Sensitivity of climate mitigation strategies to natural disturbances

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Abstract

The present and future concentration of atmospheric carbon dioxide depends on both anthropogenic and natural sources and sinks of carbon. Most proposed climate mitigation strategies rely on a progressive transition to carbon-efficient technologies to reduce industrial emissions, substantially supported by policies to maintain or enhance the terrestrial carbon stock in forests and other ecosystems. This strategy may be challenged if terrestrial sequestration capacity is affected by future climate feedbacks, but how and to what extent is little understood. Here, we show that climate mitigation strategies are highly sensitive to future natural disturbance rates (e.g. fires, hurricanes, droughts), because of the potential effect of disturbances on the terrestrial carbon balance. Generally, altered disturbance rates affect the pace of societal and technological transitions required to achieve the mitigation target, with substantial consequences on the energy sector and the global economy. An understanding of the future dynamics and consequences of natural disturbances on terrestrial carbon balance is thus essential for developing robust climate mitigation strategies and policies.

Keywords: natural disturbances, climate change, integrated assessment, climate mitigation, climate policies

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1. Introduction

A wide variety of natural disturbances significantly affect the dynamics of terrestrial ecosystems, including fires, insects and pathogens outbreaks, hurricanes, droughts and heat waves. They are largely carbon neutral under a constant long term frequency and severity regime, due to ecosystem recovery. However, there is increasing evidence that natural disturbance rates are likely to change in the future [1–5] (a selection of papers exploring this issue, and their outcome, is presented in table S1, in the supplementary material available at stacks.iop.org/ERL/8/015018/mmedia).

For example, vegetation fires produce large pulses of carbon to the atmosphere [6], and their frequency/severity could increase in regions experiencing warmer/drier climates [1, 2], or decrease with land management and fire suppression practices [7]. Insect and pathogen outbreaks are likely to intensify with warming and expand into new areas, causing carbon losses through mortality and increased fire susceptibility [8, 9]. The severity of hurricanes may increase with warmer sea surface temperatures, with extensive impacts on ecosystems [10], while their frequency may decrease in some regions due to higher wind shear [11, 12]. Droughts and heat waves generate considerable carbon fluxes to the atmosphere [13] and stress ecosystems, making them more sensitive to other disturbances [4].

Most proposed climate change mitigation strategies, however, rely on maintaining or enhancing the terrestrial
carbon sink as a substantial contribution to restrain the concentration of greenhouse gases in the atmosphere [14]. Future changes in terrestrial sequestration from altered disturbance rates would challenge these strategies. To achieve the same targets, new emissions from increasing disturbance rates would have to be offset by additional cuts in anthropogenic emissions, while reduced emissions from lower disturbance rates would relax carbon constraints on the society. The significance of these effects and how they could interact with future policy, economic, and land-use decisions have thus far not been quantified or even well constrained.

This study provides a first-order quantification of the effects of altered natural disturbance rates on climate mitigation strategies, using a state-of-the-art integrated assessment model (IAM). IAMs produce projections of the interaction between the Earth system (vegetation, oceans, climate) and human systems (land use, energy and food production, trade) within an integrated economic framework. They are extensively used to explore the implications of potential climate mitigation policies through carbon pricing. The resulting mitigation pathways have been used in a range of assessments [15–17] and are a core element of the ongoing IPCC 5th assessment [18]. The use of an IAM with a fully integrated land-use model is particularly advantageous for this study, because it avoids the problem of having to exogenously specify future land-use patterns that are unresponsive to natural disturbances and mitigation efforts. IAMs allow for the simultaneous consideration of changes in forest carbon due to disturbances, changes in land cover that arise from the demand for food, forest products, and bioenergy for carbon mitigation, and changes in land cover that arise from incentives to maintain carbon stocks in ecosystems. The future land-use evolution is therefore codetermined with the evolution of the energy system, and both are a function of the natural disturbance assumptions.

2. Methods

2.1. The GCAM model and mitigation policy

The Global Change Assessment Model (GCAM [19, 20], see description in the supplementary material, figure S1 available at stacks.iop.org/ERL/8/015018/mmedia and http://wiki.umd.edu/gcam/) is run to determine the economically optimal strategy to reach a climate mitigation target in 2095 under scenarios of stable, increasing and decreasing disturbance rates (see below). For each run, the climate policy induces a carbon market that applies to all sectors through carbon taxes and subsidies, driving the necessary changes in land use, fossil fuels and industrial production to constrain carbon emissions and achieve mitigation. The model assumes economic markets and any decision making to be fully rationalized on economic efficiency under the given constraints (e.g. demand for food, mitigation policies), and full policy enforcement (e.g. no leakage on terrestrial carbon accounting). The mitigation target considered is a stabilization at 3.7 W m$^{-2}$ radiative forcing by 2095, the second most stringent of the commonly analyzed targets (2.6, 3.7, 4.5, 6.0, 8.5 W m$^{-2}$), with an associated atmospheric CO$_2$ concentration of roughly 470 ppm (550 ppm CO$_2$-equivalent). If concentrations were held at this level, the global mean surface temperature would eventually stabilize at $\sim$3$^\circ$C above pre-industrial level based on the most likely climate sensitivity [21].

2.2. Disturbance scenarios

The most advanced quantitative estimates of future disturbance trends and impacts feature large uncertainties [5] (table S1 available at stacks.iop.org/ERL/8/015018/mmedia) and different disturbance types have specific drivers and dynamics [22]. Rather than projecting specific disturbance and geographic scenarios, we thus conduct a sensitivity analyses with a range of global disturbance trends—i.e., integrating a wide range of potential disturbance scenarios across space and time—to sketch out the potential magnitude and mechanisms of disturbance impacts on climate mitigation. The scenarios used here encompass a broad range of observed variability and future projections (see review in table S1 available at stacks.iop.org/ERL/8/015018/mmedia), from a halving (−50%) to a doubling (+100%) of global disturbance rates (i.e. 150 scenarios, 1% increment from −50% to +100%). To simulate a general climate feedback, the change in disturbance rates in each scenario is gradually implemented from 2015 to 2095 following the temperature change as simulated within the GCAM framework. Note that GCAM currently does not represent management practices aimed at reducing disturbances (e.g. thinning), or more generally enhance carbon sequestration of a given ecosystem, which is thus a mitigation option not considered in this study.

2.3. Disturbance impacts

Natural ecosystems are grouped in 5 broad types in GCAM: forests, shrublands, grasslands, tundra and deserts. They are spatially distributed through 151 agro-ecological sub-regions globally (see supplementary material available at stacks.iop.org/ERL/8/015018/mmedia), and each ecosystem type has specific carbon content and growth dynamics according to the sub-region considered. Carbon dynamics are accounted for through a parametric model (not process oriented). Aboveground carbon dynamics depend on two parameters: potential carbon density (PCD$_{abg}$, the carbon content at maturity) and mature age (M$_{age}$, the time to reach 95% of PCD$_{abg}$ after growth initiation). PCD$_{abg}$ and M$_{age}$ are derived from satellite observations (e.g. SAGE potential vegetation [23]) and literature estimates. This terrestrial module has been developed to track carbon fluxes from growth and land use, with processes such as disturbances not explicitly represented and sub-regions containing only one pool of each ecosystem type (i.e., spatial and stand-age patterns are not tracked). Soil carbon is represented in GCAM through a similar approach [24]. This study focuses on aboveground impacts because soil carbon impacts vary widely across disturbance types, but this aspect is considered in an alternative parameterization of the model (see below).

In the real world, disturbance types alter ecosystems and carbon fluxes in different ways (e.g. combustion/mortality,
aboveground/belowground impacts, carbon/nutrients), but all affect both the carbon balance and age structure of ecosystems [25, 26]. We thus modified GCAM to account for natural disturbances through PCD_{abg} and M_{age} using a generalized biomass accumulation function with a constant growth rate and a loss rate through disturbances (see supplementary material available at stacks.iop.org/ERL/8/015018/mmedia). Accordingly, any relative change in disturbance rates induces the same relative change in PCD_{abg} and M_{age}. For example, a newly allocated ecosystem originally accumulating 10 kg C m\(^{-2}\) aboveground in 80 years will accumulate 5 kg C m\(^{-2}\) in 40 years if disturbance rates double (figure S2 available at stacks.iop.org/ERL/8/015018/mmedia). In the case of a mature ecosystem, disturbance events will progressively release the difference in carbon density (5 kg C m\(^{-2}\) in the doubled rate example) over a period equivalent to its M_{age} to reach its new carbon equilibrium. This landscape-scale approach thus integrates over space and time (e.g., fire combustion losses are not explicitly simulated but are fully accounted for by the reductions in PCD_{abg} and M_{age}).

Two alternative parameterizations of disturbance impacts are applied for test for robustness (figure 1). In a more conservative approach, the carbon sequestered in a given ecosystem is assumed more resilient to disturbances and the transition toward PCD_{abg} takes twice as long (carbon emissions are stretched over twice M_{age}). In a less conservative approach, soil carbon is also affected by disturbances, following the same conceptual model as for vegetation, albeit with 25% of the carbon losses magnitude (i.e. the belowground compartment of an ecosystem originally sequestering 10 kg C m\(^{-2}\) will transition to 8.75 kg C m\(^{-2}\) if disturbance rates double).

3. Results and discussion

In the control case, with no change in natural disturbance rates, mitigation substantially relies on enhancing carbon storage in terrestrial ecosystems (figures 1 and 2(a)), in a pattern documented previously [27, 28]. Afforestation is stimulated by placing a value on carbon stocks, just as a value is placed on fossil fuel and industrial emissions (figure S3(a) available at stacks.iop.org/ERL/8/015018/mmedia), resulting in a net carbon sink of 2–3 Gt C yr\(^{-1}\) through 2050 and slightly decreasing thereafter. Such a terrestrial sink enables a temporary rise in fossil fuel and industrial emissions (figure 2(b)) to keep up with the rising demand for energy from economic and population growth (population stabilizes in 2060). After mid-century, however, fossil fuel and industrial emissions must drop sharply, reaching about 40% of today’s levels by the end of the century. Higher prices on carbon emissions (figure 2(c)) promote a significant decline in fossil fuel energy, which is projected to provide roughly half of the world’s energy by 2095, compared to 85% currently (figure 2(d)). This decarbonization of society is achieved in large part by transitioning to low-carbon technologies, which progressively become more profitable under the evolving economic context. Biofuels, nuclear power and renewable energy triple their combined share to supply the remaining half of the energy demand (figure S4(a)–(c) available at stacks.iop.org/ERL/8/015018/mmedia), and carbon capture and storage (CCS) is substantially deployed (figure S4(d) available at stacks.iop.org/ERL/8/015018/mmedia).

Mitigation strategies are very different if disturbance rates change, because changes in terrestrial emissions fundamentally alter the quantity of fossil fuel and industrial carbon that can be emitted while still maintaining the same 3.7 W m\(^{-2}\) target pathway (figure 1). In the case of rising disturbance trends, the terrestrial system has less potential for sequestration and even turns into a carbon source with disturbance rates of 135% or more (figure 1), in spite of significant afforestation (figure S3(a) available at stacks.iop.org/ERL/8/015018/mmedia). The result is a surge in carbon price (figure 2(c)) leading to compensatory mitigation with a more rapid decarbonization of society (figure 2(b)). Fossil fuel and industrial emissions in 2050 are reduced from 11 Gt C yr\(^{-1}\) in the no-change scenario to 8 and 4 Gt C yr\(^{-1}\) with disturbance rates of 135% and 200%, respectively. After mid-century, disturbances keep releasing carbon, while the value of afforestation for low-cost sequestration progressively decreases due to disturbance impacts on carbon densities. As the only remaining mitigation option, decarbonization is thus further strengthened by even higher carbon prices, which reduce energy demand and promote additional deployment of technologies such as biofuels and carbon capture and storage (figures S4(b), (d) available at stacks.iop.org/ERL/8/015018/mmedia). Higher disturbance rates thus have critical implications for transition efficiency and technological development, requiring larger investments to adapt infrastructures and upgrade technologies in the near future.
Figure 2. Impacts of disturbance scenarios on key aspects of climate mitigation along the 21st century: (a) terrestrial carbon emissions, stemming from land-use change and disturbances; (b) fossil fuel and industrial carbon emissions; (c) carbon price; (d) share of fossil fuels (coal, oil and natural gas) in the world production of energy. Disturbance rates (y-axis) are expressed as percentage of current rates (100% is the no-change disturbance scenario, shown as a dotted line). Horizontally, contours indicate changes in the considered variable in time (2016–95), throughout the transition to a low-carbon society.

Conversely, if natural disturbance rates decrease, terrestrial sequestration may relax the constraint on fossil fuel and industrial emissions (figure 1). In these scenarios, enhanced sequestration capacity and afforestation maintain a large terrestrial sink (figure 2(a)). The carbon market thus responds at a slower pace (figure 2(c)), inducing a gradual transition toward a low-carbon society, with a lower need for biofuels and active carbon removal. These results support the idea that land management policies to enhance sequestration in existing forests could greatly contribute to climate mitigation [29]. It is important to emphasize, however, that the terrestrial sink cannot be perpetually maintained, because ecosystems will progressively reach their new carbon equilibrium [30] and land availability will limit afforestation. Climate stabilization would thus ultimately require as profound a decarbonization as in other disturbance scenarios, but along a more compliant timeframe.

From a global economic perspective, altered disturbance rates imply large changes to the cost of mitigation. Mitigating climate change to the 3.7 W m$^{-2}$ level is substantially more demanding under increased disturbances, up to 2.5 times more costly in the case of doubled disturbance rates (with a nearly linear disturbance-cost relationship: 1.6 times more costly in the 130% disturbance case). These costs stem from additional decarbonization investments to offset disturbance emissions and from the need to transition sooner, when technologies are more expensive and less efficient. In the case of a mitigation strategy designed under the assumption that disturbance rates will not change, these extra costs are unexpected and require either diverting other economic resources, or missing the mitigation target. Conversely, decreasing disturbance rates imply less decarbonization investments and more time for technological development. The economic weight of mitigation is thus reduced, down to one-third of the original cost in the case of a 50% decrease in disturbance rates. The ability to project future changes in ecosystem dynamics is thus essential to develop cost-effective climate mitigation strategies, as such costs are expected to be on the scale of roughly 0.5%–10% of the world gross domestic product [16, 31].

The fundamental findings of this study are robust to alternative model parameterizations (shaded area in figure 1) and policy scenarios: the projected timing and character of the transition to a low-carbon society could be highly
affected if future disturbance rates change. This sensitivity can be generalized to other mitigation commitments and environmental contexts. Under a more aggressive climate mitigation target (e.g. 2.6 W m⁻²), offsetting increasing disturbance emissions implies comparatively much higher costs as the most efficient technologies already have to be largely deployed in the no-change scenario. Alternatively, under more moderate targets (e.g. 4.5, 6.0 W m⁻²), the additional costs of mitigation are lower as relatively inexpensive transition options remain.

Our results provide a first-order sensitivity of climate mitigation to natural disturbance rates, and reveal that assuming constant terrestrial dynamics could lead to inadequate planning of technological transitions and costs. Long term monitoring of ecosystems and terrestrial processes such as natural disturbances is thus critical to understand their drivers, identify trends, and evaluate uncertainties of future projections. Other environmental feedbacks in terrestrial ecosystems are also a key aspect to determine the necessary decarbonization effort. Some tipping points or concurrent—and potentially synergistic—feedbacks such as permafrost melting [32] are likely to amplify the sensitivity of climate mitigation strategies and costs. Others feature uncertain consequences, such as the interaction between CO₂ fertilization, N limitation, temperature and water stress changes on ecosystem productivity [33–37]. Because these feedbacks are dependent on terrestrial processes, climate and human activities, further research would benefit from the development of a new generation of advanced integrated Earth system models, in which biogeochemical, biophysical, hydrological, and human aspects of the Earth system are coupled. Ongoing work to couple integrated assessment models with Earth system and land-use models will be an essential step forward to provide greater support for policy makers [38–40].

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Author contribution

YLP and GH designed the study, YLP and PP upgraded the model and performed the simulations. GPK, KC, and MW produced the integrated agriculture and land-use model that serves as the basis for this study. All authors contributed to the implementation strategy, interpretation of the results and writing of the manuscript.

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