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Reply to comment on ‘Does replacing coal with wood lower CO₂ emissions? Dynamic lifecycle analysis of wood bioenergy’

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REPLY

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Abstract

We respond to Prisley *et al*'s (2018 *Environ. Res. Lett.* **13** 128002) critique of Sterman *et al* (2018 *Environ. Res. Lett.* **13** 015007), which found that using wood to produce electricity can worsen climate change at least through 2100, even if wood displaces coal. The result arises because (1) wood generates more CO₂/kWh than coal, creating an initial carbon debt; (2) regrowth of harvested land can remove CO₂ from the atmosphere, but takes time and is not certain; and (3) until the carbon debt is repaid, atmospheric CO₂ is higher, increasing radiative forcing and worsening climate change long after the initial carbon debt is repaid by new growth. We correct several errors in Prisley *et al*'s critique, and show that our results are robust to the harvest and land management practices they prefer.

Overview

Sterman *et al* (2018) extended the C-ROADS climate policy model (Sterman *et al* 2013) to examine the impact of wood bioenergy on greenhouse gas (GHG) emissions, finding that using wood to produce electricity can worsen climate change through at least 2100, even if wood displaces coal, the most carbon-intensive fossil fuel. The result arises because (1) wood generates more CO₂ per kWh of electricity than coal, so that the first impact of wood bioenergy is an increase in atmospheric CO₂ relative to continued coal use, creating a 'carbon debt'; (2) biomass regrowth on land harvested for bioenergy removes CO₂ from the atmosphere, but takes time and is not certain; and (3) until the carbon debt is repaid atmospheric CO₂ is higher than if wood were not used, increasing radiative forcing and worsening climate change long after the initial carbon debt is repaid by new growth.

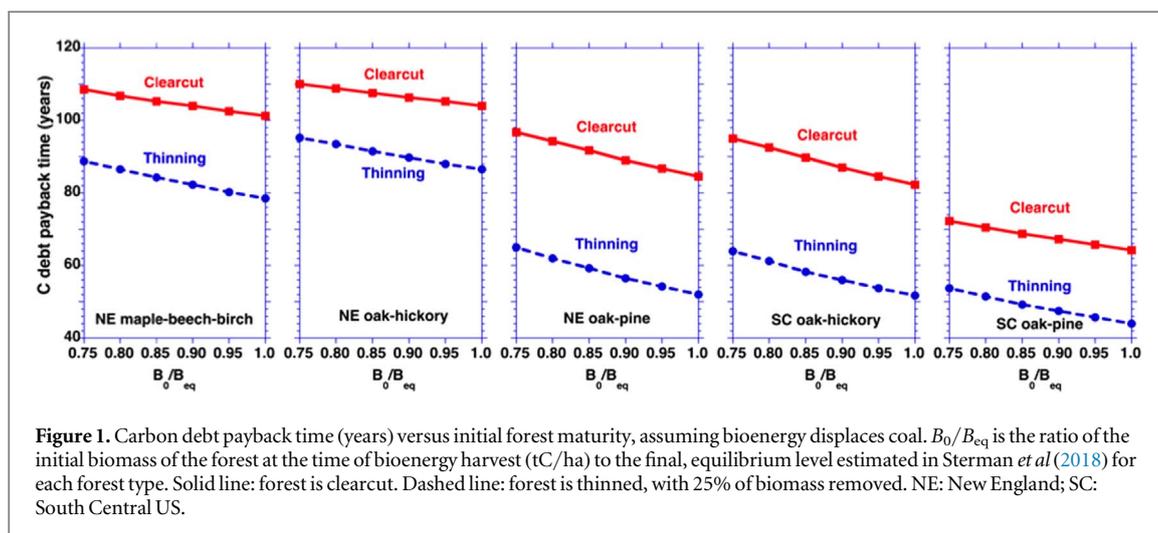
Prisley *et al* (2018) argue for different assumptions and scenarios, claiming these would show greater benefits from wood bioenergy. We appreciate their critique and suggestions. Here we clarify aspects of the original model and analysis that Prisley *et al* misinterpret, modify the model to test scenarios Prisley *et al* prefer, including thinning and rotation, and show, contrary to their claim, that the additional climate change caused by wood bioenergy persists long

after the initial carbon debt from its use is repaid by forest regrowth.

We appreciate that Prisley *et al* find our model 'to be well-documented and thorough.' The model is fully documented and freely available. We provided the model itself and all the files needed to replicate our results so that others could test other parameters, develop additional scenarios, and extend and improve the model. However, Prisley *et al* do not test their alternative assumptions or scenarios with our, or any, model.

Prisley *et al* erroneously state that the model 'does not appear to be focused on forest management in temperate regions where the area of forest is stable or growing.' The model is flexible and can be parameterized for any forest type and region, including tropical, temperate and boreal forests, as we clearly state⁴. We explicitly test scenarios parameterized for forests in the US. The scenarios we reported assumed stable forest area but the model can be used to examine cases in which total forest area is growing or shrinking due to conversion of land among forest, pasture, agriculture and other uses.

⁴ 'The model is extensible to any number of land/land use categories and geographic areas. For example, one could configure the model to represent different types of forests, with similar disaggregation for other land types, and at geographic scales from regions to nations to, if data are available, even smaller areas.' (Sterman *et al* 2018).



Crucially, Prisley *et al* do not dispute our finding that wood bioenergy generates more CO₂ per kWh of electric power generated than coal. Consequently, the first impact of wood power generation is an increase in CO₂ emissions compared to coal, causing an increase in atmospheric CO₂. Therefore, bioenergy can only lower atmospheric CO₂ later, and only if net new forest growth occurs. The initial increase in atmospheric CO₂ is known as the biofuel ‘carbon debt’, and the time required for regrowth to bring atmospheric CO₂ back to what it would have been without the biofuel is known as the ‘carbon debt payback time.’ The magnitude of the initial carbon debt and the payback time depend on the species composition, maturity and growth rates of the forests harvested for bioenergy, the fuel displaced by that wood, the processing and combustion efficiencies of the bioenergy and displaced fuel, and the management regime for the forests supplying the wood (Mitchell *et al* 2012, Walker *et al* 2013, Laganière *et al* 2017).

Prisley *et al* also do not dispute the fact that regrowth after harvest takes time, but argue that regrowth would be faster when existing forests are growing and serving as net carbon sinks. In contrast, we show that carbon debt payback times are actually longer when existing forests serve as net carbon sinks because the forests would have continued to sequester carbon had they not been harvested for bioenergy (figure 1). Prisley *et al* also argue that carbon debt payback times would be shorter if managed plantations, with thinning and rotation, are used to meet growing bioenergy demand. We show that creating new plantations by converting existing forest to plantations still yields long (multi-decadal) carbon debt payback times even with thinning and rotation, and even though plantations grow far more rapidly than natural forest (figure 2).

Regrowth is also uncertain due to the risks of fire, insects and disease. Prisley *et al* argue we overestimate these, but in fact our analysis optimistically omits them. Similarly, Prisley *et al* argue that we overestimate fertilization of plantations and resulting emissions of N₂O, a powerful GHG. In fact, we assume

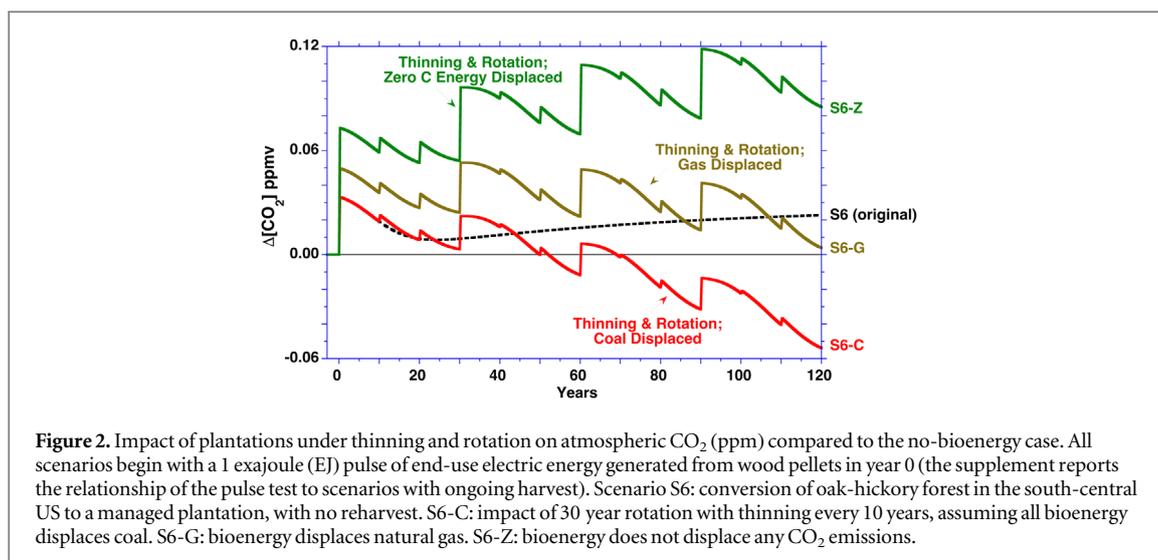
zero N₂O emissions. Accounting for any of these would worsen the climate impact of wood bioenergy.

Finally, Prisley *et al* erroneously argue that climate change is not affected by the timing of CO₂ emissions but depends only on ‘long-term cumulative CO₂ emissions.’ This is false: the initial rise in atmospheric CO₂ from wood bioenergy increases radiative forcing, leading to faster and larger increases in global mean surface temperature and the heat content of the oceans. Even if net new growth eventually brings atmospheric CO₂ below the level it would have had without wood bioenergy, the additional warming and other climate change impacts such as sea level rise (SLR) remain worse than they would have been for decades to centuries (figure 3).

Impact of net forest growth on carbon debt payback times

Prisley *et al* note that forests in the southern US have, over the last century, served as net carbon sinks, and criticize our scenarios for assuming the forest lands harvested for bioenergy are initially mature, i.e. in equilibrium, with net primary production (NPP) balanced by carbon flux from biomass and soils to the atmosphere. They suggest that growing forests, with higher NPP, will sequester more carbon than we report. This is incorrect: whether any region serves as a net sink is not relevant: what counts is what happens on the margin, that is, the incremental impact of bioenergy harvest.

Figure 1 shows scenarios in which the forest serves as a net carbon sink. Contrary to Prisley *et al* the greater the net carbon sink, the longer the carbon debt payback time: harvesting wood for bioenergy prevents the additional growth that would have occurred on that land had the forest continued to serve as a net carbon sink. To illustrate, clearcutting south-central US oak-hickory forest for bioenergy increases the carbon debt payback time from 82 years when the forest is initially fully mature to 95 years when the forest is 75% mature. Across the five forest types considered, harvesting at 75% maturity raises the C debt payback time an average of nine years when clearcut and 11 years



when thinned. Harvesting forests now serving as carbon sinks causes atmospheric CO₂ to rise further above what it would have been, and remain higher longer, than harvesting mature forests, worsening the climate change impact of wood bioenergy⁵.

Impact of thinning and rotation of managed plantations

Prisley *et al* criticize Scenario 6 in Sterman *et al* in which forest in the south-central US is harvested for bioenergy, with the land converted to a managed pine plantation that is never reharvested. They report that most plantations are thinned twice in each ≈ 30 year rotation and argue that ‘A more realistic comparative scenario would be three or four successive rotations over the course of 100 years.’

We agree. Figure 2 compares the original scenario 6 (S6) to simulations with two thinnings (at 10 year intervals) followed by harvest and replanting at 30 years, with all wood harvested supplying bioenergy. Consistent with plantation management guidelines, we assume 30% of plantation biomass is removed by each thinning (see supplement, available online at stacks.iop.org/ERL/13/128003/mmedia). Scenario S6-C shows the impact of thinning and rotation for the case in which the bioenergy displaces coal. As in S6, harvesting existing forest for bioenergy immediately increases atmospheric CO₂. The first thinning immediately increases atmospheric CO₂ slightly as the thinnings are used for bioenergy, but the plantation grows faster thereafter. By the second thinning, atmospheric CO₂ has nearly returned to the level attained in S6. The second thinning also boosts atmospheric CO₂, but the

⁵ Forests serving as C sinks today, with initial biomass, $B_0 < B_{eq}$, also require more land be harvested to supply a given amount of bioenergy because they contain less carbon per hectare compared to mature forest (e.g. $B_0/B_{eq} = 0.75$ requires 33% more land per GJ), increasing the risks of habitat loss, erosion, changes in the hydrological cycle and other ecological impacts. Note that we do not advocate harvest of old growth or mature forests.

thinned stand again grows faster thereafter. After ≈ 25 years atmospheric CO₂ falls below S6, though still remains worse than coal. In year 30 the plantation is harvested, adding CO₂ to the atmosphere, and a new rotation begins. Prisley *et al* are correct that thinning and rotation boost NPP: over the 120 years shown in figure 2 cumulative NPP is $\approx 25\%$ higher in S6-C than S6. However, the bioenergy carbon debt relative to coal is not permanently repaid for ≈ 70 years even though plantation biomass grows very rapidly, from planting to >100 tC/ha in ≈ 20 years (Smith *et al* 2006).

Figure 2 also shows the results when wood bioenergy displaces natural gas (S6-G) or a zero-carbon energy source, such as solar, wind, or nuclear (S6-Z). For natural gas, carbon debt is still not repaid after 120 years, despite thinning and rotation. If wood does not displace any fossil carbon emissions, the carbon debt is never repaid, because biomass and soil carbon on the plantation remain lower than in the forest harvested to establish the plantation.

In several places Prisley *et al* refer to the shortest C debt payback times we found to argue that plantations can repay initial carbon debt from bioenergy quickly (4–12 years; Sterman *et al* 2018, table S7). However, these short payback times apply only to *existing* plantations, which meet demand for wood products today. Demand for wood bioenergy is projected to grow rapidly, driven by policies that treat all bioenergy as carbon neutral and, in many cases, heavily subsidize wood bioenergy. Wood bioenergy advocates claim feedstocks consist largely of sawmill and logging residues, but these sources are limited, thus requiring roundwood to meet projected demand (Harris *et al* 2016, Birdsey *et al* 2018). Supplying the projected growth from plantations requires new plantations be created on land currently in other uses. Figure 2 shows that the carbon debt payback time for a new plantation established by harvesting existing forest is many decades even though plantation biomass grows quickly.

Whether the land converted to new plantations comes from existing forest or from pasture, agricultural land, or other land uses is an empirical question. We agree with Prisley *et al* that it would be better for the climate if landowners were incentivized to convert non-forested land to forest, since net growth on such land would store carbon first and release it to the atmosphere later, whereas harvesting existing forest for bioenergy and converting that land to plantations increases CO₂ emissions before new growth can occur⁶. However, satellite data show that ‘over 31%’ of forest cover in the southeastern US ‘was either lost or regrown’ from 2000 to 2012, and that such ‘colocated loss and gain...indicating intensive forestry practices, are found on all continents within the subtropical climate domain, including South Africa, central Chile, southeastern Brazil, Uruguay, southern China, Australia, and New Zealand’ (Hansen *et al* 2013). Much of the new growth is occurring on forest land that was recently cleared (Harris *et al* 2016), as in our scenarios.

Prisley *et al* also mischaracterize our results with respect to fertilization of plantations. Fertilization generates N₂O, a powerful GHG (100 year global warming potential 265 times larger than CO₂; IPCC 2013). Prisley *et al* state that ‘Pine plantations are frequently fertilized to improve growth where nutrients are limited, but not nearly at the rate suggested by the authors.’ The extent of fertilization is an empirical issue. However, as we clearly stated, all our results assume ‘no increase in N₂O from fertilization of managed plantations.’ Accounting for N₂O from fertilization would further worsen the climate impact of wood bioenergy from plantations.

The extensive margin: landscape effects

The discussion so far centers on the intensive margin: the incremental impact of bioenergy harvest on emissions from a given patch of land. Prisley *et al* also argue that growth in wood harvest for bioenergy would have positive impacts on the extensive margin by creating incentives for landowners to expand forested area. We agree that future research should consider landscape effects—and other market effects, including the effect of substituting wood for coal on coal prices and demand. However, Prisley *et al* do not support their claim that ‘growth after harvest on multiple stands results in much shorter carbon pay-back times’ with any quantitative analysis. There are several flaws in their argument:

1. The causal sequence Prisley *et al* suggest is: growing demand for wood bioenergy → higher wood prices → increased conversion of non-

forested land to forest or plantation → enhanced carbon sequestration. However, the impact of growing bioenergy demand on wood prices depends on the short-run elasticity of wood demand with respect to price. If higher wood demand for bioenergy leads landowners to increase harvest of existing forests or accelerate thinning and rotation of existing plantations, the supply of wood for bioenergy will expand quickly, limiting the increases in wood prices needed to incentivize the conversion of non-forest land to forest or plantation, while increasing CO₂ emissions.

2. Converting land currently in non-forest use to forest or plantation requires significant up-front investment and takes time, while the revenue from subsequent harvest comes only later. Landowners will not undertake costly investments until they are confident any short-run increases in prices are likely to persist. Further, carbon uptake from any resulting afforestation is gradual.
3. Even if growing wood bioenergy demand induces landowners to increase forested area, displacing coal with wood reduces coal demand, cutting coal prices and potentially leading to increases in coal demand elsewhere (York 2012). The net impact of wood bioenergy therefore depends on the demand and supply elasticities for both wood *and* coal, and the lags in their responses. Resolving these empirical issues is beyond the scope of our original analysis and this reply. Note, however, that coal demand can respond to price rapidly: lower coal prices immediately cut operating costs for existing coal-fired power plants, possibly delaying or preventing their closure, and new coal plants can be built quickly relative to the growth of new forests.

Assessing the full impact of these processes requires a general equilibrium treatment of the land, wood, coal and other energy markets that integrates the behavioral decision processes of the actors, the lags in the responses of demand and supply to prices, and the biophysical responses of land use change. Focusing on land use effects alone is not appropriate.

Carbon neutrality does not imply climate neutrality

Prisley *et al* correctly note that we presented the impact of wood bioenergy on atmospheric CO₂, not climate. However, their claim that ‘peak global mean temperature is a function of *long-term* cumulative CO₂ emissions and that global temperature is relatively insensitive to changes in CO₂ emissions in the near term’ is incorrect. Cumulative emissions as a proxy for temperature increase is an approximation derived from physically-based climate models and subject to considerable uncertainty (Matthews *et al* 2018). Further, ‘the same budget of cumulative carbon emissions may result in critically different impacts on

⁶ There is still no free lunch from afforestation: converting pasture or farmland for bioenergy might compromise livestock or crop production, boosting food prices and food insecurity (e.g. Searchinger *et al* 2015). Land suitable for afforestation but not currently providing food, fiber or other ecosystem services is limited.

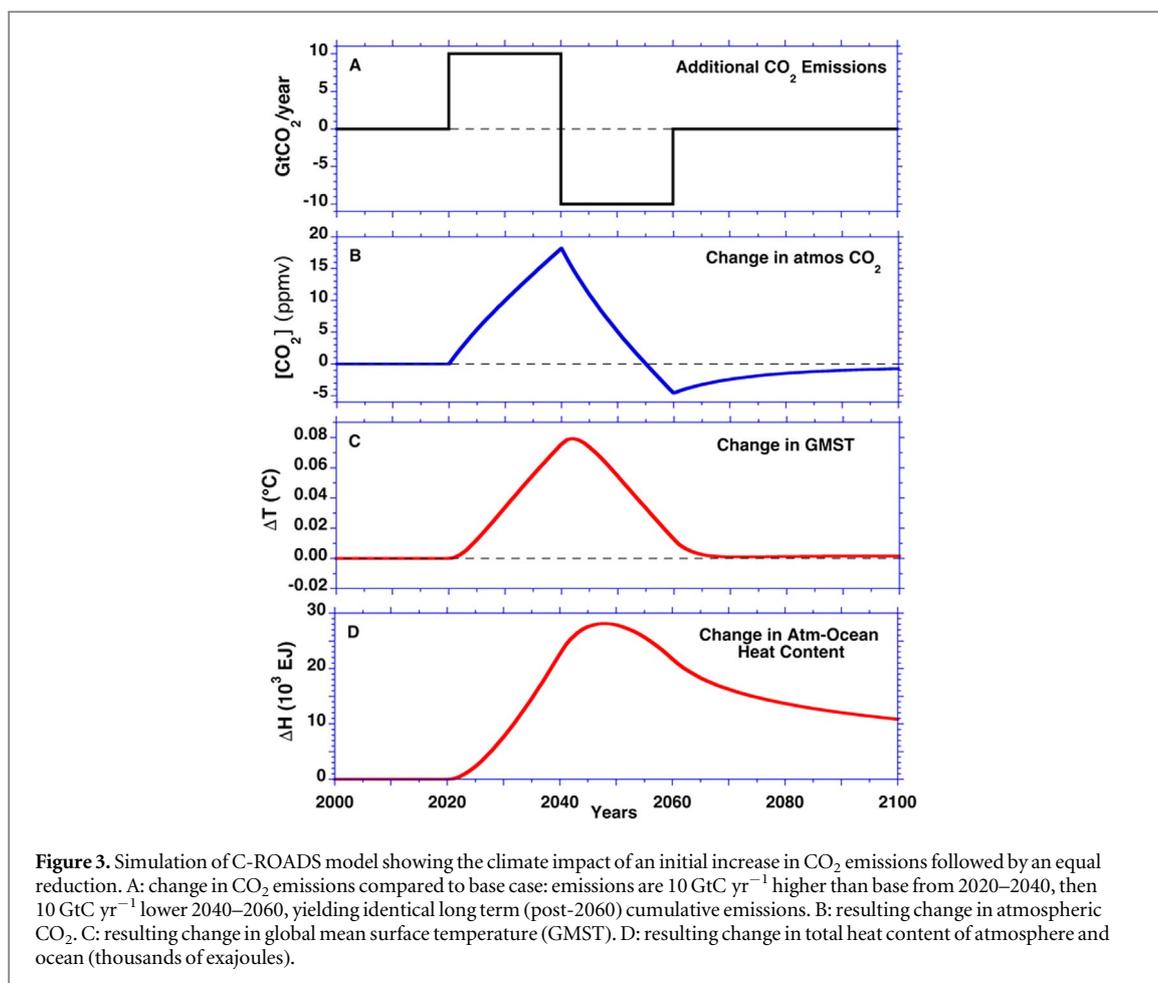


Figure 3. Simulation of C-ROADS model showing the climate impact of an initial increase in CO₂ emissions followed by an equal reduction. A: change in CO₂ emissions compared to base case: emissions are 10 GtC yr⁻¹ higher than base from 2020–2040, then 10 GtC yr⁻¹ lower 2040–2060, yielding identical long term (post-2060) cumulative emissions. B: resulting change in atmospheric CO₂. C: resulting change in global mean surface temperature (GMST). D: resulting change in total heat content of atmosphere and ocean (thousands of exajoules).

natural and human systems, depending on the amount of time over which that budget is expended' (LoPresti *et al* 2015).

Figure 3 uses C-ROADS (Sterman *et al* 2013) to show the impact of front-loading emissions relative to the business-as-usual base case. Global CO₂ emissions are increased above BAU by 10 Gt yr⁻¹ from 2020 through 2040, then fall below BAU by 10 Gt yr⁻¹ from 2040 to 2060 (panel A)⁷. Long-term cumulative emissions are therefore identical in both cases.

Nevertheless, climate change is worse through 2100 and beyond. Front-loading emissions causes atmospheric CO₂ to rise above the base case (panel B). Concentrations reach a peak ≈ 18 ppm above the base case level shortly after 2040. Removing the extra emissions 2040–2060 causes atmospheric CO₂ to fall. By about 2055 atmospheric CO₂ falls below the base case level, reaching a minimum ≈ 5 ppm below the base case in 2060. The drop in atmospheric CO₂ 2040–2060 exceeds the rise 2020–2040 because the higher

concentration through 2040 increases carbon flux to the ocean and terrestrial biosphere. For that reason, atmospheric CO₂ rises after 2060 as some of the additional carbon taken up by the ocean and terrestrial biosphere flows back into the atmosphere.

The increase in atmospheric CO₂ from front-loading emissions immediately increases net radiative forcing. The Earth warms as long as net radiative forcing is positive. Global mean surface temperature (GMST, the mean temperature across land and the surface layer of the ocean) therefore starts to rise above the base case (panel C). GMST integrates net radiative forcing less net heat transfer to the deep ocean. As some of the excess heat is transferred to the deep ocean, GMST falls, but remains slightly higher than the base case through 2100. The excess heat content of the atmosphere and ocean peaks in 2048, after GMST, and remains well above the base level through 2100 (panel D). These long lags are consistent with other models, e.g. Solomon *et al* (2009), Joos *et al* (2013), Ricke and Caldeira (2014)⁸.

⁷ C-ROADS explicitly models carbon emissions and fluxes among the atmosphere, biosphere and oceans; emissions budgets and stocks of other GHGs; the contribution to radiative forcing of each; heat exchange between the surface and deep ocean; and the resulting global temperature change. We assume the incremental emissions in figure 3 come from the terrestrial biosphere, approximating the impact of wood bioenergy where the first impact is an increase in emissions, with net sequestration occurring later.

⁸ The results underestimate climate change because we omit positive feedbacks whereby warming increases biogenic CO₂ and CH₄ emissions from thawing permafrost (Schuur *et al* 2015), warming of soils (Melillo *et al* 2017, Bond-Lamberty *et al* 2018), and increased fire, insect and disease risk in forests (Barbero *et al* 2015, Seidl *et al* 2017, Tepley *et al* 2017), all increasing risks of irreversible regime shifts (Steffen *et al* 2018).

Table 1. Responses to criticisms in Prisley *et al* (see their table 1).

Sterman <i>et al</i> conclusion	Prisley <i>et al</i> response	Rebuttal
1. 'Reductions in atmospheric CO ₂ come only later, and only if the harvested land is allowed to regrow.'	By definition, sustainably managed forests are allowed to regrow. Reduction in atmospheric CO ₂ is still the eventual result of wood feedstock use; and 'later' may be as short as four years.	Prisley <i>et al</i> do not challenge our finding that wood bioenergy emits more CO ₂ than coal. They also agree that reductions in atmos. CO ₂ are the 'eventual result of wood feedstock use' (emphasis added) even in managed forests. We found payback times 'as short as four years' only on existing plantations, but increased bioenergy harvest requires new plantations be created (see #6). When existing forest is cleared to create new plantations, the C debt payback time is many decades, even under thinning and rotation (figure 2).
2. 'Consequently, the first impact of displacing coal with wood is an increase in atmospheric CO ₂ relative to continued coal use...'	While this is true in many scenarios involving increased use of wood bioenergy, multiple studies show that the initial increase is followed by reduction in atmospheric CO ₂ relative to use of fossil fuels.	Prisley <i>et al</i> agree with our conclusion: 'the initial increase (in atmospheric CO ₂ from wood bioenergy) is followed by reduction in atmospheric CO ₂ relative to use of fossil fuels' (emphasis added). We found C-debt payback times for the US forests examined range from decades to a century. Prisley <i>et al</i> argue that thinning and rotation of managed plantations would shorten payback times, but we find payback times of ≈50–70 years in scenarios with thinning and rotation, even if wood displaces coal (figure 2).
3. 'However, before breakeven, atmospheric CO ₂ is higher than it would have been without the use of bioenergy, increasing radiative forcing and global average temperatures, worsening climate change...'	Following the breakeven period, wood bioenergy results in less CO ₂ in the atmosphere than use of fossil fuels. Importantly, it is widely understood that peak global mean temperature is a function of long-term cumulative CO ₂ emissions and that global temperature is relatively insensitive to changes in CO ₂ emissions in the near term (IPCC 2013).	The claim that peak GMST is relatively insensitive to changes in near term emissions is incorrect (e.g. LoPresti <i>et al</i> 2015). The rate of increase in GMST depends on net radiative forcing (less heat transfer to the ocean). Higher CO ₂ emissions from bioenergy (or any source) raise atm. CO ₂ and net radiative forcing, causing GMST to grow faster than it would have. If forest regrowth eventually lowers atmos. CO ₂ , GMST peaks and starts to fall, but remains higher than it would have been. Increasing near-term CO ₂ emissions followed by equal reductions cause global warming and other climate impacts to be worse than they would have been through 2100, at least, even though long-term cumulative emissions are identical (figure 3). Carbon neutrality does not imply climate neutrality. Limiting warming to <2 °C requires global emissions to fall dramatically by 2040 (IPCC 2018). Wood bioenergy raises emissions during this period.
4. 'The carbon debt incurred when wood displaces coal may never be repaid if (land use changes or calamities) limit regrowth or accelerate the flux of carbon from soils to the atmosphere.'	Forest conversion to other land uses is relatively rare in the study region, as are the other concerns expressed in this conclusion. Markets for biomass actually serve to help maintain or increase forest area (Birdsey <i>et al</i> 2018).	These 'calamities' (a word we do not use) include fire, insect damage and disease, all common in forests. Warming to date has already increased the incidence of these processes and accelerated bacterial and fungal respiration, all increasing carbon flux from forest and soils to the atmosphere. These impacts are projected to increase further as warming continues (see footnote 8). The rate at which forests are converted to other uses (development, pasture, agriculture, etc) is an empirical issue and differs in different regions of the world. Many regions exhibit deforestation and net carbon flux to the atmosphere (Hansen <i>et al</i> 2013). Whether growing bioenergy demand increases forest area and C sequestration requires analysis of the impact of bioenergy on all relevant markets (see #6).
5. 'Fifth, counter to intuition, harvesting existing forests and replanting with fast-growing species in managed plantations can worsen the climate impact of wood biofuel.'	This conclusion stems from the flaws in assumptions about plantation management that are reviewed in this response. Among these is the assumption that where plantations replace natural forest harvested for energy, the plantations will never be harvested but allowed to grow indefinitely.	Simulations of thinning and rotation for plantations do show higher average NPP compared to the original conversion scenario, speeding CO ₂ removal from the atmosphere. However, even though plantations grow faster than natural forest, the carbon debt payback time from converting existing forests to plantation is still many decades (≈50–70 years; figure 2) even under thinning and rotation.

Table 1. (Continued.)

Serman et al conclusion	Prisley et al response	Rebuttal
6. ‘...growth in the wood pellet industry to displace coal aggravates global warming at least through the end of this century...’	This conclusion results in part from the selection of an unrealistic scenario to develop projections. The researchers examined other far more realistic scenarios that yield much shorter payback periods (4–12 years 6) but did not report projections based on them. In addition, lack of market response in the model contributes to unrealistically long payback periods. In the area studied by Serman et al growing markets for wood reduce deforestation and can be expected to stimulate investment in afforestation and improved forest management. These responses mitigate, rather than aggravate, warming.	Meeting growing demand for wood bioenergy requires either (1) additional harvest of existing forests or (2) expansion of managed plantations. 1. Harvest and regrowth of existing forests, by clearcut or thinning, leads to C-debt payback times of many decades, worsening climate change through the end of the century or beyond (figures 1–3). Payback times are longer if the harvested forests currently serve as C sinks (figure 1). 2. Supplying wood bioenergy from plantations requires net new plantation area. The short C-debt payback times Prisley et al cite assume all new plantations are created on land currently not forested. When new plantations are created from existing forest, C-debt payback times remain on the order of 50 years or more (figure 2). Growing use of wood bioenergy necessarily increases wood harvest. Growing bioenergy demand reduces net deforestation only if afforestation exceeds the increase in harvest. But the CO ₂ emissions from increased harvest occur before non-forest land can be afforested and begin to store C. How much bioenergy growth raises wood prices, the rate of any new afforestation, and how much bioenergy displaces fossil fuel emissions are empirical questions. Declines in coal prices can increase coal demand elsewhere. Afforestation of pasture or farmland would reduce livestock and crop production. Assessing the market impacts of growing bioenergy demand requires consideration of all relevant markets, including those for the fuels displaced by wood and for the products and ecosystem services currently supplied by land to be afforested.
7. ‘Seventh, using wood in electricity generation worsens climate change for decades or more even though many of our assumptions favor wood.’	As noted herein, many of these assumptions are not representative of practice and not necessarily in favor of wood. Also, realistic assumptions (Scenario 2) indicate very short payback periods.	Assuming existing forests are C sinks lengthens C-debt payback times (figure 1). Thinning and rotation of plantations yield multi-decadal payback times (figure 2; #2 above). We assume no fire, disease, insect damage or increases in bacterial/fungal respiration, though all are projected to worsen with climate change (#4). Contrary to Prisley et al’s assertion, we assume zero N ₂ O emissions from fertilization of plantations. We assume wood bioenergy displaces coal, the most C intensive fossil fuel, and that displacing coal with bioenergy has no impact on coal prices or demand for coal elsewhere. These assumptions all favor wood bioenergy.

Not shown in figure 3, front-loading emissions also worsens SLR beyond 2100 even though cumulative emissions are identical after 2060. Higher GMST accelerates terrestrial ice melt, and warmer oceans speed the thermal expansion of the water column; both cause SLR to exceed the base case beyond 2100 even though cumulative emissions are equal after 2060. Many other impacts of climate change depend on the magnitude and rate of temperature rise and persist for long periods, including ocean acidification, permafrost melt, increases in water stress, crop yield decline, wildfire, changes in disease incidence, and biodiversity loss (IPCC 2013, 2018).

Although long-term cumulative emissions are identical in the two scenarios, the climate impacts of

and persist through the end of this century, at least. Burning wood to generate electric power increases atmospheric CO₂ in the short run, worsening climate change even if subsequent regrowth eventually repays the initial carbon debt. Carbon neutrality does not imply climate neutrality.

The IPCC (2018) warns that limiting warming to 1.5 °C requires ‘global net anthropogenic CO₂ emissions decline by about 45% from 2010 levels by 2030... , reaching net zero around 2050...’ and that limiting warming to 2 °C requires emissions ‘to decline by about 20% by 2030...and reach net zero around 2075...’ The long carbon debt payback times for wood bioenergy are inconsistent with the rapid emissions declines needed to

prevent significant harms to global ecosystems and human welfare (IPCC 2018).

Summary

We thank Prisley *et al* for their comments and for highlighting the need for additional research to explore the impact of wood bioenergy. However, Prisley *et al* mischaracterize key aspects of our work. We modified the model and analyzed new scenarios to address key criticisms, including the impact of forest growth (figure 1), thinning and rotation of plantations (figure 2) and the climate impacts of front-loading CO₂ emissions (figure 3). Table 1 summarizes the errors and problems in their critique.

Prisley *et al*'s criticisms do not change the conclusions of the original paper. Declaring that wood biofuels are carbon neutral, as the EU, UK, US, China and others have done, assumes forest regrowth after bioenergy harvest is rapid and certain. Neither is true. This accounting fiction promotes policies that worsen climate change, even if the wood displaces coal (see also Searchinger *et al* 2018). The enhanced model is fully documented and freely available (see supplement). We invite others to use it to shed further light on the dynamics of bioenergy.

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