Supplementary Information

For the manuscript *Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations* by Boysen et al. submitted to Environmental Research Letters: ERL-102570

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SI.1 Global distribution of BG and BT

The global distribution of both biomass types is the result of their assumed implementation following the highest accumulated annual biomass harvest potential and, respectively, the according changes in carbon pools in 2100 (Fig. S1a). The bioenergy type with the best net outcome is taken for each cell individually. If the choice is done only regarding the highest accumulated biomass harvest in 2100 without taking carbon changes into account, a different distribution results (Fig. S1b).

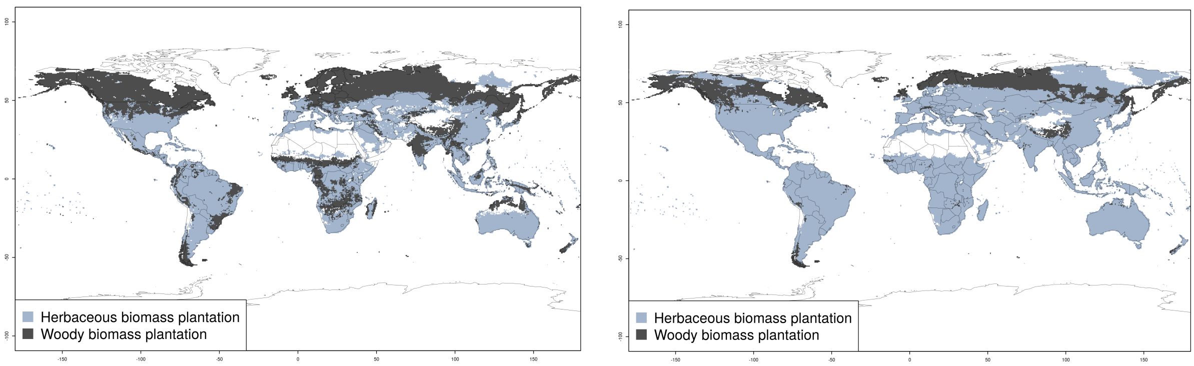

Figure S1 (left) global distribution of herbaceous and woody biomass plantations, (right) the distribution for the choice of cells regarding only the highest biomass harvest.

SI.2 Albedo calculation in LPJmL

The albedo calculation in LPJmL follows the procedures from (Strengers et al., 2010) and (Forkel et al., 2014). Albedo values for crop residues (straw, stubble) have been adapted with a mean value of 0.27 following literature (Davin et al., 2014; Horton et al., 1996; Merlin et al., 2013). BG residues were estimated with 0.32 following (Kucharik et al., 2013). Soil albedo in LPJmL is, due to the lack of detailed soil albedo representation, uniformly set to 0.4 which is higher than values given in the above-mentioned publications for agricultural land. However, since the model simulates stubble and crop residues which remain on the field and cover the soil colour, this disadvantage is partly set-off.

Choice of cells for BP

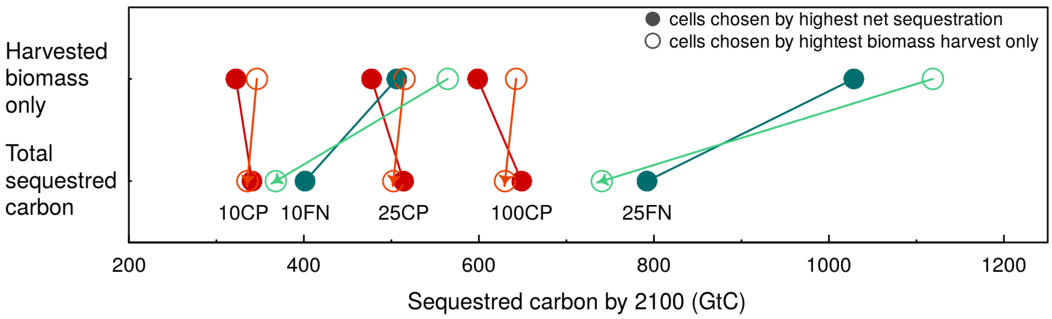

Figure S2 Comparison of the choice of cells for the sequestration potential either with focus of highest harvest only (open circle) or total sequestration potential including land carbon changes (filled circles).

Literature review on tCDR

Table S1 Literature review on tCDR as explicit climate engineering method, the physical limits and potential areas and large-scale mitigation studies including re- and afforestation projects.

Explicit tCDR				
	Time	Area (Mha)	Potential (GtC)	Annotation
Lenton (2010)	100 years	695- 1014	68 - 133	Most realistic available land for afforestation; only on abandoned agricultural land (range over A1b and B2, van Minnen 2008)
	100 years	3800-4000	150-900	Without food constraints
	Today-2100	390-750 (dedicated bioenergy area) + (695 to 1014)	~500	Overall potential with natural sink, surplus wood, afforestation on abandoned land, Biochar, BECS (50% capture rate) and reduction of emissions: 4-6 GtC/yr by 2050, 6-14 GtC/yr in 2100
Powell and Lenton (2012)	2000-2050	332-686	180-260	Annual carbon fluxes of 5.2 and 3.6 GtC over 50years with bioenergy crops in low and high meat scenarios with high efficiency (low to moderate land-use increase)
Caldeira et al. (2013)	2000-2100	437	100	3% of global land area needed to extract 1GtC/yr with biomass energy from managed temperate forests and CCS
Vaughan and (Lenton, 2011)	Until 2060	4300	165-183	Soil carbon restoration and re- and afforestation until 2060 leading to a reversal of past land-use and land cover change emissions
Heck et al. (2016)	1982-2005	4266	277-309	Year 2005's agricultural land converted to either BG or BT, irrigated on today's irrigated areas, simulations from 1901-2005, compared to carbon changes under land-use
Keller et al. (2014)	2020-2100	1548	131	Afforestation of the North African and Australian deserts under RCP8.5, irrigated.
Physical limits & potential areas				
	Time	Area (Mha)	Potential (GtC)	Annotation
Minnen et al. (2008)	Until 2100	3850- 3990	583, 913	Physical potential: A1b permanent or harvested forest (wherever more effective than baseline land-use scenario)
		3830	858	Physical potential: B2 harvested forest (as in A1b)
		831-1014	93,133	Social potential: A1b only abandoned agricultural land with permanent or harvested forest (food and nature conservation constraints)
		695	68	Social potential: B2 abandoned agricultural land with harvested forest (as in A1b)
Lambin et al. (2013)	Currently available	445		Worldbank report 2010
		598		This study, retrieved from GAEZ 3.0
		1400		IIASA/FAO prime land that could be cultivated and is not protected but low productive (Alexandratos & Bruinsma, 2012)
		2100		IIASA/FAO 2012 suitable land GAEZ3.0 (3100Mha suitable, 1000 Mha already under cultivation)

Large-scale mitigation (Re- and afforestation)				
	Time	Area (Mha)	Potential (GtC)	Annotation
Humpenöder et al. (2014)	Until 2095	2773	192	Natural afforestation of pasture and crop lands due to carbon taxes on emissions; 1.21%/yr yield increase
		508	162	Herbaceous and woods bioenergy for BECCS on food crop land; 1%/yr yield increase
		2866 = 2566 afforestation + 300 bioenergy	272	1.36%/yr yield increase
Arora and Montenegro (2011)	Until 2100	1000-2200	120-240	50 to 100% afforestation of historic crop lands between 2011 and 2060; including biogeophysical and biogeochemical climate feedbacks (CO2 fertilization, albedo and temperature effects, ocean uptake), A2 emission pathway
Vuuren et al. (2007)	Until 2100	725-940	116-146	Forestry on abandoned land (range B2, B1 and A1b)
Smith et al. (2013)	50 years	218-990	50	Land required to extract 1 GtC/yr (with 2.1 GtC/yr produced) using temperate Switchgrass or tropical eucalyptus and depending on harvest and leakage rates
Beringer et al. (2011)	2050	142-464		Sustainability requirements for conversion of land (food production, biodiversity, carbon storage)
			28-125	Rain fed
			56-188	Sustainable irrigation from surface run-off
			141-292	Irrigation with renewable water resources
Kato and Yamagata (2014)	2006-2100	415	43-160	RCP2.6's bioenergy areas (83% of 500 Mha agricultural land increase); current fertilizer input and low CCS level to high fertilizer input and CCS level to stay within 2°C target
Edmonds et al. (2013)	2020-2095	570 = 320 unmanaged natural land + 250 dedicated bioenergy land	163-391	Different combinations of CCS and bioenergy levels depending on policies; different CCS and dietary trends to secure feeding 9bn people on 250 Mha.
Reilly et al. (2012)	2000-2100	1400	178	Afforestation, avoided deforestation and bioenergy on crop land; simultaneous emission reductions
Smith et al. (2016)	2100	380-700	330	BECCS needed to limit warming to 2°C (3.3 GtCeq/yr)
		320-970	110-330	Afforestation (1.1-3.3 GtCeq/yr)

SI.2 Quantification of impacts on evapotranspiration (ET)

Table S2 Local moisture fluxes (evapotranspiration ET, transpiration and evaporation in km^3) on the areas considered for tCDR under constant land-use (2005) or BP in the year 2100.

Moisture flux	Scenario	100AGR	25AGR	10AGR	100NAT	25NAT	10NAT
ET	LU const	20498	13001	7669	43369	21914	10556
	BP	0%	+6%	+7%	+7%	+8%	+8%
Transp.	LU const	11386	7655	4609	31640	16141	7894
	BP	+35%	+40%	+40%	+5%	+6%	+6%
Evap.	LU const	8529	5009	2810	4305	1461	601
	BP	-66%	-77%	-82%	+47%	+58%	+66%

References

Arora, V.K., Montenegro, A., 2011. Small temperature benefits provided by realistic afforestation efforts. Nat. Geosci. 4, 514–518. doi:10.1038/ngeo1182

Beringer, T., Lucht, W., Schaphoff, S., 2011. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy 3, 299–312. doi:10.1111/j.1757-1707.2010.01088.x

Caldeira, K., Bala, G., Cao, L., 2013. The Science of Geoengineering. Annu. Rev. Earth Planet. Sci. 41, 231–256. doi:10.1146/annurev-earth-042711-105548

Davin, E.L., Seneviratne, S.I., Ciais, P., Olioso, A., Wang, T., 2014. Preferential cooling of hot extremes from cropland albedo management. Proc. Natl. Acad. Sci. 111, 9757–9761. doi:10.1073/pnas.1317323111

Edmonds, J., Luckow, P., Calvin, K., Wise, M., Dooley, J., Kyle, P., Kim, S.H., Patel, P., Clarke, L., 2013. Can radiative forcing be limited to 2.6 Wm−2 without negative emissions from bioenergy AND CO2 capture and storage? Clim. Change 118, 29–43. doi:10.1007/s10584-012-0678-z

Forkel, M., Carvalhais, N., Schaphoff, S., v. Bloh, W., Migliavacca, M., Thurner, M., Thonicke, K., 2014. Identifying environmental controls on vegetation greenness phenology through model–data integration. Biogeosciences 11, 7025–7050. doi:10.5194/bg-11-7025-2014

Heck, V., Gerten, D., Lucht, W., Boysen, L.R., 2016. Is extensive terrestrial carbon dioxide removal a "green" form of geoengineering? A global modelling study. Glob. Planet. Change 137, 123–130. doi:10.1016/j.gloplacha.2015.12.008

Horton, R., Bristow, K.L., Kluitenberg, G.J., Sauer, T.J., 1996. Crop residue effects on surface radiation and energy balance — review. Theor. Appl. Climatol. 54, 27–37. doi:10.1007/BF00863556

Humpenöder, F., Popp, A., Dietrich, J.P., Klein, D., Lotze-Campen, H., Bonsch, M., Bodirsky, B.L., Weindl, I., Stevanovic, M., Müller, C., 2014. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. Environ. Res. Lett. 9, 64029. doi:10.1088/1748-9326/9/6/064029

Kato, E., Yamagata, Y., 2014. BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. Earths Future 2014EF000249. doi:10.1002/2014EF000249

Keller, D.P., Feng, E.Y., Oschlies, A., 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nat. Commun. 5. doi:10.1038/ncomms4304

Kucharik, C.J., VanLoocke, A., Lenters, J.D., Motew, M.M., 2013. Miscanthus Establishment and Overwintering in the Midwest USA: A Regional Modeling Study of Crop Residue Management on Critical Minimum Soil Temperatures. PLOS ONE 8, e68847. doi:10.1371/journal.pone.0068847

Lambin, E.F., Gibbs, H.K., Ferreira, L., Grau, R., Mayaux, P., Meyfroidt, P., Morton, D.C., Rudel, T.K., Gasparri, I., Munger, J., 2013. Estimating the world's potentially available cropland using a bottom-up approach. Glob. Environ. Change 23, 892–901. doi:10.1016/j.gloenvcha.2013.05.005

Lenton, T.M., 2010. The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. Carbon Manag. 1, 145–160. doi:10.4155/cmt.10.12

Merlin, O., Chrirouze, J., Olioso, A., Jarlan, L., Chehbouni, G., Boulet, G., 2013. An image-based four-source surface energy balance model to estimate crop evapotranspiration from solar reflectance/thermal emission data (SEB-4S)

[WWW Document]. URL http://www.sciencedirect.com/science/article/pii/S0168192313002700 (accessed 3.21.16).
Minnen, J.G. van, Strengers, B.J., Eickhout, B., Swart, R.J., Leemans, R., 2008. Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. Carbon Balance Manag. 3, 3. doi:10.1186/1750-0680-3-3
Powell, T.W.R., Lenton, T.M., 2012. Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. Energy Environ. Sci. 5, 8116. doi:10.1039/c2ee21592f
Reilly, J., Melillo, J., Cai, Y., Kicklighter, D., Gurgel, A., Paltsev, S., Cronin, T., Sokolov, A., Schlosser, A., 2012. Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs. Environ. Sci. Technol. 46, 5672–5679. doi:10.1021/es2034729
Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., Vuuren, D.P. van, Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Change 6, 42–50. doi:10.1038/nclimate2870
Smith, P., Haberl, H., Popp, A., Erb, K., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Change Biol. 19, 2285–2302. doi:10.1111/gcb.12160
Strengers, B.J., Müller, C., Schaeffer, M., Haarsma, R.J., Severijns, C., Gerten, D., Schaphoff, S., van den Houdt, R., Oostenrijk, R., 2010. Assessing 20th century climate–vegetation feedbacks of land-use change and natural vegetation dynamics in a fully coupled vegetation–climate model. Int. J. Climatol. 30, 2055–2065.
Vaughan, N.E., Lenton, T.M., 2011. A review of climate geoengineering proposals. Clim. Change 109, 745–790. doi:10.1007/s10584-011-0027-7
Vuuren, D.P. van, Elzen, M.G.J. den, Lucas, P.L., Eickhout, B., Strengers, B.J., Ruijven, B. van, Wonink, S., Houdt, R. van, 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim. Change 81, 119–159. doi:10.1007/s10584-006-9172-9