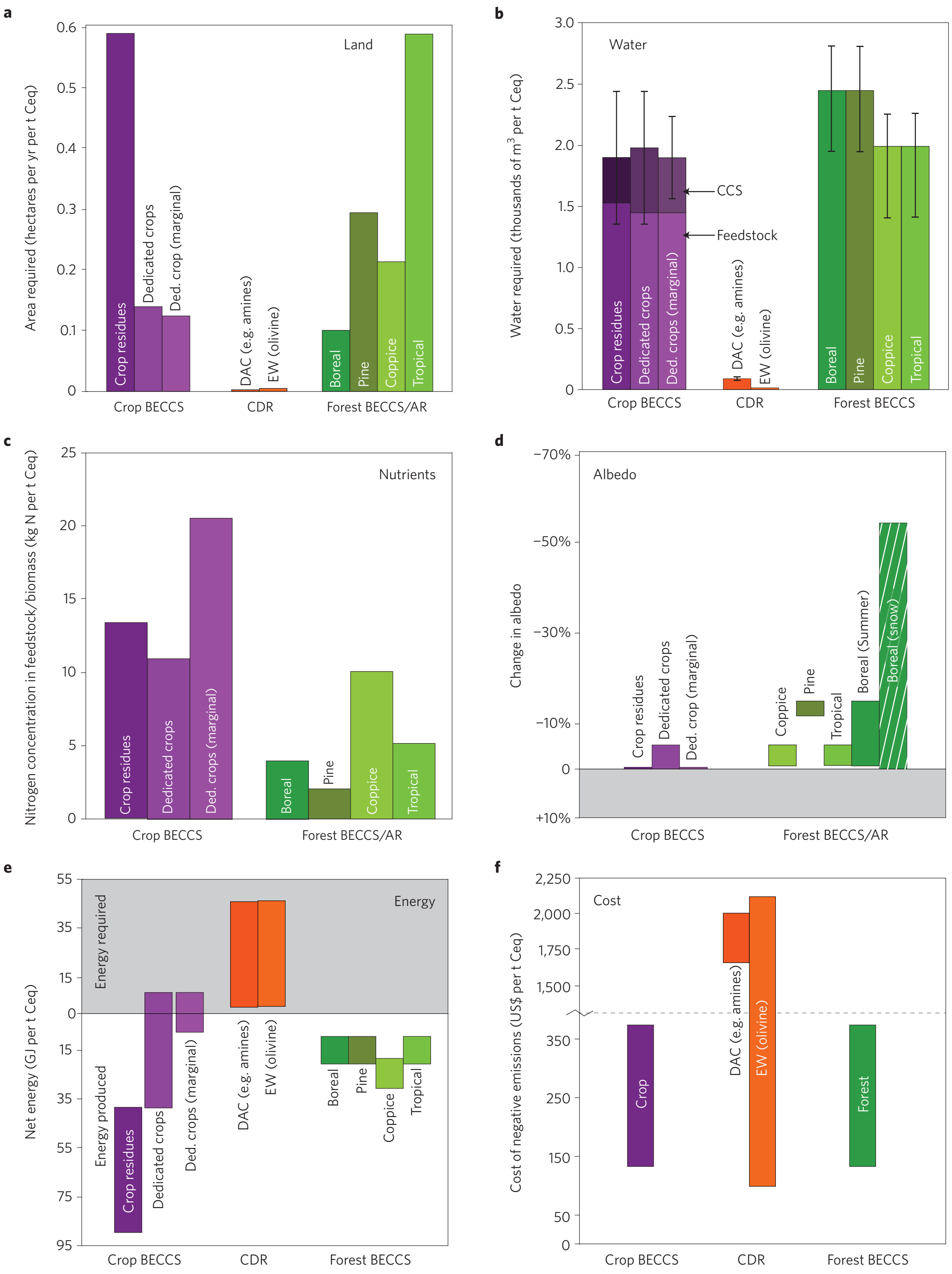

Figure 3 | The different requirements and impacts of NETs. a–f, Negative emissions technologies have different land (**a**), water (**b**) and nutrient (**c**) requirements, different geophysical impacts on climate (for example, albedo; **d**), generate or require different amounts of energy (**e**), and entail different capital and operating costs (**f**). For example, carbon dioxide removal (CDR) technologies such as DAC and EW of silicate rock tend to require much less land and water than strategies that depend on photosynthesis to reduce atmospheric carbon (**a**,**b**), but the CDR technologies demand substantial energy and economic investment per unit of negative emissions (**e**,**f**). Among BECCS options, forest feedstocks tend to require less nitrogen than purpose-grown crops (**c**), but present greater risk of unwanted changes in albedo (**d**), and generate less energy (**e**). AR has been omitted from **b**,**e**,**f** to avoid confusion with forest BECCS (where the CCS component is included). See Supplementary Methods and Table 1 for data sources.

Table 1 | Global impacts of NETs for the average needed global C removals per year in 2100 in 2 °C-consistent scenarios (430–480 ppm scenario category; Supplementary Table 3).

NET	Global C removal (Gt Ceq yr^{-1} in 2100)	Mean (max.) land requirement (Mha in 2100)	Estimated energy requirement (EJ yr^{-1} in 2100)	Mean (max.) water requirement (km^3 yr^{-1} in 2100)	Nutrient impact (kt N yr^{-1} in 2100)	Albedo impact in 2100	Investment needs (BECCS for electricity/ biofuel; US$ yr^{-1} in 2050)
BECCS	3.3	380–700	−170	720	Variable	Variable	138 billion / 123 billion
DAC	3.3	Very low (unless solar PV is used for energy)	156	10–300	None	None	>>BECCS
EW*	0.2 (1.0)	2 (10)	46	0.3 (1.5)	None	None	>BECCS
AR*	1.1 (3.3)	320 (970)	Very low	370 (1,040)	2.2 (16.8)	Negative, or reduced GHG benefit where not negative	<<BECCS

*NETs with lower maximum potential than the BECCS emission requirement of 3.3 Gt Ceq per year in 2100; their mean (and maximum) potential is given along with their impacts (see Supplementary Methods). Wide ranges exist for most impacts, but for simplicity and to allow comparison between NETs (sign and order of magnitude), mean values are presented. See main text and Supplementary Methods for full details. PV, photovoltaic.

removal by EW (including adding carbonate and olivine to both oceans and soils) has been estimated to be as great as 1 Gt Ceq yr^{-1} by 2100, but with mean annual removal an order of magnitude less[68] at 0.2 Gt Ceq yr^{-1}. Combined with the bottom-up, per-t-Ceq impact ranges (Supplementary Methods), we then assess the resource implications, and the extent to which available resources may limit the deployment of NETs globally.

Land area. DAC has a small direct land footprint (Fig. 3a) and can be deployed on unproductive land that supplies few ecosystem services[14], although the land footprint could be considerable if solar pholtovoltaic panels or wind turbines were used to provide the energy required[45]. EW has a larger land footprint if the minerals are applied to the land surface (as opposed to the oceans, or if weathering reactions occur in industrial autoclaves), although crushed olivine or carbonates could be spread on agricultural and forest land to allow the weathering to take place, with the added benefits of raising the pH of acidic soils to make them more productive[15]. Thus, EW technologies may not always compete for land with other uses, despite the large areas involved (for example, the estimated potential of 1 Gt Ceq yr^{-1} removed might require 10 Mha)[15].

Assuming per-area carbon in biomass available for capture as a feedstock for BECCS of widely applicable, high-productivity dedicated energy crops (willow and poplar short rotation coppice (SRC) and *Miscanthus*; 4.7–8.6 t Ceq ha^{-1} yr^{-1}; Supplementary Table 2), BECCS delivering 3.3 Gt Ceq yr^{-1} of negative emissions would require a land area of approximately 380–700 Mha in 2100 (Table 2), with a wider possible range that is determined by productivity (Supplementary Table 2). This emissions removal is equivalent to 21% of total current human appropriated net primary productivity (NPP) (15.6 Gt C yr^{-1} in 2000), or 4% of total global potential NPP[69]. Areas for AR that are calculated assuming a mean carbon uptake over the growth period of 3.4 t Ceq ha^{-1} yr^{-1} (Supplementary Methods; Fig. 3a) give a land area corresponding to 1.1 and 3.3 Gt C yr^{-1} removed in 2100 of ~320 and ~970 Mha, respectively, similar to other estimates[50]. Estimates of land use by BECCS and AR are consistent with the values presented in previous studies[47] for three IAMs (Global Change Assessment Model (GCAM), Integrated Model to Assess the Global Environment (IMAGE) and Regional Model of Investments and Development/Model of Agricultural Production and its Impact on the Environment (ReMIND/MAgPIE)), although other studies suggest larger areas[39]. Without global forest protection, increased bioenergy deployment would increase GHG emissions from land-use change[70].

Total agricultural land area in 2000 was ~4,960 Mha, with an area of arable and permanent crops of ~1,520 Mha[71], so area for BECCS (380–700 Mha) represents 7–25% of agricultural land, and 25–46% of arable plus permanent crop area. AR (at 1.1–3.3 Gt Ceq yr^{-1} negative emissions; 320–970 Mha, respectively) represents 6–20% of total agricultural land, and 21–64% of arable plus permanent crop area. This range of land demands are 2–4 times larger than land identified as abandoned or marginal[72]. Thus, the use of BECCS and AR on large areas of productive land is expected to impact the amount of land available for food or other bioenergy production[12,37,73–75], as well as the delivery of other ecosystem services[12,32,76], which may prove to be a limit to the implementation of BECCS[77] and AR. One uncertainty is the future rate of increase of food crop yields[37,78] and whether this will meet future food demand[79], thereby potentially freeing more cropland for BECCS or AR, even if at a higher price[37].

Water. Increasing global water stress is attributable to rising water demands and reduced supplies, both of which can be exacerbated in some locations by climate change[80]. In particular, the evaporative demand of plants increases with temperature as vapour pressure deficit increases. Evaporative loss can be 20–30 mol H_2O per mol CO_2 absorbed by an amine DAC unit[14,81], giving a water use estimate of ~92 (mean; 73–110) m^3 t^{-1} Ceq (Fig. 3b). Implementation at levels of 3.3 Gt Ceq yr^{-1} in 2100 (Table 1) would therefore be expected to use ~300 km^3 yr^{-1} of water assuming current amine technology, which is 4% of the total current evapotranspiration used for crop cultivation[82]. Sodium hydroxide for DAC, however, uses 3.7 m^3 t^{-1} Ceq (Fig. 3b)[81], so equivalent levels of implementation using sodium hydroxide in place of amines would result in water use of ~10 km^3 yr^{-1}. For EW, with a water use of 1.5 m^3 t^{-1} Ceq (Fig. 3), deployment to remove 0.2 (mean) or 1 (maximum) Gt Ceq yr^{-1} would involve water use of 0.3 and 1.5 km^3, respectively.

Water use for forests is estimated to be 1,765 (1,176–2,353) m^3 t^{-1} Ceq yr^{-1}, which includes both interception and transpiration (Fig. 3b). However, because trees replace other vegetation during AR, the total net impact must be calculated by subtracting the water use of the previous land cover. Assuming a water use similar to short vegetation of 1,450 (900–2,000) m^3 t^{-1} Ceq yr^{-1} before AR (Fig. 3b), the additional water use from AR is estimated to be around 315 m^3 t^{-1} Ceq yr^{-1}, which is 1% of the total evapotranspiration from current forests[82]. For AR delivering capture of 1.1 or 3.3 Gt C yr^{-1} (Table 1), additional water use is thus estimated to be ~370 or 1,040 km^3 yr^{-1}, respectively.

Similar calculations can be made for BECCS. For unirrigated bioenergy, evaporative loss is estimated to be 1,530 (1,176–1,822) m^3 t^{-1} Ceq yr^{-1}, which is 80 m^3 t^{-1} Ceq yr^{-1} more than for average short vegetation (Fig. 3b). Thus, deployment of

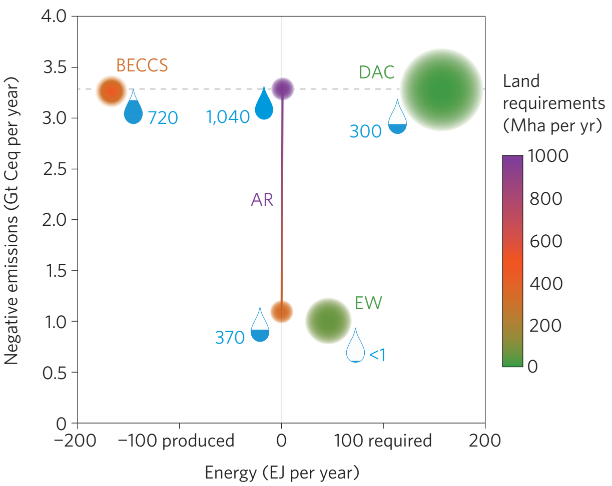

Figure 4 | The impacts and investment requirements of NETs to meet the 2 °C target. A schematic representation of the aggregate impacts of NETs on land, energy and water, and relative investment needs, for levels of implementation equivalent to BECCS (3.3 Gt C yr^{-1} negative emissions in 2100) in scenarios consistent with a 2 °C target (or mean and maximum attainable, where that level of negative emissions cannot be reached). Water requirement is shown as water droplets, with quantities in km^3 yr^{-1}. All values are for the year 2100 except relative costs, which are for 2050 (see Supplementary Methods).

BECCS at 3.3 Gt Ceq yr^{-1} in 2100 would lead to additional water use of ~260 km^3 yr^{-1} from the crop production phase. There is an opportunity cost of using soil moisture for sequestration and/or bioenergy production rather than for growing food. Our estimates for water use are an order of magnitude lower than other recent estimates for bioenergy crops[48] and for AR[50], as water use in those studies were expressed as a total rather than additional water use due to land use change, and those for bioenergy also considered irrigation[48]. Irrigated bioenergy crops were estimated to double agricultural water withdrawals in the absence of explicit water protection policies[48], which could pose a severe threat to freshwater ecosystems, as human water withdrawals are dominated by agriculture and already lead to ecosystem degradation and biodiversity loss. Land requirements for bioenergy crops would greatly increase (by ~40%, mainly from pastures and tropical forests) if irrigated bioenergy production was excluded, meaning that there will be a trade-off between water and land requirements if bioenergy is implemented at large scales[48].

For BECCS, additional water is required for CCS, adding about 450 m^3 t^{-1} Ceq yr^{-1} to the evaporative loss relative to bioenergy alone[14] (Fig. 3b), equivalent to an additional water use of ~720 km^3 yr^{-1} due to BECCS (the sum of additional evaporative loss plus CCS water use), for the 3.3 Gt Ceq yr^{-1} by 2100 level of implementation (Table 1). BECCS would thus require an additional quantity of water equivalent to ~10% of the current evapotranspiration from all cropland areas worldwide[82].

To put these figures in context, total global renewable freshwater supply on land is 110,300 km^3 yr^{-1}, of which humans appropriate 24,980 km^3 yr^{-1} (ref. 83), so the implementation of BECCS at 3.3 Gt Ceq yr^{-1} of negative emissions by 2100 represents an additional use of ~3% of the freshwater currently appropriated for human use. AR implemented at 1.1 Gt Ceq yr^{-1} by 2100 would represent 1–2% of human-appropriated freshwater. Expressing additional water use as a proportion of runoff in a region would provide a more accurate picture of the threat to water resources at a given location — but this is not feasible without a spatially disaggregated analysis. Nevertheless, with human pressures on freshwater increasing[80,84], water use could act as a significant limitation to implementation of high-water-demand NETs such as BECCS.

Energy. Bioenergy currently supplies about 10% of primary energy worldwide[55], that is, an estimated 44.5 EJ yr^{-1}. Of this, 74% comes from fuel wood, 9% from forest and agricultural residues, 8% from recovered wood, 6% from industrial organic residues and 3% from dedicated energy crops[55]. Most of this biomass, however, cannot currently be used for BECCS, as the vast majority is used in small-scale applications; for example, for household cooking and heating in developing countries[55]. BECCS delivering 3.3 Gt Ceq yr^{-1} of negative emissions would deliver ~170 EJ yr^{-1} of primary energy in 2100[10,35,44] (Table 1). Estimates of future energy potential vary greatly; there is high consensus that 100 EJ yr^{-1} could be attained, and a medium level of agreement that 100–300 EJ yr^{-1} could be attained — but there is only low consensus that primary energy above 300 EJ yr^{-1} could be supplied by bioenergy[12,32]. Stabilization scenarios from the IAM literature suggest that bioenergy could supply from 10 to 245 EJ yr^{-1} of global primary energy by 2050[70,87], and deliver a sizable contribution to primary energy in 2100[41].

The energy required by AR is very low (for site preparation only) and is assumed here to be negligible. Other NETs have large energy demands (Fig. 3e). Using our realistic estimate of 46 GJ of energy required per t Ceq removed by EW (Fig. 3), the 0.2–1.0 Gt C yr^{-1} that might be captured (Supplementary Table 2) would entail up to 46 EJ yr^{-1} of energy in 2100 (Table 1). The energy requirements of amine DAC[14] (Fig. 3e) deployed for net removal of ~3.3 Gt Ceq yr^{-1} would amount to a global energy requirement of 156 EJ yr^{-1} if all energy costs are included (Table 1). This is equivalent to 29% of total global energy use in 2013 (540 EJ yr^{-1}), and a significant proportion of total energy demand in 2100 (which the IPCC AR5 scenario database estimates will be~500–1,500 EJ yr^{-1}), which will be a major limitation unless low-GHG energy could be used, or the energy requirements significantly reduced.

Nutrients. DAC has no impact on soil nutrients, and EW may (in some cases) provide beneficial minerals and pH adjustment that are difficult to quantify at the aggregate level. Nutrient concentrations in crop biomass are often higher than in tree biomass (Fig. 3c), but nutrients are removed from cropland and grazing land in agricultural products, whereas AR on agricultural land is likely to increase the retention of nutrients within an ecosystem. However, nutrient limitation could limit productivity, which may limit carbon storage[49]. Nutrients are also removed when bioenergy feedstocks are removed from the site on which they are grown, resulting in the depletion of nutrients relative to land uses where biomass is not removed, but not necessarily at the same level as agricultural land[86]. Bioenergy feedstocks with low nutrient concentrations, such as residue, forest and lignocellulosic biomass, should hence be favoured over feedstocks with higher nutrient concentrations. Assuming the nutrient concentrations of forests are 2.0 to 5.1 kg N t^{-1} Ceq (Fig. 3c), and that most nutrients are removed at harvest for energy and food crops, AR areas of ~320 and 970 Mha (consistent with AR removing 1.1 (mean) and 3.3 (high) Gt Ceq yr^{-1} (Table 1)) would increase global nitrogen retention in biomass by 2.2–5.6 and 6.6–16.8 kt N yr^{-1}, respectively. Scaling values for implementation of 1 Gt Ceq yr^{-1} of negative emissions[50], P and N demand to balance the carbon stored is estimated to be 220–990 kt P yr^{-1} and 100–1,000 kt N yr^{-1} for AR at 1.1–3.3 Gt Ceq yr^{-1} of negative emissions — although it must be noted that these values are absolute, and do not account for the P and N in the vegetation replaced by AR.

Albedo. The effect of DAC and EW on the reflectivity of the Earth's surface is assumed to be small (excluding possible use of solar photovoltaic panels to generate energy for DAC[45]; Fig. 3d). However, the land areas required for BECCS and AR can dramatically affect albedo (Fig. 3d). Because the effect is greatly amplified by the presence of snow, the exact location (latitude and elevation) of the BECCS or AR, and the vegetation it replaces, is critical in assessing the impact on albedo (Fig. 3d). Albedo can significantly reduce[62] or even reverse net radiative forcing from AR at northern latitudes[63]. This observation could limit the value of AR for climate mitigation in northerly regions. For BECCS, the replacement of short vegetation with taller vegetation (for example, *Miscanthus* and SRC), could have similar effects on albedo, although probably less than the impact of AR with coniferous forest (Fig. 3d). Because AR is more likely to occur at high latitudes than production of BECCS feedstocks, BECCS should not have a deleterious impact on albedo. At low to mid latitudes, AR could increase radiative forcing by decreasing albedo; but, without a regional distribution, the scale of these impacts cannot be assessed.

Investment needs. The deployment of NETs (specifically BECCS) in IAM scenarios is an outcome of an optimization of costs over time. The existence of large-scale gross negative emissions even in less-ambitious stabilization pathways indicates that BECCS is selected as a cost-effective component of the energy mix, allowing higher residual emissions elsewhere, which would otherwise be more expensive to abate. Investments in BECCS provide an additional indicator for assessing the scale and speed of BECCS deployment over the next several decades. Supplementary Table 4 summarizes investment estimates from six global integrated assessment models that assessed 2 °C scenarios within the context of the LIMITS model intercomparison[87] for 2030 and 2050: US\$36.2 and 29.4 billion yr^{-1}, respectively, worth of investment is estimated as optimal by 2030 for scaling up biomass electricity and biofuels production technologies worldwide on average. By 2050, these investment levels grow to US\$138.3 and 122.6 billion yr^{-1}, respectively[87]. This represents 5 and 4%, respectively, of the projected total global energy system investments required by 2050 of US\$2,932 (intermodel range: \$1,889–4,338) billion yr^{-1} (ref. 87). Investment needs for DAC, EW and AR are not known, but given the much higher unit costs (per t Ceq) for DAC, and the higher costs of EW and the lower unit costs of AR described above, the investment needs are estimated qualitatively (relative to BECCS; Table 1).

The aggregate impacts of NETs on land, energy and water, and the relative investment needs for levels of implementation equivalent to BECCS in scenarios consistent with a 2 °C target (3.3 Gt Ceq yr^{-1}, or the mean and maximum attainable where that level of negative emissions cannot be reached) described in this section are summarized schematically in Fig. 4.

Discussion

Biophysical, biogeochemical (that is, nutrients), energy and economic resource implications of large-scale implementation of NETs differ significantly. For DAC, costs and energy requirements are currently prohibitive and can be anticipated to slow deployment. Research and development is needed to reduce costs and energy requirements. For EW, the land areas required for spreading and/or burying crushed olivine are large, such that the logistical costs may represent an important barrier, compounded by the fact that the plausible potential for carbon removal is lower than for other NETs. In contrast, AR is relatively inexpensive, but the unintended impacts on radiative forcing through decreased albedo at high latitudes, and increased evapotranspiration increasing the atmospheric water vapour content, could limit effectiveness; likewise, increased water requirements could be an important trade-off, particularly in dry regions. Competition for land is also a potential issue, as it is for BECCS[50,88,89]. BECCS may also be limited by nutrient demand, or by increased water use, particularly if feedstocks are irrigated and when the additional water required for CCS is considered. These biophysical and economic resource implications may directly impose limits on the implementation of NETs in the future, but they may also indirectly constrain NETs by interacting with a number of societal challenges facing humanity in the coming decades, such as food, water and energy security, and thereby sustainable development. In addition to the biophysical and economic limits to NETs considered here, social, educational and institutional barriers, such as public acceptance of and safety concerns about new technologies and related deployment policies, could limit implementation. The drivers, risks, and limitations of the supply of NETs, showing activities thought to increase the potential supply of NETs, as well as the risks and geophysical and societal limits to the potential of NETs, are shown in Supplementary Fig. 1. Commercialization and deployment at larger scales will also allow more to be learnt about these technologies, in order to improve their efficiency and reduce cost.

To inform society of the potential risks and opportunities afforded by all mitigation options available, more research on NETs is clearly required. Although we have collated the best available data on NET impacts and have reflected changes related to deployment scale as accurately as possible, it is clear that common modelling frameworks are required to implement learning, cost, supply and efficiency curves for all NETs. By implementing such curves, future models will be able to develop portfolios of trajectories of NET development, allowing least-cost options to be selected, and learning and efficiency improvements to be reflected. The inconsistency in coverage of NETs and their impacts highlights this key knowledge gap; this analysis will help to frame these developments in the modelling community.

For BECCS, research and development is required to deliver high-efficiency energy conversion and distribution processes for the lowest-impact CCS, and the cost of infrastructure to transport CO_2 from BECCS production areas to storage locations needs to be further evaluated. To this end, early deployment of CCS would enhance understanding of the risks and possible improvements of the technology. Integrated pilot plants need to be built (storing ~1 Mt CO_2 per year) to examine how combined BECCS functions[90]; the capital cost of 5–10 full-size demonstrations of BECCS or CCS would require the investment of approximately US\$5–10 billion[90]. There is also a need to develop socio-economic governance systems for all NETs, to provide incentives to fund this research and development, and implementation of infrastructure in the most sustainable manner, to limit adverse impacts in the transition to low-carbon energy systems, and to manage the risks associated with CCS (such as leakage, seismic action and environmental impacts)[91]. Priorities include investing in renewable and low-carbon technologies, efficiency and the integration of energy systems (to make the most of waste heat, excess electrons from photovoltaic panels and wind, and to close the carbon cycle of fossil sources by capturing and reusing CO_2 by catalysis), and the realization of additional environmental benefits. In the meantime, emission reductions must continue to be the central goal for addressing climate change.

Addressing climate change remains a fundamental challenge for humanity, but there are risks associated with relying heavily on any technology that has adverse impacts on other aspects of regional or planetary sustainability. Although deep and rapid decarbonization may yet allow us to meet the <2 °C climate goal through emissions reduction alone[8], this window of opportunity is rapidly closing[8,92] and so there is likely to be some need for NETs in the future[41,93]. Our analysis indicates that there are numerous resource implications associated with the widespread implementation of NETs that vary between technologies and that need to be satisfactorily addressed before NETs can play a significant role in achieving climate change goals. Although some NETs could offer added environmental benefits (for example, improved soil carbon storage[28]), a heavy reliance on NETs in the future, if used as a means to allow continued use of fossil fuels in the present, is extremely risky, as our ability to stabilize the climate at <2 °C declines as cumulative emissions increase[8,35,92]. A failure of NETs to deliver expected mitigation in the future, due to any combination of biophysical and economic limits examined here, leaves us with no 'plan B'[45]. As this study shows, there is no NET (or combination of NETs) currently available that could be implemented to meet the <2 °C target without significant impact on either land, energy, water, nutrient, albedo or cost, and so 'plan A' must be to immediately and aggressively reduce GHG emissions.

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Author contributions

P.S. led the writing of the paper, with contributions from all authors in the inception of the study and in writing the drafts. P.S. led the analysis with significant contributions from S.J.D., F.C., S.F., J.M., B.G., R.B.J., A.C., E.Kr., D.M. and D.V.V. Figures were conceptualized and produced by S.J.D., J.R., P.C., S.F., P.S., G.P., R.A. and J.M.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.S.

Competing financial interests

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