Climate-driven risks to the climate mitigation potential of forests

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Enhanced Abstract

Background

Forests have significant potential to help mitigate human-caused climate change and provide society with a broad range of co-benefits. Local, national, and international efforts have developed policies and economic incentives to protect and enhance forest carbon sinks – ranging from the Bonn Challenge to restore deforested areas to the development of forest carbon offset projects around the world. However, these policies do not always account for important ecological and climate-related risks and limits to forest stability (i.e. permanence). Widespread climate-induced forest die-off has been observed in forests globally and creates a dangerous carbon cycle feedback, both by releasing large amounts of carbon stored in forest ecosystems to the atmosphere and by reducing the size of the future forest carbon sink. Climate-driven risks may fundamentally compromise forest carbon stocks and sinks in the 21st century. Understanding and quantifying climate-driven risks to forest stability is a crucial component needed to forecast the integrity of forest carbon sinks and the extent to which they can contribute towards the Paris Agreement goal to limit warming well below 2 °C. Thus, rigorous scientific assessment of the risks and limitations to widespread deployment of forests as natural climate solutions is urgent.

Advances

Many forest-based natural climate solutions do not yet rely on the best available scientific information and ecological tools to assess risks to forest stability from climate-driven forest dieback caused by fire, drought, biotic agents, and other disturbances. Crucially, many of these permanence risks are projected to increase in the 21st century due to climate change and thus

estimates based on historical data will underestimate the true risks that forests face. Forest climate policy needs to fully account for the permanence risks because they could fundamentally undermine the effectiveness of forest-based climate solutions.

Here, we synthesize current scientific understanding of the climate-driven risks to forests and highlight key issues for maximizing the effectiveness of forests as natural climate solutions. We lay out a roadmap for quantifying current and forecasting future risks to forest stability using recent advances in vegetation physiology, disturbance ecology, mechanistic vegetation modeling, large-scale ecological observation networks, and remote sensing. Finally, we review current efforts to use forests as natural climate solutions and discuss how these programs and policies currently consider and could more fully embrace physiological, climatic, and permanence uncertainty about the future of forest carbon stores and the terrestrial carbon sink.

Outlook

The scientific community agrees that forests can contribute to global efforts to mitigate human-caused climate change. The community also recognizes that using forests as natural climate solutions must not distract from rapid reductions in emissions from fossil fuel combustion. Furthermore, responsibly using forests as natural climate solutions requires rigorous quantification of risks to forest stability, forests' carbon storage potential, co-benefits for species conservation and ecosystem services, and full climate feedbacks from albedo and other effects. Fusing long-term satellite records with forest plot data can provide rigorous, spatially-explicit estimates of climate change-driven stresses and disturbances that decrease productivity and increase mortality. Current vegetation models also hold substantial promise to quantify forest risks and inform forest management and policies, which currently rely predominantly on historical data.

A more holistic understanding and quantification of risks to forest stability will help policymakers effectively use forests as natural climate solutions. Scientific advances have increased our ability to characterize risks associated with a number of biotic and abiotic factors, including risks associated with fire, drought, and biotic agent outbreaks. While models that are used to predict disturbance risks of these types represent the cutting edge in ecology and Earth system science, so far, relatively few tools or infrastructure have been developed to interface between scientists and foresters, land-managers, and policymakers to ensure that science-based risks and opportunities are fully accounted in policy and management contexts. To enable effective policy and management decisions, these tools must be openly accessible, transparent, modular, applicable across scales, and usable by a wide range of stakeholders. Strengthening this science-policy link is a critical next step in moving forward with leveraging forests in climate change mitigation efforts.

Abstract

Forests have significant potential to help mitigate human-caused climate change and provide society with many co-benefits. Yet climate-driven risks may fundamentally compromise forest carbon sinks in the 21st century. Here, we synthesize current understanding of the climate-driven risks to forest stability from fire, drought, biotic agents, and other disturbances. We review how efforts to use forests as natural climate solutions currently consider and could more fully embrace current scientific knowledge to account for these climate-driven risks. Recent advances in vegetation physiology, disturbance ecology, mechanistic vegetation modeling, large-scale ecological observation networks, and remote sensing are improving current estimates and forecasts of risks to forest stability. A more holistic understanding and quantification of risks will help policymakers and other stakeholders effectively use forests as natural climate solutions.

Main text

Terrestrial ecosystems currently absorb about 30% of human carbon emissions each year (*1*) and forests comprise the vast majority of this uptake (estimated 8.8 Pg CO_2e y^{-1} of a total land C uptake of 9.5 Pg CO_2e y^{-1} over 2000-2007, (*2*, *3*)). Indeed, a broad body of literature has focused for decades on the role of forests in the climate system (*4–6*), and forest-based "natural climate solutions" have experienced growing interest in recent years as a major contributor to meeting Paris Agreement carbon targets (*7–10*). For example, forest-based strategies might provide up to 7 Pg CO_2-equivalent of climate mitigation per year by 2030 at a carbon price of US$100/Mg CO_2e, which is far and away the largest potential category of natural climate solutions (*7*). Furthermore, many of these forest-based strategies are likely to have substantial co-benefits of biodiversity, ecosystem services, and conservation (*9*, *11*).

Carbon policy that includes forest-based natural climate solutions (F-NCS) is building around the world (Fig. 1). For example, California has recognized 133 Tg CO_2e in benefits from forest carbon offset projects in the United States between 2013-2019, with these credits comprising a meaningful share of compliance with the state's cap-and-trade program (*12*). National and subnational government policies to reduce emissions have included forest projects, including policies in Japan, Australia, New Zealand, and British Columbia, Canada (Fig. 1). In addition, many F-NCS projects have occurred under the framework of the United Nations' Reducing Emissions from Deforestation and Degradation (REDD+) (*13*, *14*), as well as under local and national emissions reductions goals.

F-NCS projects include a wide array of project types but broadly fall into four categories: i) avoided forest conversion (i.e. avoided deforestation), ii) reforestation, iii) improved management of natural forests, and iv) improved forest plantation practices (*7*, *9*, *15*). An overarching commonality is that all F-NCS projects strive for "permanence," the principle that forests store carbon removed from the atmosphere in plants and soils over time-horizons of 50-100 years or longer. Given that a large fraction of human emissions of CO_2 remain in the atmosphere for centuries to millennia (*16*), permanence of forest carbon on century timescales is essential for effective climate change mitigation.

Fundamental questions remain, however, about the fate of carbon stored in forests in a rapidly changing climate, particularly the extent to which climate change and climate-driven changes in disturbance regimes might compromise forest permanence (*17–19*). Climate-induced tree mortality events have been widely observed across the globe over the past few decades (*20*, *21*). In addition to direct climate impacts on trees like drought events, additional disturbance agents including wildfire and insect outbreaks are sensitive to climate and have major carbon cycle consequences for forests (*22–25*). The biomass dynamics of an estimated 44% of forests globally are strongly sensitive to stand-replacing disturbance (including harvest) (Fig. 2) (*26*). Further, climate-driven tree mortality and disturbances are non-stationary (they change with time) and projected to increase with climate change (*25*). Finally, due in part to the large uncertainties about climate impacts, CO_2 fertilization, and disturbances in forests (*27*), Earth system model projections over the 21st century indicate that terrestrial ecosystems could sequester as much as 36.7 Pg CO_2e y^{-1} or release as much as 22 Pg CO_2e y^{-1} by 2100 for a high emissions scenario (*28*).

Non-stationary risks from climate change have the potential to compromise the current land carbon sink, the success of F-NCS projects, and also tree-based bioenergy projects, such as some types of bioenergy with carbon capture and sequestration (BECCS) (*17*, *27*, *29–31*). Non-stationary changes in disturbance rates or long-term shifts in ecosystems (e.g. loss of forest) are what fundamentally determine permanence of forest carbon stocks at large scales. The net carbon cycle effects of stationary disturbance regimes at landscape scales are small because carbon emissions from recently disturbed areas in one part of the landscape are compensated by sinks in regrowing areas (*32*, *33*). However, forests are already facing substantial and increasing climate-driven risks that could fundamentally undermine their collective ability to take up and store carbon over the 21st century (*19*, *22*, *34*, *35*). Thus, non-stationary permanence risks must be rigorously assessed using the best available scientific tools and datasets and included in policy and project planning.

Here, we provide a review of key climate-driven risks to forest carbon permanence (i.e. disturbances that could lead to substantial losses in forest carbon stocks) and how these risks are expected to change in the future. We assess key climate-driven risks from the perspective of i) carbon cycle impacts, ii) data on historical patterns and risk levels, iii) current mechanistic understanding and modeling approaches, and iv) projections of non-stationary risk for future climate change scenarios. We then discuss how ongoing and planned F-NCS projects and policies currently account for permanence risk. Next, we provide a roadmap for rigorous assessment of policy-relevant permanence risks through fusing a broad array of datasets and models. Finally, we conclude with ways forward to bridge science-policy gaps so that the best available science can inform the future of forest carbon sinks and help promote the success of natural climate solutions.

Major climate-sensitive permanence risks

Fire. Fires in forests are perhaps the most well-quantified global disturbance and permanence risk. Between 1997–2016, an average of about 500 million ha burned each year, the majority of which is outside of forest ecosystems (*36*). Although burned area is declining in grasslands and savannas, burned area is increasing in many tropical, temperate, and boreal forest ecosystems (*36*). Fire in forests emits about 1.8 Pg CO_2e y^{-1} (*37*, *38*). Fire accounts for about 12% of stand-replacing disturbances in forest ecosystems annually (*26*) and is particularly important in key forest regions like the western United States, Australia, Mediterranean-type climates, and boreal forests in North America and Asia (*39*, *40*). Climate-driven changes in fire regimes can affect permanence both through changes in burned area, and also through changes in fire behavior (i.e. fire temperature, scorch height) that influences tree mortality and, in many temperate and boreal forests, the amount of fuel consumption in organic surface soil layers (*41*). Multiple satellite datasets have mapped fire burned area and emissions at moderate or high spatial resolution globally from the late 1990s to present (*37*, *42*) and extend even further back at low resolution globally (*43*) and at high resolution in some regions such as the United States (*44*), Australia (*45*), and Canada (*46*). Paleoclimate reconstructions of fire also hold promise for informing projections of future fire regimes (*44*). Thus, long-term fire data are widely available for assessing historical permanence risks.

A wide variety of fire models also exist, including both empirical and mechanistic models that differ in complexity and mechanisms considered (*44*). Empirical models (*47*, *48*) and mechanistic models (*49*, *50*) broadly project increases in fire activity and permanence risks with climate change, but with substantial regional heterogeneity (*44*). Mechanistic fire models are an active area of research (*50*, *51*) and improved fire models are being incorporated into terrestrial biosphere models (*50*). These models aim to simulate the complex dynamics between vegetation, climate, and fire, as well as changes in human land use and populations that influence fire ignition and fire spread (see below).

Drought. Globally, droughts comprise a major and widespread permanence risk, underscored by an explosion of research relating to drought-induced tree mortality in the past decade (*21*, *52*). Drought events have major impacts on forest carbon cycling through declines in productivity and carbon losses through mortality (*20*, *27*). Major climate extremes explain up to 78% of the variation in global gross primary productivity in the past 30 years, and severe droughts made up ~60-90% of the largest extremes (*53*). As an example, the severe 2011-2015 drought in California killed more than an estimated 140 million trees and drove the full carbon balance of the state's ecosystems to be a net source of -600 Tg CO_2e from 2001 to 2015, which is equivalent to around 10% of the state's greenhouse gas emissions over that period (*54*). A 2011 drought in Texas killed 9.5% of tree cover across the state, and much of the canopy loss occurred in areas that exceeded specific climatic thresholds (*55*). Increasingly severe drought in Australia has also led to systematic increases in tree mortality and composition changes (*56*).

Substantial historical data on drought risks are available from a variety of data sources, although such data are relatively less direct and detailed than information on burned area at the global scale. Climate data from weather stations and reanalysis products allow the calculation of meteorological and agricultural drought and aridity metrics (*57*). The utility of these datasets in estimating spatial patterns of permanence risk depends on the extent to which forest vulnerability (e.g., mortality) correlates with drought severity and/or average aridity, which has been observed in several meta-analyses (*58–60*). Remote sensing data can provide spatial patterns of drought impacts on productivity and in some cases drought-driven mortality (*61*, *62*). The central difference compared with fire is that drought-driven tree mortality is often more widespread (occurring over large regions because of the widespread nature of drought) and more diffuse (i.e., smaller number of trees killed per area). Furthermore, mortality can occur both during and for multiple years after a drought event, which can lead to underestimation of the impact of drought on forest carbon (*63*). As a result of the more diffuse signal in space and time, drought-driven mortality can be more challenging to detect with moderate resolution satellite imagery, which complicates quantification of carbon cycle impacts of drought on tree mortality (*21*).

Drawing on a broad set of tree ecophysiological research, mechanistic vegetation models have rapidly improved in simulating drought risks to forest permanence. The latest results from these models suggest that regional and global drought risk estimates will be possible in the near-term (*21*). Drought is thought to drive tree mortality primarily through a failure of the plant water transport (hydraulic) system (*64–66*), and the biophysical processes that mediate this failure have been relatively well-understood for decades (*67*). Species' hydraulic traits have been shown to explain patterns in mortality risk within ecological communities (*58*, *59*), which provides a promising avenue for using widely-measured plant functional traits in permanence risk assessments. Furthermore, vegetation and land surface models have recently incorporated key aspects of hydraulic transport (see below), which should enable drought-related permanence risk forecasting in the near future.

Biotic agents. Biotic disturbance agents, including insects and pathogens, cause substantial tree mortality globally. For example, bark beetles, which feed on tree phloem and introduce fungi that interrupt tree water transport, have killed billions of trees over millions of hectares in temperate and boreal coniferous forests in the past two decades (*68–70*) and converted large regions of the Canadian boreal forest from a sink to a source over a decade (*34*). Defoliators feed on leaves and can kill trees after multiple years of severe damage. Widespread tree mortality has occurred from defoliators in both coniferous and broad-leaved forests in temperate and boreal regions (*24*, *71*). In addition to these native biotic agents, nonnative invasive biotic disturbance agents are responsible for killing many trees globally. Prominent examples include *Phytophthora*-induced sudden oak death and emerald ash borer in the US and red turpentine beetle in China (*72*).

Aerial surveys and remote sensing imagery provide estimates and constraints on permanence risks from some biotic agents over the past 40 years (*40*). The spatial patterns and impacts of major biotic agent outbreaks have been extensively mapped from surveys, plot measurements, and agency reports in many regions (*70*). For example, in the western US, bark beetle-caused tree mortality during 1997-2010 affected 5% of aboveground tree carbon stocks, about the same as wildfires during that period (*40*). As with drought, tree mortality from biotic agents is often diffuse, creating a challenge for change detection using satellite imagery. Detection efficiency depends on the severity of the outbreak, instrument spatial and spectral resolution, the quality of ground observations, the duration and frequency of the satellite observations, and the underlying change-detection algorithms. Attribution of tree mortality to a specific biotic agent, and separation from drought influences, is difficult, yet high confidence in attribution may not be needed for an initial assessment of permanence risk patterns.

Climate affects outbreaks of many biotic disturbance agents. In the case of bark beetles, warmer conditions increase winter survival and increase life stage development rates (*73*). Drought stresses host trees, decreasing defenses, altering foliage quality and leaving trees more susceptible to attack (*74*). Ambient moisture can influence pathogen survival and spread (*75*, *76*). However, insect/host systems are complicated by multiple factors and interactions, and understanding is limited about the relative importance and functional relationships of climate drivers (*77*). Thus, tree mortality from biotic disturbance agents remains remarkably difficult to model and predict, especially over larger spatial scales and longer periods (*78*, *79*). While challenging, the vulnerability of a forest stand can partially be estimated with models that evaluate stand structure (species composition, stem density, size, age, vigor) for many biotic disturbance agents (e.g., (*80*)). Biotic agent sensitivity to different climate influences (e.g., winter mortality or drought stress) have been assessed for prominent insect species, for example in the western US (*81*).

The permanence risks from biotic agents to forests are likely non-stationary and expected to increase substantially in the future (*25*). Integrated biotic agent models that combine multiple drivers, including key climate sensitivities, and predict tree mortality are needed to assess permanence of forest carbon (*79*). These models are challenging to develop even for the best-understood agents and are limited in number (e.g., (*82*)). Thus, predictive tools for biotic agent disturbance are the most limited among the disturbance types we cover here because of 1) the diversity of insects and pathogens across forest ecosystems, 2) introduction of non-native biotic agents, which often can not be predicted, and 3) the complicated cross-scale dynamics between climate, biotic agent populations, and tree populations (*77*, *79*).

Other disturbances. Other disturbances, particularly storms and wind-driven events, snow and ice events, and lightning, can also influence forest ecosystem carbon cycling (*25*, *83*). These disturbance events can matter for local- to regional-scale carbon cycling in some areas but are thought to have relatively minor-to-modest global effects (*25*, *53*). Hurricanes damage coastal forests and can have significant impacts on carbon budgets. For example, hurricane Katrina damaged 320 million large trees that contained 385 Tg CO_2e (*83*), and tropical cyclones had a net effect of a modest carbon source in the 20th century over U.S. forests (*33*). However, a key question for wind and other disturbances is whether projected future trends indicate that risks are likely to increase. A recent meta-analysis identified some projected increases in wind disturbance in some regions, but little directional change in other regions and little projected change in other disturbance events such as snow and ice events (*25*).

In addition to large-scale disturbances, climate-driven shifts in tree species' ranges and forest community assemblages are already occurring and are likely to be even more widespread in the future (*84–86*). Changes in community composition can have major carbon cycle impacts (*85*, *87*, *88*) and can mediate forest vulnerability to disturbance (*89*, *90*). A broad body of literature has explored potential range shifts and changes in community composition, although major uncertainties remain in future projections (*84*). Critically, adequate tree regeneration rates are important for maintaining forest permanence over the long-term, and thus improved understanding and models of the climate and non-climate (e.g. non-native species) drivers of regeneration rates are needed (*91*, *92*).

Disturbance interactions. Disturbances that can drive risks to forest permanence often co-occur or interact at multiple spatial and temporal scales (*25*, *93*). For example, fire often co-occurs with drought in many regions globally (*94*). Drought and biotic agent attacks also often co-occur and can interact in complex ways to mediate tree mortality (*79*, *95*, *96*). While interactions among disturbances can either dampen or magnify carbon cycle impacts on forests, a recent meta-analysis found that the interaction effects typically magnify carbon losses for the vast majority of climate-sensitive disturbances and regions (*25*).

Human interactions. Human actions can increase or decrease climate-related permanence risks. Human appropriation of forest biomass is about 9.5 Pg CO_2e y^{-1} (*97*), which is more than annual fire emissions, and thus socioeconomic changes that alter human interactions with forest biomass may have large consequences for permanence of forests. Thorough treatment of these interactions has been covered elsewhere (*20*, *49*, *98*), and we briefly highlight a few key interactions. In particular, land management such as forest thinning and fuels reduction can decrease the risks of fire, drought, and attacks by biotic agents in some forests (*99*). Humans are key ignition sources for fires around the world (*36*) and thus changes in human populations, land-use, policy, and behavior can affect projections of fire risk (*49*). Humans also frequently fight or suppress fires, and in some cases biotic agent activity, to minimize and mitigate negative outcomes on livelihoods, ecosystem services, and carbon cycling. We note that human management actions such as forest harvest and sustainable forest management can be important mechanisms to maintain forest carbon sinks and could be used strategically to decrease permanence risks. Finally, the introduction of nonnative invasive insects and pathogens by humans over the past few centuries has led to substantial tree mortality that continues today (*100*), and further introductions in the future could have similar effects.

Current efforts to address permanence risk

The degree to which current F-NCS efforts include permanence risks varies enormously and very few projects to date have considered non-stationary risks from climate change. Some F-NCS projects currently have no explicit way to address permanence risks. Other F-NCS efforts include at least some estimate of permanence risks and contain mechanisms such as a buffer pool that can account for risks across a portfolio of forest projects. Even in these cases, however, the data underpinning many protocols' risk assessments are often unclear and, where delineated, are based on average historical conditions with little spatial or ecosystem-specific granularity. Therefore, additional consideration should be given to i) whether risks have been adequately assessed and ii) if non-stationary risks due to climate change are likely. In addition, spatially-explicit and regularly-updated risk data would enable a quantitative risk assessment of given portfolios and also inform project planning.

Crucially, risk estimates developed from historical data are highly unlikely to be adequate in capturing increasing permanence risks of many disturbances, particularly fire, drought, and biotic agents, over the full 21st century (Fig. 3). For example, the mean 100-year integrated risk of moderate and severe wildfire across all U.S. ecosystems has already approximately doubled from about 4% over 1984-2000 to about 8% in the 2001-2017 (Fig. 4), much of which can be directly attributed to climate change (*101*). Furthermore, increases in the spatial extent and frequency of fire, drought, and biotic disturbances are expected in the future from climate change, yet relevant forests may not have experienced these disturbances in the recent past, suggesting that historical data may not capture future risk.

We discuss several prominent examples of different approaches currently used to account for permanence risks below.

California forest offset program example. Pursuant to the 'Global Warming Solutions Act' (A.B. 32), California established a cap-and-trade program that includes a forest offset program. This program is one of the largest "compliance" offset programs in existence and is thus an important case study (*15*). The offset program defines forest project permanence on a 100-year basis and deals with risk of unintentional loss of carbon stock by using a 'buffer pool' approach (*15*, *102*, *103*). Forest offset project owners are required to contribute a percentage of forest carbon credits earned from their projects to a common buffer pool account. Buffer pool credits are retired (i.e. removed) to mitigate for any unintentional carbon loss. The buffer pool is capitalized by taking a share of project credits (indicated in parentheses) for the following risks: wildfire (2-4%), disease or insects (3%), other natural catastrophes (e.g. drought, hurricane, tornado, wind, 3%), over-harvesting (0-2%), conversion to a non-forest land use (0-2%), and bankruptcy (1-5%) (*103*). As of 2019, an average of 16% of credits earned was submitted to the buffer pool in recognition of these risks to permanence (*104*). Intentional loss of forest carbon must be compensated by the project owner and unintentional losses are absorbed by the buffer pool, which plays the role of a carbon insurance system. Any unintentional reversal can draw on the buffer pool, no matter the type.

Given the risk percentages above, California's forest offset project portfolio currently uses an 8-10% buffer for the climate-sensitive permanence risks discussed here. For fire risk, there are two levels of risk assessed: 2% for projects that have conducted fire risk reduction work and 4% for projects that have not conducted fire risk reduction work (*103*). These risk levels are applied at a constant level across the entire United States and thus do not account for ecoregion-level or spatial differences in historical permanence risks (Fig. 4). Crucially, none of the risk categories explicitly accounts for climate change. Thus, a central question moving forward is how the best available science can inform risk estimates to reflect the combination of current and projected non-stationary risks over 100+ years.

Other approaches. Several major offset organizations in the United States and other jurisdictions have used a similar buffer pool approach to manage permanence risks. Under Japan's 'Certification Standard for Forest Carbon Sink' 3% of credits, total, are allocated to a buffer pool (*105*). The New Zealand Emissions Trading Scheme takes an approach that is different from the buffer pool and instead addresses permanence risk by instituting two types of offset credits: temporary and permanent (*98*). While a buffer pool approach remains the primary method of addressing permanence risks, other insurance approaches, such as pooling risk across a wide array (including non-forest) of carbon removal projects, have been proposed (*106*).

These are all approaches taken by forest offset programs, where emphasis is placed on measuring exact tons of carbon sequestered by forests to offset fossil fuel emissions. Other kinds of F-NCS projects where forests are not being used as offsets but instead strive to contribute to mitigation more broadly, such as "results-based finance" projects (e.g. the California Climate Investments initiative), have not consistently implemented methods for explicitly assessing permanence risk to the same degree that offset projects have.

A roadmap for rigorous permanence assessment

Rigorous quantification of current and future permanence risk is increasingly possible using vegetation ecophysiology, disturbance ecology, mechanistic vegetation modeling tools, large-scale ecological observation networks, and remote sensing imagery and products (Fig. 5). Leveraging these rapidly advancing models and observations should enable estimating permanence risk at continental and global scales. Furthermore, both empirical and mechanistic models can be driven by historical data and projections of climate, land use, land management, given scenarios of human decisions. If possible, such new risk estimates should be spatially explicit to support F-NCS project planning. We discuss some of the key tools and datasets below, along with how they can be productively integrated. Integrating these diverse datasets and tools is urgent but often challenging due to the wide range of temporal and spatial scales. An additional key scientific challenge is better understanding and testing the effectiveness of human interventions (e.g. forest management) in decreasing risks to permanence across forest systems.

Forest plot and inventory data. High quality ground-based data, such as those provided by permanent forest inventory networks, play a key role in rigorous permanence risk assessment. Given the patchy and dispersed nature of drought- and biotic agent-driven disturbances and the need to evaluate remote sensing observations, successful integration of field data with high-spatial-resolution remote sensing data will be essential for deriving global permanence risk maps and testing mechanistic models (*21*, *26*). Many countries have well-established inventory networks where both tree growth and mortality is measured at low temporal frequency, typically every 5-10 years. Scientific plot networks such as the RAINFOR, AFRITRON (*107*) and Forests-GEO networks (*108*) will be helpful in other regions where inventories do not currently exist or are not available. Spatial coverage, data availability, ease of access and use, and scale mismatches between remote sensing and ground plots remain important barriers to the widespread leveraging of these datasets.

Mechanistic models. Mechanistic vegetation models are one critical tool used for understanding how changes in climate could drive changes in ecosystem composition, structure and function, and allow projections of non-stationary forest permanence risks with novel climate regimes. Vegetation models simulate water, energy, and carbon fluxes and – when coupled to atmospheric models – ecosystem feedbacks to climate. Several critical advances in the representation of ecosystem ecology and ecophysiology make mechanistic vegetation models well-suited for understanding forest permanence risk with climate change. However, some unresolved challenges remain, and considerable diversity exists in how mortality and the types of disturbance event are represented across models (*109*). Here we summarize key model capabilities and current challenges as they relate to permanence risk prediction.

Recent advances in representations of ecosystem heterogeneity in mechanistic vegetation models hold strong promise for capturing forest permanence risks to drought, fire, and insect disturbance. Demographic ecosystem and stochastic gap models, two types of mechanistic vegetation models, capture ecosystem heterogeneity by resolving trees by size class, density, and plant functional type (*110*). Stochastic gap routines within demographic models represent disturbance-driven changes in ecosystem structure caused by processes such as treefall and fire, and resolve the subsequent changes in local micro environment due to changes in canopy structure, light availability, and plant water demand (*111*). Further, some demographic ecosystem models include dynamic vegetation, and simulate shifts in vegetation functional types, forest structure, and composition change in response to climate (*112*).

While forest demographic processes are important for forecasting the permanence of forest carbon, representations of forest demography remain highly uncertain and are not widely included in large-scale vegetation models (*110*, *113*, *114*). Although the explicit representation of fire-, drought-, and insect-driven mortality is lacking in most models, the physiological and ecological processes important for capturing these types of mortality events have been incorporated in some mechanistic vegetation models. Further, an improved representation of mortality processes is a high priority in the vegetation modeling community (e.g. (*26*, *113–115*)). Thus, there is growing potential for mechanistic vegetation models to predict non-stationary permanence risks in response to disturbance. For example, tree size and density affect fire mortality risk, the potential for insect attack, and drought-driven mortality potential. In addition, the availability of simple and predictive representations of vegetation water transport (i.e. hydraulic) processes makes it relatively straightforward to include process-based drought recovery and mortality even in large scale vegetation models (*116–118*). Climate-driven disturbances have been implemented in vegetation models without explicit demography as well, for example fire in the Community Land Model (*119*).

Modeling and predicting biotic agent-driven mortality, however, remains one of the largest unresolved challenges discussed in this review. Currently, biotic agent-driven mortality is often included in vegetation models as an implicit process included in density-independent, background mortality rates. This representation is particularly problematic because biotic-driven mortality is highly heterogeneous, affects different physiological processes depending on the type of insect or pathogen, is often responsive to climate, and can lead to catastrophic mortality events (*34*, *95*, *96*, *120*). Thus far, mechanistic vegetation models have been most useful in assessing the carbon cycle implications of insect disturbance rather than actually predicting insect-driven mortality events (*120*).

As a result of the above factors, large diversity exists in model representations of different mortality processes, scales, and structures. Some features of disturbance are also inherently hard to predict, such as the timing, extent, and magnitude of events (*121*). Because of model diversity as well as uncertainty in climate change, land use scenarios, and the timing and patterns of disturbance events, a probabilistic and multi-model approach is the most useful for generating accurate predictions of forest permanence risk with anthropogenic climate change on decadal to centennial timescales (*122*). Such an approach has the potential to include the range of uncertainties in future climate, disturbance event characteristics, and human land use/management scenarios. We also posit that the most credible estimates of forest permanence risks will be those evaluated against observations of disturbances and impacts and include confidence intervals. Continual testing and refinement of mechanistic models against remotely sensed and ground data in an "ecological forecasting" endeavor has the potential to yield results with higher confidence, similar to improvement in weather forecasting models over the past several decades (*123*).

Remote sensing data. The broad spatial coverage and increasingly long time-series of satellite remote sensing data make such datasets highly useful for quantifying permanence risks and informing mechanistic models. The forest research and policy community now has access to a 35+ year record of Landsat satellite series observations at 30m resolution globally. These datasets have allowed multi-decadal assessments of forest losses and gains (*124*) and provide key information on forest disturbance and recovery, yielding insights into the relative permanence of forest landscapes globally. A central remaining challenge is to attribute observed Landsat forest loss and gain to specific types of disturbances.

While these existing datasets provide a useful framework for monitoring global forests and assessing drivers of change, they are increasingly being augmented by new Earth observations that provide unique information on the structural and functional attributes of forest ecosystems. These include measurements of three-dimensional forest structure using light detection and ranging (lidar) (GEDI; (*125*)), solar-induced fluorescence measurements that provide information on forest photosynthesis, and very high resolution imaging with near daily temporal revisit from private satellite constellations (*126*). The next decade will bring several new satellite missions that will further enable more rigorous permanence risk assessment at global scales and promote robust ecosystem model assessments, benchmarks and comparisons. For example, two new radar missions, the P-band ESA BIOMASS and the L-band NASA-India NISAR will provide, for the first time, coincident space-based multi-frequency interferometric measurements of forest structural properties at high (~30m) spatial resolution globally including sensitivity in high biomass regions like the tropics.

Ways forward to bridge the science-policy divide

Tools to leverage the best available science. Rapid advances in global datasets and mechanistic models have the potential to shed light on the future of the land carbon sink and inform F-NCS policy. New computational methods will likely be needed to integrate data across spatial and temporal scales, blend observational and mechanistic analyses, and forecast uncertainty in statistically rigorous ways. For these advances to then be widely used, they should be wrapped in tools that are openly accessible, transparent, modular, applicable across scales, and usable by a wide range of stakeholders. Global ecologists must continue to expand code and data sharing and open-access publication of results, and leverage modern cloud technologies for processing and sharing large datasets. At this intersection, there are many opportunities for scientists to partner with the broader software community to improve the performance, documentation, interpretability, and usability of these tools to meet the needs of key stakeholders.

Uptake of new science into policy. For government policy processes to take up the most recent scientific understanding of permanence and other relevant risks, policymakers need to be aware of and open to new information. The relationship between policymakers and scientific information is complex (*127*) and may be most challenging when new information questions policymakers' prior assumptions (*128*). Frequent and formal review mechanisms in F-NCS policies and policymakers' willingness to consider new information, especially information critical of current practices, will ensure the uptake of new scientific findings concerning permanence risks to forest carbon projects. We also urge caution on calculations of F-NCS potential that ignore important constraints from biogeochemistry, biophysical feedbacks, timing, and a wide range of human dimensions (e.g. (*129*) which inflated estimates of tree restoration's realistically-feasible carbon storage potential by at least 3-10 fold (*130–133*)).

In addition to accounting for permanence risks, F-NCS projects must also demonstrate that they: i) are additional, i.e. reflect climate benefits that would not occur in the absence of the F-NCS project; ii) account for leakage, meaning that climate benefits are calculated to reflect emissions that may be increased elsewhere as a result of the F-NCS project's economic effects on drivers of forest carbon loss; and iii) have a net cooling effect on the climate by accounting for both carbon sequestration, including the full life-cycle effects such as the fate of wood products in the economy, and biophysical impacts of forests on climate through their reflectivity, evapotranspiration, and surface roughness (*15*, *134*). Many of the credits in early carbon offset programs came from projects that were subsequently estimated to be non-additional and therefore likely led to higher net emissions (*135*, *136*). Ongoing evaluation of permanence, additionality, and leakage concerns is critically important for forest offset programs because any over-crediting allows polluters to increase their emissions more than the offset project reduces emissions. In contrast, over-crediting in a "public investments" or "results-based finance" framework to protect forest carbon (i.e. not directly offsetting emissions) will only reduce the extent of climate benefits, not lead to a net societal harm via more greenhouse gases emitted to the atmosphere.

Conclusion

Forest-based NCS have the potential to contribute to climate mitigation. Crucially, however, F-NCS efforts must not distract from other urgent mitigation activities, particularly major reductions in fossil fuel emissions, and need to be informed by good science to be successful. Inadequate treatment of permanence carries major risks that disturbance-driven reversals in F-NCS projects could worsen climate change, which is especially dangerous if F-NCS are used to justify further fossil fuel emissions. The scientific community has a broad array of datasets and tools to estimate and forecast permanence risk of F-NCS projects, which are not widely used in current F-NCS efforts, and these datasets and tools will grow rapidly in coming years. Climate change will fundamentally increase permanence risks to forest ecosystems over the 21st century. An ambitious scientific research agenda that leverages large-scale datasets and mechanistic models has the potential to transform our scientific understanding of the future of

Earth's forests and provide critical policy-relevant information. A broad, multi-disciplinary effort that extends beyond scientists is needed to ensure that the best available science is available to and used in policy and management approaches.

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Figures

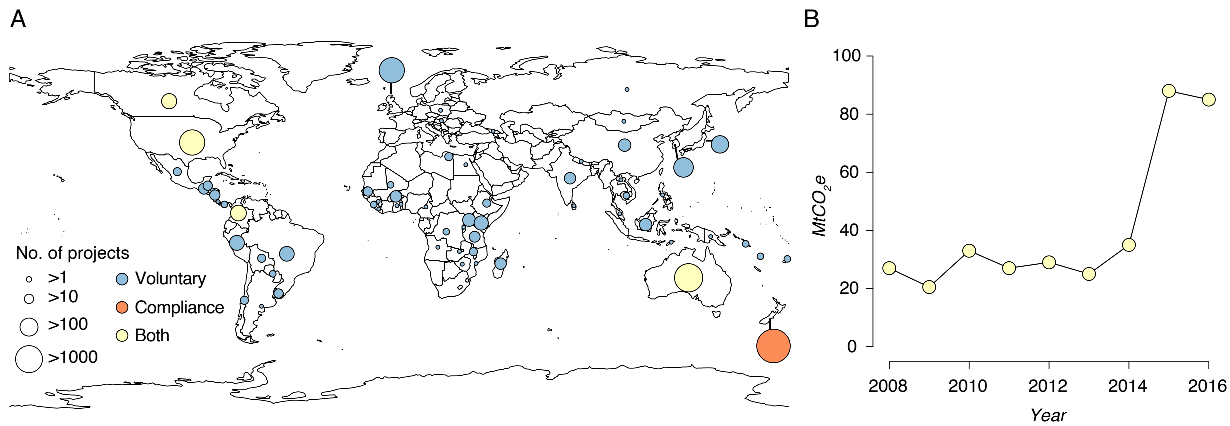

Figure 1: Forest-based natural climate solutions are being used around the world. A: Forest-based natural climate solutions projects around the world by country and type of mechanism (voluntary, compliance, or both) as of January 2017, the most recent data available. B: Carbon volume in million metric tons of carbon dioxide equivalent (Mt CO_2e) covered in compliance and voluntary forest carbon projects 2008-2016. Re-drawn from The State of Forest Carbon Finance 2017 (https://www.forest-trends.org/publications/fertile-ground/).

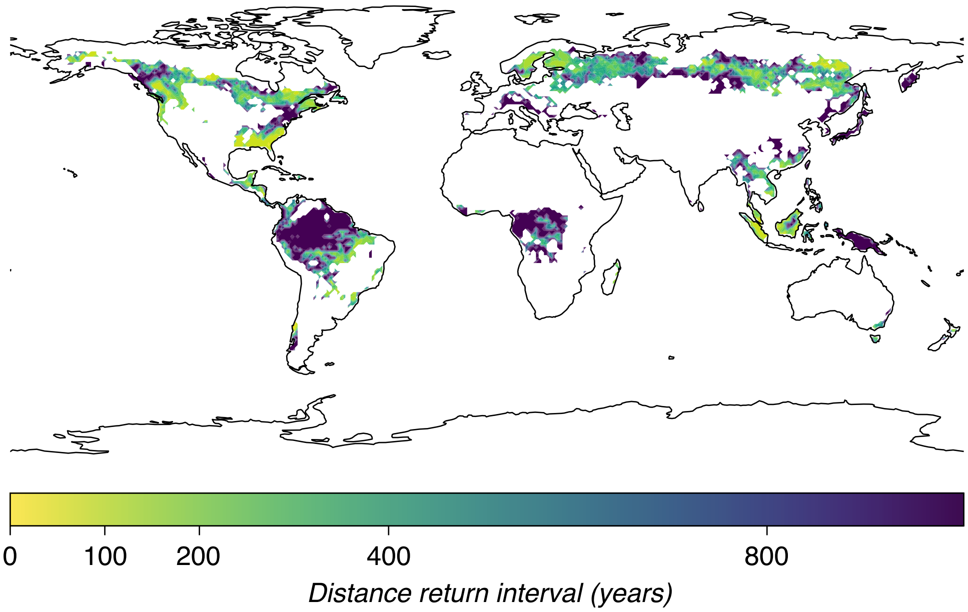

Figure 2: Sensitivity of global forest biomass dynamics to stand-replacing disturbance (excluding human land use changes) captured by disturbance return interval (years). Hot colors indicate areas where biomass dynamics are highly sensitive to the frequency stand-replacing disturbance and cool colors indicate areas that are relatively less sensitive. Re-drawn from Ref. (26).

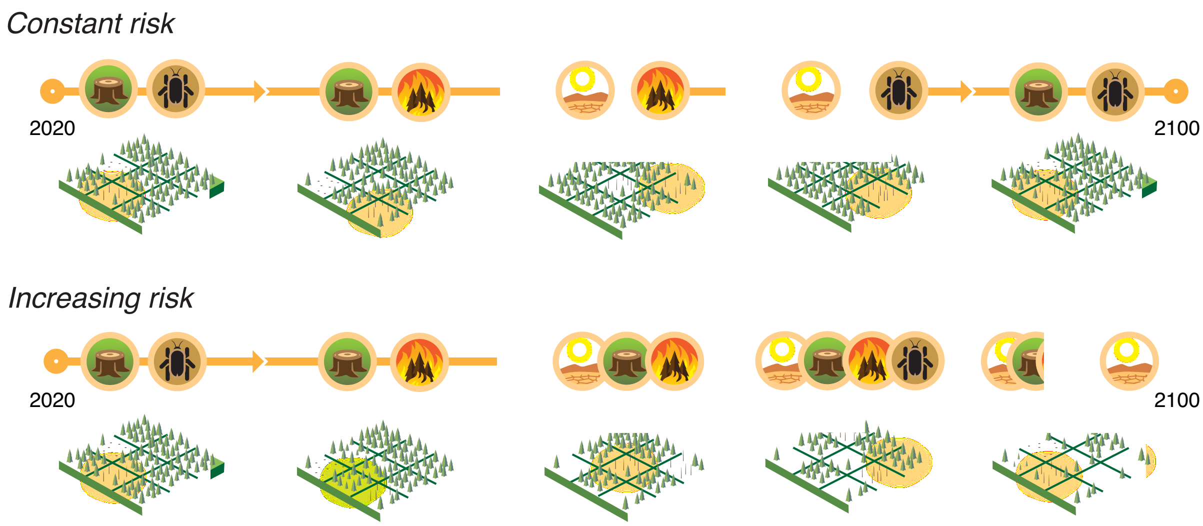

Figure 3: Increasing climate-driven disturbance risk over time has major impacts on forest carbon. Conceptual diagram of stationary/constant (top) versus non-stationary/increasing (bottom) permanence risks from disturbance at a landscape scale in a changing climate. Disturbance risks are illustrated via circles and include fire, drought, biotic agents, and human disturbance. Illustration by David Meikle.

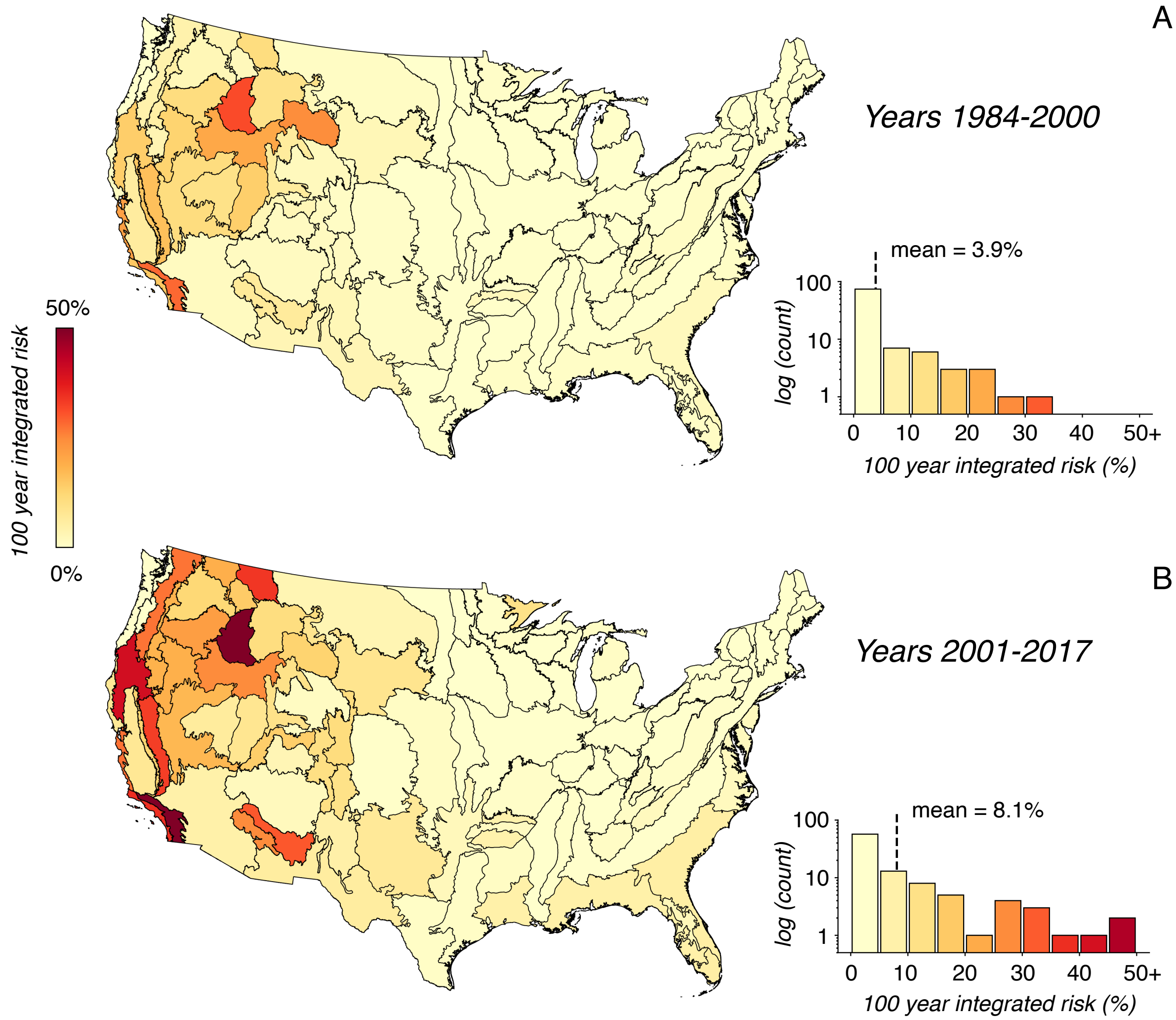

Figure 4: Climate change has already increased fire risk in ecosystems. Integrated 100-year fire risk of moderate or high severity fire from the Monitoring Trends in Burn Severity (MTBS) dataset based on years 1984-2000 fire occurrences and aggregated to ecoregions (A) and for years 2001-2017 fire occurrences and aggregated to ecoregions (B). Fire risk was computed as follows. First, within each ecoregion and year, a pixel-wise burn probability was computed as the fraction of pixels in that ecoregion labeled as moderate or severe fire, and these probabilities were then averaged in each time period. To project an integrated 100-year risk, we computed the probability of any pixel experiencing at least one fire under a binomial distribution with 100 trials and success probability given by the pixel-wise annual risk described above. This is a simple analysis that does not account for spatial or temporal autocorrelation or attempt to model any drivers of fire risk. Raw data obtained from https://www.mtbs.gov/direct-download, and Python code to create figures is available at [github link to be provided].

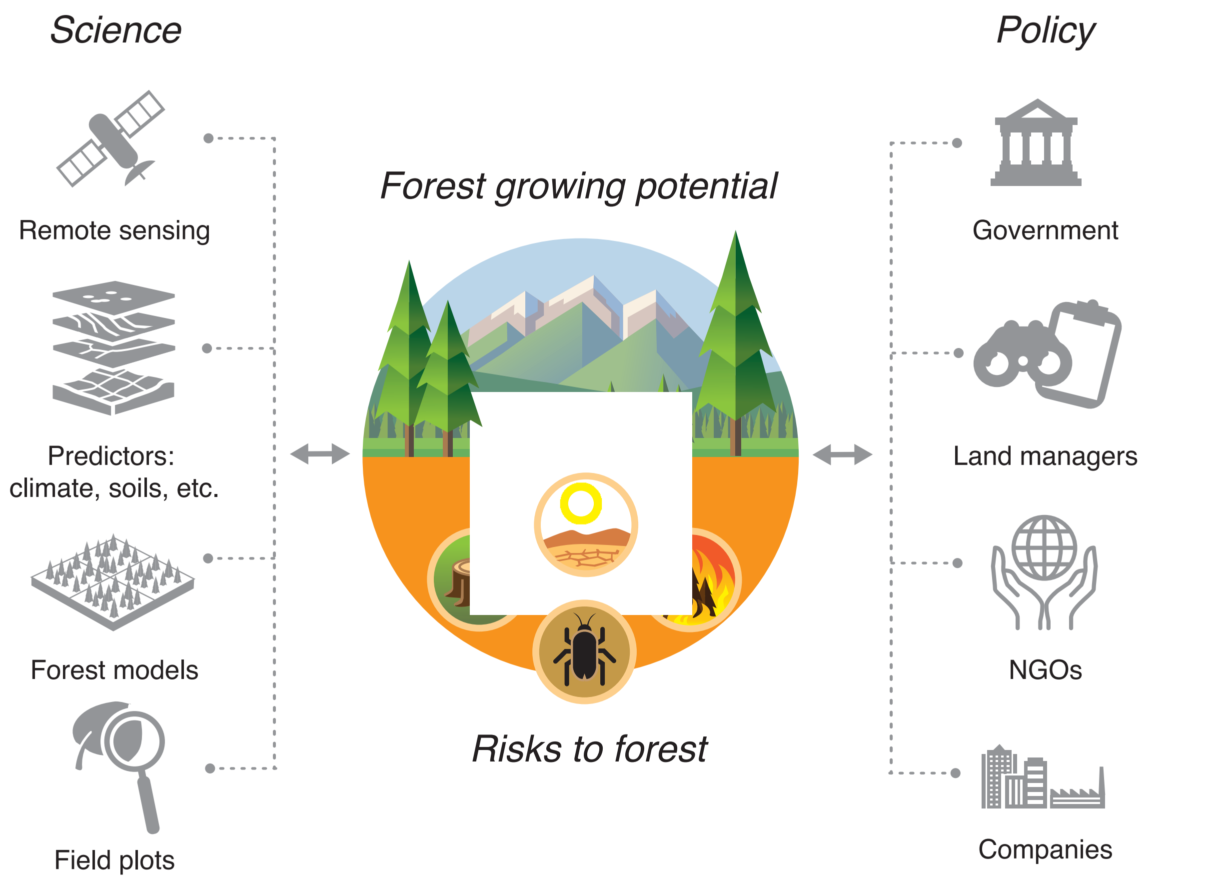

Figure 5: Bridging science-policy divide on forest-based natural climate solutions projects. Key information needed at the science-policy nexus includes the carbon storage (current and potential) and the risks to forest permanence, among others. Central components of a rigorous scientific quantification of this information are presented on the left and example key stakeholder groups are presented on the right. Illustration by David Meikle.