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Reply on CC1

Jiajun Wu et al.

Author comment on "Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study" by Jiajun Wu et al., Earth Syst. Dynam. Discuss., <https://doi.org/10.5194/esd-2021-104-AC2>, 2022

Dear Ken Caldeira,

Thank you very much for your very useful and constructive comments on our manuscript. We appreciate your concern about correctly quantifying the amount of carbon removed, and have carried out a few additional model runs with reduced emissions to compare against the various possible metrics for calculating carbon removal via Macroalgae Open-ocean mariculture and Sinking (MOS). There are some differences compared to geological storage of CO₂ because sinking of macroalgae to the ocean's abyss will not only remove carbon but also nutrients from the surface ocean in contact with the atmosphere, with consequences for the marine biology and carbon cycle.

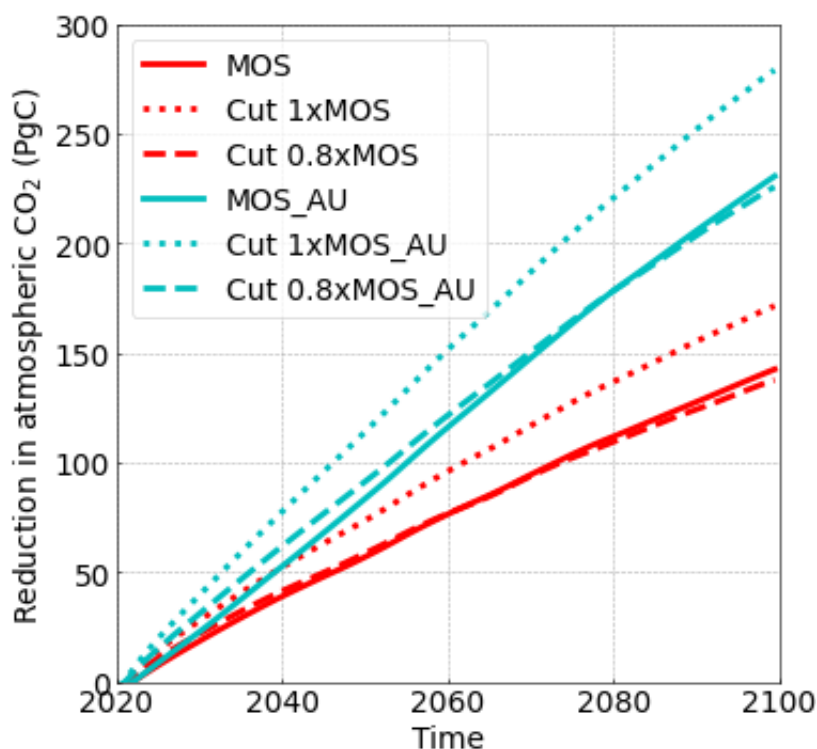


Fig. 1. The solid lines refer to the reduction in atmospheric CO₂ by normal MOS and MOS_AU. The **dotted** and **dashed** lines refer to the reduction in atmospheric CO₂

achieved by emission reduction **1.0** and **0.8** times the total CDR of MOS and MOS_AU, where CDR is measured as the amount of macroalgae carbon sunk to the sea floor. Red and cyan colors represent MOS and MOS_AU.

To estimate the size of CO₂ emissions offset by MOS, we performed a series of simulations without MOS, but with reduced CO₂ emissions relative to the RCP4.5 scenario by an amount proportional to the total CDR by MOS and MOS_AU experiments from the year 2020 to 2100.

In the original MOS simulation, the reduction of atmospheric CO₂ (142.6 Pg C) accounts for ca. 53% of the total carbon sequestration by MOS (270 PgC), which the smaller airborne reduction being to a large part due to CO₂ back fluxes between terrestrial, oceanic and atmospheric reservoirs - in the same way as the airborne fraction of CO₂ emissions is only about half. As discussed in Sec. 4.3.2, the offset of MOS CDR compared to an emission reduction by the same magnitude is generally caused by the reduced phytoplankton NPP (PNPP) due to nutrient competition and canopy shading effect of MOS.

Table 1. Amount of CO₂ emissions avoided in the emission reduction runs by year 2100 and reduction in atmospheric CO₂ in emission reduction runs without MOS and in MOS simulations.

	CO₂ Emission reduction vs. RCP4.5 (PgC)	Atm. CO₂ reduction by yr2100 vs. RCP4.5 (PgC)
MOS	/	142.6
Cut 1.0xMOS_CDR	270	171.5
Cut 0.8xMOS_CDR	216	137.7
MOS_AU	/	230.7
Cut 1.0xMOS_AU_CDR	446.8	279.1
Cut 0.8xMOS_AU_CDR	357.4	225.8

In a model run without MOS but with CO₂ emissions reduced the annual equivalents of the MOS-induced carbon exports, yielding a total amount of 270 PgC by year 2100 (**Cut 1.0xMOS_CDR**, Table. 1), the 270 PgC emissions removal yields a reduction of atmospheric CO₂ by 171.5 GtC by year 2100 (solid red line in Fig. 1). This is 20% more than the atmospheric CO₂ reduction of 142.6 PgC realized in the original MOS simulation where the MOS-induced shading and removal of nutrients from the surface layers reduces the biological carbon pump and the associated carbon storage in the ocean.

With emission cuts 20% less than the MOS-induced carbon export (**Cut 0.8xMOS_CDR**), atmospheric CO₂ concentrations simulated by the MOS-free emission-cut runs agree closely with those of the respective MOS experiments (dashed lines in Fig. 1). That is, each ton of CO₂ sequestered in the ocean by MOS is, in our model and on a 100 year timescale, equivalent to an emission cut of about 0.8 tons of CO₂.

Similar trends are obtained for the MOS_AU tests (Tab. 1 and Fig. 1).

We have added these information in the revised manuscript at the last paragraph of Sect. 4.3.2, which reads:

"The current model results provide additional evidence that the CDR potential of MOS is partly offset by its negative impacts on the pelagic biological production and the biological carbon pump. In an additional model run (not shown) without MOS but with CO₂ emissions reduced by the annual equivalents of the MOS-induced carbon exports, yielding a total amount of 270 PgC by year 2100, the 270 PgC emissions removal yields a reduction of atmospheric CO₂ by 171.5 GtC by year 2100. This reduction is 20% more than the atmospheric CO₂ reduction of 142.6 PgC realized in the original MOS simulation where the MOS-induced shading and removal of nutrients from the surface layers reduces the biological carbon pump and the associated carbon storage in the ocean. When CO₂ emissions are instead cut by an amount corresponding to 80% of the MOS-induced carbon export, atmospheric CO₂ concentrations simulated by the MOS-free emission-cut runs agree closely with those of the respective MOS experiments. That is, each ton of CO₂ sequestered in the ocean by MOS is, in our model and on a 100 year timescale, equivalent to an emission cut of about 0.8 tons of CO₂."

On another topic: A key issue is what are the C:N:P ratios in the macro-algae export relative to the background organic carbon export. For the macroalgae C:N is 20 and C:P is 111, so that is C:N:P to be 111:5.6:1.

I don't think you report the C:N and C:P ratios for the plankton export. I think Eby et al 2012 that you cite uses 106:16:1.

I am going to guess that the main reason that the macroalgae does something is because you can export 20 molC for each molN with the macro-algae but only 6.6 molC for each molN with phytoplankton. Is this understanding correct?

If so, why don't phosphate constraints govern? The 111 vs 106 differs by less than 5%. So why does using macroalgae give you only a 5%.

I guess my main issue with this paper on a superficial quick read is that I do not understand why the authors got the result that they got.

- What if the Redfield ratios of the macroalgae were the same as the Redfield ratios of the phytoplankton? Would the macroalgae then be effective?
- What if the remineralization depth of the macroalgae were the same as that of the phytoplankton? Would the macroalgae then be effective?

In short, and I admit a superficial reading, I don't understand why you obtained the results you obtained.

A good thing to ask yourself in any modeling study is: What assumption would have to be false to lead to a qualitatively different conclusion? This is often a good way to state the factors that are critical to your conclusions and what features of your model are additional ornamentation not central to your result.

Citation: <https://doi.org/10.5194/esd-2021-104-CC1>

Response: Sorry for the confusion, we will use this opportunity to clarify how the model works and why we obtained the results that we did. First, the detritus (or export) from macroalgae is considered separately from the standard detritus pool of the model, i.e., there are two detritus pools, one with the macroalgae C:N:P ratio (400:10:1, and not 111:5.6:1 as erroneously mentioned in the original manuscript and already in our brief reply on 17 January 2022) and another one with the Redfield ratio (106:16:1). Second, macroalgae detritus is not exported in the traditional way in the model with sinking and remineralization along the way, but instead the model assumes that the macroalgae biomass is instantly sunk to the seafloor (i.e., organic C, N and P are instantly transferred from the macroalgae farm at the surface directly to the seafloor with no remineralization along the way). Remineralization of macroalgae detritus can then occur, but only at the seafloor. The assumed macroalgae C:N:P ratio (see lines 100-101 for references), which is much higher than the ratio typically found in phytoplankton, is one of the reasons why sinking macroalgae has been proposed as a CDR method. The other reason is that directly sinking the biomass would avoid remineralization on the way down and thus, much carbon would be efficiently exported to the deep sea. To answer your 1st question, if the standard Redfield ratio were used for macroalgae instead of the one that we used, then no, the simulated CDR would not be as effective. However, by directly moving biomass from the ocean surface to the seafloor, remineralization along the way would be avoided and the

approach would still be somewhat more effective at transferring carbon to the deep ocean than normal biological pump processes. The answer to the 2nd question is also similar. If detritus from macroalgae were required to sink naturally to the seafloor, then much of the C would be lost along the way, as currently happens to phytoplankton biomass via the biological pump. Due to the macroalgae's higher C:N:P ratio, more C would end up in the deep ocean, but how much is an open question (see discussion on this in Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, 9(10), 737–742. <https://doi.org/10.1038/ngeo2790>).

We have added some text to the introduction to address the issues that you raise, by pointing out that the C:N:P ratio of macroalgae is higher than that of phytoplankton in the UVic ESCM model. In the introduction we have pointed out (line 65-67) that by sinking macroalgae biomass directly to the seafloor we avoid the loss of much organic C along the way. These texts are:

"..... The assumed constant C:N:P ratio is 400:10:1, which is higher than the stoichiometric ratio of the general phytoplankton in the UVic ESCM (C:N:P=106:16:1, the Redfield ratio). The immediate transfer to depth can be thought of as a short circuiting of the biological pump by bringing marine biomass directly to the seafloor without having it remineralized along the way."