Environmental Research Letters

COMMENT • **OPEN ACCESS**

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To cite this article: Stephen P Prisley *et al* 2018 *Environ. Res. Lett.* **13** 128002

Environmental Research Letters

OPEN ACCESS

RECEIVED
14 June 2018

REVISED
31 July 2018

ACCEPTED FOR PUBLICATION
19 November 2018

PUBLISHED
18 December 2018

COMMENT

Comment on 'Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy'

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Keywords: biomass energy, forest management, CO_2 emissions

Abstract

An analysis by Sterman *et al* (2018 *Environ. Res. Lett.* **13** 015007) suggests that use of wood for bioenergy production results in a worse climate outcome than from using coal. However, many of the assumptions on which their primary wood bioenergy scenario is based are not realistic and therefore are not informative. Assumptions of uncharacteristically long rotations for southern pine plantations, no utilization of wood for longer-duration products, and a single harvest over 100 years understate the carbon performance of current forest management practices. We provide references that support realistic modeling of forest carbon dynamics that are reflective of current practice and therefore more informative.

Introduction

Sterman *et al* (2018) used a modeling framework (C-ROADS) to evaluate the atmospheric carbon implications of multiple scenarios involving the use of bioenergy from forests to substitute for fossil fuels. While a thorough review of the C-ROADS model is beyond the scope of our comments, it appears to be well-documented and thorough, designed for ease and speed of operation rather than highly detailed representation of complex systems. According to the model documentation, the primary role of the forest sector in the model is in the analysis of emissions from land-use change. It does not appear to be focused on forest management in temperate regions where the area of forest is stable or growing, or where multiple harvest-regrowth cycles provide ongoing benefits (the US South).

The authors concluded that 'although bioenergy from wood can lower long-run CO_2 concentrations compared to fossil fuels, its first impact is an increase in CO_2, worsening global warming…'. We respectfully suggest that some aspects of the authors' modeling approach and assumptions about forest management may have led to incorrect conclusions, and would like to offer some insights from the rich forest science literature that could inform efforts to better model forest carbon dynamics.

We offer comments in three areas. First, key elements of some of the scenarios are unrealistic and therefore less useful than scenarios that better reflect common practice.

Second, adoption of a landscape, next to single-stand perspective adds valuable insights into forest carbon dynamics. Third, some factual misconceptions about contemporary forest management may lead to faulty interpretations.

Scenario realism and coherence

We wish at the outset to acknowledge the proper and important assumptions and results reported by Sterman *et al* regarding their scenarios 4 and 5 involving deforestation. If there is an area of solid agreement among forest carbon modelers, it is that deforestation (i.e. permanent land-use change to other uses such as urban development) following woody biomass harvest leads to the worst outcome for atmospheric CO_2 among reasonable scenarios. Fortunately, due to demand for renewable building products, packaging products, and energy, both forest area and forest carbon sequestration have been *increasing* for decades in the US South, the focus of their primary example.

However, one unrealistic assumption used for all bioenergy scenarios is that there is never a subsequent harvest of a regenerated forest. This diverges from common practice in several ways (Duden *et al* 2017), making it of questionable value for use in a bioenergy reference case. While the authors suggest that this assumption favors bioenergy, it actually does the opposite. It is also unrealistic in light of the demand for wood for building products for the highest value wood, and pulp and energy for the lower value wood. It prevents repeated rotations of young, fast-growing forests which provide continued displacement of cement and steel used in buildings as well as fossil fuel for energy. As noted by Tian *et al* (2018), intensification of forest management provides long-term carbon stock benefits.

In fact, while the article purports to evaluate scenarios responding to increased demand for wood fuels, the authors do not consider any scenarios involving short-rotation woody biomass crops, which are likely to be part of a supply response to higher demand for woody biomass (Hinchee *et al* 2011).

Most of the attention in Sterman *et al* (2018) was devoted to Scenario 6, in which a mature oak-hickory forest is clearcut and replanted to loblolly pine[11]. In making this assumption, it appears that Sterman *et al* model the forest uptake of CO_2 using curves starting at time zero (young trees). Had Sterman *et al* used growth curves in the coal scenario that started with mature trees, one assumes that the age of the original stand would have been mentioned or discussed; there is no mention of age at biomass harvest in either the article or supporting information. If we are correct in our understanding, it represents a significant modeling error. The proper approach would be to model forest carbon uptake from a mature forest (at the age of the harvest) and in subsequent years. Using growth curves starting with mature stands in the coal-based system would have resulted in significantly lower uptake of CO_2 for many years compared to a newly established stand, increasing its calculated CO_2 emissions.

Although the authors appropriately note the importance of net primary productivity (NPP) in computation of CO_2 dynamics, their scenarios involving pine plantations reflect unreasonably low NPP. In scenarios in which pine plantations replace oak-hickory forest, the planted stands simply stop growing around age 40 and are left unharvested and thus unmanaged for a century. This assumption results in an NPP ‘penalty’ for fast-growing pine plantations. Data from the US Forest Service Forest Inventory and Analysis (FIA) program (Miles 2018) indicate that 85% of planted loblolly and shortleaf pine stands on private lands in the South are less than 40 years old, and only 0.08% are at least 100 years old. Therefore, the assumption that a loblolly pine plantation would be grown without harvest for 100 years is without basis in practice and therefore is not a useful or informative counterfactual. A more realistic comparative scenario would be three or four successive rotations over the course of 100 years. For example, following Scenario 6 (using data from Smith *et al* 2006), a single 100 year rotation stores 138.6 t C/ha in live trees, for an annual NPP of 1.39 t C/ha/yr. Repeatedly harvesting at ages 25–30 and replanting would remove 4.47–4.97 t C/ha/yr from the atmosphere in the same period, resulting in a threefold increase in NPP.

Construction of realistic scenarios requires an understanding of forest ownership characteristics because forest harvest and management practices are related to land ownership. In the US South, 87% (about 75 million hectares) of forests are owned by non-industrial private landowners (60%), forest product companies or financial institutions (27%) (European Commission 2015). Whereas corporate ownerships are acquired and managed for financial returns from timber or real estate development, non-industrial private landowners or ‘family forests’ are typically smaller holdings with a wide range of ownership objectives and varying levels of interest and experience in forest management (European Commission 2015). Nevertheless, even within this group some basic management is usually assumed to take place to maintain property value (e.g. for conservation or recreational purposes) (Lamers *et al* 2018). Considering the cost incurred by a landowner in site preparation and re-planting trees, it is unrealistic to assume they would never harvest a planted stand or at minimum try to retain its (sawtimber) value (e.g. through thinnings).

Next, the authors assume that 95% of material harvested from clearcuts goes to bioenergy[12]. However, most harvests are initiated based on the return from

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[11] The authors repeatedly refer to shortleaf loblolly plantations. It should be noted that shortleaf pine and loblolly pine are two distinct species, either of which may be planted in single-species plantations.

[12] The supplemental material states ‘However, for the purposes of this study, which focuses on biomass, we do not treat the harvest of forests for lumber and assume no C fluxes into or out of that stock.’

higher-value products (e.g. sawtimber), and biomass for energy is a low-value byproduct, often trading for pulpwood prices or lower. This is especially true for situations like Scenario 6. For example, a 50 year-old oak-hickory stand, when harvested, would yield a mixture of 78 green tons of sawtimber and 65.5 green tons of pulpwood (data from Smith *et al* 2006). Using prices reported by Forest2-Market[13], the value per hectare to the landowner would be about $2700. A landowner choosing to forgo the higher sawtimber value and sell all wood at pulpwood/fuelwood prices would lose about $1300 per hectare. A realistic scenario would allocate only the pulpwood portion to fuelwood, usually less than 50% of total biomass in the forest types/ages reported. Neglecting longer-lived wood product fractions in regular timber harvest leads to a significant underestimation of the potential carbon benefits achieved through substitution of, e.g. alternative building materials by sawtimber use in construction. Given the unrealistically low NPP for pine plantations in Scenario 6 and the lack of accounting for harvest of other products, the most realistic of the scenarios examined by Sterman *et al* is therefore Scenario 2, in which 25% of stand biomass is removed by thinning and devoted to wood pellet production. In the supporting information, this scenario results in a 'carbon debt payback time' of four years for harvest of wood from pine plantations.

Landscape perspective and market effects

A landscape perspective, encompassing harvest and regrowth patterns occurring simultaneously across multiple stands, is required to comprehensively simulate and account for forest management and related carbon dynamics across a region supplying wood to a facility. Such a perspective puts the 'carbon debt' of a single stand (as modeled by Sterman *et al*) into a realistic multi-stand aggregate context and allows for the consideration of market dynamics between wood demand and supply over time.

The authors report payback times for carbon debt from 44–104 years after harvest. Carbon debt is an artifact of the arbitrary choice of the temporal starting point and spatial area that is used for carbon accounting. In forested landscapes, multiple individual landowners are making decisions whether to maintain or regenerate forests in anticipation of eventual commercial harvests and in response to demand for wood. A landscape perspective enables consideration of the well-documented effects of active wood markets. Extensive literature confirms that the presence of an active market for forest products (including energy) provides incentives for landowners to (1) maintain or increase land in forest cover and (2) increase the productivity of their forests (Hardie *et al* 2000, Lubowski *et al* 2008, Abt *et al* 2010, 2014, Dwivedi *et al* 2014, Costanza *et al* 2016, Dale *et al* 2017, Birdsey *et al* 2018). A more realistic treatment of the landscape perspective would have been to consider not only the plot being harvested but to include the whole landscape on which additional planting will occur due to increased demand. From this perspective, growth after harvest on multiple stands results in much shorter carbon payback times.

Factual misconceptions

Other statements made by the authors about management of pine plantations warrant clarification to avoid analyses based on incorrect assumptions. The authors state 'In reality, plantations are thinned every few years and harvested about every decade'. The citation used in support (US Forest Service 2000) does not corroborate this statement. In the definitive (if dated) work on loblolly pine silviculture (Schulz 1997), 'typical' plantation management regimes for wood products included a rotation of 30 years with at least one thinning. More recently, a 2014 survey of the largest private timberland owners in the US South[14] indicated that rotations averaged 28.8 years. Nearly all respondents (97%) conducted a first thinning and two-thirds conducted a second.

The authors also state that 'repeated harvests can degrade the productivity of the soils, lowering NPP. To compensate, managed plantations are typically fertilized several times per rotation, increasing N_2O emissions that would further worsen the climate impact of Scenario 6.' In a comprehensive review of forest harvesting impacts, Vance *et al* (2018) found highly variable results regarding forest productivity impacts. They concluded that there is insufficient evidence in the extensive literature to form a reliable default assumption that intensive harvesting leads to productivity loss. Pine plantations are frequently fertilized to improve growth where nutrients are limited, but not nearly at the rate suggested by the authors. In 2004, of approximately 13 million hectares of pine plantation in the US South, less than 0.5 million hectares were fertilized (Fox *et al* 2007); forest fertilization rates between 1969 and 2009 averaged 0.125 million ha/yr (Albaugh *et al* 2012). If managed plantations were fertilized three times per rotation as Sterman *et al* suggest, and rotations average 25 years, then we would expect to see 1.56 million hectares fertilized annually[15], 12.5 times the most recently reported rate. Furthermore, Albaugh *et al* (2012) found that mid-rotation fertilization resulted in net sequestration benefits compared to no fertilization.

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[13] From Forest2Market, 'Wood Supply Trends in the US South, 1995–2015' (figures 4–12) (http://nafoalliance.org/images/issues/pellets/Forest2Market_USSouthWoodSupplyTrends.pdf).

[14] https://forestresources.org/item/479–14-r-22-forest-management-practices-of-private-timberland-investors-and-managers-in-the-u-s-south.

[15] 13 million hectares managed on 25 year rotations would lead to 520 000 ha per age class. Three age classes fertilized annually would imply 1.56 million hectares being fertilized annually.

Table 1. Conclusions from Sterman *et al* (2018) and responses.

Sterman *et al* conclusion	Response
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[a].
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.
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 (Intergovernmental Panel on Climate Change IPCC 2013).
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 *et al* 2018).
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.
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[a]) 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 Sterman *et al* growing markets for wood reduce deforestation and can be expected to stimulate investment in afforestation and improved forest management (Tian *et al* 2018). These responses mitigate, rather than aggravate, warming.
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[a].

[a] In table S7 of the Sterman *et al* supplemental materials, the carbon debt payback time for scenario 2 for pine plantations is four years. For scenario 3 it is 12 years.

Responses to the conclusions from Sterman *et al* (2018)

Table 1 lists the seven conclusions from Sterman *et al* (2018) and our responses. In a number of these conclusions, worsening of warming or climate change is mentioned, although results are only presented for changes in CO_2 concentrations (not on climate variables such as temperature). It is inaccurate to infer short-term climate impacts from short-term changes in CO_2 emissions (Intergovernmental Panel on Climate Change IPCC 2013).

Summary

The most realistic and informative scenario examined by Sterman *et al* (2018) is scenario 2, in which only a portion of stand biomass is used for energy production. Conclusions regarding scenario 6, highlighted in the article, are highly suspect due to (a) low NPP of a pine plantation resulting from an uncharacteristically long rotation, and (b) lack of consideration given to harvested wood products with longer storage duration, and (c) the single-harvest assumption. Analyses such as this one would benefit from the recognition of the well-documented responses of landowners increasing production of wood in response to markets and anticipation of future harvests.

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