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COMMENTS

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Key Points:
- Natural mitigation of climate change, when coupled with fossil fuel emission reductions, could help to minimize warming.
- Natural mitigation could cease, which could cause CO₂ emissions to revert to levels similar to those without natural mitigation.
- Other solutions that can reduce CO₂ emissions rapidly and remove CO₂ from the atmosphere and permanently store it are needed.

Supporting Information:
- Supporting Information S1
- Supporting Information S2
- Data Set S1
- Data Set S2

Correspondence to:
J. Crusius,
john.crusius@gmail.com

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Author Contributions:
Conceptualization: John Crusius
Formal analysis: John Crusius
Investigation: John Crusius
Methodology: John Crusius
Project administration: John Crusius
Supervision: John Crusius
Validation: John Crusius
Visualization: John Crusius
Writing - original draft: John Crusius
Writing - review & editing: John Crusius

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“Natural” Climate Solutions Could Speed Up Mitigation, With Risks. Additional Options Are Needed.

John Crusius1
1Seattle, WA, USA

Abstract
Mitigation of climate change by intentionally storing carbon in tropical forests, soils, and wetlands and by reducing greenhouse gas fluxes from these settings has been promoted as rapidly deployable and cost-effective. This approach, sometimes referred to as “natural climate solutions,” could keep post-industrialization warming below 1.5 °C, when coupled with reductions in fossil fuel emissions, as confirmed here with a simple numerical model of future emissions. However, such mitigation could cease in response to changes in future climate, land use, or natural resource policies, or there could be CO₂ released from reservoirs of stored carbon. Model simulations suggest cumulative emissions could be similar, under scenarios where carbon storage ceases, or stored carbon is released, to emissions expected in the absence of any natural mitigation. If climate change is to be minimized, no-regrets approaches to natural mitigation should be considered (e.g., by reducing deforestation), as emissions targets that could limit warming to 1.5 °C cannot be met without mitigation of this magnitude. However, additional mitigation options should also be evaluated that can reduce CO₂ emissions and remove CO₂ from the air (and store it permanently).

Plain Language Summary
One option for fighting climate change involves “natural climate solutions” that would remove atmospheric CO₂ by storing carbon in tropical forests, soils, and wetlands and would minimize greenhouse gas fluxes from such environments. With a simple computer code to predict future emissions, I confirm that such natural mitigation could, along with reductions in fossil fuel emissions, help keep the average global post-industrialization temperature rise below 1.5 °C and could help delay impacts of climate change. However, future changes in climate, land use, or natural resource policies could cause natural mitigation to cease and emissions to increase, and modeling suggests levels could approach those expected in the absence of natural mitigation, which would negate much of the intended benefit. We should prioritize “no-regrets” natural mitigation, including stopping deforestation, that can provide time to develop other needed mitigation options to remove atmospheric CO₂ and permanently store it.

1. Introduction
Many approaches considered for minimizing the risks of climate change involve combinations of reducing CO₂ emissions from fossil fuel combustion and from land use and taking up CO₂ from the atmosphere using various “negative emissions” technologies (e.g., Fuss et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2019). Enhancing carbon storage (sequestration) in naturally occurring biological reservoirs such as forests, soils, and wetlands represents one such negative emissions approach. Reducing greenhouse gas fluxes from these settings, which I will refer to here as “avoidable emissions” (modified from Griscom et al., 2017), could also contribute to climate change mitigation. Enhancing carbon storage in, and reducing CO₂ emissions from, biological reservoirs have collectively been referred to as “natural climate solutions” (as defined by Griscom et al., 2017) and have been promoted as readily available and cost-effective (e.g., Griscom et al., 2017). It has also been suggested that such natural approaches could achieve mitigation more rapidly, and keep the global average post-industrialization temperature change lower, than is possible from fossil fuel emissions reductions alone (Griscom et al., 2017; Houghton et al., 2015).

The largest available carbon storage term (CO₂ sink) for natural mitigation lies in planting trees in the tropics on land that has not been forested for some time (termed afforestation; Houghton & Nassikas, 2018; Lewis et al., 2019; Bastin et al., 2019; Brancalion et al., 2019). The largest step that could reduce avoidable emissions (CO₂ sources) is slowing tropical deforestation (avoiding forest conversion; e.g., Griscom
et al., 2017). Modest additional carbon storage (sinks) could be achieved in non-forested soils via conservation agriculture and storage of biochar, while avoidable emissions (sources) could be reduced in such soils via nutrient management and improving feed for grazing animals (Griscom et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2019; Smith, 2016). Avoidable emissions could be lowered as well by reducing loss of saltwater and freshwater wetlands (Griscom et al., 2017; Pendleton et al., 2012). Only a small amount of carbon storage is available in saltmarshes, mangroves, and seagrasses (termed “blue carbon”; Ouyang & Lee, 2014; Griscom et al., 2017). Note that there is a legitimate claim that carbon storage from growing trees in temperate and high-latitude forests may not cool global climate, because the cooling potential of carbon storage might be negated by warming effects caused by reduced albedo, changes in evapotranspiration, and release of volatile organics (e.g., Luyssaert et al., 2018).

Estimates of the cumulative magnitudes of these natural climate solutions are presented in Table 1, while detailed discussion of the contributing processes and their uncertainties can be found in the references cited there. Note that I do not consider mitigation by ocean-based processes in this work simply because the available options are less established and less accepted than the (largely) terrestrial options considered here, but the conclusions reached suggest that mitigation options in the ocean should be considered.

In this work I examine several plausible scenarios for aggressive mitigation via combinations of these natural biological processes, and fossil fuel emissions reductions, that together have been suggested could keep the average global temperature increase within 1.5 °C of pre-industrial values (e.g., Griscom et al., 2017). I also consider processes that could make the impact of natural mitigation efforts temporary. For the model I use values for the natural CO2 sink and source terms cited by Griscom et al. (2017). Roughly half of the mitigation stems from eliminating “avoidable emissions,” while the other half stems from implementing biological carbon sequestration (Griscom et al., 2017; Table 1), with the total summing to ~3.1 Pg C a−1 (Table 1). These values represent conservative estimates, as they are at the low end of most published estimates (Table 1). This choice for the magnitudes of the mitigation terms is somewhat arbitrary, but for reasons I will discuss later, the assumed magnitudes do not substantially change some of my important conclusions. While not the focus of this work, these values are estimates of “cost-effective” mitigation, as defined by Griscom et al., 2017, that can be achieved, at present, for less than $100 per ton of CO2 ($370 per ton of carbon). Mitigation costs were examined as well in Fuss et al. (2018).

### Table 1

**Published Estimates of the Global Potential for “Natural Climate Solutions” (Sensu Griscom et al., 2017) Between ~2020 and 2100 (All in Units of Pg C a−1) From Processes in Forests (Largely Tropical), Non-Forested Soils, and “Blue Carbon” (Saltmarshes, Mangroves, and Seagrasses)**

| Processes in Forests (Largely Tropical) | Maximum mitigation, 95% CI bounds (C storage + avoidable emissions) | C storage Avoidable emissions | Reference |
|----------------------------------------|-------------------------------------------------|-------------------------------|-----------|
| Forests                                | 3.1–7.7                                         | 1.2 (CE) 0.8 (CE)             | Griscom et al. (2017) |
|                                        | 1.1–3.3                                         | Two estimates in National Academies of Sciences, Engineering, and Medicine (2019) |
|                                        | 1.5a                                            | Houghton and Nassikas (2018)  |
|                                        | 2.6b                                            | Bastin et al. (2019)          |
|                                        | 0.14–1.0                                        | Fuss et al. (2018)            |
| Soils (non-forested)                   | 1.2–1.9                                         | 0.4 (CE) 0.3 (CE)             | Griscom et al. (2017) |
|                                        | 0.4–2.2                                         | Eight estimates in National Academies of Sciences, Engineering, and Medicine (2019) |
| Saltmarshes, mangroves, and seagrasses | 0.7–1.2                                         | 0.03 (CE) 0.4 (CE)            | Griscom et al. (2017) |
|                                        | 0.1–0.16                                        | Many estimates in Ouyang and Lee (2014) |
| Total                                  | 4.9–10.8                                        | 1.6 (CE) 1.5 (CE)             | Griscom et al. (2017) |

*Note. This includes estimates of biological carbon sequestration (C storage), of avoidable emissions reduction, and estimates that combine both (see text). Estimates of “cost-effective” mitigation (Griscom et al., 2017) are in bold, include the letters CE after the number and were used in the modeling. See the listed references for detailed discussion.

a This assumes 130 Pg of net cumulative negative emissions, averaged from 2016 to 2100, from stopping deforestation, allowing secondary forests to grow, extending the life of wood products, and subtracting committed emissions from wood products. b Assumes 208.5 Pg C stored from global tree restoration, averaged from 2020 to 2100.*
Seminal work by Allen et al. (2009) first pointed out that “peak warming” (the maximum expected warming) can be reasonably predicted from the cumulative emissions of CO2, independent of the emissions timing, owing to the long residence time of CO2 in the atmosphere. Recent work suggests that by keeping global cumulative CO2 emissions (post-2015) below approximately 200 Pg C it could be possible to keep the average global temperature increase within 1.5 °C of pre-industrial values (Millar et al., 2017; Rogelj et al., 2019). If we are to keep global temperature change below 2 °C, the cumulative post-2015 emissions will need to remain below ~400 Pg C (Millar et al., 2017; Rogelj et al., 2019). For perspective, present-day CO2 emissions are ~11 Pg C a\(^{-1}\) (Le Quéré et al., 2018). The cumulative CO2 emissions limits required to meet these temperature targets could be higher if significant non-CO2 mitigation were put in place (Millar et al., 2017), or they could be lower, owing to a variety of earth system feedbacks (e.g., Rogelj et al., 2019), including methane release from permafrost (Gasser et al., 2018) and possible future decreases in the strength of the land and ocean carbon sinks (Mengis et al., 2018). These feedbacks are poorly understood. For brevity, I will use the term “cumulative CO2 emissions” to refer to the sum of all CO2 emissions since 1 January 2015, a reference date that facilitates comparison to other recent work. The use of the word “cumulative” does not imply that the emissions accumulate in the atmosphere.

In this work I use a simple numerical model to simulate the degree to which natural climate solutions, or reductions in fossil fuel emissions, or both, might help to achieve these emission targets. I also simulate the impact on emission targets if such natural mitigation were to cease as a result of climate change, human changes in land use, or changes in natural resource policies. What is new in this work is my simple numerical modeling of CO2 emissions and their impact on reaching these climate goals. Because of limited space, I do not specify pathways of fossil fuel emissions reduction but assume they could occur via many different possible steps. At the end I consider the need for climate change mitigation by additional processes.

2. Model Description

I simulate future CO2 emissions with a simple numerical model that draws upon published estimates of current and past fossil fuel and land use CO2 emissions (Le Quéré et al., 2018). I ignore possible scenarios in which CO2 emissions might increase over time. Numerous publications have explored scenarios with future increases in emissions (e.g., Allen et al., 2009; Intergovernmental Panel on Climate Change, 2013). In this work I choose to focus on scenarios with reduced CO2 emissions that could be achieved by both natural climate solutions, as discussed above, and a range of plausible rates of fossil fuel emissions reductions. This allows closer scrutiny of nuances of those scenarios that are suggested could keep the post-industrialization temperature increase below ~1.5 °C. In the absence of natural mitigation, I assume the land use-derived CO2 emissions remain constant at 1.45 Pg C a\(^{-1}\) (the average of 2008–2017; Le Quéré et al., 2018).

In the model, total CO2 emissions are described by:

\[
E_{\text{tot}}(t) = -rE_{\text{ff}}(t) + E_{\text{terr}} + E_{\text{nat}}(t),
\]

where

- \(E_{\text{tot}}\) = annual total flux of CO2 to the atmosphere from both fossil fuel and land use sources, expressed as petagrams (Pg) C a\(^{-1}\) (Pg equivalent to a gigaton (Gt)). The mass in Pg of C can be multiplied by 3.664 to convert to Pg of CO2.
- \(E_{\text{ff}}\) = annual flux of CO2 to the atmosphere from fossil fuels (Pg C a\(^{-1}\)).
- \(r\) = annual reduction rate, fraction a\(^{-1}\), of the CO2 flux to the atmosphere from fossil fuel emissions reductions.
- \(E_{\text{terr}}\) = the annual flux of CO2 from land use change.
- \(E_{\text{nat}}\) = the annual flux of CO2 into or out of the biological reservoirs as a result of natural mitigation of climate change (Pg C a\(^{-1}\)).

The model invokes the natural mitigation steps alluded to in the introduction, using values for the carbon sink and source terms given in Table 1, with natural climate solutions ramping up linearly over 10 years.
I use these estimates as a reasonable summary of the state of current knowledge and a starting point for discussion that is reasonably independent of the actual flux estimates. For clarity, methane and nitrous oxide emissions are considered but converted to CO$_2$ equivalents, in Griscom et al. (2017). The model also assumes for simplicity that no other mitigation occurs than is described here. The simulations are carried out to 2100 because doing so helps to clarify some important points, although the value of the simulations decreases with time in the modeled future, given uncertainties about future climate, technology, population, and so forth.

3. “Natural” Climate Solutions Plus Varying Fossil Fuel Emissions Reductions

Some economic models have suggested that the maximum feasible rate of fossil fuel emissions reduction is 5% $a^{-1}$ (den Elzen et al., 2007; Stocker, 2013), which I use as a starting point for considering emissions reductions. I also include simulations with reductions of 1% $a^{-1}$ and 3% $a^{-1}$, representing plausible slower transitions to emissions-free energy. Later, I consider higher rates of reduction. For perspective, I compare these model-simulated emissions to RCP2.6, the representative concentration pathway envisioned over a decade ago to represent an aggressive approach to emissions reductions (van Vuuren et al., 2007; to avoid overloading the graphs, I do not plot RCP1.9, a more aggressive mitigation pathway). The combined impacts of the natural mitigation and fossil fuel reductions of 1–5% $a^{-1}$ yield emissions pathways that range from decreasing more rapidly than RCP2.6 to decreasing less rapidly (Figure 1a). All of the modeled scenarios yield pathways with emissions decreasing more rapidly than for RCP4.5, a pathway of less aggressive mitigation (Clarke et al., 2007; Figure 1a).

In the absence of any natural mitigation, but with fossil fuel emissions reductions of 3% $a^{-1}$ and 5% $a^{-1}$, annual emissions in 2100 approach the levels caused by land use change alone (Le Quéré et al., 2018), while cumulative emissions in 2100 would be 360–470 Pg C, and still increasing (Figure 1b), values far greater than the 200 Pg C target. These results suggest that achieving the goal of keeping the global temperature increase below 1.5 °C might require additional mitigation measures. If these same 3–5% $a^{-1}$ reductions in fossil fuel emissions are accompanied by all of the natural climate solutions discussed in the introduction (Table 1), annual CO$_2$ emissions would decrease rapidly and reach negative values in a few decades (Figure 1a). The maximum in cumulative CO$_2$ emissions would be reduced to 170–235 Pg C (Figure 1b), and cumulative emissions would be decreasing by 2100.

Minimizing avoidable emissions (e.g., by stopping deforestation, by soil nutrient management, and by stopping wetland loss) could constitute a simple, “no-regrets” approach to mitigation that offers climate benefit with little risk. If fossil fuel emissions reductions of 5% $a^{-1}$ were accompanied only by elimination of avoidable emissions (but not biological carbon sequestration), annual CO$_2$ emissions would decrease to zero by 2100, when cumulative CO$_2$ emissions would plateau at close to 240 Pg C (Figure 1b). These simple model simulations substantiate what others have noted, that natural climate solutions of this magnitude could plausibly help to reduce global CO$_2$ emissions more rapidly than could occur via fossil fuel emissions reductions alone, and could help to achieve the cumulative emissions goals that could keep global temperature increase below 1.5 °C (Millar et al., 2017; Rogelj et al., 2019). However, the scenarios presented span a large range of CO$_2$ removal potential, leading to a range in possible cumulative emissions in 2050 that spans 135 Pg C (Figure 1b).

Natural climate change solutions cannot prevent post-industrial warming of 1.5 or 2 °C without fossil fuel emissions reductions. To illustrate this point, when fossil fuel emissions are reduced at a rate of 1% $a^{-1}$, and natural climate solutions are fully implemented as described here, cumulative emissions exceed 400 Pg of C by ~2075 while still increasing (Figure 1b). “Natural” mitigation of climate change can serve as a complement to fossil fuel emissions reductions to help limit warming to 1.5 or 2 °C, however.

4. Scenarios in Which Natural Mitigation Ceases

Tempering this encouraging outlook, however, is the fact that such natural mitigation must persist for many decades, or longer, to be of most value. Before I use the simple model to explore some idealized scenarios, I discuss many factors that could cause natural mitigation processes to stop or even lead to CO$_2$ release. Carbon sequestration could decrease in the future in tropical forests if droughts occur, as they have in...
recent decades (Feldpausch et al., 2016; Yang et al., 2018), because droughts have been shown to reduce carbon storage in tropical forests (Feldpausch et al., 2016; Gatti et al., 2014; Qie et al., 2017; Schwalm et al., 2017; Yang et al., 2018) and in savannahs (Liu et al., 2015). Furthermore, carbon stored in tropical forests could be released to the atmosphere in the event of fire, an important contributor to recent
deforestation in the Amazon region (Gatti et al., 2014). Release of CO₂ from fire could effectively reverse considerable prior carbon sequestration. The concern that climate change could soon cause the climate benefits of reforestation in the tropics to cease was echoed by Bastin et al. (2019). Even without any change in climate or fire, a change in land ownership, or in a nation’s natural resource policies, could plausibly cause both biological carbon sequestration to stop and avoidable emissions to recommence. This could occur, for example, from implementation of policies that encourage agricultural development on land currently covered by tropical rainforest. This has recently occurred in the Brazilian Amazon region (Science, 2019). In soils, carbon sequestration could cease as the soil sink saturates on timescales of 20–40 years (Fuss et al., 2018; Smith, 2016). The sink in soils and in wetlands could also cease in response to a change in land ownership. There remain uncertainties, also, in the carbon storage benefits of mitigation focused on soils, reviewed recently by Schlesinger and Amundson (2019). There are claims that the carbon storage benefits of no-till agriculture are small and could plausibly be offset by an increased flux of nitrous oxide (N₂O; Powlson et al., 2014). There is also uncertainty regarding the long-term impacts of addition of biochar to soils, because of a dearth of long-term field experiments examining the fluxes of other greenhouse gases (e.g., N₂O) from amended soils (Gurwick et al., 2013; Song et al., 2016).

Carbon storage in “blue carbon” settings, including coastal salt marshes, mangroves, and seagrass (e.g., Pendleton et al., 2012) could make a small contribution to natural climate solutions (Table 1). The most important contribution related to “blue carbon” may stem from minimizing avoidable emissions by preserving existing carbon stocks (e.g., Pendleton et al., 2012). However, if sea level rise were to increase at a faster rate than wetlands could grow, wetland drowning could cause the carbon burial rate to plummet once sea level rise exceeds a certain threshold (National Academies of Sciences, Engineering, and Medicine, 2019, Figure 2.4). Predicting the fate of these various coastal carbon stocks in response to sea level rise is beyond the scope of this work. It is likely that a fraction of the carbon would be eroded and degraded, resulting in slow release of dissolved inorganic carbon to the ocean. A smaller fraction would be degraded and released to the atmosphere (as CO₂). These impacts on coastal blue carbon could continue for centuries, given our likely global commitment to eventual sea level rise of a few meters caused by the long atmospheric lifetimes of many greenhouse gases (Levermann et al., 2013).

5. Natural Mitigation Still Delays Climate Impacts, if Mitigation Ceases

I used the model to simulate some idealized, simple scenarios in which natural mitigation ceases, or reverses, after a few decades, to highlight some impacts of the possible impermanence of natural climate solutions. For simplicity, these modeled scenarios all included reduction in fossil fuel emissions at 3% a⁻¹. In addition, these simulations consider (Figures 1c and 1d): (1) cessation of natural climate solutions after 20 years (e.g., in response to drought, land use change or changes in natural resource policies); (2) cessation of natural climate solutions after 20 years, followed by release of the carbon previously stored during those 20 years, at a rate of 5% a⁻¹ (e.g., in response to fires, deforestation, tillage of previously unutilized soil, and loss of wetlands); (3) cessation of natural mitigation after 40 years. These are simple scenarios that are unlikely to occur exactly as modeled, but they are designed to demonstrate semi-quantitatively how cumulative CO₂ emissions would be impacted if natural climate solutions were to cease after a few decades, and how this would impact our ability to meet aggressive climate change mitigation targets. In all of these scenarios the annual and cumulative emissions are diminished while the natural mitigation persists (Figures 1c and 1d), after which the annual emissions increase quickly as natural mitigation stops (Figure 1c). In a sense, such biological mitigation still offers a delay of the worst impacts of climate change by temporarily reducing emissions. However, under these scenarios, the cumulative emissions are reduced only slightly compared to scenarios with no natural mitigation (Figure 1d), reaching 400–500 Pg C, and still increasing rapidly, by 2100. Furthermore, CO₂ loss from sites of biological carbon storage could easily be worse than modeled here, because fires and/or deforestation could lead to CO₂ release from portions of the large regions of long-existing forest, not just the newly reforested regions depicted by this simple model.

We cannot predict with any certainty when natural mitigation might cease to be effective, but we know that it may offer only a limited, temporary delay of climate change impacts, as well as providing ecosystem benefits that include improved nutrient retention, soil quality, and biodiversity (Fuss et al., 2018). Our awareness of the impermanence of biological carbon sequestration merely heightens the need for pursuing
longer-term permanent solutions, including emissions reductions and efforts that remove CO₂ from the air and store it permanently. The challenge of rapidly scaling up more permanent CO₂ storage approaches illustrates that natural climate solutions can still play an important role as an intermediate step to minimize cumulative CO₂ emissions until more permanent CO₂ removal and storage mechanisms are scaled up and also accepted by society.

### 6. Staying Below 1.5 °C With Reduced Energy Demand and No-Regrets Mitigation

Recent work suggests that it might be possible to keep post-industrialization warming below 1.5 °C by substantially reducing energy demand, without the need for negative emissions technologies (Grubler et al., 2018), or by invoking a range of aggressive measures, including electrification of energy and reduction of non-CO₂ greenhouse gases, with reduced need for negative emissions technologies, (van Vuuren et al., 2018). With the model I explore scenarios with 7% a⁻¹ and 9% a⁻¹ reductions in fossil fuel emissions (greater than the previously assumed maximum of 5% a⁻¹) to simulate such rapid reduction in energy demand, both with and without “no-regrets” natural mitigation (as discussed in section 3). If fossil fuel emissions reductions of ~7% a⁻¹ or faster could be achieved, along with no-regrets natural climate solutions, annual emissions could be reduced to zero (Figure 1e), and cumulative emissions could be stabilized below 200 Pg C (Figure 1f) by mid-century. This confirms that if fossil fuel emissions could be curtailed this rapidly, the post-industrialization warming could plausibly be kept below 1.5 °C with no need for negative emissions technology, as others have recently suggested (Grubler et al., 2018). Such efforts constitute a difficult global challenge, as achieving this would require cooperation by all countries that are the primary emitters of fossil fuels and by countries that are home to the major biological carbon reservoirs (e.g., tropical forests).

![Figure 2](image-url)

**Figure 2.** Date when global CO₂ emissions could be reduced to 50% of the 2019 value, as a function of the rate of fossil fuel (FF) emission reduction and possible natural climate change mitigation. The 50% reduction is reached faster in scenarios in which all biological mitigation steps are carried out (and continue effectively; green X) than when only “avoidable emissions” are eliminated (yellow diamonds), which achieves 50% reduction faster than scenarios with no natural mitigation (red X with vertical line). The time difference for 50% reduction between scenarios with and without natural mitigation diminishes at faster rates of fossil fuel emissions reduction. The dates presented here would change if mitigation of warming agents other than CO₂ were implemented and would cease to be valid if the natural mitigation ceased to be effective (see text and Figures 1c and 1d).
Reducing energy demand at the rate envisioned in these scenarios would be difficult, which merely accentuates the value of a multi-faceted, global approach that encourages all avenues of emissions reductions, and carbon storage that, in the ideal case, provide permanent benefit.

The modeling also highlights another important point, namely, that as long as emissions from land use (primarily tropical deforestation) continue at current rates (section 2; Figure 1e), cumulative CO₂ emissions will continue to increase, even when fossil fuel emissions are reduced as rapidly as 9% a⁻¹ (Figure 1f). This merely accentuates the importance of minimizing land use emissions as a necessary step toward keeping the post-industrialization global temperature increase below 1.5 °C. Note that countering emissions from land use could conceivably also be effected by some other “negative emissions” technology, but no such technology is currently available at the scale required (see Fuss et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2019) nor is the cost as low as it is for minimizing avoidable emissions (see Fuss et al., 2018; Griscom et al., 2017).

Examining the dates at which CO₂ emissions could be reduced by 50%, under these mitigation scenarios, draws attention to some important points. Fifty percent emissions reductions could occur sooner with effective, continuous natural mitigation than without such mitigation, for a given rate of fossil fuel emissions reductions, but the degree to which natural mitigation speeds up 50% CO₂ emissions reductions decreases at faster rates of fossil fuel emissions reduction (Figure 2). Of course, whether natural mitigation is invoked or not, 50% CO₂ emission reductions could occur more rapidly at faster rates of fossil fuel emissions reductions. Finally, the only scenarios explored here which limit cumulative emissions to approximately 200 Pg C and have thus been suggested capable of limiting post-industrial warming to approximately 1.5 °C, all achieve CO₂ emissions reductions of ~50% by ~2030 (Figures 1b and 1f), consistent with the interpretation of Rogelj et al. (2018, Ch 2 p. 95). However, the uncertainties in earth system feedbacks, for example, from future possible reductions in natural carbon sinks, and possible future increases in methane emissions from thawing permafrost, are large enough that some recent work suggests we cannot rule out the possibility that we have already exceeded emissions limits that could restrict warming to 1.5 °C (Mengis et al., 2018). Furthermore, the uncertainties in these feedbacks, together with large interannual variability in the magnitude of the inferred terrestrial biological sink (e.g., Le Quéré et al., 2018), may mean that accurate assessment of the success of “natural” mitigation could only be inferred from long-term (>5 year) averages of carbon budgets, if and when large-scale natural mitigation occurs.

7. Conclusions: More Permanent Mitigation Options Are Needed

The stakes in climate change mitigation are high, and I end by emphasizing that (1) minimizing the impacts of future climate change will be difficult, but not impossible; (2) natural climate solutions are among the few tools that are currently available at a scale that could help to speed up mitigation compared to what can be achieved with fossil fuel emissions reductions alone. However, many natural mitigation processes are inherently at risk of stopping or reversing. Choosing natural mitigation pathways that are least vulnerable to disruption by climate change or human activities, including minimizing tropical deforestation, would help to maximize their potential benefit. Indeed, keeping post-industrial warming below 1.5 °C could, in theory, be possible by implementation of “no-regrets” emissions reduction from forests, soils, and wetlands, together with fossil fuel emissions reductions of ~7% a⁻¹, without the need for negative emissions technologies. (3) However, given the likelihood that many natural climate solutions represent a temporary benefit that cannot be guaranteed to persist in perpetuity and that international efforts to reduce emissions have achieved limited success, it is important to continue research, development, and implementation of other promising strategies offering removal and storage of atmospheric CO₂ on a scale comparable to natural climate solutions (~3 Pg C a⁻¹). There is a need for strategies that could offer carbon storage that can be proven to be more permanent than the “natural” mitigation discussed here. There are too many ongoing efforts to list here, although none have yet been demonstrated at the scale required. Mitigation aimed at reducing the fluxes and/or concentrations of non-CO₂ warming agents, including other greenhouse gases and black carbon would also be beneficial. Even if they prove temporary, the natural climate solutions can help reduce emissions until such permanent CO₂ sinks can be developed at the scale required. (4) Keeping post-industrialization warming below 1.5 °C can be achieved, but it will take
an ambitious, concerted, long-term, globally collaborative effort that greatly exceeds what is currently being done.

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