Supplementary Materials for

Sustainability limits needed for CO_2 removal

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This file includes:

Supplementary Materials for

Sustainability limits needed for CO_2 removal

Supplement S1. Supporting analysis for Fig. 1. Supporting analysis for Figure 1. Sustainability thresholds to land-based carbon dioxide removal (CDR) using bioenergy with carbon capture and storage (BECCS), and afforestation/reforestation and 'Nature-Based' CDR

Supplement S1 includes:

- **METHODS**: for Fig. 1
- **TABLE S1.1** Sustainability thresholds behind Fig. 1
- **FIGURES**
    - Fig. S1.1 Land-based CDR sustainability thresholds: land-footprint and sequestration
    - Fig. S1.2: BECCS – Land footprint sustainability thresholds (million km^2)
    - Fig. S1.3: BECCS – Sequestration sustainability thresholds ($GtCO_2$ yr^{-1})
    - Fig. S1.4: Bioenergy potential and sustainability: energy crops and residues (EJ yr^{-1}).
    - Fig. S1.5: Afforestation/Reforestation – Land footprint sustainability thresholds (million km^2)
    - Fig. S1.6: A/R & Nature-Based CDR – Sequestration sustainability thresholds ($GtCO_2$ yr^{-1})
- **TABLES** S1.2- S1.6, backing-up Figs. S1.2 – S1.6

Methods for Fig. 1

This Supplementary Material describes the development of Fig. 1 in the main manuscript which shows our assessment of sustainability limits to land-based carbon dioxide removal (CDR) using bioenergy with carbon capture and storage (BECCS) & afforestation/reforestation (A/R) and 'Nature Based' CDR) and corresponding risk levels. Fig 1 also shows how these are significantly lower than the CDR technical mitigation potential evaluated in the Intergovernmental Panel on Climate Change's Sixth Assessment Working Group III report (IPCC AR6 WGIII) (*3*).

The IPCC technical mitigation potentials and economic potential are reported in IPCC AR6 WGIII (*3*), Chapter 7 "Agriculture, Forestry, and Other Land Uses (AFOLU)": for BECCS - Chapter 7.4.4; for A/R - Chapter 7.4.2.2; and for other land-based CDR: improved forest management - Chapter 7.4.2.3, agroforestry - Chapter 7.4.3.1. For additional information, see Tables S1.3 and S1.5.

Method

We used the following method to develop our estimates of the sustainability limits (or thresholds – we use these terms interchangeably) and risk levels of sequestration potential ($GtCO_2$ yr^{-1}):

1. We first assessed a precautionary land-footprint threshold (million square kilometers: million km^2) for both bioenergy crops for BECCS and for A/R – based on our analysis of

recent literature and our expert assessment (see below for a description of how we selected the literature assessed) – as well as corresponding land thresholds for medium, high, and very high risk. For further explanation of our selection of land footprints see S1.1, and for a summary of our underlying literature analysis see: Fig. S1.2 (and Table S1.2) for BECCS, and Fig. S1.5 (and Table S1.5) for A/R and 'nature-based' CDR.

   i. For bioenergy crops for BECCS we set a land-footprint sustainability threshold, following the approach in (*6*), and findings in (*6, 7, 16*). The land footprint of bioenergy crops clearly impacts negatively biodiversity integrity (as assessed by (*16*)), as well as risks overstepping other planetary boundaries, including freshwater use and biogeochemical flows, as assessed by (*5*) and (*16*), respectively.
   ii. We also set a land-footprint sustainability threshold for A/R, given: (i) the literature indicates large land-use change implies key ecological and social risk factors (*3, 9, 10*), (ii) for consistency with our approach to BECCS above (especially important given various other differences that complicate comparability).

2. Drawing on our BECCS and A/R land-footprint sustainability thresholds, we estimate the corresponding sequestration levels (GtCO$_2$ yr^{-1}), using conversion factors drawn from the literature (in particular from (*9*) and (*16*), as detailed below).
   BECCS conversion factors are drawn from the high and low carbon capture rates[1] in (*16*), as well as a theoretical medium capture rate we calculate (a mean between the high and low capture rates in (*16*)).

	Heck et al. (*16*) conversion rates: with SSP1 ag baseline					
	High capture rate (B2H2)		Medium capture rate		Low capture rate (B2L)	
GtCO$_2$ yr^{-1}	23.10	1	14.30	1	5.50	1
Million km^2	8.70	0.38	8.70	0.61	8.70	1.58
Million km^2	8.70	1	8.70	1	8.70	1
GtCO$_2$ yr^{-1}	23.10	2.66	14.30	1.64	5.50	0.63

High and low capture rates from Heck et al., 2018 (*16*); medium capture rate calculated by authors

We use these three different conversion rates to reflect that the amount of CO$_2$ sequestration from BECCS derived from a specific amount of bioenergy cropland can vary widely, with carbon capture rate and conversion efficiency to energy carriers being key factors accounting for the variation (*5, 16*). Indeed, "the carbon capture rate and conversion efficiency [to energy carriers] are important parameters and have a large impact on the BECCS potential. For example, with lower capture ratios, the BECCS potential could be reduced to 50% or 75% of current estimates" ((*5*), p. 886). Other non-stationary factors that impact the rate of land to CO$_2$ sequestration include bioenergy

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[1] The high capture rate corresponds to the highly efficient conversion pathway of biomass to hydrogen (B2H2) rates, the low capture rate to the less efficient conversion of biomass to liquid fuel (B2L).

crops yields,[2] land productivity, and land-use prior to bioenergy deployment (*3, 17*). In Fig. 1, we present the sequestration potentials corresponding to the low and medium capture rates, in a precautionary approach that accounts for the fact that obtaining a high capture rate and high efficiency in biomass conversion is optimistic (*5, 16*).[3]
For A/R, we use an averaged conversion rate from the range in (*9*). See Table S1.1 for further details on the calculations.

3. We then make additional adjustments:
    - To estimate the BECCS sustainable sequestration levels, we add to the BECCS sequestration levels from dedicated bioenergy crops, our estimate of sustainable BECCS sequestration potentials from residues (from crops and forestry) (~0.4 $GtCO_2\ yr^{-1}$). This estimate is drawn from our analysis of: (i) the five recent studies (*18-21*)[4] that underpin the IPCC AR6 WGIII's (*3*) estimated 'technical biomass potential' in Chapter 7.4.4, (ii) other recent studies included in our analysis of BECCS land-footprint potential (*22-24*, see further detail below) and also cited by the IPCC AR6 WGIII (*3*). This analysis is detailed in Fig. S1.4 and Table S1.4, which also shows that the studies taking stricter sustainability constraints estimate levels of sustainable biomass (dedicated crops and residues) significantly below the IPCC AR6 WGIII technical biomass potential "constrained by food security and environmental considerations" ((*3*), p. 751).
    - To estimate the 'Nature-Based' CDR[5] sequestration potential sustainability thresholds, we add to the A/R potential 1.3 $GtCO_2\ yr^{-1}$, based on our expert judgement, and in line with the two primary studies we base our analysis on (*9, 10*, see further details below). See Fig. S1.6 and Table S1.6 for further detail on our an

4. We finally compare resulting BECCS, A/R and 'Nature-Based' sequestration potential with our assessment of sustainable potentials listed in recent literature, and adjust for coherence, on the basis of our expert judgement (for BECCS see Fig. S1.3 and Table S1.2; for A/R and Nature-Based CDR see Fig. S1.6, and Table S1.4). To enable comparability across a set of studies that are heterogenous in terms of e.g., the units they

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[2] A recent study (*21*) notes that "expectations on future energy crop yields are intrinsically uncertain and appear as a main contributing factor to vast differences in biomass potential assessments," ((*21*), p.12) finding that extent of sustainable biomass potential from bioenergy crops without expanding agricultural land could be a range of 10-85 EJ by 2050, which remains low as compared to other studies assessed here on bioenergy potential. See Figure S1.4 and Table S1.4 for further detail.
Note too that scenarios typically make optimistic assumptions about increasing agricultural productivity into the future. For example, see: A. Popp, K. Calvin, S. Fujimori, P. Havlik, F. Humpenöder, E. Stehfest, B. L. Bodirsky, J. P. Dietrich, J. C. Doelmann, M. Gusti, T. Hasegawa, P. Kyle, M. Obersteiner, A. Tabeau, K. Takahashi, H. Valin, S. Waldhoff, I. Weindl, M. Wise, E. Kriegler, H. Lotze-Campen, O. Fricko, K. Riahi, D. P. van Vuuren, Land-use futures in the shared socio-economic pathways, *Global Environmental Change* **42**,331-345 (2017).

[3] For further information on our analysis of (*16*), see Table S1.3.

[4] We excluded from our final analysis one of the five references, Hansen et al., as it did not have relevant data for the global estimate of bioenergy from crop residues, which is the topic at hand here. J.H. Hansen, L. Hamelin, A. Taghizadeh-Toosi, J.E. Olesen, and H. Wenzel, Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways. *GCB Bioenergy,* **12,** 1002–1013 (2020).

[5] We define 'Nature-Based' CDR here as: limited reforestation; forest restoration; reduced forest harvest; agroforestry; silvopasture – drawing from (*9, 10*).

take (GtC, GtCO2, or EJ for BECCS), we harmonize the units via calculations: any conversion calculations we make are noted in the Figures and Tables.

Our land-based CDR sustainability thresholds are initial estimates for this article. They could be further developed and improved through a more extensive and detailed assessment, such as in the context of the sustainable CDR budget we call for in the main manuscript, building on previous calls to 'right-size' CDR (e.g., *5, 6, 9, 25*). While soil carbon sequestration is sometimes deemed 'nature-based' CDR, we have chosen to exclude it from our present analysis develop more precise estimates of realistic and sustainable soil carbon sequestration, which we have chosen to exclude it from our present analysis given the lack of permanence of carbon storage (*9*), and additional complexity and challenges (including assessing "achievable rates" (*9*)).

Selection of literature to assess the sustainability thresholds of BECCS, A/R and 'Nature-Based' CDR

Our assessment focuses on recent academic papers and reports (since 2018) that explicitly look at 'stricter' sustainability criteria of BECCS, A/R and 'Nature-Based' CDR, namely taking an approach on sustainability risk. Some of these studies (e.g., *1, 5, 6, 16*) integrate or primarily frame their analysis through the planetary boundaries framework, which allows assessing risk of overstepping multiple planetary boundaries (e.g., biodiversity intactness, biogeochemical flows, biosphere integrity, freshwater use, sustainable boundary for permanent cropland). Very few papers assess 'strict' sustainability thresholds for land-based CDR approaches. Hence, we consider that our assessment, while intending to be illustrative for the purpose of encouraging a larger research agenda, is exhaustive in terms of its inclusion of recent literature that provides an assessment of sustainability levels.

Our assessment of the sustainability thresholds of BECCS is primarily based on an analysis of a selection of studies that examine in further detail the ecological, biophysical, and societal impacts and feasibility of BECCS deployment, namely using the planetary boundaries framework: (*1, 5, 6, 16*), as well as the Scientific outcome of the IPCC-IPBES co-sponsored workshop on biodiversity and climate change (*22*). We assess these studies in comparison to key underpinning literature of the IPCC AR6 WGIII Report's Chapter 7 (on AFOLU), Section 7.4.4 on 'Bioenergy and BECCS.' Specifically, we reviewed the recent studies (*18-21*)[6] (from 2018 onward) that Section 7.4.4 cites to advance the "estimates of technical biomass potentials constrained by food security and environmental considerations" ((*3*), p. 802) and those studies (*18, 23, 26, 27*)[7] that Section 7.4.4 uses to estimate the "technical net CDR potential of BECCS

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[6] We excluded from our final analysis one of the five references IPCC AR6 WGIII Section 7.4.4 cites on "estimates of technical biomass potentials constrained by food security and environmental considerations"–Hansen et al., (2020)– as it does not have relevant data for the global estimate of bioenergy from crop residues. J.H. Hansen, L. Hamelin, A. Taghizadeh-Toosi, J.E. Olesen, and H. Wenzel, Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways. *GCB Bioenergy*, **12,** 1002–1013 (2020).

[7] We excluded from our analysis one of the studies IPCC AR6 WGIII Section 7.4.4 uses to estimate the "technical net CDR potential of BECCS […] by 2050"–Cowie et al., (2021)–as it does not provide estimates of BECCS potential. A.L. Cowie, G. Berndes, N. S. Bentsen, M. Brandão, F. Cherubini, G. Egnell, B. George, L. Gustavsson, M. Hanewinkel, Z. M. Harris, F. Johnsson, H. M. Junginger, K. L. Kline, K. Koponen, J. Koppejan, F. Kraxner, P. Lamers, S. Majer, E. Marland, G. J. Nabuurs, L. Pelkmans, R. Sathre, M. Schaub, C. T. Smith, S. Soimakallio, F.

[…] by 2050” ((*3*), p. 802). To this selection of studies we also added (*17*), which is cited across Section 7.4.4 namely on bioenergy and BECCS’ co-benefits and adverse effects, and uncertainties, as well as (*24*), cited in (*17*) on sustainability implications of large-scale bioenergy deployment (with specific examples of land amounts), and (*28*), cited in (*17*) on types of bioenergy feedstocks and specifically residues (from crops and forestry). We draw from each of these studies their evaluation of bioenergy and BECCS sustainability: in terms of land footprint (million km^2) in Fig. S1.2 (with further details in Table S1.2), and sequestration ($GtCO_2$ yr^{-1}) in Fig. S1.3 (with further details in Table S1.3).

For A/R and Nature-Based CDR, we assessed a review (*9*) of 33 studies estimating ‘Nature-Based’ CDR potential, and a study (*10*) of the potential of five ecosystem-restoration based CDR measures (limited reforestation; forest restoration; reduced forest harvest; agroforestry; silvopasture). We also looked at two studies extensively cited and highly prominent across the IPCC AR6 WGIII (*3*) land-based CDR assessments (Chapter 7): a review (*23*) of the costs, potentials, and side effects across CDR measures including BECCS and A/R, and a review (*27*) of the potential of 20 land-based mitigation and CDR measures which examines side-by-side the potential from sectoral estimates in the literature, and the potential in integrated assessment models. We draw from each of these studies their evaluation of A/R and/or Nature-Based CDR potential: in terms of land footprint (million km^2) in Fig. S1.5 (with further details in Table S1.5), and sequestration ($GtCO_2$ yr^{-1}) in Fig. S1.6 (with further details in Table S1.6).

For the food security implications of large-scale BECCS and A/R, we draw from the Summary for Policymakers of the IPCC Special Report on Climate Change and Land (*29*).

Note on terms: sustainability risk, thresholds, and sustainable potential

The primary studies that we used for our CDR sustainability thresholds assessment (i.e., *1, 5, 9, 10*, *16*) all include as part of their analysis an evaluation of relatively strict sustainability risk, trade-offs, and/or constraints. This is a common denominator of the studies even though they vary in the approaches taken (e.g., planetary boundaries framework (*5, 16*)), and the sustainability criteria included (see Figures S1.2, S1.3, S1.5, S1.6 and Tables S1.2, S1.3, S1.5, S1.6 for a more extensive overview). Each of these studies bases their assessment of sustainability risk on either reviews of the literature (*1, 6, 9*), their own modeling (*5, 10, 16*) to provide estimates of ‘sustainable’ CDR potentials. We present these estimates of ‘sustainable’ CDR potentials in Figures S1.2, S1.3, S1.5, S1.6 for readers’ visual reference (and also under quantified form in Tables S1.2, S1.3, S1.5, S1.6). Our sustainability thresholds assessment is an evaluation of risk, not ‘feasibility’ per se – we primarily extract from the underlying literature sustainability risk, rather than their specific evaluations of feasibility.

We then compared our levels sustainability risk to the levels of cost, feasibility ‘concerns’, sustainability constraints and technical limits as evaluated by the IPCC, which are a very heterogeneous set of types of limits. Key questions we seek to ask with this include: how do different levels of mitigation potential identified by the IPCC correspond to different levels of risk for sustainability? So, for example, what are the implications for sustainability of deploying

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Van Der Hilst, J. Woods, F. A. Ximenes, Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy*, **13** (8), 1210–1231 (2021).

all the potential that can be done for less than \$100? Deploying all the potential with low feasibility concern? Deploying all within the upper limit of technical potential?

Assessing a ‘sustainable CDR potential’ is beyond the scope of this specific paper, but it is what we call for in a broader research agenda, and the development of a ‘sustainable CDR budget’.

TABLE S1.1 Sustainability thresholds behind Figure 1, for BECCS (panel (a)) and for afforestation/reforestation (A/R) and ‘Nature Based’ CDR (panel (b)). The table quantifies the sustainability thresholds presented visually in Fig. 1 of the main manuscript. Panels (a) and (b) below provide further detail for our process to reach the specific land footprint risk threshold numbers, which, as detailed in the methods section and in the main manuscript, are estimates, and to be well understood need to be placed in the context of the broader method described in S1 ‘Methods’; and visually presented in Figures S1.2, S1.3, S1.5, S1.6 (with more detailed information of underlying literature presented in Tables S1.2, S1.3, S1.5, S1.6) As such, and as described in Fig. 1, the transitions between risk levels are more gradual than indicated by the color changes.

Panel (a): Sustainability thresholds for BECCS (in bold boxes – the thresholds detailed in Fig. 1)

			Risk level						
			Low		Medium		High		Very high
Land footprint – bioenergy crops		Million km^2	**0**	**0.5**	**0.5**	**1.5**	**1.5**	**4.5**	**> 4.5**
Sequestration	LOW capture rate (1 million km^2= 0.6 GtCO$_2$ yr^{-1})	GtCO$_2$ yr^{-1}	0	0.3	0.3	1	1	2.9	> 2.9
	LOW capture rate + 0.4 GtCO$_2$ yr^{-1} residues		**0**	**0.7**	**0.7**	**1.4**	**1.4**	**3.3**	**> 3.3**
	MEDIUM capture rate (1 million km^2= 1.7 GtCO$_2$ yr^{-1})		0	0.8	0.8	2.5	2.5	7.4	> 7.4
	MEDIUM capture rate + 0.4 GtCO$_2$ yr^{-1} residues		**0**	**1.2**	**1.2**	**2.9**	**2.9**	**7.8**	**> 7.8**
	HIGH capture rate (1 million km^2= 2.7 GtCO$_2$ yr^{-1})		0	1.4	1.4	4.1	4.1	12.2	> 12.2
	HIGH capture rate + 0.4 GtCO$_2$ yr^{-1} residues		0	1.8	1.8	4.5	4.5	12.6	> 12.6

BECCS carbon capture rates based on Heck et al., 2018 (*16*)

‘Land footprint’ bioenergy crops sustainability risk thresholds:

- The ‘low’ sustainability risk threshold land footprint level is set at 0.5 million km^2 – the current estimated bioenergy land area (*6*). This is based on the analysis in (*6*) that to respect planetary boundaries and avoid greater risk, the bioenergy crop footprint should be kept at this ‘precautionary sustainability threshold’ level. This also reflects the findings of two other studies we assess, which conclude that when respecting planetary boundaries, available land for bioenergy is extremely limited (*16*), or already surpassed (*1*). Dooley et al. (*1*) note that: "the area of global cropland has already reached sustainability thresholds [c.f. the ‘planetary boundary for permanent cropland’ assessed by Springmann et al. 2018, Willet et al. 2019], indicating there is no available land for energy crop or monoculture plantation expansion" ((*1*), p. 26).[8]

- The 'medium' sustainability risk threshold is set at 1.5 million km^2: the mean between: 1 million km^2, assessed by (*21*) as the maximum bioenergy land with no grazing intensification; and 1.9 million km^2, assessed by (*5*) as land conversion area implied by the 'maximum sustainable BECCS potential' considering water stress, biodiversity loss and competition with food production.
- The 'high' sustainability threshold (4.5 million km^2) is an evaluation based on the authors' expert judgement, informed by the risks detailed in the underlying literature we base our overall assessment on (in particular, *1*, *5*, *6*, *16*). As detailed in the main manuscript, we call for a clear consideration by future research of risk, to further improve the quantification of these risk levels.

Panel (b): Sustainability thresholds for afforestation/reforestation (A/R) and 'Nature-Based' CDR

Afforestation/Reforestation (A/R) and 'Nature-Based' CDR			Risk						
			Low		Medium		High		Very high
Land footprint – (A/R)		Million km^2	0	1	1	3	3	5	> 5
Sequestration	**A/R**	$GtCO_2$ yr^{-1}	0	1.3	1.3	3.8	3.8	6.3	> 6.3
	'Nature-Based' CDR A/R + 1.3 $GtCO_2$ yr^{-1}		0	2.6	2.6	5.1	5.1	7.6	> 7.6

Sequestration rate based on Nolan et al.,2021 (*9*): 1 million km^2 =1.3 $GtCO_2$ yr^{-1}

A/R footprint sustainability risk thresholds:

- The thresholds are estimations, informed by the underlying literature, including (*1*) which finds: "local knowledge is needed to better assess suitable areas for restoration. Further work has been developed by FAO on mapping tree restoration potential to assist countries in identifying areas that are suitable for restoration (FAO and UNEP, 2020) and in developing guidelines to incorporate biodiversity into landscape restoration (Beatty et al., 2018). Overall, the area suitable for expanding forest cover is uncertain and depends on principles of ecology and human rights" ((*1*), p. 26).[9]

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[8] The two assessments are: W. Willett, J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L. J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J. A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S. E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, C. J. L. Murray, "Food in the Anthropocene: the EATLancet Commission on healthy diets from sustainable food systems," (The Lancet, 393(10170), 2019); https://doi.org/10.1016/S0140-6736(18)31788-4; and M. Springmann, M. Clark, D. Mason-D'Croz, K. Wiebe, B. Leon Bodirksy, L. Lassaletta, W. De Vries, S. J. Vermeulen, M. Herrero, K. M. Carlson, M. Jonell, M. Troell, F. DeClerck, L. J. Gordon, R. Zurayk, P. Scarborough, M. Rayner, B. Loken, J. Fanzo, H. C. J. Godfray, D. Tilman, J. Rockström, W. Willett, Options for keeping the food system within environmental limits. *Nature*, **562**(7728), 519-525 (2018).

[9] "The state of the world's forests: forests, biodiversity and people" (FAO and UNEP, 2020); available at: https://doi.org/10.4060/ ca8642en

- The ‘low’ sustainability risk A/R threshold land footprint is set at 1 million km^2 based on the imperative to limit land-use change to minimize risk (*1*, *9*, *10*).
- The ‘medium’ sustainability risk threshold is set at 3 million km^2 by the authors’ expert judgement, based on an analysis of the sustainability constraints assessed by the underlying literature (*1*, *9*, *10*). This range is further bolstered by the IPCC AR7 WGIII Report (*3*) on the impact on food security of bioenergy land-use: “The land area that could be used for bioenergy or other land-based mitigation options with low to moderate risks to food security depends on patterns of socio-economic development, reaching limits between 1 and 4 million km^2 (Hurlbert et al. 2019; IPCC 2019a; Smith et al. 2019c)” ((*3*), Chapter 12, p. 1302).[10]
- The ‘high’ sustainability threshold (5 million km^2) is an evaluation based on the authors’ expert judgement, informed by the risks detailed in the underlying literature we base our overall assessment on (in particular, *1*, *9*, *10*). As detailed in the main manuscript, we call for a clear consideration by future research of risk, in order to better to quantify these levels of risk.
- See Figure S1.5 and Table S1.5 for an overview of the literature that informed the assessment of these thresholds.

C. Beatty, N. A. Cox, M. Kuzee, “Biodiversity guidelines for forest landscape restoration opportunities assessments (1st ed.)” (International Union for Conservation of Nature (IUCN) 2018).

[10] **‘Hurlbert et al. 2019’:** M. Hurlbert, J. Krishnaswamy, E. Davin, F.X. Johnson, C.F. Mena, J. Morton, S. Myeong, D. Viner, K. Warner, A. Wreford, S. Zakieldeen, Z. Zommers, 2019: Risk Management and Decision Making in Relation to Sustainable Development. In: “Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems,” P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, Eds. (2019); https://doi.org/10.1017/9781009157988.001

‘IPCC 2019a’: “Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems,” P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, Eds. (2019); https://doi.org/10.1017/9781009157988.001

‘Smith et al. 2019c’: P. Smith, J. Nkem, K. Calvin, D. Campbell, F. Cherubini, G. Grassi, V. Korotkov, A.L. Hoang, S. Lwasa, P. McElwee, E. Nkonya, N. Saigusa, J.-F. Soussana, M.A. Taboada, 2019b: Interlinkages between Desertification, Land Degradation, Food Security and GHG fluxes: Synergies, Trade-offs and Integrated Response Options. In: “Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems,” P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, Eds. (2019); https://doi.org/10.1017/9781009157988.001

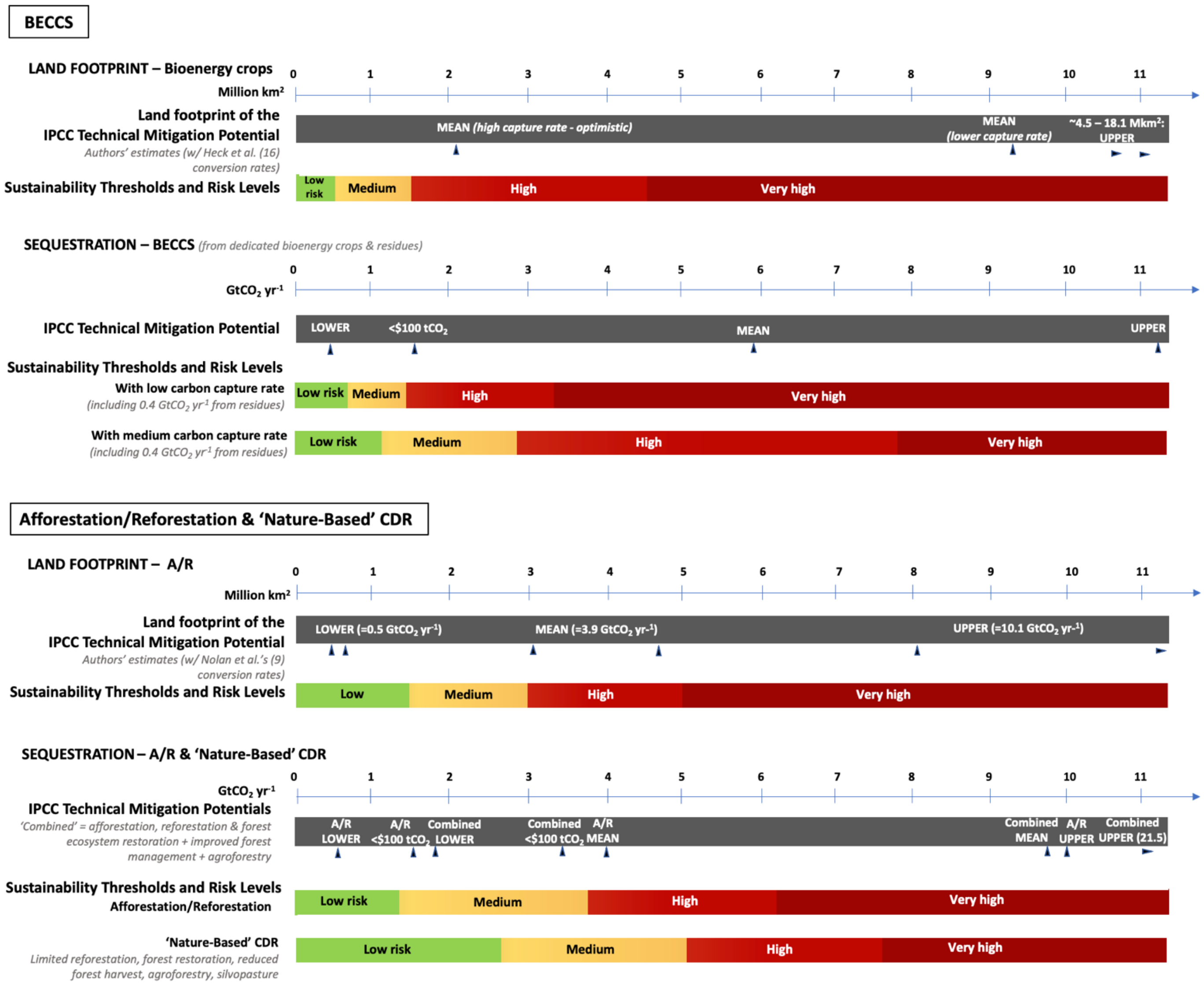

Figure S1.1. Land-based CDR sustainability thresholds: land footprint and sequestration. The figure depicts that sustainability thresholds of BECCS, A/R and 'Nature-Based' CDR (calculated by authors based on precautionary land footprints and recent literature) are significantly below the technical potential assessed in the IPCC AR6 WGIII Report (*3*). Triangles represent key values. For further detail on the analysis underlying Fig. S1.1, see Figs. S1.2 – S1.6 and Tables S1.2 – S1.6.

IPCC upper technical potential (**11.3 Gt CO_2 yr-1**) ~ **4.5 – 18.1 million km² bioenergy crops**

"Unless there are large future efficiency gains in agriculture and/or available areas are identified that will have no impact on biodiversity and food security[...] **land used for bioenergy should not exceed the current amount of land used for bioenergy, about 0.5 million km²** ("**precautionary threshold value**"), to avoid adding pressure on land use" ((*6*), p. 513).

"**With the regional safe constraint** [i.e., adhering to regional planetary boundaries], **almost no biomass plantations can be implemented**" ((*16*), p. 152).

Dooley et al. argue: "the area of global cropland has already reached sustainability thresholds [c.f. Springmann et al. 2018, Willet et al. 2019], **indicating there is no available land for energy crop or monoculture plantation expansion**" ((*1*), p. 26).

"**Large energy crop potentials are not readily and unconditionally available.** They are conditional on intensification and considerable changes in global land-use patterns" ((*21*), p. 15).

133 EJ yr^{-1} = +180% land use change emissions, +49% unsustainable water usage, +16% fertiliser use, ~7.7–9.4 million km² bioenergy crops (3.1 million km² w/ high conversion rates).

300 EJ yr^{-1} (on **6.7 million km²**, with optimistic high capture rate) = +437% land use change emissions, +34% nitrogen losses, +142% unsustainable water use +28% food prices.

Figure S1.2. BECCS – Land footprint sustainability thresholds (million km²). The figure depicts the bioenergy land footprint sustainability thresholds – assessed by authors based on recent literature and expert judgement – alongside the BECCS technical mitigation potential from the IPCC AR6 WGIII report (gray bar), and the current global agricultural cropland land footprint. The figure shows that the land footprint sustainability thresholds for BECCS are well below the mean technical mitigation potential assessed by the IPCC, considering that the planetary boundaries for sustainable permanent cropland are already overstepped (*1*). Triangles represent key values. **Total current agricultural cropland:** calculated from FAOSTAT, cited in (*1*);[11] current bioenergy crops are ~ 0.5 million km² (*6*). The 'planetary boundary for permanent cropland' is based on two assessments on sustainable global cropland boundary level cited in

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[11] "Land, Input and Sustainability," (FAOSTAT, 2022, updated 2022-07-15); available at: https://www.fao.org/faostat/ en/#data/RL

(*1*).[12] **IPCC technical mitigation potential**: The land footprint of the IPCC technical mitigation potential is estimated by authors, using Heck et al.'s (*16*) conversion rates with low and high carbon capture rates (see Table S1.2 for further details). **BECCS land footprint sustainability thresholds**: Sustainability thresholds are assessed by authors based on precautionary land footprint thresholds (including a 'precautionary sustainability threshold' set at 0.5 million km^2) and underlying literature (*1, 5, 6, 16*) (see Table S1.1 for underlying numbers). **Recent studies informing in the sustainability thresholds assessment:** Color gradient bars illustrate the land footprint sustainability assumed in each study, as reflected by key values and argumentation in the studies. The studies in green examine more strongly ecological and biophysical boundaries, and societal impacts and feasibility; as such, they are the studies that most strongly inform our sustainability threshold assessment. For further detail on the analysis underlying Fig. S1.2, see Table S1.2.

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[12] W. Willett, J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L. J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J. A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S. E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, C. J. L. Murray, "Food in the Anthropocene: the EATLancet Commission on healthy diets from sustainable food systems," (The Lancet, 393(10170), 2019); https://doi.org/10.1016/S0140-6736(18)31788-4 ;
M. Springmann, M. Clark, D. Mason-D'Croz, K. Wiebe, B. Leon Bodirksy, L. Lassaletta, W. De Vries, S. J. Vermeulen, M. Herrero, K. M. Carlson, M. Jonell, M. Troell, F. DeClerck, L. J. Gordon, R. Zurayk, P. Scarborough, M. Rayner, B. Loken, J. Fanzo, H. C. J. Godfray, D. Tilman, J. Rockström, W. Willett, Options for keeping the food system within environmental limits. *Nature*, **562**(7728), 519-525 (2018).

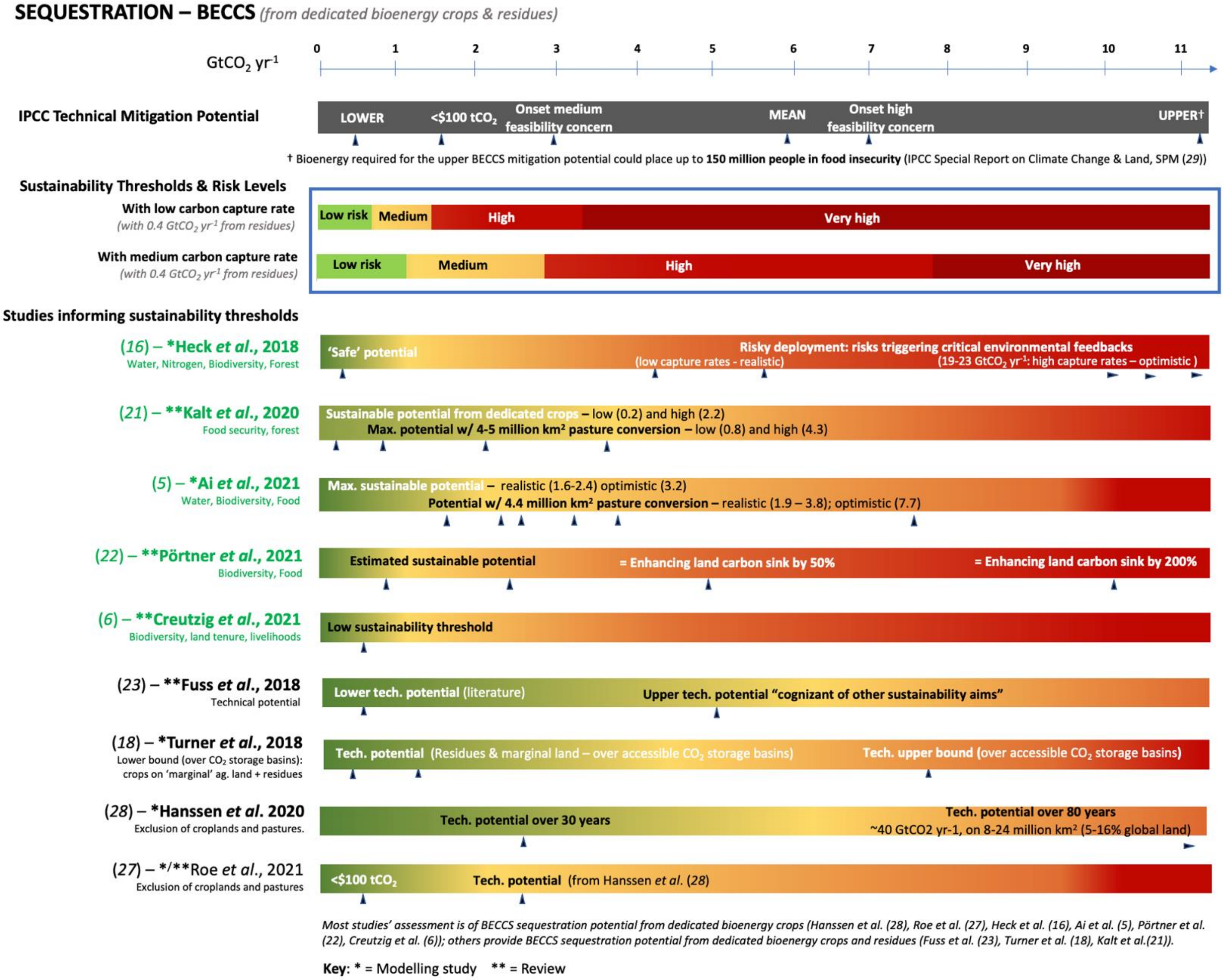

Figure S1.3: BECCS – Sequestration sustainability thresholds (GtCO2 yr^{-1}). The figure presents the BECCS sequestration sustainability thresholds – assessed by authors based the precautionary land footprint thresholds and recent literature (listed in the figure) – alongside the IPCC technical mitigation potential. The figures shows that the sustainable thresholds for BECCS are at the lowest end of the IPCC technical mitigation potential. Triangles represent key values. **IPCC technical mitigation potential:** Reported in IPCC AR6 WGIII (*3*) (Chapter 7 – Section 7.4.4); BECCS 'onset of medium and high technological feasibility concern' reported in IPCC AR6 WGIII – Annex III – "Scenarios and Modelling Methods"). **BECCS sequestration sustainability thresholds**: BECCS sustainability thresholds include 0.4 GtCO$_2$ yr^{-1} from residues, which authors assess as a sustainable amount, based on the literature and expert judgement. The two sets of BECCS sustainability thresholds are to account for the variation in carbon sequestration, which depends importantly on the carbon capture rate and conversion efficiency (*5*) (other factors of BECCS sustainability include evolving bioenergy crops' yield and land productivity (*17*, *3*) (see Table S1.1 for underlying numbers). **Recent studies informing the sustainability thresholds assessment:** Studies in green examine more strongly ecological and biophysical boundaries, and societal impacts and feasibility; as such, they are the studies that most strongly inform our sustainability threshold assessment. The study bars' color gradient illustrates the land footprint sustainability assumed in each study, as reflected by key values and argumentation in the studies. Most studies assessed BECCS sequestration potential from dedicated bioenergy crops, and some from bioenergy crops and residues (see note below Fig. S1.3); studies also differ on whether they are based on a literature review, and/or on modelling. For further detail on the overarching analysis underlying Fig. S1.3, see Table S1.3; for further information specifically on bioenergy potential from bioenergy crops and from residues see Fig. S1.4 and Table S1.4.

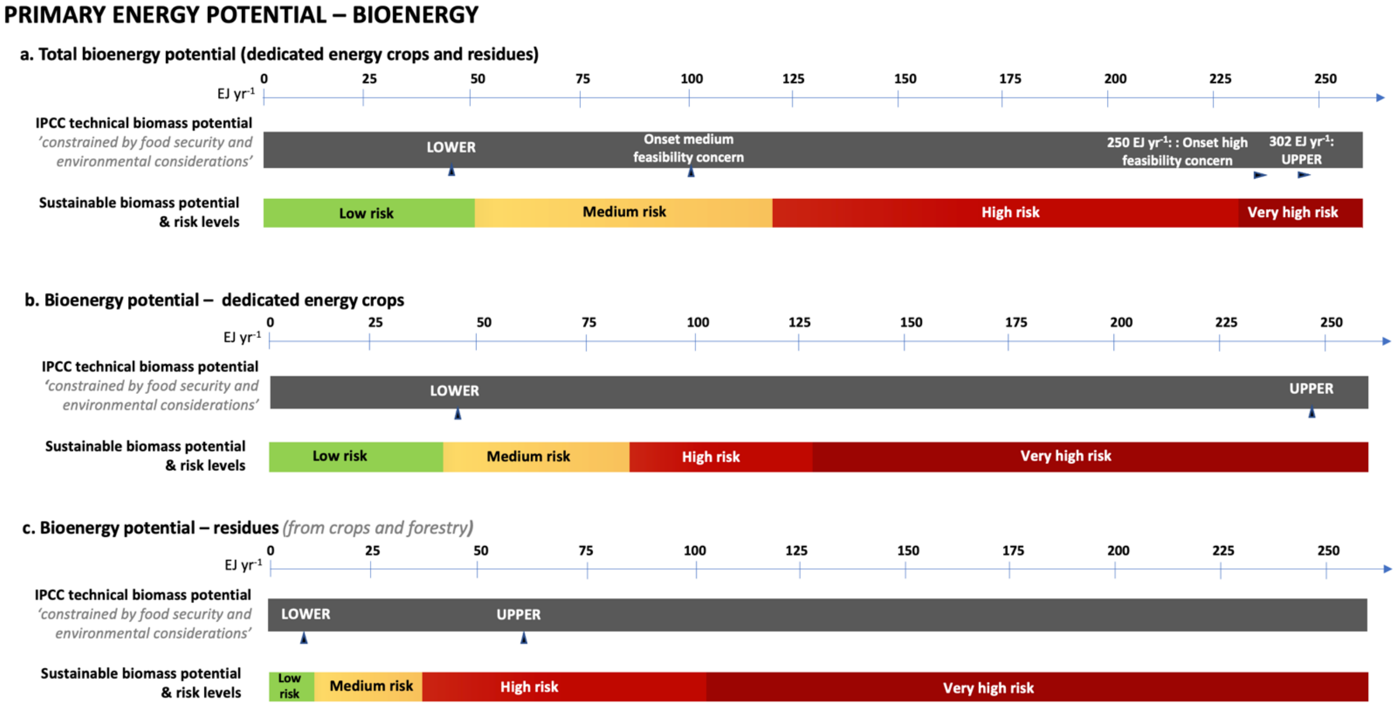

Figure S1.4. Bioenergy energy potential and sustainability: energy crops and residues (EJ yr^{-1}). The figure compares the IPCC AR6 WGIII technical biomass primary energy potential "constrained by food security and environment considerations" ((*3*), Chapter 7, p. 802), and sustainable potentials. Sustainable potentials are assessed by authors based on an analysis of studies that take 'strong' sustainability constraints, across a series of studies cited in IPCC AR6 WGIII Report (*3*) Section 7.4.4, including some underpinning the Report's assessment of technical biomass potentials ((*3*), p. 802). Fig. S1.4 shows that the sustainable biomass potential levels (from dedicated crops and residues) are significantly lower than the IPCC technical biomass potential. Panel (a) assesses the total bioenergy potential from dedicated energy crops and residues; panel (b) and (c) break this down into bioenergy potential from dedicated crops, and from residues (from crops and forestry), respectively. Note that biomass waste (municipal and industrial) could increase sustainable bioenergy potential (although current waste-to-energy energy supply remains minimal: 2.59 EJ yr^{-1}),[13] and that sustainable bioenergy potentials also depend on various non-stationary factor such as crop yield (which are accounted for in several underlying studies, most prominently by (*21*)). For further information on the underpinning analysis and full list of sources, see Table S1.4.

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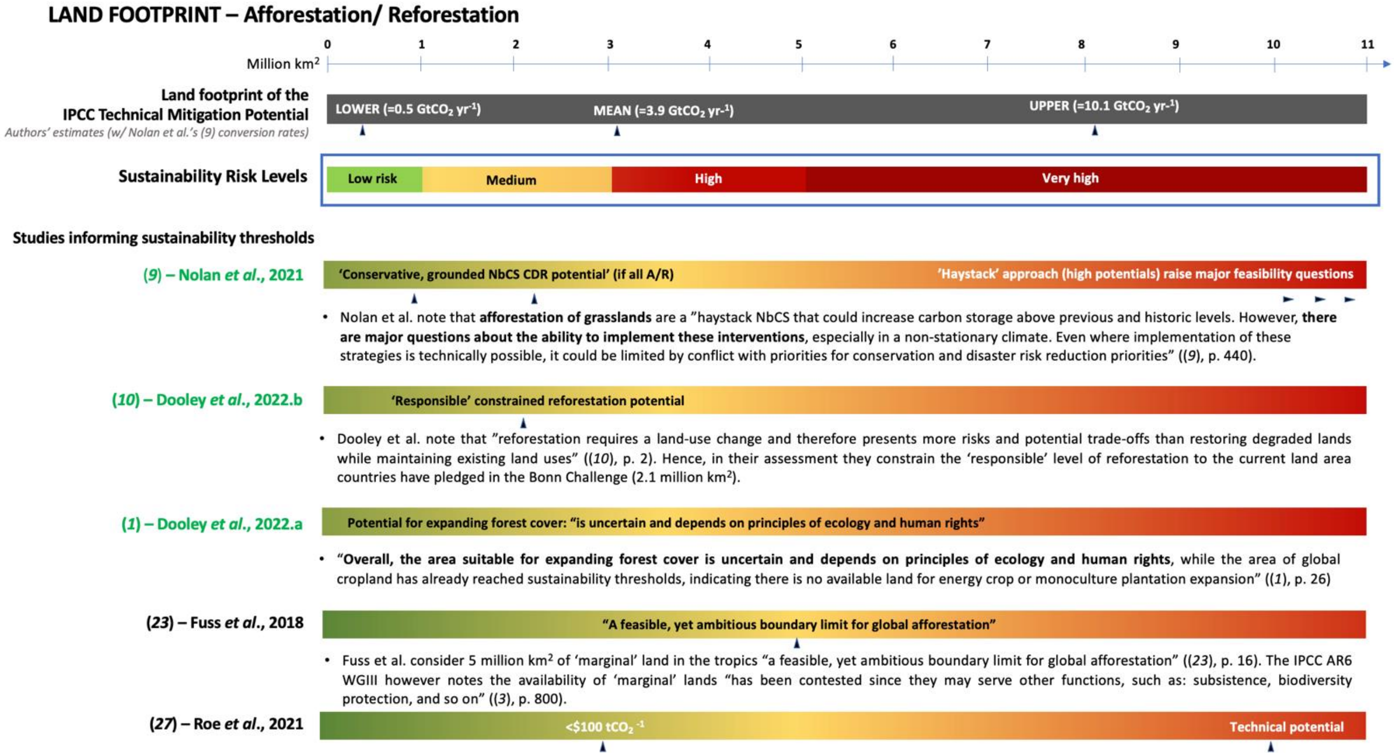
[13] World Bioenergy Association, "Global Bioenergy Statistics 2021," (December 14, 2021); https://www.worldbioenergy.org/news/640/47/Global-Bioenergy-Statistics-2021/



- Nolan et al. note that **afforestation of grasslands** are a "haystack NbCS that could increase carbon storage above previous and historic levels. However, **there are major questions about the ability to implement these interventions**, especially in a non-stationary climate. Even where implementation of these strategies is technically possible, it could be limited by conflict with priorities for conservation and disaster risk reduction priorities" ((*9*), p. 440).

- Dooley et al. note that "reforestation requires a land-use change and therefore presents more risks and potential trade-offs than restoring degraded lands while maintaining existing land uses" ((*10*), p. 2). Hence, in their assessment they constrain the 'responsible' level of reforestation to the current land area countries have pledged in the Bonn Challenge (2.1 million km^2).

- "**Overall, the area suitable for expanding forest cover is uncertain and depends on principles of ecology and human rights**, while the area of global cropland has already reached sustainability thresholds, indicating there is no available land for energy crop or monoculture plantation expansion" ((*1*), p. 26)

- Fuss et al. consider 5 million km^2 of 'marginal' land in the tropics "a feasible, yet ambitious boundary limit for global afforestation" ((*23*), p. 16). The IPCC AR6 WGIII however notes the availability of 'marginal' lands "has been contested since they may serve other functions, such as: subsistence, biodiversity protection, and so on" ((*3*), p. 800).

Figure S1.5. Afforestation/Reforestation – Land footprint sustainability thresholds (million km^2). The figure depicts the afforestation/reforestation (A/R) land footprint sustainability thresholds alongside the A/R technical mitigation potential from the IPCC AR6 WGIII report (gray bar), and illustrates that the sustainability thresholds of A/R are at the lowest end of the IPCC technical mitigation potential. **IPCC technical mitigation potential**: The land footprint of the IPCC technical mitigation potential (IPCC AR6 WGIII, Section 7.4.2.2) is estimated by authors, using Nolan et al.'s *(9)* conversion rates[14] (see Table S1.5 for further details). **A/R land footprint sustainability thresholds**: Sustainability thresholds are assessed by authors based on precautionary land footprint thresholds (considering the need to limit land-use change to minimize risk) and underlying literature (*1, 9, 10*), and specifically informed from the assessment of sustainable bounded reforestation found by (*10*) (see Table S1.1 for underlying numbers). **Recent studies informing the sustainability thresholds assessment:** Color gradient bars illustrate the land footprint sustainability assumed in each study, as reflected by key values and argumentation in the studies. The studies in green they examine in greater depth ecological and biophysical boundaries, and societal impacts and feasibility; as such, they are the studies that most strongly inform the authors' sustainability threshold assessment. For further detail on the analysis underlying Fig. S1.5, see Table S1.5.

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[14] The study (*9*) notes: "removing 1 GtCO2 per year via afforestation or reforestation would need 70–90 Mha, roughly twice the size of California." From this we derive a mean A/R conversion rate of 1 $GtCO_2$ = 80 million ha, and 1 million ha = 1.25 $GtCO_2$.

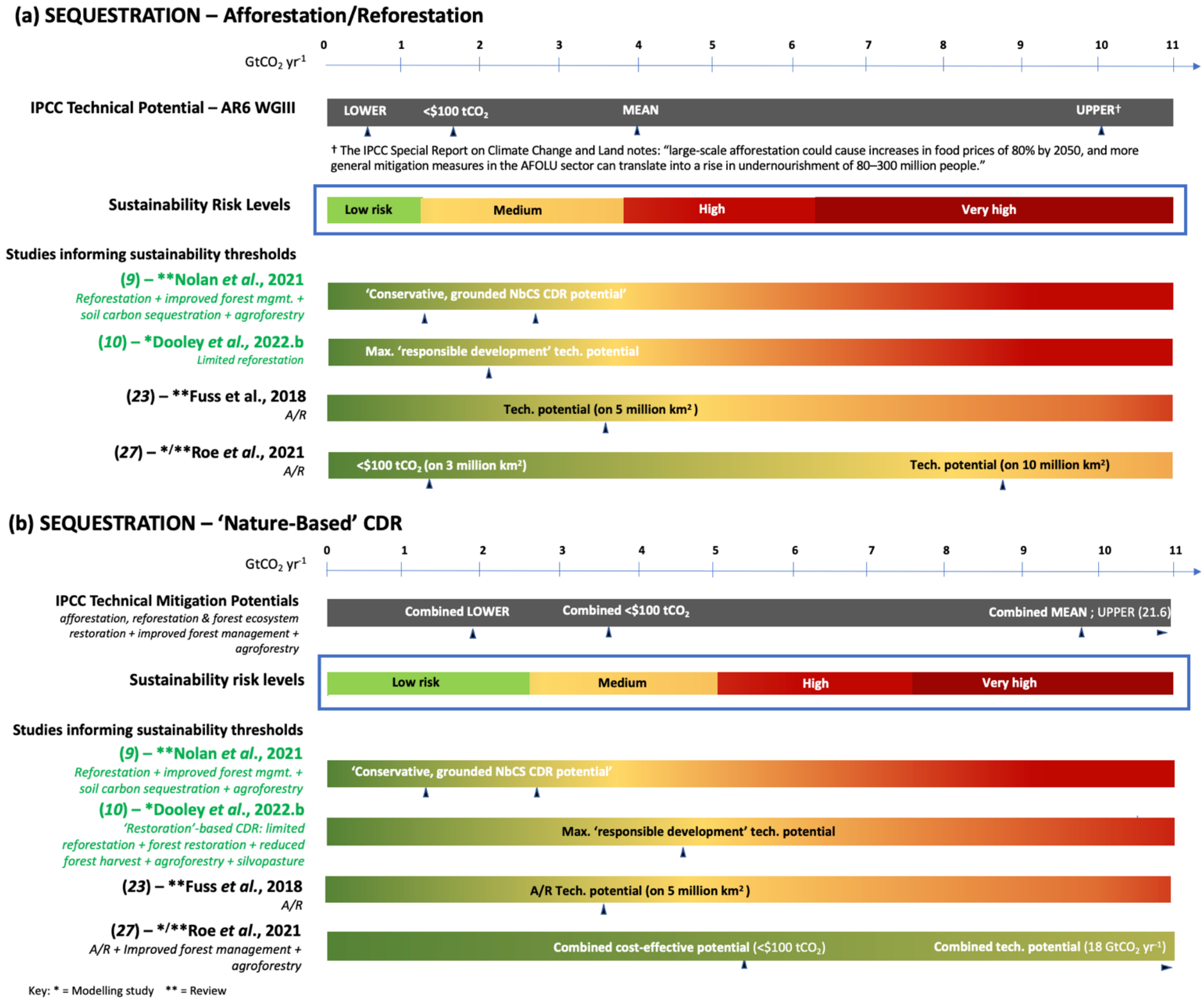
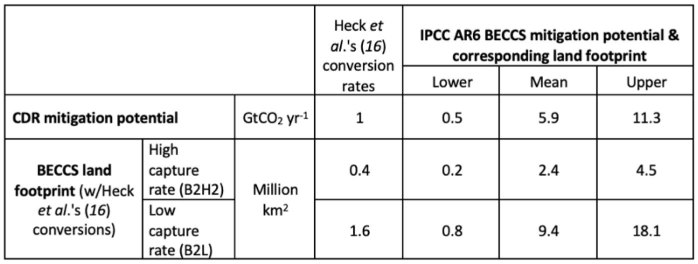


Figure S1.6. A/R & Nature-Based CDR – Sequestration sustainability thresholds (GtCO$_2$ yr^{-1}). The figure presents the sequestration sustainability thresholds of A/R and 'Nature-Based' CDR, alongside the IPCC technical mitigation potentials. The figures shows that the sustainable thresholds for A/R and 'Nature-Based' CDR are at the lowest end of the IPCC technical mitigation potentials. Triangles represent key values. Fig. S1.6 separates out the sustainability thresholds of A/R and Nature-Based CDR for two reasons: (i) to be able to apply the sustainability thresholds to assess the CDR in the mitigation pathways of IPCC AR6, where A/R is one of the most used CDR methods (while 'Nature-Based' CDR does not appear); (ii) to clearly distinguish between A/R and 'Nature-Based' CDR, which in our definition includes only limited reforestation, given the significant social and ecological risks of large-scale land-use change. **Panel (a): IPCC A/R technical mitigation potential:** The data comes from IPCC AR6 WGIII ((*3*), Chapter 7, Section 7.4.2.2). **A/R sequestration sustainability thresholds**: Sustainability thresholds are assessed by authors based on the levels found in precautionary land footprint thresholds (considering the need to limit land-use change to minimize risk) and underlying literature (*1*, *9*, *10*), and specifically informed from the assessment of sustainable bounded reforestation found by (*10*) (see Table S1.1 for underlying numbers). **Panel (b): IPCC**

technical mitigation potentials: This adds up the IPCC AR6 WGIII (*3*) technical mitigation potentials for afforestation, reforestation and forest ecosystem restoration (Section 7.4.2.2); improved forest management (Section 7.4.2.3); and agroforestry (Section 7.4.3.3). **'Nature-Based' CDR sequestration sustainability thresholds**: Sustainability thresholds are assessed by authors based on precautionary land footprint thresholds (considering the need to limit land-use change to minimize risk) and recent literature, and specifically informed from the assessment of sustainable bounded reforestation found by (*10*), and a review (*9*) of 33 'Nature-Based' CDR studies. **Recent studies informing the sustainability thresholds assessment:** Studies in green examine more strongly ecological and biophysical boundaries, and societal impacts and feasibility; as such, they are the studies that most strongly inform the authors' sustainability threshold assessment. The asterisks show whether the studies are based on a literature review, and/or on modelling. The study bars' color gradient illustrates the land footprint sustainability assumed in each study, as reflected by key values and argumentation in the studies. For further detail on the overarching analysis underlying Fig. S1.6, see Table S1.6.

Table S1.2: BECCS/Bioenergy – Land footprint sustainability thresholds (million km^2). The table details – for each study included in Fig. S1.2 – the key values listed, and its arguments on sustainability thresholds of bioenergy and/or BECCS.

<table>
<tr><th colspan="3">BECCS/Bioenergy – Land footprint sustainability thresholds (million km^2)</th></tr>
<tr>
<td>(<i>3</i>) – IPCC AR6 WGIII, 2022</td>
<td>2.4 – 9.4 million km^2
Median BECCS tech. potential
0.2 – 0.8 million km^2
Lower end BECCS tech. potential
4.5 – 18.1 million km^2
Upper end BECCS tech. potential</td>
<td>• IPCC BECCS Technical mitigation potential: 5.9 (0.5 – 11.3) Gt GtCO$_2$ yr^{-1} (Ch. 7.4.4). Applying Heck et al.'s (<i>16</i>) capture rates: high (B2H2) and lower (B2L) (assuming a SSP1 agricultural baseline), results in the following bioenergy land-footprint estimates. Note that Ai et al. (<i>5</i>) mention that a high capture rate is optimistic.

<table>
<tr><th colspan="3"></th><th>Heck <i>et al.</i>'s (<i>16</i>) conversion rates</th><th colspan="3">IPCC AR6 BECCS mitigation potential & corresponding land footprint</th></tr>
<tr><th colspan="3"></th><th></th><th>Lower</th><th>Mean</th><th>Upper</th></tr>
<tr><td colspan="2">CDR mitigation potential</td><td>GtCO$_2$ yr^{-1}</td><td>1</td><td>0.5</td><td>5.9</td><td>11.3</td></tr>
<tr><td rowspan="2">BECCS land footprint (w/Heck <i>et al.</i>'s (<i>16</i>) conversions)</td><td>High capture rate (B2H2)</td><td rowspan="2">Million km^2</td><td>0.4</td><td>0.2</td><td>2.4</td><td>4.5</td></tr>
<tr><td>Low capture rate (B2L)</td><td>1.6</td><td>0.8</td><td>9.4</td><td>18.1</td></tr>
</table>
• IPCC AR6 WGIII Chapter 7 states: "Bioenergy and BECCS can be associated with a range of co-benefits and adverse side effects (Smith et al. 2016; Jia et al. 2019; Calvin et al. 2021) (Section 12.5). It is difficult to disentangle bioenergy development from the overall development in the AFOLU sector given its multiple interactions with food, land, and energy systems. It is therefore not possible to precisely determine the scale of bioenergy and BECCS deployment at which negative impacts outweigh benefits"(Ch. 7.4.4), ((<i>3</i>), p. 800). Nevertheless, several studies here do in fact provide – if not an exact number – estimates of sustainability bioenergy thresholds, considering current and future global agricultural cropland and the need for unprecedented large-scale protection of natural ecosystems to redress the anthropogenic 6th mass extinction.</td>
</tr>
<tr>
<td>(<i>16</i>) – Heck et al., 2018
Biomass-based negative emissions difficult to reconcile with planetary boundaries</td>
<td>~0 million km^2
("Almost no biomass plantations") 'Safe' bioenergy amount
7.8 -8.7 million km^2
'Risky' bioenergy amount explored</td>
<td>Bioenergy plantations for BECCS:
• 'Safe' bioenergy amount (not overstepping regional planetary boundaries): "Under the 'regional safe' optimization scenario (i.e. "maximization of global biomass harvest (H) given fixed regional boundary constraints of biosphere integrity (B), land system change (L), nitrogen flows (N) and freshwater use (W)") "land-use expansion for bioenergy is allowed where regional environmental limits according to the planetary boundary concept are not transgressed in the agricultural baseline and until they are reached" ((<i>16</i>), 'Methods'). "Even though regional environmental limits are being considered, allocation of additional biomass plantations adds to the transgression of boundaries at the global scale. [...] With the regional safe constraint, almost no biomass plantations can be implemented" ((<i>16</i>), p. 152).
• 'Risky' level of bioenergy plantations: Heck et al. also explore a scenario of extensive bioenergy plantations on 7.8 to 8.7 million km^2, resulting in a "transgression of regionally safe environmental limits up to the upper end of the regional uncertainty zones" ((<i>16</i>), p. 152). Heck et al. caution this is a "riskier strategy that discards the precautionary principle and could trigger critical environmental feedbacks to the Earth system" ((<i>16</i>), p. 152).</td>
</tr>
<tr>
<td>(<i>21</i>) – Kalt et al., 2020
Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different foodsystem pathways</td>
<td>0.6 – 1 million km^2
Bioenergy w/no grazing intensification
2.4 – 3.1 million km^2
W/ selective intensification
4 – 4.9 million km^2
W/ universal intensification</td>
<td>Land available for bioenergy crops:
• No grazing intensification: 0.6 – 1 million km^2
• Grazing intensification on highly productive sites: 2.4 – 3.1 million km^2
• Universal grazing intensification: 4 – 4.9 million km^2: "Large energy crop potentials are not readily and unconditionally available. They are conditional on intensification and considerable changes in global land-use patterns [...] 4.9 million km^2 of agricultural land [would] need to be diverted to energy crop production to mobilize the maximum potential of 85 EJ/yr" ((<i>21</i>), p. 15).</td>
</tr>
</table>

<table>
<tr><th colspan="3">BECCS/Bioenergy – Land footprint sustainability thresholds (million km^2) (continued)</th></tr>
<tr>
<td>(<i>6</i>) – Creutzig et al., 2021
Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments</td>
<td>0.5 million km^2
"Precautionary threshold value" for bioenergy</td>
<td>Land available for bioenergy crops:
• 'Sustainable threshold' for dedicated bioenergy crops: "Unless there are large future efficiency gains in agriculture and/or available areas are identified that will have no impact on biodiversity and food security, we assume that land used for bioenergy should not exceed the current amount of land used for bioenergy, about 0.5 million km^2 (“precautionary threshold value”), to avoid adding pressure on land use" ((<i>6</i>), p. 513).
• "Higher bioenergy potentials would be possible only if global livestock systems are restructured, which would raise difficult implementation issues" ((<i>6</i>), p. 512).</td>
</tr>
<tr>
<td>(<i>5</i>) – Ai et al., 2021
Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation</td>
<td>1.9 million km^2
"Maximum sustainable BECCS potential"
4.4 million km^2
w/ pastureland conversion</td>
<td>Bioenergy plantations for BECCS:
• Maximum sustainable BECCS potential: The scenario that Ai et al. consider being the "maximum BECCS potential with strict consideration of water and land sustainability that would not lead to additional water stress, biodiversity loss or competition with food production" ((<i>5</i>), p. 887) implies bioenergy plantations on 1.9 million km^2.
• Ai et al. also explore a scenario with 4.4 million km^2 of pastureland converted to bioenergy crops.</td>
</tr>
<tr>
<td>(<i>1</i>) – Dooley et el., 2022
The Land Gap Report</td>
<td>~ 0.5 million km^2
"We cannot expand global cropland further if we wish to stay within a safe boundary for land-use change "</td>
<td>Planetary boundary for permanent cropland:
• Food production in 2050: 10.5 – 21.1 million km^2 (12.6 million km^2 in 2010).
• "Threshold for sustainable global cropland use" ((<i>1</i>), p. 24): 13 million km^2 (range: 11 – 15 million km^2) (Willet et al., 2019)
• "Sustainable boundary level of global cropland use" (Springmann et al., 2018, in (<i>1</i>), p. 24) : 12.6 million km^2 (range 10.6 – 14.6 million km^2)
Dooley et al. conclude:
• "With cropland in 2022 reported by the FAO to be 1 561 million ha (FAOSTAT, 2020), this implies that we cannot expand global cropland further if we wish to stay within a safe boundary for land-use change (Steffen et al., 2015; Campbell et al., 2017). [...] Expansion of cropland in the global South poses risks to indigenous peoples and local communities who may face encroachment on their land (especially from large-scale, commercial agriculture or feedlots), as well as biodiversity risks. A business-as-usual scenario for cropland suggests expansion of 89 million ha onto vital biodiversity hotspots towards 2050 (Molotoks et al., 2018)" ((<i>1</i>), p. 24).
• "the area of global cropland has already reached sustainability thresholds, indicating there is no available land for energy crop or monoculture plantation expansion" ((<i>1</i>), p. 26).</td>
</tr>
<tr>
<td>(<i>24</i>) – Humpenöder et al., 2018
Large-scale bioenergy production: how to resolve sustainability trade-offs?</td>
<td>3.1 million km^2
Max. bioenergy potential w/ "sustainability criteria"
(= 133 EJ yr^{-1})
7.7 – 9.4 million km^2
Amount of land for 133 EJ yr^{-1} bioenergy (w/ using Kalt et al.'s conversion rates)</td>
<td>• Maximum global potential to grow bioenergy crops, "if sustainability criteria are considered": Humpenöder et al. find this is 133 EJ yr^{-1}, which requires 3.1 million km^2. "If sustainability criteria are considered, the maximum global potential to grow dedicated bioenergy crops is estimated 133 EJ yr^{-1} in 2050 on average, based on three studies with completely different methods (intensification of grazing areas, constraints on land and water resources in a dynamic global vegetation model, study with an IAM considering constraints such as soil degradation and water scarcity)" ((<i>24</i>), p. 11). However, Kalt et al. (<i>21</i>) find that 85 EJ yr^{-1} is the maximum when expanding bioenergy onto 4-5 million km^{2}of grazing land.
• Humpenöder et al.'s sustainability criteria are less stringent than other studies (e.g., Heck et al., Creutzig et al., Ai et al.). While Humpenöder et al. argue 133 EJ yr^{-1} to be the maximum global potential of bioenergy crops when accounting for sustainability criteria, they find that this scale of bioenergy demand "causes a rise in nitrogen losses due to increased fertilizer use (+16%) and water use above [environmental flow, i.e., unsustainable water withdrawal] (+49%), besides higher [land use change] emissions (+180%)" ((<i>24</i>), p. 5).
• Humpenöder et al. also appear to use very optimistic conversion rate of bioenergy crop land area required to get a specific amount of EJ; using Kalt et al.'s conversion rates, the amount of land required more than doubles or triples.
<table>
<tr><th colspan="2" rowspan="3"></th><th colspan="3">Bioenergy land footprint</th></tr>
<tr><th rowspan="2">Humpenöder <i>et al.</i>’s (<i>24</i>) conversion rate</th><th colspan="2">Kalt <i>et al.</i>’s (<i>21</i>) conversion rate</th></tr>
<tr><th>High</th><th>Low</th></tr>
<tr><td>Energy</td><td>EJ yr^{-1}</td><td colspan="3">133</td></tr>
<tr><td>Bioenergy land footprint</td><td>Million km^2</td><td>3.1</td><td>7.7</td><td>9.4</td></tr>
</table>
</td>
</tr>
</table>

BECCS/Bioenergy – Land footprint sustainability thresholds (million km^2) (continued)		
Continued (*24*) – Humpenöder et al., 2018 **Large-scale bioenergy production: how to resolve sustainability trade-offs?**		• **Method and critique:** Humpenöder et al. take as a starting assumption that "large-scale 2nd generation bioenergy deployment is a key element of 1.5ºC and 2ºC transformation pathways" ((*24*), p. 1) and hence base their analysis on a linear increase in bioenergy demand from 0 EJ in 2010 to 300 EJ in 2100, with the aim to "analyze the upper end of environmental and social implications bioenergy crop production may entail" ((*24*), p. 2). Humpenöder et al.'s analysis does not assess how bioenergy demand can be reduced, e.g., via reducing energy demand and increasing non-biomass renewable energy, as illustrate the three AR6 WGIII SPM Illustrative Mitigation Pathways (IMP) that reach 1.5ºC with limited to no overshoot (category C1), in which primary energy from bioenergy in 2100 is only 69, 107 and 100 EJ yr^{-1} (for IMP-LD, IMP-SP and IMP-REN, respectively). In contrast, IMP-Neg, (C22; 1.5ºC w/ high overshoot) in 2100 primary energy from bioenergy reaches 406 EJ yr^{-1}, with total energy demand in 2100 three times higher than in IMP-LD and IMP-SP.
(*27*) – Roe et al., 2021 **Land-based measures to mitigate climate change: Potential and feasibility by country**	**7.4 million km^2** BECCS tech. potential **1.6 million km^2** BECCS economic potential	**Bioenergy plantations for BECCS (literature review of sectoral studies)** • **Economic potential**: 0.5 GtCO$_2$ yr^{-1}, requiring bioenergy crops on **1.6 million km^2** • **Technical potential**: 2.5 GtCO$_2$ yr^{-1}, requiring bioenergy crops on **7.4 million km^2**
(*17*) – Calvin et al., 2021 **Bioenergy for climate change mitigation: Scale and sustainability**	"It is not possible to quantify the amount of biomass that can be produced sustainably"	**Sustainable bioenergy:** • Calvin et al. state: "Global modelling studies show that large-scale deployment of energy crops is associated with trade-offs and risks for adverse side effects, where the extent of negative consequences depends on the socioeconomic context (Hurlbert et al., 2019) and specific land use scenario. For example, Humpenöder et al. (2018) showed limited effects on sustainability with 6.7 million km^2 of bioenergy plantations in scenarios with low population and less resource-intensive food demand. In a similar scenario, Heck et al. (2018) found significant pressure on land and water resources if the area with monoculture plantations providing biomass solely for bioenergy exceeded 8.7 million km^2. There can also be food security impacts due to increasing food prices if food and feed crops are diverted to biofuel production, or lands previously used for food crops are used for energy crops" ((*17*), p. 1353). • While Calvin et al. note "Humpenöder et al. (2018) showed limited effects on sustainability with 6.7 million km^2 of bioenergy plantations" Humpenöder et al. (*24*) in fact state that bioenergy crops at this scale (300 EJ yr-1 on 6.7 Mkm2) "adverse side effects of bioenergy crop production further increase" ((*24*), p. 5) with use change emissions +437%, nitrogen losses +34%, unsustainable water use +142%, and food prices 28% higher than in 2010. • Calvin et al. also argue: "Given the uncertainties in the area of unused and degraded land and the future requirement of land for food production, the current lack of comprehensive global studies that investigate the potential to integrate biomass production with agriculture and forestry, and other factors, it is not possible to quantify the amount of biomass that can be produced sustainably" ((*17*), p. 1354). However, our analysis shows that in fact various detailed studies do provide – if not an exact number – estimates of sustainability bioenergy thresholds, considering current and future global agricultural cropland and the need for unprecedented large-scale protection of natural ecosystems to redress the anthropogenic 6th mass extinction.

Table S1.3: BECCS – Sequestration sustainability thresholds (GtCO$_2$ yr^{-1}). The table details – for each study included in Fig. S1.3 – key values, overview of the method, key arguments on sustainability thresholds of BECCS, and inclusion in the IPCC AR6 WGIII (*3*).

<table>
<tr><th colspan="3">BECCS Sustainability Thresholds – GtCO$_2$ yr^{-1}</th></tr>
<tr>
<td>**(*3*) – IPCC AR6 WGIII Report, 2022**</td>
<td>**5.9 (0.5 – 11.3)** GtCO$_2$ yr^{-1} Tech. potential
1.6 – 1.8 GtCO$_2$ yr^{-1} Eco. potential
3; 7 GtCO$_2$ yr^{-1} Onset tech. feasibility concern (medium; high)</td>
<td>**1. BECCS**
• **Technical BECCS mitigation potential*** : 5.9 (0.5 – 11.3) GtCO$_2$ yr^{-1} (Ch. 7.4.4)
• **Economic potential of BECCS* (up to USD100 per GtCO2 yr-1) :** 1.6 (0.5 – 3.5) GtCO$_2$ yr^{-1}, drawing from sectoral studies; 1.8 (0.2–9.9) GtCO$_2$ yr^{-1}derived from Integrated Assessment Models (IAMs) (Ch. 7.4.4)
• **Onset of feasibility concerns– technological feasibility of BECCS scale-up*:** Onset of medium concern: 3 GtCO$_2$ yr^{-1}; onset of high concern: 7 GtCO$_2$ yr^{-1} (Annex III - Scenarios and Modelling Methods)
• **CDR potential "when applying constraints reflecting sustainability concerns":** 0.5 to 5 GtCO$_2$eq yr^{-1} – this is a single data-point from (Fuss et al., 2018 (*23*))
***Feedstock**: Presumably from dedicated crops and residues (given underlying studies), even though does not specify explicitly. The IPCC only explicitly mentions dedicated crops vs. residues in its assessment of technical biomass potential.</td>
</tr>
<tr>
<td>**(*16*) – Heck et al., 2018**
Biomass-based negative emissions difficult to reconcile with planetary boundaries</td>
<td>**< 0.4** GtCO$_2$ yr^{-1}: Safe BECCS potential (adherence to regional planetary boundaries)
'Risky' BECCS potential (on 7.8 to 8.7 M km2):
4.4 - 5.5 GtCO$_2$ yr^{-1} (lower capture rate -B2L)
19.8 - 23.1 GtCO$_2$ yr^{-1} (high capture rate B2H2)</td>
<td>**1. BECCS sustainability thresholds and potentials**
• **'Safe' BECCS potential:** While ensuring adherence to 'regional planetary boundaries' (i.e., amount of remaining forest cover, biodiversity intactness index (BII), environmental flow requirements and imposed nitrogen fertilization limits): <0.37 GtCO$_2$ yr^{-1} (converted from <0.1 GtC yr^{-1}).
• **'Risky' BECCS potential resulting from "transgression of regionally safe environmental limits up to the upper end of the regional uncertainty zones"** ((*16*), p. 152)**:** Heck et al. caution this is a "riskier strategy that discards the precautionary principle and could trigger critical environmental feedbacks to the Earth system" ((*16*), p. 152), requiring extensive bioenergy plantations (on 7.8 to 8.7 million km^2):
<table>
<tr><th rowspan="2">Agricultural baselines</th><th rowspan="2">Bioenergy crop plantations</th><th colspan="2">CDR potential based on</th></tr>
<tr><th>Lower capture rate (B2L)</th><th>High capture rate (B2H2)</th></tr>
<tr><td>SSP2</td><td>7.8 million km^2</td><td>4.4 GtCO$_2$ yr^{-1}</td><td>19.8 GtCO$_2$ yr^{-1}</td></tr>
<tr><td>SSP1</td><td>8.7 million km^2</td><td>5.5 GtCO$_2$ yr^{-1}</td><td>23.1 GtCO$_2$ yr^{-1}</td></tr>
</table>
Conclusions: "socio-economic pathways requiring substantial BECCS bear the risk of triggering potentially irreversible changes in the Earth system through extensive land-use change, water use, alteration of biogeochemical flows and compromising biosphere integrity. [...] relying on BECCS as a key decarbonization strategy should be considered highly risky" ((*16*), p. 153).
2.Methods and further details
Feedstock: Dedicated 2nd generation biomass plantations: lignocellulosic herbaceous (Miscanthus/switchgrass) and woody crops (willows/poplars and eucalyptus); **Sustainability constraints:** Regional planetary boundaries for biosphere integrity, biogeochemical flows, land-system change and freshwater use; **Methods:** Heck et al.'s assessment is based on a "multi-objective optimization model for the spatial allocation of biomass plantations [...] the optimization is driven by constraints and objectives according to global and regional representations of the planetary boundaries" ((*16*), ' Methods').; **Caveat on optimistic outcomes:** "All simulated NE [negative emissions = CDR] potentials are to be considered rather optimistic because they imply implementation of large-scale modern irrigation and fertilization management of second-generation biomass plantations" ((*16*), p. 153).; **Capture rates:** "To obtain NE and bioenergy potentials we consider two alternative conversion pathways: biomass conversion to hydrogen (B2H2) with high capture rates (90%) and conversion efficiencies (55%), and conversion to liquid fuels (B2L) with lower capture rates (48%) and efficiencies (41%)" ((*16*), p. 151).</td>
</tr>
</table>

BECCS Sustainability Thresholds – GtCO2 yr-1 (continued)		
Continued – (*16*) Heck et al., 2018 **Biomass-based negative emissions difficult to reconcile with planetary boundaries**		**3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII does not cite Heck et al.'s sustainable BECCS potentials, nor cite it in main section on BECCS and bioenergy (7.4.4).** Heck et al. are cited in chapter 4: "Large-scale BECCS may push planetary boundaries for freshwater use, exacerbate land-system change, significantly alter biosphere integrity and biogeochemical flows (Heck et al. 2018; Fuhrman et al. 2020; Stenzel et al. 2021; Ai et al. 2021)" (Section 4.2.5.3) ((*3*), p. 438), and in more general terms in chapter 6, and chapter 12: bioenergy production "may raise conflicts with SDGs relevant to environmental and societal priorities" (Section 6.4.2.6) ((*3*), p. 645); "A/R and biomass production for BECCS and biochar potentially compete for land, water and other resources, implying possible adverse outcomes for ecosystem health, biodiversity, livelihoods and food security" (Section 12.3.2))" ((*3*), p. 1274); "larger scale and higher expansion rate [of biomass-based systems] generally translates into higher risk for negative outcomes such as competition for scarce land, freshwater and phosphorous resources, displacement of natural ecosystems, and diminishing capacity of agroecosystems to support biodiversity and essential ecosystem services, especially if produced without sustainable land management and in inappropriate contexts" (Section 12.5.3))" ((*3*), p. 1299).
(*21*) – Kalt et al., 2020 **Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different foodsystem pathways**	**0.1 – 1.1** GtCO$_2$ yr^{-1} Crop residues potential* **0.2 – 2** GtCO$_2$ yr^{-1} 'sustainable' potential* from dedicated crops **0.8 – 4.3** GtCO$_2$ yr^{-1} potential* on 4-5 Mkm2 (*derived w/ Rogelj et al. conversion factors)	**1. BECCS sustainability thresholds and potentials** • **'Sustainable' crop residues potential:** Kalt et al. estimate the sustainable bioenergy potential from crop residues at 4-22 EJ yr^{-1}. **Derived potential by authors (Deprez et al.):** using the conversion factors from Rogelj et al. (2018): 0.02-0.05 GtCO$_2$ EJ yr^{-1} (as done by Pörtner et al., 2021) results in a potential of **0.1 to 1.1 GtCO$_2$ yr^{-1}** CDR from crop residues. • **Dedicated bioenergy crop potential without expansion into grazing areas and limited grazing land intensification:** Kalt et al. estimate the bioenergy potential under these conditions to be 10-40 EJ yr^{-1}. **Derived potential by authors (Deprez et al.):** using the conversion factors from Rogelj et al. (2018): 0.02-0.05 GtCO2 EJ yr^{-1} – results in a potential of **0.2 to 2 GtCO$_2$ yr^{-1}** • **Dedicated bioenergy crop potential with expansion into grazing areas (4 - 5 Mkm2) and global grazing land intensification:** ~ 40-85 EJ yr^{-1}. Creutzig et al. (2021) assess this "would raise difficult implementation challenges" ((*6*), p. 512). **Derived potential by authors (Deprez et al.):** using the conversion factors from Rogelj et al. (2018): 0.02-0.05 GtCO$_2$ EJ yr^{-1}– results in a potential of **0.8 - 4.3 GtCO$_2$ yr^{-1}** **2. Methods and further details** **Feedstock:** Dedicated 2nd generation biomass plantations and crop residues; **Sustainability constraints:** food security, and 'environmental limitations': Kalt et al. constrain their models to "not allow agricultural land (cropland and grazing land) to encroach into forests" ((*21*), p. 4); **Methods:** Kalt et al. attain their results of energy crop and residues bioenergy potential by running the global biomass balance model (BioBaM), with four scenarios (based on FAO data) with various diets and crop yields. To estimate the sustainable bioenergy potential from crop residue, Kalt et al. apply a 'low' (40%) and 'high' (60%) sustainable residue removal rates (i.e., vs amount of residues left on the field), noting that their lower estimate (40%) "is not exceptionally conservative" ((*21*), p. 12). Removal of residues contributes to loss of soil organic carbon (SOC). **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII cites Kalt et al. in its technical biomass potential assessment** and on uncertainties related to BECCS and bioenergy (Ch. 7.4.4), and in Box 7.7.
(*5*) Ai et al., 2021 **Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation**	Maximum BECCS potential with strict water & land sustainability: 1.6 – 2.4 GtCO$_2$ yr^{-1} (Precautionary potential) 3.2 GtCO$_2$ yr^{-1} (Optimistic potential)	**1. BECCS sustainability thresholds and potentials** • Maximum sustainable BECCS potential: Optimistic sustainable potential (high carbon capture rate*): 3.2 GtCO$_2$ yr^{-1} (0.88 GtC yr^{-1}): "Our simulation of only 0.88 GtC yr^{-1} under PP_SI can be regarded as the maximum BECCS potential with strict consideration of water and land sustainability that would not lead to additional water stress, biodiversity loss or competition with food production" ((*5*), p. 887). PP=Scenario with pastureland protection (bioenergy crop plantations on 1.9 Mkm2) SI= sustainable irrigation; Precautionary sustainable potential (lower carbon capture rate*): 0.8 – 1.6 GtCO$_2$ yr^{-1}. Calculated based on Ai et al.'s assessment that lower capture rates could reduce BECCS potential by 25-50% (see *Caveat below): 3.2/0.5= 1.6 3.2/0.75=2.4 • BECCS potential with pasture conversion on 4.4 million km^2: Optimistic potential: 7.7 GtCO$_2$ yr^{-1} (2.09 GtC yr^{-1}) This is the result from Ai et al.'s PC_SI scenario. PC= Scenario with pastureland conversion over 4.4 million km^2; Precautionary potential (lower carbon capture rate*): 1.9 - 3.8 GtCO$_2$ yr^{-1}. Calculated based on Ai et al.'s assessment that lower capture rates could reduce BECCS potential by 25-50% (see *Caveat below): 7.7/0.5 = 3.8 7.7/0.75=5.8

BECCS Sustainability Thresholds – GtCO2 yr-1 (continued)		
Continued – (*5*) – Ai et al., 2021 **Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation**	BECCS potential with pasture conversion (on 4.4 Mkm2): **1.9 – 3.8** $GtCO_2$ yr^{-1} (Precautionary potential) **7.7** $GtCO_2$ yr^{-1} (Optimistic potential)	**2. Methods and further details** **Feedstock:** Dedicated 2nd generation biomass plantations: miscanthus and switchgrass; **Sustainability constraints:** biodiversity, food production, land-use-change emission, land degradation and desertification due to large-scale land conversion, freshwater use; **Methods:** Ai et al. develop two land scenarios for 2nd generation bioenergy plantations, and to address the sustainability constraints listed above, adopt "protections in the scenarios for areas protected for biodiversity, areas of cropland, forest and wetland, and areas under land degradation and desertification" ((*5*), p. 884). Scenario 1 (PP) protects pastureland, allowing bioenergy crops to be planted on 1.8 million km^2. Scenario 2 (PC) allows for conversion of 4.4 million km^{2}of pastureland, to account for potential dietary changes (e.g., shift toward less livestock products). They cross these two land scenarios with three irrigation scenarios: no irrigation (rain fed; RF), full irrigation – without constraints (FI); some irrigation with sustainable water availability constraints (sustainable irrigation; SI); ***Caveat on optimistic capture rate: "**Note that the carbon capture rate and conversion efficiency are important parameters and have a large impact on the BECCS potential. For example, with lower capture ratios, the BECCS potential could be reduced to 50% or 75% of current estimates (Supplementary Fig. 1). Therefore, our estimates appear optimistic because the calculation was based on the assumption of converting the biomass into synthetic natural gas with a higher capture rate" ((*5*), p. 886). **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII does not cite Ai et al.'s sustainable thresholds and BECCS potentials.** It cites Ai et al. in Ch. 7.4.4 in general terms on updates since AR5, and in Chapter 4: "Large-scale BECCS may push planetary boundaries for freshwater use, exacerbate land-system change, significantly alter biosphere integrity and biogeochemical flows (Heck et al. 2018; Fuhrman et al. 2020; Stenzel et al. 2021; Ai et al. 2021)" (Ch.4.2.5.3) ((*3*), p. 438).
(*22*) – Pörtner et al., 2021 **Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change**	**1 – 2.5** $GtCO_2$ yr^{-1} (dedicated crops)	**1. BECCS sustainability thresholds and potentials• Estimate of sustainable BECCS potential:** 1 - 2.5 $GtCO_2$ yr^{-1}. Estimate based on sustainable bioenergy potential estimate, drawn from the literature (see, Methods below).• **Conclusions:** "BECCS CO_2 uptake rates of 10-15 $GtCO_2$ a^{-1} would be equivalent to approximately doubling the total carbon sink on land estimated for the last decade (Friedlingstein et al., 2020), which raises severe doubt about their environmental and societal realism, given today's already extensive use of the total ice-free land area. Even more moderate scenarios, which project potential of BECCS around 5 $GtCO_2$ a^{-1} would still aim to enhance today's total land carbon sink by 50%. In addition to jeopardizing SDG 15 (life on land), attempting to use millions of hectares of land for bioenergy (Rogelj et al., 2018) rather than food production would seriously undermine the fight against hunger (SDG 2) (Dooley & Kartha, 2018), if these modelled scenarios were to be realized" ((*22*), p. 53). **2. Methods and further detailsFeedstocks:** Dedicated 2nd generation bioenergy crops; **Sustainability constraints:** Based on literature: excluding expansion on currently protected areas, avoiding expansion affecting food security; **Method:** Pörtner et al. arrive at an estimate of 1-2.5 $GtCO_2$ yr^{-1} of sustainable BECCS, by using the conversion factor from Rogelj et al. (2018) (0.02-0.05 $GtCO_2$ EJ yr^{-1}) on 50 EJ yr^{-1} of bioenergy. They draw this bioenergy potential from Schueler et al., 2016: "A global 2nd generation bioenergy potential of 88 EJ a^{-1} has been estimated in a study that applied EU renewable energy sustainability criteria everywhere, with the authors cautioning that this may reduce to 50 EJ a-1 when uncertainties related to future crop yields have been considered." Pörtner et al. also cite Fuss et al., 2018: "a potential of around 60 EJ a^{-1} (for illustration, around 10% of today's primary energy production) have also been suggested as a conservative estimate, based on studies that restrict bioenergy crops to 'marginal' land and exclude expansion into currently protected areas" ((*22*), p. 53). **3. Inclusion in IPCC AR6 WGIII? AR6 WGIII does not cite Pörtner et al.'s sustainability thresholds and BECCS potentials.** It cites Pörtner et al. on CDR more generally: "When trade-offs exist between biodiversity protection and mitigation objectives, biodiversity is typically given a lower priority, especially if the mitigation option is considered risk free and economically feasible (Pörtner et al. 2021). Approaches that promote synergies, such as sustainable forest management, reducing deforestation rates, cultivation of perennial crops for bioenergy in sustainable farming practices, and mixed-species forests in A/R, can mitigate biodiversity impacts and even improve ecosystem capacity to support biodiversity while mitigating climate change (Pörtner et al. 2021)" (Ch. 12.3.2) ((*3*), p. 1277).

BECCS Sustainability Thresholds – GtCO2 yr-1 (continued)		
(*6*) – Creutzig et al., 2021 Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments	**0.5** GtCO$_2$ yr^{-1} Low sustainability threshold	**1. BECCS sustainability thresholds and potentials** • Alongside **Creutzig et al.'s 'Maximum sustainable threshold' for dedicated bioenergy plantations of** 0.5 million km^2 (see 'Method'), Creutzig et al. also cite Fuss et al.'s low estimate of sustainable BECCS potential: 0.5 GtCO$_2$ yr^{-1}. • **Conclusions:** Creutzig et al. underscore the limited sustainable BECCS potential and high risks that depending on large-scale BECCS entail: (i) "The assumption of producing a certain amount of land-use change-related emissions first, and then relying on uncertain emission reductions several decades later **entails a significant risk**. It assumes a long-term commitment on land use, even as climate, water, and political circumstances are changing, and does not consider economic incentives to dedicate land for other purposes" ((*6*), p. 513); (ii) Creutzig et al. also note **high risk** of temperature overshoot and resulting tipping points, from a strategy of high upfront emissions and large BECCS deployment later in the 21st century: "The timescales underlying the BECCS potentials across the IPCC models **render BECCS a highly risky technology** and mismatch with the urgency of fast GHG reduction underlying the Paris Agreement (Norton et al., 2019)" ((*6*), p. 513); (iii) "The large-scale deployment of BECCS later in the century to offset emissions from earlier in the century **poses potentially higher levels of risk for the biosphere and anthroposphere than captured in the SRCCL risk assessment"** ((*6*), p. 513). **2. Methods and further details** **Feedstock:** Dedicated 2nd generation bioenergy crops (on residues, see 'method' below); **Sustainability constraints:** Biodiversity, land tenure, livelihoods, and the risk of land carbon loss: "while acknowledging diverse land use and biodiversity impacts from different bioenergy feedstock (Ale et al., 2019), a bioenergy-reliant mitigation strategy above certain thresholds, through the loss of natural habitats of probably unprecedented dimensions, would be much more detrimental to global biodiversity than in a counterfactual higher climate change scenario (Hof et al., 2018)" ((*6*), p. 512); "In short, the scale of land use change implicit in large-scale BECCS deployment would cause enormous social dislocation. Even much smaller bioenergy cropland expansion plans will still need to address and avoid risks related to land tenure, livelihoods, and Indigenous rights" ((*6*), p. 513); **Method:** Given that large-scale BECCS may approach or overstep planetary boundaries (Heck et al. 2018), and the need for large-scale conservation efforts to reverse the 6th mass extinction (Leclère et al., 2020), Creutzig et al. estimate a '**sustainable threshold' for dedicated bioenergy crops:** "Unless there are large future efficiency gains in agriculture and/or available areas are identified that will have no impact on biodiversity and food security, we assume that land used for bioenergy should not exceed the current amount of land used for bioenergy, about 0.5 Mkm2 ("precautionary threshold value"), to avoid adding pressure on land use" ((*6*), p. 513). Creutzig et al. note that sustainability thresholds "may include both sequestration and land use," ((*6*), p. 512) citing Fuss et al.'s (*23*) sustainable BECCS potentials (0.5-5 GtCO$_2$ yr^{-1}) and Kalt et al. (2020) (*21*) on their realistic bioenergy potentials (25 EJ yr^{-1} from residues and manure, and 10-50 EJ yr^{-1} from dedicated crops). **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII does not cite Creutzig et al., although it was published before the publication cut-off date.**
(*23*) – Fuss et al., 2018 Negative emissions—Part 2: Costs, potentials and side effects	**0.5 – 5** GtCO$_2$ yr^{-1} Technical potential "cognizant of other sustainability aims"	**1. BECCS potentials** **Qualitative assessment of global technological potential "that remains cognizant of other sustainability aims":** The analyses from Fuss et al. are qualitative and related to the following assessment of the authors: "Authors' assessment. Overall, by 2050 we see BECCS at costs of US\$100–200/tCO$_2$ that accrue inter alia from the necessity to guarantee limited sustainability and land-use carbon cycle effects, and which will require high management intensity on a case-by-case basis. Our estimate of 2050 potentials ranges is 0.5– 5 GtCO$_2$ (considering here a technological potential that remains cognizant of other sustainability aims). As for all land-intensive options, we remain conservative in our suggested values as they refer to mid-century where population pressures are highest according to recent projections (Samir and Lutz 2017). A range of 5 GtCO$_2$ and possibly higher requires global land governance, integrating multiple land use concerns for the global common good" ((*23*), p. 14). **2.Methods and further details** Feedstock: Presumably dedicated crops and residues (given some studies cited contain residues), although Fuss et al. are not explicit about it, nor present a breakdown between the two; Sustainability constraints: Fuss et al. note that in the literature "bioenergy is confronted with substantial concerns regarding competition for land, including impact on food prices, biodiversity, water and nutrients" ((*23*), p. 13); Methods: Fuss et al.'s study represents a 'systematic review of the literature'. The authors do not specify the method used to arrive at their qualitative assessment, nor do they specify how their estimates "remain cognizant of other sustainability aims" ((*23*), p. 14).

BECCS Sustainability Thresholds – GtCO2 yr-1 (continued)		
Continued – (*23*) – Fuss et al., 2018 **Negative emissions—Part 2: Costs, potentials and side effects**		For example, although they note that studies taking stricter sustainability constraints (e.g., growing bioenergy crops only on marginal or degraded lands, and outside of protected areas) arrive at sustainable bioenergy potential estimates around ~60 EJ yr^{-1}; when applying conversion factors in (Rogelj et al., 2018)[15] Fuss et al.'s upper end 'sustainability' BECCS potential (5 Gt $GtCO_2$ yr^{-1}) would require roughly 100 - 250 EJ yr^{-1} bioenergy. **3. Inclusion in IPCC AR6 WGIII?** AR6 WGIII cites Fuss et al. in its estimate of BECCS technical potential, and as having provided the SR1.5 sustainable BECCS potential estimate (and does not provide an update): "The SR1.5 reported a range for the CDR potential of BECCS (2100) at 0.5 to 5 $GtCO_2eq$ yr^{-1} when applying constraints reflecting sustainability concerns, at a cost of 100–200 USD tCO_2^{-1} (Fuss et al. 2018)." (Ch. 7.4.4) ((*3*), p. 800). It also cites extensively Fuss et al. throughout Chapter 7, Ch. 6.4.2.6, Ch. 12.3.2, etc.
(*18*) – Turner et al., 2018 **The global overlap of bioenergy and carbon sequestration potential**	**1.5** GtCO2 yr-1 'lower bound' potential (over CO2 basins) (0.4 and 1.1 $GtCO_2$ yr^{-1} from crop residues and crops on marginal lands, respectively) **7.6** $GtCO_2$ yr^{-1} upper technical bound (over CO2 basins)	**1. BECCS potentials** • **BECCS 'technical upper bound' above 'highly prospective' CO2 storage basins:** 7.6 $GtCO_2$ yr^{-1}, yet "most land overlying basins is either forested or linked to food production" ((*18*), p. 1). • **BECCS 'lower bound' above 'highly prospective' CO2 storage basins:** 0.4 $GtCO_2$ yr^{-1} from cropland residues, and 1.1 $GtCO_2$ yr^{-1} from marginal agricultural land. **2. Methods and further details** **Feedstock:** Dedicated bioenergy crops and crop residues; **Sustainability constraints:** None explicit – mention biodiversity and food; **Method:** Turner et al.'s study's primary constraint is "convenient access to suitable storage basins" ((*18*), p. 3), under the assumption that constructing a "widespread pipeline network, potentially much larger than the existing network of oil and gas pipelines [to transport biomass] is a major undertaking" ((*18*), p. 2). On this basis they calculate the: (i) the BECCS 'technical upper bound' as "total conversion of existing vegetation types [above CO_2 storage basins] to energy crops" ((*18*), p. 3); (ii) the BECCS 'lower bound': "as the sum of biomass from agricultural residues plus conversion of infrequently cropped agricultural lands to continuous energy crop cultivation" ((*18*), p. 3). **BECCS potential:** Turner et al. calculate BECCS potential as a result of the 'sustainably harvestable' biomass, which they define as: "1/3 of total [Net Primary Production] as the sustainably harvestable fraction" ((*18*), p. 4), assuming "current NPP is a useful proxy for energy crop NPP" ((*18*), p. 1). Turner et al. define **'infrequently cropped' or 'marginal' agricultural lands** as land used for crop production fewer than 11 of 13 years (MODIS record)" ((*18*), p. 7). Turner et al. do not explicitly for land-use change and supply chain emissions that may reduce the BECCS potential. **Available residue:** 17% of total aboveground NPP. **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII does not cite Turner et al.'s BECCS potentials, but cites it in its technical biomass potential:** "Recent estimates of technical biomass potentials constrained by food security and environmental considerations fall within previous ranges corresponding to medium agreement, (e.g., **Turner et al. 2018b;** Daioglou et al. 2019; Wu et al. 2019, Hansen et al.2020; Kalt et al. 2020) arriving at 4–57 and 46–245 EJ yr^{-1} by 2050 for residues and dedicated biomass crops, respectively." (Ch. 7.4.4) ((*3*), p. 802). It also cites it in Box 7.7 "Emissions associated with primary biomass supply in 2050" ((*3*), p. 802). It also cited Turner et al. regarding uncertainties around BECCS and bioenergy, and advances in modelling since AR5.
(*26*) – Hanssen et al., 2020	**2.5** $GtCO_2$ yr^{-1} (28 EJelec yr^{-1}) over 30 years	**1. BECCS potentials** • **Over 30-year time period:** 2.5 $GtCO_2$ yr^{-1} (28 EJ electricity with negative emissions = 32% of the current global electricity production) • **Over 80-year period:** 40 $GtCO_2$ yr^{-1} (220 EJ electricity with negative emissions), requiring 8 to 24 Mkm2 for bioenergy crops (5-16% of the Earth's total land surface area).

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[15] J. Rogelj, A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D. P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, M. Tavoni, Scenarios towards limiting global mean temperature increase below 1.5 degrees C. *Nature Climate Change* **8** (4), 325 (2018).

BECCS Sustainability Thresholds – GtCO2 yr-1 (continued)		
Continued – **(*26*) –** **Hanssen et al., 2020** **The climate change mitigation potential of bioenergy with carbon capture and storage**	**40** GtCO$_2$ yr^{-1} (220 EJelec yr^{-1}) over 80 years	**2. Specifications** **Feedstock:** Dedicated bioenergy crops (2nd generation lignocellulosic grasses and woody, short rotation coppiced trees, and sugarcane) and agricultural residues; **Sustainability constraints:** Exclusion of croplands and pasture from areas available to grow bioenergy crops; **Method:** Hanssen et al. estimate the technical, biophysical potential achieved over 30-year period (and also 80-year period). For this they calculate Emission factors (EFs), i.e. " the amount of GHG emissions per unit bioenergy produced" ((*26*), p. 1023). Hanssen et al.'s EFs "include emissions from [land use change], the lost carbon sequestration capacity of natural vegetation (foregone sequestration), bioenergy supply chain emissions including fertilizers and CO$_2$ sequestered through CCS over a set evaluation period " ((*26*), p. 1023). They determined the availability of land for bioenergy using the image model and SSP2 pathway; **Optimistic capture rates:** Hanssen et al. use a 90% carbon capture rate, which other authors (e.g., Heck et al., Ai et al.) highlight are being very high, and hence complement in their studies with lower, less optimistic, capture rates (e.g. 48% in Heck et al.). **80-year evaluation period:** "Longer evaluation periods lead to substantially higher BECCS energy potential at low EFs, predominantly as initial LUC emissions are amortized over longer periods, and to a lesser extent due to projected yield increases and levelling off of foregone carbon sequestration in the natural vegetation benchmark scenario" ((*26*), p. 1024). They also note "these [8-24 million km^2] extreme levels of land demand partly arise due to the time profile of, in particular, the S2 pathway, and from our assumption to use residues before crops. The cumulative sequestration these pathways demand by 2100 could biophysically be achieved with lower land requirements if deployment of crop based BECCS starts even earlier on" ((*26*), p. 1026). **Hanssen et al.'s caveats on 80-year BECCS potential evaluation period:** "Care should be taken when drawing conclusions based on longer evaluation periods, as BECCS capacity that is installed later in the century may only achieve net-negative emissions beyond the target year 2100" ((*26*), p. 1024). **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII cites Hanssen et al. on BECCS technical potential,** land carbon loss, uncertainties, updates since AR5, Box 7.7, and synergies and trade-offs (Ch. 7.4.4).
(*27*) – Roe et al., 2021 **Land-based measures to mitigate climate change: Potential and feasibility by country**	**0.5** GtCO$_2$ yr^{-1} cost-effective potential (\$100/CO$_2$eq) (on 1.6 Mkm2) **2.5** GtCO$_2$ yr^{-1} technical potential (on 7.4 Mkm2)	**1. BECCS potentials** • **Sectoral estimate:** technical potential: 2.5 GtCO$_2$ yr^{-1} (requiring land area of 7.4 million km^2) ; economic potential: 0.5 GtCO$_2$ yr^{-1} (requiring land area of 1.6 million km^2). • **IAMs estimate:** cost-effective potential: 0.7 (0.01–7.7) GtCO$_2$ yr^{-1}in 2050. "Both sectoral and IAM potentials are lower than previous studies largely due to the \$100/ tCO$_2$eq cost constraint. BECCS potential in IAMs increase substantially with higher carbon prices" ((*27*), p. 6041). **2. Methods and further details** **Feedstock:** Dedicated 2nd generation bioenergy crops (Miscanthus, switchgrass, short-rotation coppiced trees such as poplar and Eucalyptus); **Sustainability constraints:** Exclusion of croplands and pasture from areas available to grow bioenergy crops; **Methods: Sectoral technical BECCS potential:** adapted from Hanssen et al.'s (2020) estimate of the biophysical potential over a 30-year period. Drawing from Hanssen et al. 2020, the "land availability assumed in determining biophysical potential is constrained by excluding projected urban and agricultural land (cropland and pastures according to an SSP2 land-use projection of the IMAGE model as presented in Doelman et al. (2018)), as well as areas with low bioenergy crop yields (5% of global maximum) or < no potential to deliver net negative emissions through BECCS" ((*27*), p. 6034). Cost effective potential: calculated "by adding costs for biomass production, and conversion to electricity mitigation potential up to \$100/tCO$_2$ combined with CCS" ((*27*), p. 6034). **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII cites Roe et al. in its estimate of BECCS technical potential,** and in its BECCS cost-effective potential (comprising the lower end of the range): "1.6 (0.5–3.5) GtCO$_2$ yr^{-1} is available at below USD100 tCO$_2^{-1}$ (medium confidence) (Lenton 2010; Koornneef et al. 2012; McLaren 2012; Powell and Lenton 2012; Fuss et al. 2018; Turner et al. 2018a; Hanssen et al. 2020; Roe et al. 2021)" (Ch. 7.4.4) ((*3*), p. 802). It also cites Roe et al. in Ch. 6.4.2.6 on bioenergy sustainability implications.
(*29*) – IPCC Special Report on Climate Change and Land, SPM, 2019	**up to 150 million people** at risk of food insecurity	**The IPCC SRCCL SPM** notes that growing bioenergy to a scale of the BECCS 'upper technical mitigation' (11.3 GtCO$_2$ yr^{-1}) could place to up to 150 million additional people at risk of food insecurity (Figure SPM.3) ((*29*), p. 27).

Table S1.4: Bioenergy Potential: Energy crops and residues (EJ yr^{-1}). The table summarizes the key values of sustainable primary bioenergy potential from dedicated crops, and from crop and forestry residues, across a series of studies cited in IPCC AR6 WGIII Report (*3*) Section 7.4.4, including those that underpin the Report's assessment of technical biomass potentials. Table S1.4 shows that the studies taking stricter sustainability constraints estimate levels of sustainable biomass (dedicated crops and residues) significantly below the IPCC technical

	Bioenergy primary energy potential by 2050			
	Dedicated energy crops		**Residues**	
IPCC AR6 WGIII: Technical biomass potentials – (*3*), Ch. 7.4.4	**46 – 245 EJ yr^{-1}** **Dedicated energy crop[1] potential 'constrained by food security and environmental considerations'**		**4 – 57 EJ yr^{-1}** **Residues[2] potential 'constrained by food security and environmental considerations'**	
Sustainable biomass potentials: stricter constraints	**Up to 40 EJ yr^{-1}: Low risk** (no to low grazing intensification) **40 - 85 EJ yr^{-1}: Medium risk** (expansion on 4-5 million km^2 agricultural land)		**Up to 12 EJ yr^{-1}: Low risk** (high sustainability) **12- 35 EJ yr^{-1}: Medium risk** (lower sustainability)	
	10 - 40 EJ yr^{-1}	Without expanding into grazing areas, without global grazing land intensification, based on FAO scenarios – Kalt *et al.*, 2020 (*21*)[3]	4 - 22 EJ yr^{-1}	Crop residues: sustainable potentials based on FAO scenarios, respecting environmental limitations and food security, and with, respectively, 'low' (40%) and 'high' (60%) sustainable residue removal rates – Kalt *et al.*, 2020 (*21*)
	40 - 85 EJ yr^{-1}	Requiring expansion into grazing areas (4–5 Mkm2), and global intensification of grazing land, based on FAO scenarios – Kalt *et al.*, 2020 (*21*)[3]	12 EJ yr^{-1}	Crop and forestry residues: with stricter sustainability constraints (residue extraction from natural forests, 70% of agricultural residues unavailable) – Searle et Malins, 2015, and Cornelissen *et al.* 2012; in Hanssen *et al.*, 2020 (*28*)
	40 - 110 EJ yr^{-1}	Maximum produced on marginal land – Searle et Malins, 2015; in Fuss *et al.*, 2018 (*23*)	13 EJ yr^{-1}	Crop and forestry residues: low estimate – Slade *et al.,* 2014; in Wu *et al.*, 2019 (*20*)
	50 - 88 EJ yr^{-1}	Maximum when applying EU renewable energy sustainability criteria globally – 50 EJ yr-1 when accounting for uncertainties on future crop yields – Schueler et al., 2016; in Pörtner et al., 2021 (*22*)	20 - 28 EJ yr^{-1}	Crop residues: "Ecological potential minus amount used as animal feed" – Daioglou *et al.,* 2016; in Kalt *et al.*, 2020 (*21*)
	60 EJ yr^{-1}	Conservative estimate across studies limiting bioenergy crops to 'marginal' land and excluding expansion into protected areas – Fuss et al., 2018 (*23*); in Pörtner et al., 2021 (*22*)		
Higher biomass potentials: less stringent or no sustainability constraints	**85 – 133 EJ yr^{-1}: High risk** **133 – 245 EJ yr^{-1}: Very high risk**		**35 - 101 EJ yr^{-1}: High risk** **>101 EJ yr^{-1}: Very high risk**	
	122 EJ yr^{-1}	Dedicated crop potential projected in IMAGE 3.0 SSP2-1.9 – Daioglou *et al.*, 2019 (*19*)[4]	55 EJ yr^{-1}	Crop and forestry residues: mean literature-estimated potential – Hanssen *et al.,* 2020 (*28*)
	133 EJ yr^{-1}	'Maximum global potential' with 'sustainability criteria': yet this implies expansion onto 3.1 million km^2, "increased fertilizer use (+16%) and water use above EF (+49%) besides higher LUC emissions (+180%)" – Humpenöder *et al.,* 2018 ((*24*), p. 5).	66 - 74 EJ yr^{-1}	Crop and forestry residues: potential projected in SSP scenarios run through the IMAGE 3.0 model, 'limited by environmental factors and competing demand' – Daioglou *et al.*, 2019 (*19*)[4]
	149-186 EJ yr^{-1}	Maximum under environmental (biodiversity and soil) policies; and under environmental policies with 'societal transformations' (diets, trade, irrigation) – Wu *et al.,* 2019 (*20*)[5]	101 EJ yr^{-1}	Crop and forestry residues: high estimate – Slade *et al.*, 2014; in Wu *et al.*, 2019 (*20*)
	190 EJ yr^{-1}	Biophysical limit: "grown outside existing croplands, infrastructure, wilderness and denser forests" – Haberl *et al.*, 2013; in Humpenöder *et al.*, 2018 (*24*)		
	245 EJ yr^{-1}	Maximum with no environmental policies – Wu *et al.*, 2019 (*20*)[5]		

[1] 1st generation (maize); 2nd generation lignocellulosic crops (miscanthus, switchgrass); woody crops (willow, eucalyptus)

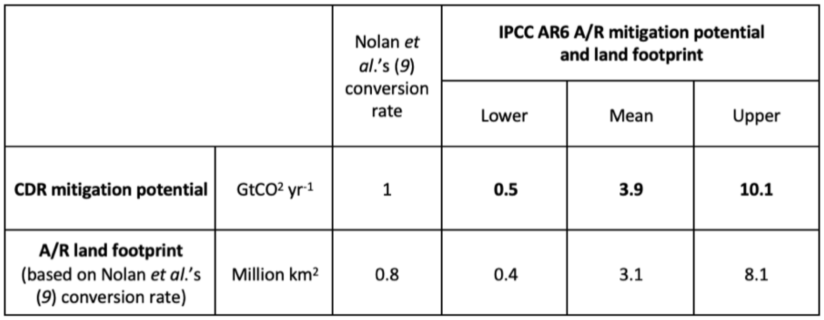
[2] Crop and forestry residues (presumably: the IPCC AR6 WGIII Report (*3*) does not specify this, although some of the studies it cites cover both)

[3] Kalt *et al.*, (*21*) note: "assumptions that energy crops would be cultivated in low-productivity areas (marginal land) are also dubious. Economic rational and empirical evidence [...] suggest that energy crop production will (i) enhance competition for existing cropland and (ii) foster intensification and cropland expansion into highly productive grassland" ((*21*), p. 14).

[4] Daioglou *et al.*, (*19*) note that the total 115-180 EJ yr^{-1} (residues and dedicated crops) projected in IMAGE 3.0 "can only be achieved without extreme levels land use change if agricultural yields improve significantly and effective land zoning is implemented" ((*19*), p. 88).

[5] Wu *et al.* (*20*) do not specify the land use change implications, or encroachment onto agricultural or other lands. The policies applied are: Biodiversity: "current established protected areas are excluded from food and bioenergy production," and bioenergy production is "restricted in the biodiversity sensitive areas (identified by a biodiversity index)" ((*20*), p. 1045). Soil protection: degraded land is used not for food but for bioenergy production.

biomass potential. **Table S1.5: Afforestation/Reforestation – Land footprint sustainability thresholds (million km^2).** The table details – for each study included in Fig. S1.2 – the key values listed, and its arguments on sustainability thresholds of A/R.

<table>
<tr><th colspan="3">Afforestation/Reforestation – Land footprint sustainability thresholds (million km^2)</th></tr>
<tr><td>(<i>3</i>) – IPCC AR6 WGIII, 2022</td><td>3.1 million km^2
A/R mean tech. potential
0.4 million km^2
A/R lower end tech. potential
8.1 million km^2
A/R upper end tech. potential</td><td>IPCC A/R technical mitigation potential: 3.9 (0.5-10.1) GtCO$_2$ yr^{-1} (Ch. 7.4.2.2). Using the mean of Nolan et al.'s conversion rates (i.e., 1 GtCO$_2$ yr^{-1} requires 0.8 million km^2), the land footprint would amount to:

<table>
<tr><th></th><th></th><th>Nolan <i>et al.</i>'s (<i>9</i>) conversion rate</th><th colspan="3">IPCC AR6 A/R mitigation potential and land footprint</th></tr>
<tr><td></td><td></td><td></td><td>Lower</td><td>Mean</td><td>Upper</td></tr>
<tr><td>CDR mitigation potential</td><td>GtCO^2 yr^{-1}</td><td>1</td><td>0.5</td><td>3.9</td><td>10.1</td></tr>
<tr><td>A/R land footprint (based on Nolan <i>et al.</i>'s (<i>9</i>) conversion rate)</td><td>Million km^2</td><td>0.8</td><td>0.4</td><td>3.1</td><td>8.1</td></tr>
</table></td></tr>
<tr><td>(<i>9</i>) – Nolan et al., 2021
Constraints and enablers for increasing carbon storage in the terrestrial biosphere</td><td>0.9 – 2.3 million km^2
'Grounded, conservative NbCS' potential if all A/R</td><td>• Conservative, grounded CDR potential of 'Nature based Climate Solutions': Nolan et al. find this to be 1.3 to 2.6 GtCO$_2$ yr^{-1}
Nolan et al. note: "removing 1 GtCO$_2$ per year via afforestation or reforestation would need 70–90 Mha, roughly twice the size of California" ((<i>9</i>), p. 442).
From this we derive that a conservative, grounded CDR potential of NbCS, if it were all A/R, would require 0.9 – 2.3 million km^2 (1.3*0.8 = 0.9 million km^2 and 2.6*0.8= 2.3 million km^2)
• Nolan et al. note that large-scale afforestation represents a 'haystack' approach, which rases major questions: "Afforestation of grasslands and disturbance exclusion provide examples of haystack NbCS that could increase carbon storage above previous and historic levels. However, there are major questions about the ability to implement these interventions, especially in a non-stationary climate. Even where implementation of these strategies is technically possible, it could be limited by conflict with priorities for conservation and disaster risk reduction priorities, and by questions about whether they are sufficiently natural" ((<i>9</i>), p. 440).</td></tr>
<tr><td>(<i>10</i>) – Dooley et al., 2022
Carbon removals from nature restoration are no substitute for steep emission reductions</td><td>2.1 million km^2
'Responsible', constrained reforestation potential</td><td>• Dooley et al. assess the 'responsible', constrained reforestation potential as 2.1 million km^2 (the amount pledged by countries under the Bonn Challenge). Dooley et al. take this approach to reflect that "reforestation requires a land-use change and therefore presents more risks and potential tradeoffs than restoring degraded lands while maintaining existing land uses" ((<i>10</i>), p. 2), in the broader context of their study which assesses the ‘responsible’ sequestration potential of 'nature restoration' CDR, i.e. "within social and environmental constraints that go beyond avoiding urban and agricultural areas to base restoration activities on ecological principles" ((<i>10</i>), p. 2). The associated average reforestation sequestration potential is 2 GtCO$_2$ yr^{-1}.</td></tr>
<tr><td>(<i>1</i>) – Dooley et el., 2022
The Land Gap Report</td><td>"The area suitable for expanding forest cover is uncertain and depends on principles of ecology and human rights"</td><td>• Sustainable reforestation/afforestation potential: Dooley et al note: "Local knowledge is needed to better assess suitable areas for restoration. Further work has been developed by FAO on mapping tree restoration potential to assist countries in identifying areas that are suitable for restoration (FAO and UNEP, 2020) and in developing guidelines to incorporate biodiversity into landscape restoration (Beatty et al., 2018). Overall, the area suitable for expanding forest cover is uncertain and depends on principles of ecology and human rights, while the area of global cropland has already reached sustainability thresholds, indicating there is no available land for energy crop or monoculture plantation expansion" ((<i>1</i>), p. 26).
• Dooley et al. also note that very large scale potentials, advanced by for example, Bastin et al.'s estimate of biophysical potential of increased forest cover (afforestation/reforestation: 17 – 18 million km^2) "has been criticised for not accounting for existing ecosystems or land tenure rights" ((<i>1</i>), p. 26).</td></tr>
</table>

Afforestation/Reforestation – Land footprint sustainability thresholds (million km^2)		
(*23*) – Fuss et al., 2018 **Negative emissions—Part 2: Costs, potentials and side effects**	**5 million km^2** "Feasible, yet ambitious boundary limit for global afforestation"	• **Afforestation/reforestation technical potential:** Fuss et al. advance a technical potential of 3.6 GtCO$_2$ yr^{-1} by 2050, declining to zero by 2100 (based on Houghton *et al.* 2015). This would entail afforesting 5 million km^2 of "marginal land in the tropics", which Fuss et al. consider a "feasible, yet ambitious boundary limit for global afforestation" ((*23*), p. 16). However, the IPCC AR6 WGIII notes that the availability of 'marginal' lands "has been contested since they may serve other functions, such as: subsistence, biodiversity protection, and so on." (Ch.7.4.4) ((*3*), p. 800).
(*27*) – Roe et al., 2021 **Land-based measures to mitigate climate change: Potential and feasibility by country**	**10 million km^2** Technical A/R potential **3 million km^2** Cost-effective A/R potential	•**A/R: Technical potential:** 8.5 GtCO$_2$ yr^{-1} (requiring land area of ~10 million km^2). **Cost-effective potential** (up to USD100 per GtCO$_2$ yr^{-1}): 1.2 GtCO$_2$ yr^{-1} (requiring ~3 million km^2) The technical potential rate implies a conversion rate of 1 GtCO$_2$ yr^{-1} of removals = 1.2 million km^2 land.

Table S1.6: A/R & Nature-Based CDR – Sequestration sustainability limits ($GtCO_2$ yr^{-1}). Table S1.6 details–for each study included in Fig. S1.6–key values, method, elements on sustainability limits of A/R or Nature-Based CDR, and inclusion in IPCC AR6 WGIII (*3*).

Afforestation/Reforestation & Nature-Based CDR – Sequestration sustainability thresholds ($GtCO_2$ yr^{-1})		
(*3*) – IPCC AR6 WGIII Report, 2022	**3.9 (0.5 – 10)** $GtCO_2$ yr^{-1} A/R **1.7 (1 – 2.1)** $GtCO_2$ yr^{-1} Improved Forest Management **4.1 (0.3 – 9.4)** $GtCO_2$ yr^{-1} Agroforestry **9.7 (1.8 – 21.5)** $GtCO_2$ yr^{-1} **Combined**	**1. Afforestation, Reforestation and Forest Ecosystem Restoration – Technical mitigation potential:** 3.9 (0.5 to 10.1) $GtCO_2$ yr^{-1} (Ch. 7.4.2.2); **Economic potential** (up to USD100 per $GtCO_2$ yr^{-1}): 1.6 (0.5–3.0) $GtCO_2$ yr^{-1} (Ch. 7.4.2.2); **Onset of feasibility concern:** Unlike for BECCS, no mention of feasibility concerns onset; **Mention of sustainability concerns:** "The rising public interest in nature-based solutions, along with high profile initiatives being launched [...] has prompted intense discussions on the scale, effectiveness, and pitfalls of A/R and tree planting for climate mitigation (Luyssaert et al. 2018; Bond et al. 2019; Anderegg et al. 2020; Heilmayr et al. 2020; Holl and Brancalion 2020). The sometimes sole attention on afforestation and reforestation – suggesting it may solve the climate problem to large extent, in combination with the very high estimates of potentials – have led to polarisation in the debate, resulting in criticism to these measures or an emphasis on nature restoration only (Lewis et al. 2019)" (Ch. 7.4.2.2) ((*3*), p. 780). **2. Improved forest management – Technical mitigation potential:** 1.7 (1–2.1) $GtCO_2$ yr^{-1} (Ch. 7.4.2.3); **Economic potential** (up to USD100 per $GtCO_2$ yr^{-1}): 1.1 (0.6–1.9) $GtCO_2$ yr^{-1} (Ch. 7.4.2.3) **3. Agroforestry – Technical mitigation potential:** 4.1 (0.3–9.4) $GtCO_2$-eq yr^{-1} (Ch. 7.4.3.3); **Economic potential** (up to USD100 per GtCO2 yr-1): 0.8 (0.4–1.1) $GtCO_2$-eq yr^{-1} (Ch. 7.4.3.3) **Total technical potential for A/R, improved forest management, agroforestry** (excluding ranges): combined lower mitigation potential: 1.8 $GtCO_2$ yr^{-1}; combined mean mitigation potential: 9.7 $GtCO_2$ yr^{-1}; combined high mitigation potential: 21.5 $GtCO_2$ yr^{-1}; economic potential (up to USD100 per GtCO2 yr-1): 3.5 $GtCO_2$ yr^{-1} **Note**: While Chapter 7 provides the assessed technical mitigation potential with the full range (e.g., for A/R 3.9 (0.5 - 10.1) $GtCO_2$ yr^{-1}), Table 12.6 "Summary of status, costs, potentials, risk and impacts, co-benefits, trade-offs and spillover effects and the role in mitigation pathways for CDR methods" ((*3*), p. 1275), also located in the Technical Summary (as Table TS.7), only provides the full mitigation potential range of each CDR method, rather than the mean, with no further detail on the feasibility of the upper potential. This leaves unquestioned the feasibility of the upper potential, especially when combined with the Technological Readiness Level (8-9 out of 10 for A/R, improved forest management, and agroforestry).
(*9*) – Nolan et al., 2021 **Constraints and enablers for increasing carbon storage in the terrestrial biosphere**	**1.3 – 2.6** $GtCO_2$ yr^{-1} NbCS CDR: conservative potential	**1. Sustainable potential** • **Conservative, grounded CDR potential of 'Nature based Climate Solutions':** 1.3 to 2.6 $GtCO_2$ yr^{-1}. Expert assessment by Nolan et al., on the basis of systematic literature review of biogeochemical NbCS CDR potential up to 2100 (which provide a range of 100-1000 $GtCO_2$), and a qualitative review across a series of constraints: "Given near-term implementation challenges and long-term biogeochemical constraints, a reasonable value for the expected impact of NbCS is up to 100–200 $GtCO_2$ in negative emissions for the remainder of the twenty-first century" ((*9*), p. 436) (100-200 divided by 80 = annual potential of 1.3 to 2.6 $GtCO_2$ yr^{-1}) **2. Methods and further details** **Measures included:** Reforestation, improved forest management, soil carbon sequestration and agroforestry; **Methods:** To estimate 'conservative, grounded' NbCS CDR potential, Nolan et al. translate the NbCS biogeochemical potential into implementable potential, accounting for a suite of feasibility challenges and constraints. Nolan et al.'s systematic review of 42 studies (on several NbCS CDR measures, including afforestation/reforestation, soil carbon sequestration, and other forest measures) results in a mean biogeochemical NbCS CDR potential of 400 $GtCO_2$ (>100 $GtCO_2$ to <1,000 $GtCO_2$) up to 2100, or 5 $GtCO_2$ yr^{-1} (1.25 - 12.5 $GtCO_2$ yr^{-1}) (when divided by 80). Nolan et al. then review the following implementation constraints: effects of net climate forcing, economic constraints (cost), ecosystem services (including biodiversity), land competition, socio-political constraints (including land tenure and governance). From this, Nolan et al. then note that across the studies reviewed, cost-constrained potential is "100 $GtCO_2$ low-cost NbCS (~10–20 USD per tCO_2), and around 400 $GtCO_2$ could be possible at carbon prices of around 100 USD per tCO_2" ((*9*), p. 443). They then conclude: "These estimates do not include consideration of governance, financing and socio-political constraints, and, thus, the implementable capacity is likely significantly less. High quality, highly constrained global estimates are generally around 200 $GtCO_2$ or less. Based on all of these lines of evidence, **a conservative, grounded potential for NbCS contributions to negative emissions is 100–200 $GtCO_2$ during the remainder of the twenty-first century"** ((*9*), p. 444). **3. Inclusion in IPCC AR6 WGIII?** No - published after cut-off date.

Afforestation/Reforestation & Nature-Based CDR – Sequestration sustainability thresholds (GtCO$_2$ yr^{-1}) (continued)		
(*27*) – Roe et al., 2021 **Land-based measures to mitigate climate change: Potential and feasibility by country**	**8.5** GtCO$_2$ yr^{-1} A/R **1.3** GtCO$_2$ yr^{-1} Improved forest management **5.7** GtCO$_2$ yr^{-1} Agroforestry	**1. Technical potentials** • **A/R – Technical potential:** 8.5 GtCO$_2$ yr^{-1} (requiring land area of ~10 Mkm2) **Cost-effective potential** (up to USD100 per GtCO$_2$ yr^{-1}): 1.2 GtCO$_2$ yr^{-1} (requiring ~3 Mkm2) • **Improved forest management – Technical potential:** 1.3 GtCO2 yr-1 **Cost-effective potential** (up to USD100 per GtCO$_2$ yr^{-1}): 1 GtCO$_2$ yr^{-1} • **Agroforestry – Technical potential:** 5.7 GtCO$_2$ yr^{-1} **Cost-effective potential** (up to USD100 per GtCO$_2$ yr^{-1}): 1.1 GtCO$_2$ yr^{-1} • **Combined – Technical potential:** 18 GtCO$_2$ yr^{-1}; **Cost-effective potential** (up to USD100 per GtCO$_2$ yr^{-1}): 5.1 GtCO$_2$ yr^{-1} **2.Methods and further details** **Method:** Sectoral estimates: "based on an extensive literature review and combines mitigation potentials from individual or sectoral studies with available country-level data, and estimates “technical” potential (possible with available technology, regardless of the cost) and “cost-effective” economic potential (possible up to $100/tCO2eq) in 2020–2050 for 20 land- based measures in the 250 countries in the IPCC AR6 Working Group III (WGIII) country and region list" ((*27*), p. 6027). **3. Inclusion in IPCC AR6 WGIII?** **AR6 WGIII cite Roe et al. throughout Chapter 7** for 'bottom-up', sectoral potential estimates to complement IAM estimates.
(*29*) – IPCC Special Report on Climate Change and Land, SPM, 2019	**80-300 million** people at risk of undernourishment	**The Summary for Policymakers of the IPCC Special Report on Climate Change and Land notes: “large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people” (Figure SPM.3)** ((*29*), p. 27). In relation to 'large-scale afforestation' the SPM refers to afforestation at scales of 8.9 GtCO$_2$ yr^{-1} and 10.1 GtCO$_2$ yr^{-1}.

Supplementary Materials for

Sustainability limits needed for CO_2 removal

Supplement S2. Sustainability risks for land-based carbon dioxide removal (CDR) for the five IPCC Illustrative Mitigation Pathways (IMPs) compatible with the Paris Agreement (Table S2.1), and supporting analysis

Supplement S3 includes:

- **METHODS**: for Table S2.1 and Table S2.2
- **TABLE S2.1**: Sustainability risks for land-based carbon dioxide removal (CDR) for the five IPCC Illustrative Mitigation Pathways (IMPs) compatible with the Paris Agreement
- **TABLE S2.2**: Extended version of Table S2.1

This Supplementary Material describes the development of Table S2.1 which assesses the sustainability of CDR sequestration and land-footprint of the five IPCC AR6 WGIII Illustrative Mitigation Pathways (IMPs), and S2.2 (detailed version of S2.1).

The IMPs are presented namely in IPCC AR6 WGIII Summary for Policymakers (*31*) Figure SPM.5 "Illustrative Mitigation Pathways (IMPs) and net zero CO2 and GHG emissions strategies" (building from WGIII Chapters 3.3 and 3.4), and in the Summary for Policymakers of the IPCC AR6 WGIII Synthesis Report (*32*), Figure SPM.5 "Figure SPM.5: Global emissions pathways consistent with implemented policies and mitigation strategies". In both these IPCC figures, the IMPs are used to illustrate different pathways compatible with the Paris Agreement temperature goals, and emissions and CDR profiles at the point of net zero CO_2 (for WGIII SPM.5 panel (e)), and net zero GHG (for SYR SPM.5 panel (e)). The figure WGIII SPM.5 also presents graphically the net emission pathways for the IMPs, up to 2100 (panel (a)).

Neither of the two IPCC figures, however, detail the IMPs' associated CDR land footprint.

Table S2.1 therefore aims, for two key dates (2050 and 2100) to:

1. Present the five IMPs' CDR sequestration ($GtCO_2\ yr^{-1}$) and corresponding land-footprint profile (million km^2), side by side with some of the IMPs' key data points on CO_2 emissions (emissions reduction relative to 2020; residual CO_2 emissions in 2050) and energy (total primary energy, and primary energy from fossil fuels), all while making more explicit the distinction between the 1.5ºC high overshoot IMP ('IMP-Neg') and the three 1.5ºC limited overshoot IMPs ('IMP-LD', IMP-SP', 'IMP-Ren') – a distinction absent in the two IPCC figures mentioned above;
2. Assess the sustainability of CDR in these pathways – sequestration ($GtCO_2\ yr^{-1}$) and land-footprint (million km^2) – based on the sustainability thresholds developed by the authors in Figure 1 and S1.

METHODS For Table S2.1 and Table S2.2

Data:

The data for Table S2.1 and Table S2.2 is developed in the following manner. For more information and underlying data and calculations, see Excel file 'Supporting Data for Tables S2.1 and S2.2', publicly available at: https://doi.org/10.7910/DVN/5JEQ9V (*15*).

Sections 'CO$_2$ emissions & energy' and 'CDR- sequestration'

Lines in these sections are calculated from data drawn from the AR6 Scenarios Database hosted by IIASA (*30*) for the five scenarios behind the five IMPs. Specifically, the following lines are calculated from the variables:

- **CO2 emissions change and residual emissions:** variable 'Emissions|CO2'
- **Total primary energy:** variable 'Primary Energy'
- **Primary energy: fossil fuels:** variable 'Primary Energy|Fossil'
- **BECCS [sequestration]:** variable 'Carbon Sequestration|CCS|Biomass'
- **Afforestation/Reforestation [sequestration]:** variables 'Carbon Sequestration|Land Use|Afforestation' when present (for 'IMP-GS', 'IMP-SP', and 'IMP-Ren'). When 'Carbon Sequestration|Land Use|Afforestation' is absent (in the scenarios 'IMP-Neg' and 'IMP-LD'), we use as a proxy 'Carbon Sequestration|Land Use' (which according to the IPCC AR6 database glossary includes 'afforestation, soil carbon enhancement, and biochar'), under the assumption that it mostly includes afforestation. We base this assumption on the fact that the IPCC AR6 WGIII Technical Summary (*33*) states that soil carbon enhancement (or sequestration) and biochar are "not yet in global mitigation pathways simulated by IAM" ((*33*), Table TS.7). Further, we work under the assumption that the reference to 'afforestation' in 'Carbon Sequestration|Land Use|Afforestation' and 'Carbon Sequestration|Land Use' also covers 'reforestation', given the IPCC AR6 WGII refers to afforestation and reforestation together when discussing the inclusion of this method within IAMs ((*33*), Table TS.7).
- **DACCS, Enhanced Weathering, other [sequestration]:** an addition of the variables 'Carbon Sequestration|Direct Air Capture', 'Carbon Sequestration|Enhanced Weathering', and 'Carbon Sequestration|Other'
- **Total CDR [sequestration]:** is a sum of lines 'BECCS', 'A/R', and 'DACCS, Enhanced Weathering, Other'.

Section 'CDR land footprint'

Lines in this section are calculated drawing from the data in the 'CDR Sequestration' section, combined with the conversion rates also used behind Figure 1, as follows:

- **For BECCS:** high and low capture rates are calculated from (*16*). The medium capture rate is the mean of the low and high.
- **For A/R:** the conversion is the mean of the range given by (*9*).

We decided on this approach for calculating the CDR land-footprint, instead of that of using the land-footprint variables in the AR6 scenarios database (*30*). We found the following limitations to using the variables:

- Limit of comparability across the IMPs: This difficulty of comparability is linked to the fact that (i) the variables 'Land Cover|Forest|Afforestation and Reforestation' and 'Land Cover|Cropland|Energy Crops' were not present for all IMPs (absent for IMP-Neg); (ii) comparing the data points for the CDR land-use scenario variables and for the CDR sequestration variables demonstrates that the conversion rates used by the different IMPs vary widely, and hence distorts the comparison.

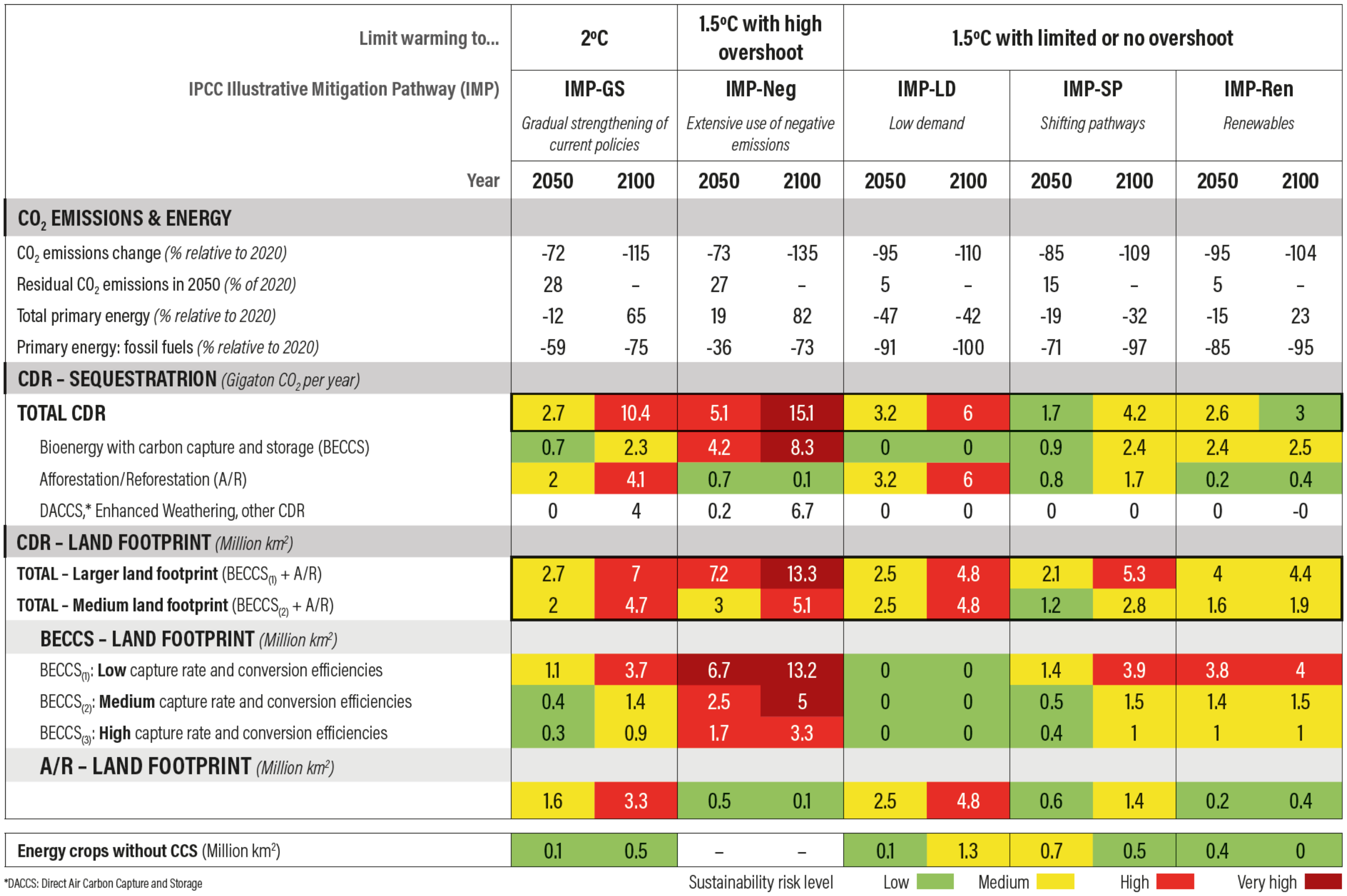
The standalone line 'Energy crops w/o CCS'

This line is calculated: for 'IMP-GS' from 'Land Cover|Cropland|Energy Crops', 'Capacity|Electricity|Biomass,' and 'Capacity|Electricity|Biomass|w/ CCS'; for 'IMP-LD' from line 'Land Cover|Cropland|Energy Crops'; for 'IMP-SP' and 'IMP-Ren' from 'Land Cover|Cropland|Energy Crops', 'Primary Energy|Biomass|Energy Crops', and 'Primary Energy|Biomass|Modern|w/ CCS'

Color coding:

The CDR sequestration and land-footprint cells of Table S2.1 and Table S2.2 are colored in line with authors' CDR sustainability thresholds assessment (see Figure 1 and S1 for further details).

Table S2.1: Sustainability risks for land-based carbon dioxide removal (CDR) for the five IPCC Illustrative Mitigation Pathways (IMPs) compatible with the Paris Agreement. Lowest risks (green shading) of overstepping sustainability bounds are mostly achieved by the scenarios with faster and deeper reductions in CO₂ emissions (‘IMP-SP’ and ‘IMP-Ren’) or with low energy demand (‘IMP-LD’); nevertheless, even these scenarios include some medium (yellow) and high (red) risks, particularly if involving larger land footprints and low carbon capture rates. The highest risks arise from scenarios with slower emission reductions (‘IMP-GS’ and ‘IMP-Neg’). Note that the high carbon capture rate and conversion efficiency level is considered very optimistic *(5, 16)*. Color codes for sustainability risk levels are the same as in Figure 1 in the main manuscript (see also S1). Table S2.1 makes visible how the CDR use of the 1.5°C high overshoot (‘IMP-Neg’) oversteps sustainability thresholds significantly more than the 1.5°C limited or no overshoot IMPs (‘IMP-LD’, IMP-SP’, ‘IMP-Ren’). The CDR use and land-footprint of the ‘2°C’ IMP (‘IMP-GS’) falls between that of the ‘1.5°C high overshoot’ IMP and the ‘1.5°C limited or no overshoot’ IMPs. See ‘S2 Methods’ and Table S2.2 for further details.

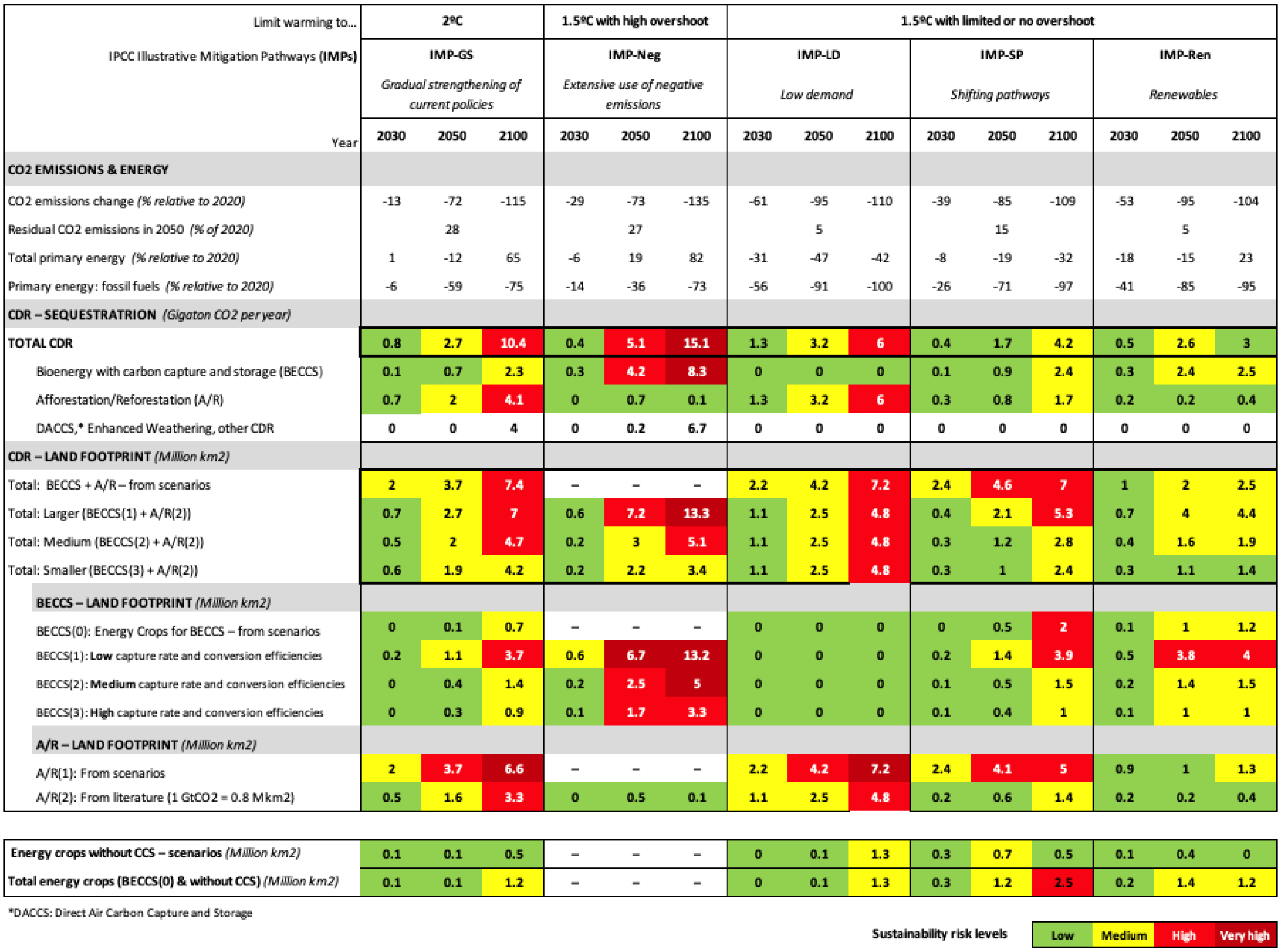


Limit warming to...	2°C		1.5°C with high overshoot		1.5°C with limited or no overshoot					
IPCC Illustrative Mitigation Pathway (IMP)	**IMP-GS** *Gradual strengthening of current policies*		**IMP-Neg** *Extensive use of negative emissions*		**IMP-LD** *Low demand*		**IMP-SP** *Shifting pathways*		**IMP-Ren** *Renewables*	
Year	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**
CO_2 EMISSIONS & ENERGY										
CO_2 emissions change *(% relative to 2020)*	-72	-115	-73	-135	-95	-110	-85	-109	-95	-104
Residual CO_2 emissions in 2050 *(% of 2020)*	28	-	27	-	5	-	15	-	5	-
Total primary energy *(% relative to 2020)*	-12	65	19	82	-47	-42	-19	-32	-15	23
Primary energy: fossil fuels *(% relative to 2020)*	-59	-75	-36	-73	-91	-100	-71	-97	-85	-95
CDR – SEQUESTRATRION *(Gigaton CO_2 per year)*										
TOTAL CDR	2.7	10.4	5.1	15.1	3.2	6	1.7	4.2	2.6	3
Bioenergy with carbon capture and storage (BECCS)	0.7	2.3	4.2	8.3	0	0	0.9	2.4	2.4	2.5
Afforestation/Reforestation (A/R)	2	4.1	0.7	0.1	3.2	6	0.8	1.7	0.2	0.4
DACCS,* Enhanced Weathering, other CDR	0	4	0.2	6.7	0	0	0	0	0	-0
CDR – LAND FOOTPRINT *(Million km^2)*										
TOTAL – Larger land footprint ($BECCS_{(1)}$ + A/R)	2.7	7	7.2	13.3	2.5	4.8	2.1	5.3	4	4.4
TOTAL – Medium land footprint ($BECCS_{(2)}$ + A/R)	2	4.7	3	5.1	2.5	4.8	1.2	2.8	1.6	1.9
BECCS – LAND FOOTPRINT *(Million km^2)*										
$BECCS_{(1)}$: **Low** capture rate and conversion efficiencies	1.1	3.7	6.7	13.2	0	0	1.4	3.9	3.8	4
$BECCS_{(2)}$: **Medium** capture rate and conversion efficiencies	0.4	1.4	2.5	5	0	0	0.5	1.5	1.4	1.5
$BECCS_{(3)}$: **High** capture rate and conversion efficiencies	0.3	0.9	1.7	3.3	0	0	0.4	1	1	1
A/R – LAND FOOTPRINT *(Million km^2)*										
	1.6	3.3	0.5	0.1	2.5	4.8	0.6	1.4	0.2	0.4
Energy crops without CCS (Million km^2)	0.1	0.5	–	–	0.1	1.3	0.7	0.5	0.4	0

*DACCS: Direct Air Carbon Capture and Storage

Sustainability risk level Low 🟩 Medium 🟨 High 🟥 Very high 🟥

Table S2.2: Extended version of Table S2.1: Sustainability risks for land-based carbon dioxide removal (CDR) for the five IPCC Illustrative Mitigation Pathways (IMPs) compatible with the Paris Agreement. As compared to Table S2.1, Table S2.2 includes an additional year (2030), and several additional lines under the section 'CDR – land footprint', specifically land footprints assumed by the scenarios, and additional calculations of possible land-use totals. Data in 'CO2 Emissions & Energy' and 'CDR-Sequestration' (and in lines 'Energy crops without CCS', and 'Total energy crops (BECCS and w/o CCS)') are drawn and calculated from data in the IPCC AR6 scenarios database. Data in 'CDR-Land Footprint' are calculated based on the 'sequestration' data and conversion rates from the literature (*9*, *16* and see 'S2 Methods' for further details). Bioenergy land footprint for BECCS can vary widely (illustrated in Table S2.2 with the three carbon capture rates); a high capture rate is overly optimistic (*5*, *16*). In Table S2.2 we also include the land footprint assumed for BECCS and A/R by the IMPs; the table shows that the IMPs use different land-footprint assumptions, which makes comparability across IMPs difficult (see S2 methods for details). Colored cells show risk levels of CDR deployment and land footprint; they are filled using authors' CDR sustainability thresholds assessment (see Figure 1, and S1). Table S2.2 shows how the CDR use of the 1.5°C high overshoot ('IMP-Neg') extensively overstep sustainability thresholds, significantly more than the 1.5°C limited or no overshoot IMPs ('IMP-LD', IMP-SP', 'IMP-Ren'). The CDR use and land-footprint of the '2°C' IMP ('IMP-GS') falls between that of the '1.5°C high overshoot' IMP and the '1.5°C limited or no overshoot' IMPs. See 'S2 Methods' for more details.



Limit warming to...	2ºC			1.5ºC with high overshoot			1.5ºC with limited or no overshoot								
IPCC Illustrative Mitigation Pathways (IMPs)	IMP-GS			IMP-Neg			IMP-LD			IMP-SP			IMP-Ren		
	Gradual strengthening of current policies			*Extensive use of negative emissions*			*Low demand*			*Shifting pathways*			*Renewables*		
Year	**2030**	**2050**	**2100**	**2030**	**2050**	**2100**	**2030**	**2050**	**2100**	**2030**	**2050**	**2100**	**2030**	**2050**	**2100**
CO2 EMISSIONS & ENERGY															
CO2 emissions change *(% relative to 2020)*	-13	-72	-115	-29	-73	-135	-61	-95	-110	-39	-85	-109	-53	-95	-104
Residual CO2 emissions in 2050 *(% of 2020)*		28			27			5			15			5	
Total primary energy *(% relative to 2020)*	1	-12	65	-6	19	82	-31	-47	-42	-8	-19	-32	-18	-15	23
Primary energy: fossil fuels *(% relative to 2020)*	-6	-59	-75	-14	-36	-73	-56	-91	-100	-26	-71	-97	-41	-85	-95
CDR – SEQUESTRATRION *(Gigaton CO2 per year)*															
TOTAL CDR	0.8	2.7	10.4	0.4	5.1	15.1	1.3	3.2	6	0.4	1.7	4.2	0.5	2.6	3
Bioenergy with carbon capture and storage (BECCS)	0.1	0.7	2.3	0.3	4.2	8.3	0	0	0	0.1	0.9	2.4	0.3	2.4	2.5
Afforestation/Reforestation (A/R)	0.7	2	4.1	0	0.7	0.1	1.3	3.2	6	0.3	0.8	1.7	0.2	0.2	0.4
DACCS,* Enhanced Weathering, other CDR	0	0	4	0	0.2	6.7	0	0	0	0	0	0	0	0	0
CDR – LAND FOOTPRINT *(Million km2)*															
Total: BECCS + A/R – from scenarios	2	3.7	7.4	–	–	–	2.2	4.2	7.2	2.4	4.6	7	1	2	2.5
Total: Larger (BECCS(1) + A/R(2))	0.7	2.7	7	0.6	7.2	13.3	1.1	2.5	4.8	0.4	2.1	5.3	0.7	4	4.4
Total: Medium (BECCS(2) + A/R(2))	0.5	2	4.7	0.2	3	5.1	1.1	2.5	4.8	0.3	1.2	2.8	0.4	1.6	1.9
Total: Smaller (BECCS(3) + A/R(2))	0.6	1.9	4.2	0.2	2.2	3.4	1.1	2.5	4.8	0.3	1	2.4	0.3	1.1	1.4
BECCS – LAND FOOTPRINT *(Million km2)*															
BECCS(0): Energy Crops for BECCS – from scenarios	0	0.1	0.7	–	–	–	0	0	0	0	0.5	2	0.1	1	1.2
BECCS(1): **Low** capture rate and conversion efficiencies	0.2	1.1	3.7	0.6	6.7	13.2	0	0	0	0.2	1.4	3.9	0.5	3.8	4
BECCS(2): **Medium** capture rate and conversion efficiencies	0	0.4	1.4	0.2	2.5	5	0	0	0	0.1	0.5	1.5	0.2	1.4	1.5
BECCS(3): **High** capture rate and conversion efficiencies	0	0.3	0.9	0.1	1.7	3.3	0	0	0	0.1	0.4	1	0.1	1	1
A/R – LAND FOOTPRINT *(Million km2)*															
A/R(1): From scenarios	2	3.7	6.6	–	–	–	2.2	4.2	7.2	2.4	4.1	5	0.9	1	1.3
A/R(2): From literature (1 GtCO2 = 0.8 Mkm2)	0.5	1.6	3.3	0	0.5	0.1	1.1	2.5	4.8	0.2	0.6	1.4	0.2	0.2	0.4

Energy crops without CCS – scenarios *(Million km2)*	0.1	0.1	0.5	–	–	–	0	0.1	1.3	0.3	0.7	0.5	0.1	0.4	0
Total energy crops (BECCS(0) & without CCS) *(Million km2)*	0.1	0.1	1.2	–	–	–	0	0.1	1.3	0.3	1.2	2.5	0.2	1.4	1.2

*DACCS: Direct Air Carbon Capture and Storage

Sustainability risk levels

Low	Medium	High	Very high
🟩	🟨	🟥	🟥

Supplementary Materials for

Sustainability limits needed for CO_2 removal

Supplement S3: IPCC AR6 WGIII 1.5ºC pathways and CDR sustainability thresholds

This Supplementary Material describes our assessment of the number of scenarios across categories C1 (1.5ºC with no to limited overshoot), C2 (1.5ºC with large overshoot), and C3 (2ºC) included in the AR6 Scenarios Database hosted by IIASA (*30*), that overstep the CDR sustainability thresholds we calculate in Fig. 1 and S1.

Supplement S3 includes:

- **METHODS**
- **TABLE** S3.1 BECCS sustainability thresholds applied to IPCC C1, C2, and C3 category scenarios
- **TABLE** S3.2 A/R sustainability thresholds applied to IPCC C1, C2, and C3 category scenarios

Methods

All analyses were derived directly from the IPCC's AR6 Scenarios database (*30*), using the categorical codes found in the metadata for each scenario. The analysis were conducted as follows:

- **BECCS:** Analysis of the percentage of scenarios of categories C1, C2, and C3 in the AR6 Scenarios Database that deploy BECCS beyond the low, medium and high-risk sustainability thresholds assessed by authors (in Figure 1 and Supplement S1), considering (a) medium carbon capture rate, and (b) low carbon capture rate, in the years 2050 and 2100. The variable assessed across the C1-C3 categories is: 'Carbon Sequestration|CCS|Biomass.'
- **Afforestation/Reforestation:**
    - Analysis of the percentage of scenarios of categories C1, C2, and C3 in the AR6 Scenarios Database that deploy A/R beyond the low, medium and high-risk sustainability thresholds assessed by authors (in Figure 1 and Supplement S1), in the years 2050 and 2100.
    - The variable assessed across the C1-C3 categories is: 'Carbon Sequestration|Land Use|Afforestation.' Note that this variable is only present in a subset of category C1-C3 scenarios: in 40% of C1 scenarios, 49% of C2 scenarios, and 29% of C3 scenarios. Note also that the variable 'Carbon Sequestration|Land Use' is present in a broader subset of C1-C3 scenarios (in 55% of C1 scenarios, 69% of C2 scenarios, and 53% of C3 scenarios); yet we do not use this variable for our analysis as its data refers to three CDR methods – afforestation, soil carbon sequestration, and biochar – which it is not possible to disaggregate based on the information in the dataset. We do not assess soil carbon sequestration and biochar in our analysis.
    - Note that the variable 'Carbon Sequestration|Land Use|Afforestation' only includes 'afforestation' rather than also reforestation. This highlights the lack of granularity within scenarios in distinguishing between afforestation and reforestation (and between monoculture reforestation and diverse species reforestation), methods whose sustainability impacts differ strongly (*1, 9*).

The code developed to conduct this analysis is publicly available at: https://doi.org/10.7910/DVN/5JEQ9V (*15*).

Table S3.1 BECCS sustainability thresholds applied to IPCC C1, C2, and C3 category scenarios. The table shows the percentage of C1, C2, and C3 category scenarios that deploy, in 2050 and 2100, BECCS to scales that overstep the sustainability thresholds assessed by authors in Figure 1 in the main manuscript, and Supplement S1. Panel (a) shows the sustainability thresholds when considering a low carbon capture rate – implying a larger BECCS land footprint; and Panel (b) when considering a medium carbon capture rate – implying a smaller land footprint.

Panel (a)

	1.5ºC and 2ºC scenarios exceeding BECCS sustainability thresholds (considering a LOW carbon capture rate)					
	2050			2100		
	Number of scenarios which overstep…			Number of scenarios which overstep…		
	LOW risk threshold (0.7 GtCO$_2$ yr^{-1})	MEDIUM risk threshold (1.4 GtCO$_2$ yr^{-1})	HIGH risk threshold (3.3 GtCO$_2$ yr^{-1})	LOW risk threshold (0.7 GtCO$_2$ yr^{-1})	MEDIUM risk threshold (1.4 GtCO$_2$ yr^{-1})	HIGH risk threshold (3.3 GtCO$_2$ yr^{-1})
C1: 1.5ºC with no to limited overshoot	93%	82%	70%	94%	94%	86%
C2: 1.5ºC with high overshoot	90%	72%	52%	99%	99%	97%
C3: 2ºC	84%	67%	39%	97%	97%	93%

Panel (b)

	1.5ºC and 2ºC scenarios exceeding BECCS sustainability thresholds (considering a MEDIUM carbon capture rate)					
	2050			2100		
	Number of scenarios which overstep…			Number of scenarios which overstep…		
	LOW risk threshold (1.2 GtCO$_2$ yr^{-1})	MEDIUM risk threshold (2.9 GtCO$_2$ yr^{-1})	HIGH risk threshold (7.8 GtCO$_2$ yr^{-1})	LOW risk threshold (1.2 GtCO$_2$ yr^{-1})	MEDIUM risk threshold (2.9 GtCO$_2$ yr^{-1})	HIGH risk threshold (7.8 GtCO$_2$ yr^{-1})
C1: 1.5ºC with no to limited overshoot	84%	70%	21%	94%	87%	54%
C2: 1.5ºC with high overshoot	72%	58%	15%	99%	97%	78%

C3: 2ºC	70%	43%	6%	97%	95%	62%

Table S3.2 A/R sustainability thresholds applied to C1, C2, and C3 scenarios in the IPCC AR6 Scenarios Database. The table shows the percentage of C1, C2, and C3 category scenarios that deploy in 2050 and 2100 A/R to scales that overstep the sustainability thresholds assessed by authors in Figure 1 in the main manuscript and Supplement S1.

	1.5ºC and 2ºC scenarios exceeding afforestation/reforestation sustainability thresholds					
	2050			2100		
	Number of scenarios which overstep…			Number of scenarios which overstep…		
	LOW risk threshold (1.3 $GtCO_2$ yr^{-1})	MEDIUM risk threshold (3.8 $GtCO_2$ yr^{-1})	HIGH risk threshold (6.3 $GtCO_2$ yr^{-1})	LOW risk threshold (1.3 $GtCO_2$ yr^{-1})	MEDIUM risk threshold (3.8 $GtCO_2$ yr^{-1})	HIGH risk threshold (6.3 $GtCO_2$ yr^{-1})
C1: 1.5ºC with no to limited overshoot	66%	39%	16%	61%	45%	5%
C2: 1.5ºC with high overshoot	83%	29%	10%	77%	62%	3%
C3: 2ºC	76%	7%	4%	77%	71%	1%

Supplementary Materials for

Sustainability limits needed for CO_2 removal

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