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More diverse benefits from timber versus dedicated bioenergy plantations for terrestrial carbon dioxide removal

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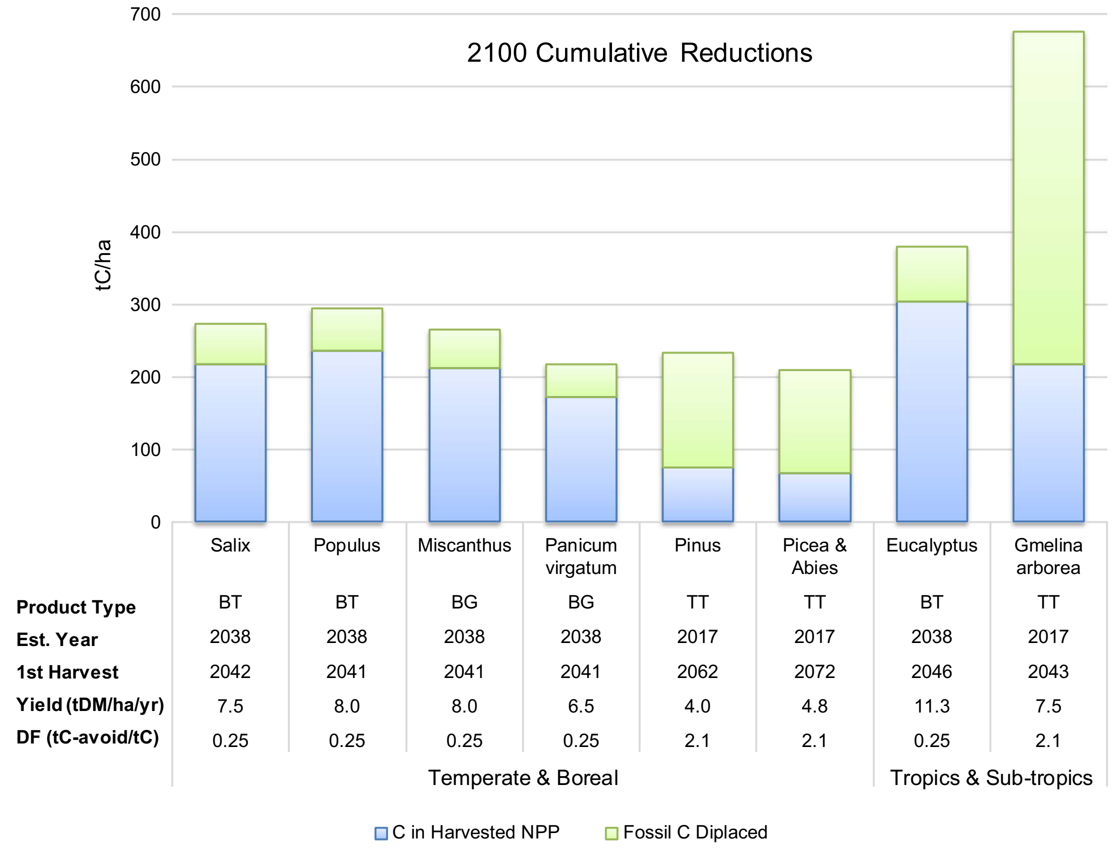
Climate engineering (CE) projects implemented mid-century may be necessary should mitigation efforts fail in the short term. Reducing atmospheric CO_2 concentrations by way of large-scale enhancement of terrestrial carbon sinks is one CE strategy that requires comprehensive scrutiny given its complexity. To that end, Boysen and colleagues make an important contribution with their analysis of the potential for biomass plantations (BPs) to provide rapid terrestrial carbon dioxide removal (tCDR) in the second half of this century (Boysen *et al* 2016). Their results suggest BPs may deliver the deep emission offsets needed to limit peak warming to 2 °C at 2100, but only at a hefty price to both biodiversity and food production. However, given the complexity of such an analysis, Boysen *et al* (2016) choose to simplify the additional task of assessing the fate of C in carbon pools outside the terrestrial biosphere. Here we focus on this element of their analysis to show that avoided C emission through a targeted substitution of emission-intensive products can approximately offset reduced primary productivity on land when timber replaces dedicated bioenergy biomass species. We argue that biomass utilization is equally relevant to consider when evaluating climate engineering or mitigation strategies involving terrestrial carbon sinks, since biomass products dictate the types of biomass species that must be deployed. BP systems deploying native tree species to produce timber, for example, can deliver greater biodiversity and local biogeophysical cooling benefits in many regions relative to BP systems deploying dedicated energy crops.

To evaluate the potential of biomass plantations to provide climate engineering in the second half of the 21st century, Boysen *et al* used a dynamic global vegetation model (DGVM) to evaluate a series of land use transitions based on replacing either natural vegetation or existing agricultural areas with highly productive biomass crops. In their study, transition locations and biomass feedstocks ('Bioenergy Trees': willow, poplar or eucalyptus, vs. 'Bioenergy grasses': miscanthus or switchgrass) were chosen based on the areas of maximum productivity simulated by the DGVM (Bondeau *et al* 2007) forced with offline climate model data (i.e. temperature, precipitation and atmospheric CO_2 concentration) from a societal transition scenario resembling RCP4.5 (Thomson *et al* 2011). This location selection scheme was chosen to develop an upper bound on the tCDR potential of BPs by maximizing productivity. Given their approach (highest-productivity sites targeted; CO_2 fertilization included without C-cycle and climate feedbacks; GHG emissions from N-fertilizers (e.g. Wood and Cowie 2004) excluded, etc), one could argue that the work represents an upper limit to the tCDR potential of a CE strategy that focuses on the rapid and large-scale deployment of productive (photosynthesis-enhancing) biomass species on land. However, by setting their analysis to utilize a simple 50% capture rate for NPP, the authors limit the full potential of tCDR.

When C in biomass is used directly as a replacement for the C in fossil fuel (as bioenergy), or indirectly as a product that replaces a material such as steel or concrete whose own production is emission-intensive, then the fossil C avoided by choosing biomass is analogous to a permanent C sink (Smith *et al* 2014). It is well-understood that using biomass to replace emission-intensive materials in the construction sectors can result in greater carbon cycle benefits than if used directly to replace energy (Kauppi *et al* 2001, Nabuurs *et al* 2007, Smith *et al* 2014). Carbon dioxide removal strategies involving terrestrial carbon sinks therefore need to be assessed with regard to net C fluxes in both the terrestrial biosphere and in industrial society (Smith *et al* 2014). A focus solely on the maximization of C sinks on land inherently limits the biomass species options to those which have little or no value for use as anything other than bioenergy, obfuscating the emission reduction potential that exists by way of



	Salix	Populus	Miscanthus	Panicum virgatum	Pinus	Picea & Abies	Eucalyptus	Gmelina arborea
Product Type	BT	BT	BG	BG	TT	TT	BT	TT
Est. Year	2038	2038	2038	2038	2017	2017	2038	2017
1st Harvest	2042	2041	2041	2041	2062	2072	2046	2043
Yield (tDM/ha/yr)	7.5	8.0	8.0	6.5	4.0	4.8	11.3	7.5
DF (tC-avoid/tC)	0.25	0.25	0.25	0.25	2.1	2.1	0.25	2.1

Figure 1. Cumulative carbon (C) reduction potentials in 2100 per hectare linked to the share of NPP appropriated for human consumption (blue segments) and its use as a product that replaces C emissions either directly (as bioenergy; green segments) or indirectly (as a construction material; green segments). Bioenergy trees ('BT') and bioenergy grasses ('BG') are those included in Boysen *et al* (2016) and are typically higher yielding with a lower time to maturity than trees grown for timber ('TT'). However, products from BG and BT species have lower potentials to displace fossil fuel emissions outside the land sectors, resulting in lower displacement factors ('DF'). On the other hand, material products from TT typically have higher DFs and hence afford a larger potential to reduce emissions outside the land system (green segments). Yields for BT and BG are global means realized at the commercial scale (>1 ha) adapted from refs. (Searle and Malins 2014, Wullschleger *et al* 2010). For TT, commercial scale yields are from ref. (FAO 2000). The global average DF for BT and BG is adapted from refs. (Chum *et al* 2011, Creutzig *et al* 2015), while the global average DF for TT is from ref. (Sathre and O'Connor 2010). Differences in ecosystem respiration and non-harvested NPP across biomass species are considered negligible and are excluded here. Given the longer rotation times, TT species are established in 2017 rather than 2038 (the year in which 1.5 °C is crossed in the RCP4.5-like scenario of Boysen *et al* 2016) and can hence be seen as climate mitigation rather than climate engineering.

product substitution and a reduced consumption of fossil fuels.

Despite often being lower in productivity, BPs that produce timber products (i.e. forests) can contribute to deeper GHG reductions *outside* the land system than those producing bioenergy, as illustrated in figure 1. Additionally, management of commercial timber species is often less intensive with regards to fertilizer and pesticide application (Heilman and Norby 1998) while being more sensitive to the preservation of wildlife habit through practices that mimic natural stand structure. In general, forestry plantations often harbor greater biodiversity than conventional agriculture, the latter of which more closely resembles BPs producing dedicated crops for energy (Brockerhoff *et al* 2008). Further, recent empirical evidence suggests that, locally, forests directly cool the surface relative to crops and other herbaceous vegetation species in many regions (Alkama and Cescatti 2016, Peng *et al* 2014, Zhao and Jackson 2014).

As figure 1 illustrates, in a timber focused tCDR strategy, the tradeoff between weaker C sinks on land can be balanced by greater reductions in C emissions off the land. By ignoring this latter contribution, studies risk overlooking the greater biodiversity and local biogeophysical climate benefits that timber stands likely confer over BPs that produce dedicated energy crops (Zhao and Jackson 2014, Peng *et al* 2014, Alkama and Cescatti 2016). Arguably, however, maximizing the carbon reduction potential that exists in the way of avoided emissions will be more challenging to realize as it requires effective coordination amongst additional actors and greater governance across sectors. Further, given the long rotation times for some commercial timber species – particularly those in boreal regions – deployment of such a carbon reduction strategy cannot afford to wait until the 1.5 °C threshold is crossed (i.e. 2038 in Boysen *et al* 2016), but would need to be deployed immediately in these regions. Subsequently, the concomitant biogeophysical effects on both local and global climate need to be evaluated more rigorously – and urgently (Jones *et al* 2013). Boysen *et al* (2016) reference the importance of albedo in their analysis, but without measuring the climate forcing (or response) in common units like radiative forcing (e.g. O'Halloran *et al* 2012), or change in temperature, it is difficult to meaningfully weigh the reported albedo changes against the reported emission reductions. Selecting BP deployment locations in future assessments should focus on maximum climate benefit rather than maximum CDR, facilitated with spatially-explicit metrics that inform about the relevance of biogeophysical effects both locally (West *et al* 2011) and globally (Bright *et al* 2016). Siting based on the optimization of multiple climate regulation services, in addition to other ecosystems services like biodiversity and food production, could increase net climate benefits while also addressing social barriers (Moser and Ekstrom 2010) to large-scale implementation of these projects.

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