Title: Delayed impact of natural climate solutions

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To limit global temperature rise, scientists have proposed significant potentials for climate change mitigation from protecting and managing natural systems (Griscom et al., 2017; Paustian et al., 2016; Roe et al., 2019; Smith et al., 2019). However, we show that the speed at which nature's power is unleashed is as important as the mitigation potential. Depending on the time taken for technology deployment and natural carbon gain, actual mitigation can be dramatically delayed, and total mitigation by 2030 or 2050 can be more than halved compared to the estimated potential. Delayed or lack of action on implementation would push back the timeline to reduce greenhouse gas emissions, largely undermining the Paris goal. Launching actions learning from past experience can help deliver climate mitigation and sustainable development goals.

Natural climate solutions

Meeting the Paris goal will be extremely difficult without significant removal of greenhouse gases (GHGs) from the atmosphere (Roe et al., 2019; Smith et al., 2019). Globally, total GHG emissions need to drop by 50% (about 25 Gt CO_2e) in the next decade, and reach net zero by 2050 before the 1.5 °C target is surpassed. Any delay in action will require even more aggressive reduction efforts later as remedial measures, making meeting the Paris goal even more challenging (IPCC, 2018). Mitigating climate change by land-based systems, recently called natural climate solutions (NCS) (Griscom et al., 2017), has consistently been promoted as one of the most effective, readily available technological options. It represents opportunities to increase carbon sequestration in biomass and soils and/or avoid GHG emissions across global ecosystems (i.e., forest, grasslands, agriculture, and wetlands) (Paustian et al., 2016; Roe et al., 2019; Smith et al., 2019).

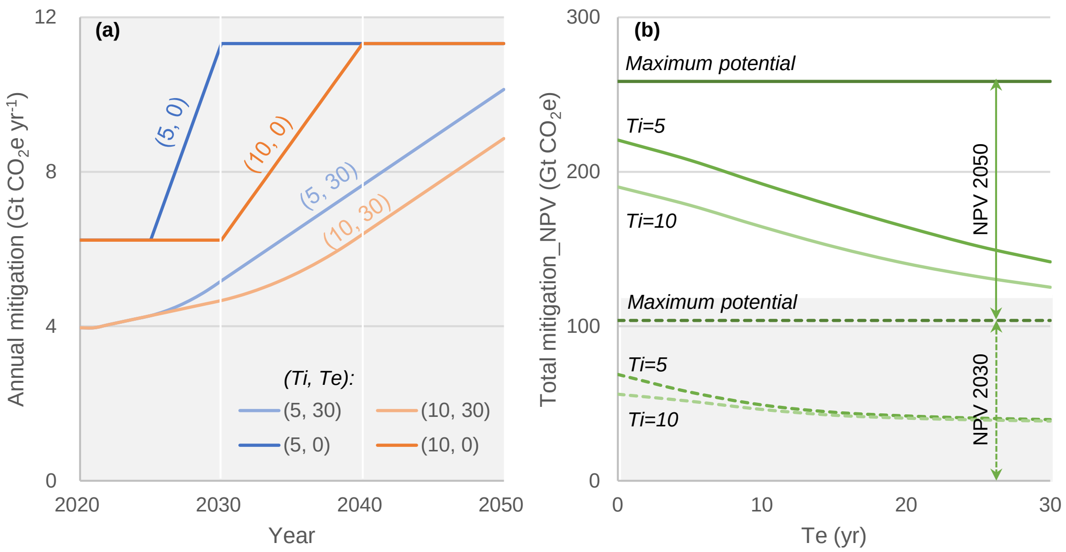
However, the impact of delay in NCS mitigation has been underappreciated. The delay falls into three major categories, delayed action (*type 1*), delayed extent (*type 2*), and delayed intensity (*type 3*) (Fig. 1). Like energy-related sectors, delayed action postpones the start in implementation of NCS pathways, which inevitably delays meaningful mitigation. Moreover, even with immediate action, most NCS pathways still require years to decades to reach their estimated maximum mitigation levels. The annual mitigation potential of a specific pathway is a product of extent (avoidable rate or applicable land area) and intensity (avoidable emissions or enhanced sequestration per unit of extent) (Griscom et al., 2017). The actual mitigation each year is proportional to its annual potential, depending on the time taken to reach full extent (*Te*) (*type 2*) and maximum mitigation intensity (*Ti*) (*type 3*) (Fig. 1a). *Te* is largely dependent on the speed and coverage of technology deployment, and *Ti* heavily relies on ecosystem processes.

Time is not on our side

Globally, about half of total habitable lands (~5 billion ha) could become available for better use or management under NCS, which could deliver global cost-effective mitigation potential of up to 11.3 Gt CO_2e annually (Griscom et al., 2017). However, the actual mitigation achieved each year is somewhat limited due to delayed impact (i.e., *type 2* and *3*). Among the 20 NCS pathways reported by Griscom *et al*. (2017), four could be implemented without any delay (i.e., avoided conversion of forest, grassland, peatland and coastal wetland), and seven would be delayed in extent (i.e., biochar, cropland nutrient management, avoided woodfuel, natural forest management, improved feed in grazing, improved animal in grazing, and fire management). The remaining nine pathways would be constrained by delays in both extent and intensity (Griscom et al., 2017). *Te* can vary greatly among pathways and nations, from years to decades (Lu et al., 2018). Here, we set the maximum *Te* at 30 yr (i.e., until 2050). *Ti*, however, is mainly due to land use change between ecosystems. It normally takes 5-10 years to see measurable carbon gains in soil and vegetation systems (Deng et al., 2016). We assume a linear change of extent expansion and intensity increase, and that the maximum potential in 2020 would be the same as in 2016 (base year in (Griscom et al., 2017)).

The simulations show that time dilutes mitigation by both delaying maximum potential and reducing total net present value (NPV) of mitigation (Fig. 1a-b). The longer the delay (*Te or Ti*), the later the NCS pathways reach their maximum mitigation potential. If delayed too long, they may even totally miss the maximum level before the target year of 2030 or 2050 (Fig. 1a). In terms of NPV (Fig. 1b), the total mitigation by 2050 is 125-220 Gt CO_2e, depending on *Te and Ti*, while the maximum potential without any delay would have been 260 Gt CO_2e. The mitigation by 2030 is affected even more, with only 40-70% of maximum potential being realized over the next ten years. With each additional year of delayed *Te*, an average of about 0.8-1.5% and 0.9-1.1% of total mitigation would be diminished by 2030 and 2050, respectively (Fig. 1b).

Moreover, our estimates excluded impacts from delayed action (i.e., *type 1*) that applies to all NCS pathways, including those unaffected by *Te* or *Ti*. The timeline to reduce global GHG emissions would be pushed back if NCS remains as “armchair strategy”. We are simply losing the race with time, and the Paris goal is on the brink of becoming impossible (IPCC, 2018; Roe et al., 2019).



(c)

Delay types	Lessons learned and best practices to minimize delays
Type 1 (delayed action)	✓ **Act now!** ✓ **Global** coordination efforts and engagement with stakeholders and land users (e.g., 4p1000, UN SDGs[1]) ✓ **Government** incentivization and subsidization ✓ Increasing **public awareness** of climate change and multiple economic and social benefits of NCS
Type 2 (delayed extent)	✓ **Protecting** existing ecosystems with rich and irrecoverable carbon pools (e.g., wetlands, peatlands and tropical forest) ✓ **Prioritizing** NCS pathways, starting with pathways with instantaneous mitigation responses and those requiring less intensive investment ✓ **Speeding up** mitigation technology deployment by initializing NCS projects across the country ✓ **Selecting** region-specific best NCS pathways to avoid failure and unintended consequences
Type 3 (delayed intensity)	✓ **Minimizing** disturbances to native ecosystems during land transitions (e.g., reducing soil disturbances during establishment of plantations and reforestation) ✓ **Improving** management practices to ***speed up*** carbon sequestration in vegetation and soils. For instance, making use of applied nucleation strategy to facilitate forest recovery; increasing organic carbon inputs in agricultural soils; applying grazing exclusion, re-seeding and reduced grazing intensity measures in grasslands; shifting species or improving community composition to improve carbon storage, and reduce methane emissions in wetlands

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[1] Sustainable Development Goals of the United Nations: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

Fig. 1. Delayed mitigation and potential measures to lessen the delay impact. (a) Depending on *Te* and *Ti*, the time taken to reach maximum annual mitigation can be dramatically delayed (a). Therefore, net present value (NPV) of mitigation by 2030 (NPV2030) or 2050 (NPV2050) becomes smaller than the estimated maximum potential (b). Learning from past experience and adopting best management practices can help to lessen the delay impact (c). *Te* and *Ti* represent the time taken to reach full extent and maximum mitigation intensity, respectively. NPV is based on a discount rate of 2% (IPCC, 2007).

Actions to minimize delays

There is still a credible scientific basis for mitigation and other ecosystem services via ecosystem restoration and other NCS pathways, if we take global actions to minimize delayed impact in time (Bradford et al., 2019; Griscom et al., 2017; Roe et al., 2019). First of all, *Type 1* delays can be minimized with global immediate actions: the best time to act is now (if not already) (Fig. 1c). For instance, China has launched six nationwide ecological projects since the 1970s, covering about half of its national forests and one-fifth of grasslands (Lu et al., 2018). As a result, a total of 0.5 Gt CO_2e yr^{-1} was sequestered in natural ecosystems during the 2000s (Lu et al., 2018), equaling to 12% of global low-cost mitigation (Griscom et al., 2017). The legacy effects of existing restored ecosystems and continuing efforts for project expansion is having a local and even global impact on climate mitigation (Lu et al., 2018). Policies at national and global scales play an irreplaceable role in promoting NCS to avoid delays of all types, especially delayed action (*type 1*). Governments can initiate and incentivize certain pathways, and speed up pathways with potential delays in meeting full extent. Also, actions on NCS demand global coordination efforts and engagement with stakeholders and land users, based on cultural, political and socioeconomic understanding (Goldstein et al., 2020; Paustian et al., 2016; Roe et al., 2019; Smith et al., 2019). NCS pathways share a fundamental basis and similar goals with many ecological restoration projects and international initiatives (e.g., 4p1000, Sustainable Development Goals) (Bradford et al., 2019; Roe et al., 2019) (Fig. 1c).

Delays in extent (*type 2*) can be further shortened via ecosystem protection, pathway prioritization, and local and global planning (Fig. 1c). For instance, priority can be given to pathways with instantaneous mitigation responses and those requiring less intensive investment, i.e., avoiding conversions of existing lands with rich carbon pools (e.g., forests and wetlands) and protecting irrecoverable carbon ecosystems (e.g., peatlands and mangroves) (Goldstein et al., 2020; Roe et al., 2019). From the experience of China's ecological projects, nationwide planning and regular local inspection can speed up mitigation technology deployment across the country and also avoid unintended failure or consequences (Lu et al., 2018).

Finally, to minimize delays in reaching maximum mitigation intensity (*type 3* delay), best management should be encouraged in NCS pathways to accelerate carbon gains in ecosystems (Fig. 1c). For example, estimated reforestation potential is based on meta-analyses of field studies, in which a range of initial delays in forest stand initiation are included in decadal mean sequestration rates, as a function of observed barriers to stand initiation (Griscom et al., 2017). Measures can be taken to assist natural forest regeneration (e.g. applied nucleation) that accelerate and thus increase decadal growth rates. Similarly, other ecosystems (i.e., agriculture, grasslands and wetlands) can be managed with best practices to facilitate carbon accumulation or emission reduction, and therefore to lessen the delay impact.

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