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Forest policy and management approaches for carbon dioxide removal

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Forests increasingly will be used for carbon dioxide removal (CDR) as a natural climate solution, and the implementation of forest-based CDR presents a complex public policy challenge. In this paper, our goal is to review a range of policy tools in place to support use of forests for CDR and demonstrate how concepts from the policy design literature can inform our understanding of this domain. We explore how the utilization of different policy tools shapes our ability to use forests to mitigate and adapt to climate change and consider the challenges of policy mixes and integration, taking a close look at three areas of international forest policy, including the Kyoto Protocol's Clean Development Mechanism, Reducing Emissions from Deforestation and Forest Degradation (REDD+) and voluntary carbon offset markets. As it is our expertise, we then examine in detail the case of the USA as a country that lacks aggressive implementation of national climate policies but has potential to increase CDR through reforestation and existing forest management on both public and private land. For forest-based CDR to succeed, a wide array of policy tools will have to be implemented in a variety of contexts with an eye towards overcoming the challenges of policy design with regard to uncertainty in policy outcomes, policy coherence around managing forests for carbon simultaneously with other goals and integration across governance contexts and levels.

1. Introduction: the role of forests in carbon sequestration

The world's forests greatly contribute towards carbon dioxide removal (CDR), with significant potential to play a larger role [1–4], but facilitating enhanced CDR presents a challenge for policy design and integration. Forest-based CDR involves shifting land use and land management to support forest carbon storage and sequestration. Proponents argue that it offers a natural climate solution (i.e. one that relies on ecological processes to sequester carbon) that is better developed than technological carbon capture approaches [5]. Fargione *et al*. [5] estimate that strategies such as reforestation, avoiding forest conversion, natural forest management of private forests and fire management can account for 50% of the CDR potential of a variety of natural climate solutions in the USA [5], and Bastin *et al*. [6] estimate that as much as 25% of the current global atmospheric carbon pool could be stored in forests [6]. While forest-based CDR offers significant potential, some have highlighted that these global accounting mechanisms are overly optimistic in the potential for forests to draw down carbon dioxide in a quick or permanent way and run the risk of creating a narrative that forests should serve primarily as carbon sinks, overlooking their many uses, meanings and effects on human livelihoods [7–9].

Promoting forest-based CDR requires a variety of policy tools, including informational, incentive, regulatory, educational and procedural tools. Many existing CDR policy tools emphasize gathering information on forest carbon

stocks and fluxes associated with disturbances. Incentive tools aim to encourage landowners to prioritize CDR over other potentially more lucrative land uses. Regulatory tools require that landowners or managers consider CDR in their decision-making. Educational tools complement voluntary mechanisms and incentive opportunities by giving people the information they need to act. Procedural tools ensure that participants creating CDR policies are held accountable and provide avenues for collaborative problem-solving. Procedural tools that promote networks of landowners can facilitate CDR arrangements at scales large enough to ensure substantive impacts and to diffuse disturbance impacts affecting individual landowners. The mix of policy tools for CDR will take different forms depending on governance contexts and levels [10].

Policy integration (i.e. ensuring that policy goals and tools work together) is a significant challenge worthy of attention, given that new forest-based CDR policies will be built into existing policy mixes that represent the wide range of demands society places on forests. CDR must be integrated with other tools designed to achieve pre-existing forest management goals, such as management for resilient landscapes and provision of other ecosystem services (e.g. clean water, recreation or wildlife habitat).

To address the interest in and potential for forests to contribute to CDR from a policy design perspective, this paper has two primary objectives. First, we use selected case studies of policy tools for forest management to illustrate how forest-based CDR plays out in several contexts, both internationally and specifically in the USA. Second, we examine how different policy tools might be mixed in different contexts and integrated (or not) with each other and with existing forest policies.

In the remainder of this Introduction, we explore what management strategies are thought to contribute to enhanced carbon sequestration in forests, and we discuss the synergies and trade-offs of managing forests for climate mitigation and adaptation. In §2, we begin with an overview of policy design and then in §3 delve into three prominent policy approaches for forest-based CDR in international climate policy. This is followed in §4 by a detailed look at the USA as an informative domestic case. While there are many forest-based CDR policy tools in existence globally, we have chosen examples in §3 to illustrate CDR specifically in the form of verified carbon offsets with international funding. We then focus on the USA because of our expertise in the region and explore a representative sample of policy tools and associated challenges for CDR management on public and private forests (for a comprehensive analysis of US CDR policy tools on farmland, forests and grasslands, see McGlynn *et al*. [11]). Finally, §5 explores the challenges of policy mixes and coherence in managing forests for CDR and synthesizes our perspective on the value of considering forest-based CDR through the lens of policy design.

1.1. How forests can be managed for CDR

Different management strategies can affect carbon storage (the amount of carbon stored on site) and carbon sequestration (the rate of removal of carbon from the atmosphere) [12]. The most impactful method of using forests for CDR is through management that both maintains existing forests (avoided deforestation) and increases total forest coverage (reforestation or afforestation). Reforestation of forests involves growing forests in recently and previously forested areas, with afforestation occurring in areas that have not been forested in the past 50 years [13]. Avoided deforestation is key as well, as the conversion of forest to non-forest releases the carbon stored in them, although the net amount of carbon released depends on the methods of clearing, the destination of the wood products and future land use.

Another method of managing forests for CDR is to consider how existing forests are managed in order to increase growth or reduce threats of disturbances [14]. Forests managed for timber production can be moved towards longer harvesting rotations than would be ideal from a profit-maximizing standpoint, allowing trees to approach their peak carbon sequestration rates but cutting them and replanting before these rates start to decline [1,5,12,15]. Adding inputs to intensively managed forests, such as fertilizers or irrigation, can facilitate rapid tree growth, although the carbon footprint of these inputs must be taken into consideration in determining best practices for CDR [15]. Planting selected species can help in sequestration; for example, if they are fast-growing or less susceptible to disturbances such as fire, wind damage or disease outbreaks [15–17]. Managers can also limit carbon loss via soils (soils can account for 30–60% of a forest ecosystem's total carbon [3]) in actively managed forests via reduced-impact logging, which includes monitoring soil and water, building logging roads in stable areas and harvesting during stable soil conditions [12]. Removing uncharacteristically high fuel loads that have resulted from fire suppression in regions like the western USA, while contributing to a short-term loss of carbon stocks, may decrease the likelihood of disturbance and associated carbon loss in the future, making fuel reduction efforts in frequent-fire forests an effective carbon sequestration strategy [18–20].

CDR policies around forest management can also take into account the final destination of the harvested biomass. Harvested wood used in creating durable products, such as furniture, wood-framed structures or even paper, continues to store carbon during the product's lifetime and its slow decomposition upon disposal [13,14,21]. Wood products in construction can also be used as substitutes for other materials, such as steel and concrete, that rely more heavily on fossil fuels for their production [12,13,22]. Additionally, if harvested biomass is burned for energy in place of fossil fuels, then carbon emissions are further reduced [13]. Complete life cycle assessments are necessary to assess total emissions mitigation associated with any of these uses.

There are also active debates around the certainty of how management actually affects carbon sequestration and storage. For example, many carbon inventories focus on above-ground biomass in woody species, without consideration of litter, soil or root carbon content; others include these components but acknowledge that there is uncertainty in their calculations [3,14]. There are divergent recommendations for how to manage existing forests for increased carbon sequestration, and much of this debate centres on initial conditions of forests before management interventions [1,15]. Some argue for suppressing undergrowth to facilitate increased carbon sequestration in larger trees [5,14], yet others advocate for increased biodiversity and a variable height and age-class structure that can enhance 'carbon packing' on the landscape [12]. Increasing forest growth rates can also be achieved through the use of fertilizers, although this is

coupled with concerns of nitrous oxide release, which is a much more potent greenhouse gas than carbon dioxide [14].

1.2. Synergies and trade-offs between managing for climate adaptation and climate mitigation

While forests can function as carbon sinks, they are also vulnerable to climate change [23]. Accordingly, managing forests for CDR also requires ecosystem adaptation to a changing climate. Research on adaptation and mitigation in forest management ultimately highlights the importance of considering how to integrate these goals, synergies and trade-offs between adaptation and mitigation, and the effects of ecological disturbance dynamics at different scales [24–26].

In the western USA, for instance, a key vulnerability of forests to climate change results from its exacerbation of existing disturbance processes, including wildland fire and insect outbreaks [27]. Efforts to adapt forests to climate change tend to focus on managing for forests that are resistant and resilient to more frequent and intense disturbance regimes [28]. In frequent-fire forest types where fire suppression has led to uncharacteristically high fuel loads, these adaptation efforts involve thinning forests and reintroducing fire as a critical ecological process. At first glance, these management activities that remove biomass in the short term would seemingly conflict with the goal of CDR. If these practices reduce the severity of future disturbances and allow remaining disturbance-resilient trees to grow, however, they will contribute to carbon sequestration; in essence, in fire-prone systems, adaptation and mitigation goals can be well aligned [18]. In recognition of the potential convergence between adaptation in the form of fuels reduction and mitigation, efforts like the California Forest Carbon Plan allow for use of funds from the California Carbon Market for fuel reduction on federal forestlands with the overall goal of ensuring long-term carbon storage [29]. In other forests, there may be trade-offs between carbon sequestration strategies and protection of habitat for certain species, which may be a critical climate adaptation need [30]. As a result, scholars emphasize that forest managers should prioritize managing for resilience, consider trade-offs between mitigation and adaptation, and be guided by the specific ecologies of forest types and forest ecosystem services in different locations [31].

2. Policy design and tools for forest-based CDR

Policy design refers to the process of identifying policy goals, determining the mix of policy tools used to achieve those goals, and engaging in an iterative process to select and calibrate policy tools for specific contexts across levels of governance. These choices are nested within pre-existing governance arrangements that reveal overarching objectives and implementation philosophies, and create a context that constrains new policy tool choices to those aligned with the governance paradigm [32]. For instance, incentive-based tools that emphasize individual choice are more widely accepted in places like the USA than regulatory tools [33]. Often a portfolio of tools is needed to meet policy goals, and there are frequently trade-offs and tensions associated with different types of policy tools. For example, while financial incentive tools such as payments for ecosystem services are often more politically palatable than regulatory tools, significant analytical capacity is needed to tailor them to specific policy targets (i.e. actors who could respond to incentives) and may offer less certainty of achieving policy goals [34]. Procedural tools like collaborative decision-making forums are often costly and time consuming to implement but can support overcoming scale mismatches and leveraging of capacity that can be essential for addressing today's environmental governance challenges [26]. Policy mixes frequently combine substantive tools (e.g. regulatory, incentive or information-based tools) and procedural tools (e.g. collaborative forums or access to judicial oversight). Because of their trade-offs and the diversity of targets (e.g. public and private forest landowners or land management and regulatory bodies at different levels of governance, such as state and federal), multiple tools are needed to achieve complex CDR policy goals.

Addressing climate change in diverse forest ecosystems across multiple sectors and levels of governance makes for a policy design and integration challenge. Policy integration occurs when policy goals and policy tools are coherent (e.g. multiple goals are not contradicting each other or leading to significant trade-offs) and consistent (e.g. policy tools support the achievement of these goals and do not work at cross-purposes), and with consideration of integration across sectors and vertically across levels of the system (e.g. from international to national and more local levels) [10,35]. Coherence within forest-based CDR policy is a challenge, as forests provide many other functions that can at times conflict with managing them for carbon storage or sequestration, such as biodiversity conservation, recreation or supporting livelihoods. Achieving policy integration is also complicated by the layering of new policy goals and tools onto existing approaches. Effective collaboration and coordination across sectors and organizations are essential for achieving policy integration but require political commitment and overcoming the entrenched interests of economic interest groups and state bureaucracies that may seek to preserve the status quo [35–37]. Examining differential benefits to actors that result from tools, using collaborative policy design processes and tailoring tools to local contexts are all important strategies for preventing marginalization of disadvantaged groups in efforts to combat climate change.

3. Case studies of international forest-based CDR policy tools

Designing tools for forest-based CDR in international climate policy has faced challenges around managing forests for multiple goals and among different actors and verifying carbon outcomes. With these dynamics in mind, in this section we explore three major policy initiatives that use international funding streams to pay for verified forest-based CDR. To illustrate the necessity and challenges of mixing tools within and across initiatives, we look at the Clean Development Mechanism (CDM), REDD+ and voluntary carbon markets.

3.1. The Kyoto Protocol and the Clean Development Mechanism

The Kyoto Protocol, an international climate agreement signed in 1997, included a limited role for forests in climate

mitigation because of uncertainty around the ability to demonstrate carbon reductions. Industrialized countries that were signatories to the Protocol were required to reduce greenhouse gas emissions by 2012; economically developing countries were not bound by targets but could participate by hosting projects that reduced emissions [38]. The Protocol's CDM permitted economically developing countries to sell Certified Emissions Reductions (CERs) to industrialized countries, provided that these reductions came from sustainable development projects that would not have occurred otherwise (i.e. projects had demonstrable additionality). Thus, the Protocol integrated multiple substantive policy tools, including regulatory and market-based tools. The first CDM projects were accredited in 2000, and largely ended around 2012 [39]. Reforestation and afforestation projects were permitted under the CDM, although these represented a tiny fraction: only 0.9% of over 7000 CDM projects in 2016 (table 1). Most projects instead focused on reducing emissions in energy production, transportation and industry [39]. Because of concerns with the permanence of forest-based reductions, forest CDM projects were issued temporary CERs (for 5 years) or long-term CERs (for a single 30 year period or 20 year periods renewable twice) that buyers had to replace with permanent CERs upon their expiration [40].

Tensions emerged between regional European approaches and international climate agreements on how to verify carbon reductions in forests; this limited the proliferation of forest-based CDM projects. The European Union's Emissions Trading System (EU ETS), begun in 2005 as part of its compliance policy for the Kyoto Protocol, would not accept forestry CDM projects [38,39]. The EU ETS and other emissions trading systems cited concerns around leakage (i.e. where maintaining forests in one location may simply lead to deforestation elsewhere), permanence (i.e. when protected forests could be harvested in the future, or be vulnerable to disturbances) and accounting (i.e. where there are uncertainties around how best to quantify carbon in forests and in harvested wood products) [39]. Project developers found forestry projects to be riskier than other CDM projects because of the longer time scale associated with tree growth and high initial and transaction costs, which made it difficult for smaller scale projects to join [39–41]. The temporary nature of the credits made them unattractive to buyers as well, since they would have to be replaced in the future with new CERs [40]. Thus, the first-generation forestry projects included in the international climate agreement arena were limited in their scope, with the few offsets created being limited to afforestation or reforestation projects.

The policy tools developed under the Kyoto Protocol reflected the global trend over the last several decades towards market-based governance preferences and policy tools [32]; this trend has shaped policy design for CDR and resulted in market-based tools. The Protocol and the CDM, in not specifying exactly how emissions were to be reduced and in including some flexibility for trading of offsets, suffered less from the challenges of policy integration, as it could be layered without significant conflict on top of other policies. The larger challenge was determining how to mix the regulatory cap of the Kyoto Protocol with a market-style CDM calibrated such that it led to significant use of forest-based CDR. Additionally, the CDM intended to integrate carbon removal objectives with sustainable development in countries hosting these projects, but coordinating these objectives remained difficult and sustainable development benefits were often sidelined [38,42].

3.2. REDD+: Reducing Emissions from Deforestation and Forest Degradation

A next iteration in forest-based CDR policy tools was REDD+, which is perhaps the best-known international forestry-based CDR effort and an important mechanism for climate mitigation under the 2015 Paris Agreement (table 1). While the basic premise of REDD+ has remained unchanged—that economically developing countries should be financially compensated for forest-based CDR—the initiative has evolved significantly since its inception [43,44]. First conceptualized at the United Nations Framework Convention on Climate Change (UNFCCC) in 2007 as Reducing Emissions from Deforestation (RED), the scope of the initiative soon expanded to encompass other CDR strategies such as forest degradation (termed REDD, Reducing Emissions from Deforestation *and* Degradation) and then conservation of carbon stocks and sustainable forest management (termed REDD+) in response to demands from economically developing countries with stable but valuable forest carbon reserves [45]. The scope of REDD+ also has expanded significantly as a result of concerns that REDD+ would lead to the 'carbonization' and centralization of forest governance at the expense of non-carbon values. In recognition of the need for integration with other public policy objectives, 'co-benefits' and safeguards (poverty reduction, biodiversity conservation, and stakeholder consultation and participation) were subsequently integrated into the international REDD+ framework beginning in 2010 [43,44].

There has also been an evolution in the primary tools associated with REDD+. REDD+ was originally conceptualized as a payments for ecosystem services programme, with conditional financial incentives provided through an international carbon market. A viable carbon market has yet to materialize, however, and REDD+ funding has come instead in the form of aid from development funds and national budgetary allocations. REDD+ funding also has been minimal compared with expectations, with most going to pre-implementation capacity-building activities rather than results-based payments for CDR [46]. Further, REDD+ has also shifted from an emphasis on small-scale, non-governmental organization (NGO)-led projects that target communities and small landholders to larger jurisdictional approaches that use a mix of tools to address land-use drivers emanating from outside the forestry sector [47,48].

REDD+ therefore now encompasses a heterogeneous mix of goals and policy tools designed and implemented by government and non-government actors across multiple levels of governance under the broad scope of the UNFCCC framework [44,49,50]. Specifically, REDD+ policy design and implementation within participating countries occurs under a three-phase approach: (i) REDD+ readiness and capacity building, (ii) REDD+ action plans and policy reforms, and (iii) payments based on verified emissions. Institutions such as the UN REDD+ and the World Bank's Forest Carbon Partnership Facility provide funding and technical assistance for phases 1 and 2, in which governments customize international REDD+ goals and tools for domestic contexts. This involves analysing emissions drivers, identifying appropriate objectives (e.g. reducing deforestation or sustainable management of carbon stocks) and evaluating existing and potential

Table 1. Selected policy tools for forest-based CDR.

policy	primary tool types	description	scale	financing	benefits	concerns
Clean Development Mechanism (CDM)	market-based within regulatory Kyoto Protocol	countries bound by Kyoto climate treaty can buy offsets, a tiny fraction of which are forest-based (afforestation/reforestation only)	international (projects in economically developing nations, buyers in industrialized nations)	from those regulated by the Kyoto Protocol	—flexible mechanisms for reducing carbon —funds sustainable development in developing nations	—forest projects are relatively costly and risky —uncertainty in carbon accounting —risks of leakage or lacking additionality and permanence —offsetting carbon can reduce focus on source reductions and places burden on developing nations —carbon reductions not always synergistic with sustainable development goals
Reducing Emissions from Deforestation and Forest Degradation (REDD+)	financial and market-based incentives, regulatory, informational tools	paying for avoided deforestation and forest degradation, conservation, sustainable management and enhancing forest carbon stocks	international (projects in economically developing nations)	bilateral and multilateral development funds and state budgetary allocations	—integrated co-benefits and safeguards —funds forest work in developing nations	—equity concerns —offsetting carbon can reduce focus on source reductions and places burden on developing nations —trade-offs with non-carbon forest benefits —marginal livelihood gains —lack of policy coherence —risks of leakage or lack of additionality or permanence —not addressing fundamental drivers of deforestation

(*Continued*.)

Table 1. (*Continued.*)

policy	primary tool types	description	scale	financing	benefits	concerns
Voluntary Carbon Markets	market-based, voluntary, with accountability tools	voluntary carbon offset payments available for purchase by anyone (forest-based projects are 46% of total value of voluntary markets)	international	from those who choose to buy offsets (individuals, sectors with no current carbon cap)	—addresses sectors not currently regulated —flexibility in production and price, testing ground for new project types —buyers select desired co-benefits	—small market volume, which also varies greatly —uncertainty in carbon accounting —risks of leakage or lack of additionality or permanence —offsetting carbon can reduce focus on source reductions
US Forest Service (USFS) climate change performance scorecard	informational management tool	assessment of climate-related activities in USFS lands	USFS lands	no specific funding for carbon sequestration	information gathered on each unit's carbon stocks and stewardship potential	no specific incentives, not binding activities
US Forest Service 2012 planning rule	regulatory tool	requires assessment of baseline carbon stocks on USFS lands and writing management plans that include carbon sequestration	USFS lands	no specific funding for carbon sequestration	—information gathered on each unit's carbon stocks —encourages considering carbon sequestration as an important ecosystem service	—no fundamental change to USFS management priorities —not explicitly addressing CDR
Natural Resources Conservation Service's (NRCS) Healthy Forests Reserve Program	incentive tool	US government shares costs of habitat restoration plans and conservation easements on private lands with threatened or endangered species	private and tribal US forests	funds designated in US Farm Bill	—reduces cost burden for private landowners —provides technical assistance —one of few federal programmes prioritizing carbon	—extremely limited scope (only $54 000 in obligations in 2019, down from $17 million in 2011)[a] —forests must have threatened and endangered species, not only high-value carbon

(*Continued.*)

Table 1. (*Continued.*)

policy	primary tool types	description	scale	financing	benefits	concerns
California Carbon Market	regulatory market-based tool	industries bound by emissions regulations can buy offsets for a fraction of their emissions, some are forestry-based (a/reforestation, improved management, avoided conversion)	mostly US private lands, but a few projects in Canada and Mexico	regulated industries (electricity, manufacturing (pulp and paper, etc.))	—fills a gap in California due to lack of national policy —funds forest work —rigorous standards to prove permanence	—forestry projects are prohibitively expensive for small landowners to join —uncertainty in carbon accounting —risks of leakage or lacking additionality and permanence —offsetting carbon can reduce focus on source reductions —little awareness among potential participants

[a]Natural Resources Conservation Service. 2019 *NRCS Conservation Programs: Healthy Forests Reserve Program (HFRP)*. Farm Bill Report (fiscal year 2009 to fiscal year 2019). See https://www.nrcs.usda.gov/Internet/NRCS_RCA/reports/fb08_cp_hfrp.html (accessed 14 April 2020).

policies needed to operationalize results-based payments, benefit sharing mechanisms and safeguard systems. Participating countries must also establish Forest Reference Emissions Levels (quantitative benchmarks for forest carbon emissions), Monitoring Reporting and Verification (MRV) systems to track forest carbon emissions and implementation outcomes, and information systems for ensuring compliance with UNFCCC safeguards. Ideally national policy frameworks provide the sideboards for subnational policies and implementation structures, which in turn support project-level implementation.

Despite the diversity of REDD+ approaches, there are some common themes that have emerged from project-level implementation. First, there is the challenge of achieving carbon and non-carbon goals and objectives. For instance, there are often tensions between REDD+ goals for carbon and biodiversity conservation in that priorities for each may not be co-located. Synergies between carbon mitigation and climate adaptation also often go unrealized in the context of REDD+ projects [34]. Second, the achievement of social co-benefits also has proven to be particularly challenging; while analyses of project-level REDD+ implementation have shown some benefits for forest carbon mitigation, livelihood benefits have been marginal [51]. Indeed, the development of equitable and effective benefit distribution strategies has been particularly challenging at project levels owing to limited state and civil society capacity, corruption and political resistance [52]. Where the achievement of CDR and social benefits has occurred at local scales, it is often because of the presence of a well-designed mix of regulatory, informational and financial tools. Indeed, regulatory tools are often most effective for conserving forest cover, with financial payments then needed to compensate stakeholders whose livelihoods may suffer as a result [49].

A third lesson of REDD+ project implementation has been that interventions that target small-holders and stakeholders often fail to address the most significant drivers of deforestation (e.g. industrial agricultural development) and are difficult to 'scale up' without enabling policy frameworks at national and subnational levels [47]. The resolution of tenure conflicts, for instance, which are essential for equitable benefit sharing, often requires higher-order policy change and political commitment. At national levels of countries participating in REDD+, there has been significant progress in the development of legal frameworks and implementation structures for informational tools such as MRV systems. However, opportunities for transformational policy change have been limited when national governments respond to interest groups invested in maintaining 'business as usual' [53]. For instance, in many countries, REDD+ policy incentives for CDR must compete with existing incentives for agricultural development that result in deforestation. Even when REDD+ goals are integrated across sectors, effective coordination across different ministries responsible for land use governance is complicated by internal dynamics in bureaucracies, which limit the achievement of new policy goals, particularly when administrative roles and responsibilities are not well defined. Vertical integration is also a challenge. In many cases, project-level and subnational strategies were developed before national-level enabling policies were in place, leading to implementation difficulties [54–56].

Given these issues, approaches to REDD+ are increasingly being designed and implemented at subnational

jurisdictional levels. Subnational political jurisdictions (e.g. a state or province) are seen as a strategic scale and level for REDD+ implementation because of their potential to support vertical integration (national to project level), horizontal integration across sectors and initiatives, coherence with other initiatives (e.g. zero deforestation commitments and indigenous rights) and context-specific policy design [54,57]. For instance, in Brazil's state of Acre, subnational jurisdictional tools such as land use regulation through zoning, economic incentives for local stakeholders and sustainable timber management practices have led to considerable achievements for CDR. However, jurisdictional approaches require political commitment from subnational government officials who may face heavy pressures for resource development. There is also significant variation in formal authority for land use governance at subnational levels across different countries, and limited funding and capacity in subnational jurisdictions is a common challenge. While there are some notable successes and significant momentum for jurisdictional approaches to REDD+ and CDR, it remains too early to judge their success in many contexts.

The policy design of REDD+ has shifted over the years in efforts to achieve integration with additional goals for forests as complex socio-ecological systems. REDD+ continues to evolve but so far has faced significant integration challenges where carbon priorities can conflict with provision of other ecosystem services and the equitable distribution of social co-benefits. The layering of REDD+ on top of existing policies has also led to obstacles to effectively tackling root drivers of deforestation, as entrenched interests have a stake in maintaining the status quo. REDD+ offers an example of the potential large scope of forest-based CDR, as well as many of the policy design and integration challenges.

3.3. Voluntary carbon offsets

Another form of incentivizing forest management for carbon sequestration is through the voluntary carbon marketplace, a different set of policy tools designed to reach other policy targets not involved in formal international climate agreements (table 1). Voluntary markets involve buyers who are not obligated by compliance markets to produce reductions in carbon, such as individuals hoping to offset their carbon footprint or companies that want to demonstrate their social responsibility or prepare themselves for future compliance regulations [58]. In contrast to compliance markets, where generally all reductions are priced the same per ton of CO_2 equivalent (CO_2e), voluntary offsets vary in price by project type and location, as buyers choose offsets for a variety of reasons (e.g. wanting to fund projects that are operating in a certain part of the world or that offer co-benefits) [59]. Voluntary offsets operate beyond the scope of compliance markets, international climate agreements and national governments, instead relying on accountability tools like a variety of third-party verification standards to create market-tradable units of CO_2e that demonstrate permanence and additionality and limit leakage or double-counting [58,59].

The voluntary carbon market is smaller in volume than compliance markets like the CDM or other regional markets [39], and its growth has varied drastically over the years [59]. Voluntary offsets are issued for a variety of projects, but a large portion of the market (46% of the volume in 2016) is forestry and land use offsets that include projects such as afforestation/reforestation, improved forest management (e.g. reducing logging impacts, extending harvest rotations) and avoided deforestation [13,59]. Because there is more flexibility in production methods and price, methodologies for compliance markets are often first tested in voluntary credits [39,59]. Voluntary markets also provide opportunities for buyers to selectively fund projects that have co-benefits beyond carbon sequestration (like those recently integrated into REDD+), such as sustainable development, poverty alleviation or enhancement of other ecosystem services beyond carbon; forestry offsets with co-benefits are often more popular and command higher prices [58]. In the USA, voluntary markets served as a venue for companies to earn offsets for reducing their emissions in anticipation of passing a national emissions trading system into law in 2009. The volume of the voluntary market increased because companies expected that these 'early action' credits would shift into compliance credits upon the law's passage until the US Senate failed to approve the bill [60]. Most voluntary offset purchasers are those who do so unrelated to anticipated compliance, as there has been uncertainty in these compliance markets coming to fruition.

Because of the lack of regulatory climate policy tools, sectors with no carbon caps have turned towards self-regulation and voluntary tools to meet their own climate goals. The voluntary carbon market as a policy tool reflects a global governance context that has increasingly moved towards market mechanisms and away from mandatory state regulation. Voluntary market standards also attempt to integrate the carbon offsets with other goals such as sustainable development and biodiversity protection, marketing these synergies to fetch higher prices. These markets thus rely heavily on adequate information and purchasers who are actually motivated to obtain offsets with co-benefits. The addition of third-party certification as an accountability tool was necessary in order to create legitimacy and increase demand. In summary, voluntary offsets encompass a suite of tools and complement other compliance-based tools to fill in gaps.

4. CDR and policy integration in US forest policy

Here we take a deeper look at current forest management in the USA, which reveals a range of additional policy tools beyond the markets discussed above and how tools are calibrated to a specific implementation context. International forest-climate mitigation policies largely focus on incentivizing forest conservation and management for carbon in economically developing countries, which are often seen as ideal places for this work because projects are thought to be cheaper to implement and tropical forests can rapidly sequester carbon. The impacts on livelihoods of these interventions may also be less visible or directly felt by actors paying for these offsets. Relatively less literature explores the various policy tools for forest-based CDR that are being developed or implemented in an industrialized nation such as the USA (a notable exception being [11]). The USA lacks implementation of holistic federal policies regarding forest-based CDR and is home to regrowing but ageing forests, which may slow their rate of carbon sequestration in decades to come without additional interventions [4,11]. From a policy design perspective, it is interesting to pay attention to the difference in public and private land management, as

policy mixes to support CDR must be tailored to the unique conditions of each land tenure type. Across all land ownerships, CDR represents a newer management goal that comes on top of, rather than in place of, other management goals; existing governance structures and mechanisms will need to be repurposed to support CDR. As a result, the policy integration perspective offers a useful lens for understanding CDR in the USA.

4.1. US public forestlands and CDR

Public lands owned and managed by the federal government account for 31% of forestlands in the USA [61]. The US Forest Service, the largest single public entity holding forestland, manages 193 million acres (78 million hectares) of forests and grasslands across the country; these are organized into 154 national forest units. By law, the agency manages these lands for 'multiple uses', including timber, water, outdoor recreation, grazing, and fish and wildlife habitat. The US Forest Service has also increasingly emphasized ecosystem services in addition to a continued focus on multiple uses.

Since 2008, the Forest Service's internal climate change policies have provided guidance regarding both adaptation and mitigation, with the recognition of the role that forests play in storing carbon and their vulnerability to climate change. At the national level, the agency is encouraging units to engage in climate change vulnerability and other types of climate-related assessments (e.g. fire risk assessment) [62]. For instance, the first iteration of the agency's Climate Change Performance Scorecard, developed in 2011 to facilitate assessment of climate-related activities on national forests, asked, 'Does the Unit have a baseline assessment of carbon stocks and an assessment of the influence of disturbance and management activities on these stocks? Is the Unit integrating carbon stewardship with the management of other benefits being provided by the Unit?' (table 1) [63]. To support management units in achieving this goal, analysts with the agency's national headquarters developed a series of assessments of changes in carbon stocks and the effects of disturbance, management and environmental factors in the regions and individual national forests [64]. This policy tool focused on collecting information about carbon in forests, but did not provide specific incentives to manage for CDR.

In 2012, the Forest Service promulgated administrative regulations interpreting their multiple-use mission and guiding land management planning by national forests and grasslands (table 1). These regulations, collectively referred to as the 2012 planning rule, replace regulations from 1982 and represent one of the most significant policy changes for the agency in decades [65]. Given the nature of comprehensive planning in an agency with multiple goals, planning processes integrate across a range of functional areas. These regulations include several requirements relevant to CDR, but do not explicitly address this goal. Notably, the regulations require that planning teams develop an assessment of available information on a series of topics, which then informs the development of the actual land management plan. One required topic is a 'baseline assessment of carbon stocks', including carbon stored in vegetation, dead biomass and soils (36 CFR 291.6(b)(4)). The planning rule also requires that plans 'provide for ecosystem services and multiple uses' (36 CFR 219.10) and defines 'long-term storage of carbon' as an example of a regulating ecosystem service (36 CFR 219.19). In line with these regulatory requirements, management plans developed by the Forest Service have begun to include references to carbon sequestration as an ecosystem service provided by national forests, although there is no evidence that this consideration of carbon has fundamentally changed management priorities.

For the US Forest Service, CDR is unlikely to become a management goal that supersedes the agency's existing mission of providing for multiple uses for current and future generations. Long-term carbon storage is, however, coherent with some other management goals, notably the expectation to manage forests for ecological sustainability, ecological integrity and resilience [31,66]. Managing for ecological integrity means limiting the occurrence of severe, uncharacteristic disturbances, including wildfires, that would result in large releases of carbon. In light of the fact that the agency's *de facto* priority across much of the system today is reducing the threat of uncharacteristic or catastrophic wildland fire, managing for natural fire processes and ecological integrity, which would support both climate adaptation and mitigation, may become the Forest Service's primary focus, regardless of whether CDR is an explicit priority [67]. Accordingly, ongoing efforts to manage for ecological resilience in light of climate change may offer a path to maintaining carbon stocks contained in national forests [28]. At the same time, at present the Trump administration's primary focus for US forests is their active management. Targets for timber volume removal have been increased with little focus on other objectives [68]. While active management might be part of a climate-driven forest management strategy, this push also is not clearly linked to a strategy of ecological integrity or resilience to disturbances or to climate change mitigation or adaptation planning processes in any systematic way.

These efforts by the US Forest Service offer some insight into potential approaches for large forest land management agencies to promote consideration of CDR in forest management. At the same time, they reveal the challenges associated with layering new goals upon old ones, the influence of national politics and the potential push back on new approaches from those aligned with extractive interests. In general, public land managers will focus on measurable goals that yield political support and revenue [69]; managing for CDR may remain as a secondary goal without policy tools that create new mandates or incentives to shift the calculus of large public bureaucracies like the Forest Service.

4.2. US private forestlands and CDR

The majority (58.5%) of US forestland is owned by private landowners, which include individuals and families, corporate timber companies, conservation organizations and other groups [70]. Similar to public forestlands, there has not been substantive federal policy widely implemented that prioritizes incentivizing forest-based CDR on private forestlands [11]. However, states, regional coalitions and NGOs have advanced some efforts to promote CDR among private forest owners, who have an important role to play in CDR management [71].

There are a variety of potential policy tools to more explicitly prioritize CDR in private forests, and a mix of tools will be essential. Theoretically, governments could mandate management activities that benefit CDR, such as immediate

replanting following harvest or extended harvest intervals [14,72]. However, regulatory tools of this nature seem unlikely in the USA given their high monitoring costs and conflicts with its culture of strong private property rights [72]. Policy tools supporting CDR on private forestlands are also likely to be quite different for corporate timber companies compared with family forest owners, who may own much smaller tracks of forestland for reasons other than timber extraction [73].

Advancing CDR among private forest owners in the USA largely relies on informational or incentive-based policy tools. In addition to administering federal public lands, the US Forest Service supports private forest management through programmes administered by state forestry agencies. These include the Forest Legacy Program, which funds conservation easements on private forests (legal agreements ensuring environmental benefits of forests will be left intact), and the Forest Stewardship Program, which assists non-industrial landowners in preparing forest management plans [11,74,75]. While CDR has not been a central element of these programmes, they already represent a procedural policy tool in the form of planning, which could support CDR efforts if coupled with a tool that incentivized landowners to manage for this goal. However, the only federal conservation programme to explicitly prioritize CDR on private lands is the Natural Resources Conservation Service's Healthy Forest Reserve Program. This programme offers cost-sharing for habitat restoration agreements and conservation easements on private lands that provide habitat for threatened and endangered species and lists enhancing carbon sequestration as one of its main goals; however, this programme is constricted by very limited and decreasing funding (table 1) [11,76,77].

Other tools do not prescribe forest producers' actions but instead attempt to make forest management for CDR more lucrative [72]. This indirect approach reflects trends in environmental governance generally and particularly in the USA that prioritize flexibility, protection of private property rights and the role of government as primarily a market facilitator rather than regulator. Markets for wood products and bioenergy are influenced by federal grants and purchasing and assistance programmes, as well as EU climate policies that have increased demand for wood pellets from US producers [11,78]. These tools aim to expand the market for forest-based products, in an effort to prevent forest land conversion and potentially replace more fossil-fuel-intensive alternatives [11]. Treasury tools such as tax deductions for forest management expenses, tax credits for reforestation and reduced tax rates for income derived from timber currently encourage landowners to maintain forest; these could be shifted to offer tax incentives for carbon management of forests [11]. Alternatively, a more punitive tax could be put into place in the future, taxing carbon-releasing forest practices [72].

Carbon offset programme participation has been very limited among private US landowners. Among US family forest owners (families, individuals and trusts), only 2% who have leased or collected money for use of their forests received those payments specifically for CDR [79]. Options to participate in carbon payments have included the now defunct Chicago Climate Exchange (CCX, which ended in 2010 because of insufficient activity), various voluntary carbon market standards, the Regional Greenhouse Gas Initiative (RGGI) in nine northeastern states and the growing California Carbon Market. Several studies argue that there is potential for carbon payments to induce management changes, and more landowners would be willing to join if the price of carbon increases, although these results are based on hypothetical models or interviews with potential participants instead of actual participants' experiences [80–82]. With the historically and currently low price of carbon, other studies have found that very few landowners are willing to actually join [80,81,83]. For example, as few as 2% of surveyed Massachusetts family forest owners in one study were interested in participating in a programme similar to the CCX protocol [83]. Forestry projects have also largely not materialized in the RGGI because of the continually low price of carbon [11]. Others are optimistic that low payments, while not inducing much management change, could at least help prevent land conversion [84]. The national conservation organizations American Forest Foundation and The Nature Conservancy have partnered to develop a Family Forest Carbon Program to target landowners with small holdings who face particularly high barriers to involvement in larger carbon markets [85].

The California Carbon Market offers an example of a growing state initiative to limit greenhouse gas emissions that includes a limited role for forestry offsets. Established in 2013, the market mandates emissions reductions for regulated sectors and allows them to purchase a limited percentage of offset credits (table 1) [86]. In addition to offset projects in other sectors, forestry projects can include reforestation and afforestation, avoided conversion and improved forest management [59,87]. These forestry projects are found in California, as well as in other US states, Mexico and Canada. Landowners must go through a rigorous series of qualification testing and commit to a minimum participation duration of 100 years, with heavy penalties for early termination [88]. Third-party verification of forests' carbon storage and other associated costs are prohibitive to smaller landowners joining the programme [89]. The stringent requirements of the California market have made landowners less likely to participate than they were in previous voluntary forestry offset programmes with more flexible requirements [90]. Changes in the market's structure in 2017 reduced the role of offsets so as to encourage more emissions reductions and limited out-of-state projects [91,92]. While the programme in its current format seems unlikely to spur large-scale involvement in CDR from a range of forest owners, the overall structure may support future CDR efforts if changes are made to enable more participation.

There remain barriers to private US landowners' participation in any form of carbon offset programme. The price of carbon has not remained consistent, reflecting varying demand for offsets and a lack of clear national climate commitments [81,83,88]. The price of carbon has also remained lower than many expected, often too low to entice landowners to participate [73,83,93]. As seen in California, there are often high joining and transaction costs for participation in carbon forestry programmes because of complicated procedures to ensure the validity of the forest offsets, which excludes smaller landowners [73,83,88]. Landowners' perceptions of climate change can also strongly influence desires to participate; forest owners with a strong belief in and understanding of the ability of forests to mitigate climate change or who already manage private forests with outside input are more likely to consider joining offset programmes [81,83].

Thus, policy tools for managing private US forests for CDR are limited in their current influence in light of the multiple objectives for forest management across a wide array of landowners. Our analysis above suggests that a combination of educational tools that involve forestry professionals providing technical assistance to small forest owners, procedural tools that emphasize forest management planning and incentive tools that make managing for carbon appealing and lucrative can all support CDR on private lands. Many of these tools currently exist but operate with a limited scope or without an explicit focus on CDR; efforts to promote CDR may benefit from repurposing these existing tools rather than creating entirely new planning processes. For example, the US Department of Agriculture (USDA) published its *Building Blocks for Climate Smart Agriculture and Forestry* plan in 2015 [94] with the intention of using existing voluntary, incentive-based programmes to promote climate mitigation practices in agriculture, ranching and forestry on both public and private lands. Forest-related components included enrolling more privately owned acres in the USFS's Forest Legacy and Stewardship programmes and promoting wood product markets, repurposing existing efforts to more explicitly reduce carbon emissions and promote sequestration [94,95]. The Trump administration, however, has de-emphasized these goals in recent years [95,96].

5. Policy design in forest-based CDR: policy tools, coherence and mixes

Our review of several policy tools that aim to enhance CDR in forest management illustrates that successful forest-based CDR will require a mix of tools tailored to specific contexts. Based on this analysis, we highlight three issues in policy design for CDR in forest management that warrant further discussion. First, because forests produce a diverse array of benefits beyond carbon sequestration, many CDR policy tools face the issue of policy coherence in that CDR tools must integrate with existing policy tools focused on other goals. Well-designed policy can help align CDR management with other objectives, although sometimes these tensions cannot be avoided. Second, because of the nature of carbon and the global scale of mitigation, CDR tools must take into account the continual struggles with measurement, verification, scale and permanence; this often requires a well-designed and well-calibrated set of tools. Third, it is important to recognize that there are groups who benefit and groups who are harmed by CDR policy tool implementation, and there is a need for transparent procedural tools to minimize negative effects of strengthening CDR policy.

5.1. CDR policy coherence

Forests provide an abundance of ecosystem services, and management for these other services can at times be complementary to and in other cases competitive with CDR. There have been many concerns raised that prioritizing carbon sequestration in land management policy can lead to a 'bio-perversity' by sidelining other ecosystem services through a singular focus on carbon if policies are not coherent across multiple objectives [14,97,98]. These poor outcomes can be seen in projects that plant monocultures of non-native, but fast-growing, trees, destroying intact non-forest ecosystems (e.g. afforestation in native, biodiverse grasslands) [15]. The urgency in climate change narratives emphasizing the immediate need for climate change mitigation in part drives these types of practices, as a price is often placed on carbon but not explicitly on many other ecosystem services, values and relationships with forests.

In practice, trade-offs and synergies with other ecosystem services strongly depend on the form of CDR management implemented, the prior land cover and use (e.g. native grasslands versus degraded forests) and what services are being measured in what ways. Planting trees for carbon generally complements the ecosystem service of erosion control, particularly if reforestation occurs on marginal steep lands or in areas impacted by high severity fires [99–101]. Managing forests for CDR has the potential to enhance local biodiversity if, for example, reforestation occurs on degraded lands with a variety of native species [98,102,103]. Impacts on biodiversity are not uniform either, with some CDR management practices enhancing wildlife habitat for certain species but reducing habitat for others [30,104]. Similarly, there are active debates around whether afforestation and reforestation increase water yield; forests may reduce yields at a local scale but the effects at larger scales are still unknown [105–109]. A focus on forests for CDR has the potential to bring attention and funding to forest restoration or reforestation in ways that can enhance the health or extent of forest ecosystems. Well-designed policy tools can create procedural processes for inclusively exploring trade-offs and can promote management techniques that are complementary to other priority ecosystem services and values.

5.2. Uncertainty in CDR policy implementation

There remain major uncertainties to measuring carbon sequestration and storage, which influence policy design for forest-based CDR. Allometric equations used to calculate carbon in above-ground biomass are still being refined, particularly for non-timber species; biomass in root systems and soils remains understudied [14,110]. There is still active debate on the best techniques for enhancing carbon sequestration in existing forests, such as optimal rotation intervals or thinning practices. Differences in quantification techniques pose issues in particular for carbon payments, where variable methods of measurement can lead to vastly different payment and offset amounts [111,112]. There are additional complexities when the quantified carbon is monetized in the marketplace, creating a fungible unit of CO_2e. The messiness of this translation from invisible greenhouse gas taken out of its local forest context to priced commodity spurred the development of a series of standards (e.g. third-party verifications in the voluntary markets or stringent compliance requirements) that aim to legitimize this conversion, but there remains much discretion and uncertainty [113,114].

Proving additionality (that the project would not have occurred without offset funding) continues to be challenging, and research into offset programmes often does not examine the counterfactual adequately to show that improvement of an ecosystem service would *not* have occurred *without* payment [115,116]. Accounting for leakage remains a huge obstacle, as deforestation shifts to other locations, including other continents, when forests are protected for carbon. Offset policy tools have attempted to address these uncertainties by reducing the number of credits granted to a forestry

project to account for leakage or ambiguous measurement, but there justifiably remains a reluctance to equate forestry offsets to emissions reductions. It is important to bring these assumptions and struggles with measurement and verification to the forefront in order to understand that these policy tools represent important international attempts to remove carbon but must continually be questioned, debated and improved [112,117].

Inherent to these debates around uncertainty is the challenge of comparing techniques on how best to manage carbon when assumptions and boundaries are defined differently. For example, some studies do not account for the reduction of carbon emissions from forest products replacing more fossil-fuel-intensive energy sources or materials; this is because some researchers want to avoid assuming where and how forest products from a particular harvest site will actually be used [1], although others take this into account. When studies use different spatial and temporal scales, it becomes more difficult to draw conclusions on best carbon practices. If considering carbon mitigation on a very short time line, thinning and prescribed burning of forests to support climate adaptation would immediately release carbon, but, as noted above, over a longer time frame adaptation and mitigation management goals may be complementary [18–20]. Sometimes adaptation management that releases carbon in the short term is discouraged because of a focus on immediate climate mitigation, a problem of temporal scalar mismatches [26]. Thus, making key decisions around CDR policies requires careful consideration and explicit acknowledgement of assumptions, boundaries and scale.

There are also concerns that forest-based carbon sequestration lacks the permanence needed to adequately tackle climate change. Forests are susceptible to both disturbance (with frequency and intensity often increasing in a changing climate) and future human-caused landscape change (despite commitments to retain forests) [3,118,119]. Policy design can attempt to account for this risk, such as requiring 100 year commitments in California Carbon Market forest offset projects or limiting the percentage of emissions reductions that can be claimed through offsets. Some argue that CDR overly reliant on forests cannot achieve the scale needed and faces many obstacles to acceptability and rapid implementation [120,121]. Forest-based CDR is likely to be a key component of climate solutions but will need to be coupled with other approaches to achieve CDR and emissions reductions, particularly given these permanence concerns.

5.3. Inequality in CDR policy

Implementation of CDR policies in forests, like all climate policies, will benefit some and sideline others. In particular, there are major concerns with international forest-based climate policies, like the CDM, REDD+ or international voluntary offset standards, whereby reductions in carbon emissions in industrialized countries can be avoided through offsets and forest management changes in economically developing countries, which historically have contributed very little to climate change. Carbon offset programmes may provide some local benefits, depending on the context and policy design, but there have been numerous documented cases of negative outcomes for participants in economically developing nations, such as inadequate payments, loss of access to the ability to use land for other livelihood purposes and loss of local control over natural resources [113,122,123]. Termed 'carbon colonialism', critics of offsets see climate change as the most recent justification for foreign interventions in developing nations [124,125]. Creating offset programmes as 'flexible' methods of achieving climate change mitigation sets up a bidding war between economically developing nations offering offsets and wealthier nations hoping to offset emissions in other locations [126]. This highlights the importance of using transparent and accessible procedural tools in policy design to ensure that those affected by CDR policies are able to shape them, although this process continues to face the profound challenges posed by existing power imbalances.

There has been little exploration of the impacts of these emergent carbon offset programmes or forest sequestration policies operating within the USA thus far because of their limited scope. However, as noted above, concerns have already emerged that smaller forest holders cannot feasibly participate in many types of carbon offset programmes. This reflects critiques of international carbon offset programmes, under which smaller landowners or those lacking funds to cover enrolment costs are excluded from programmes, with local elites benefitting most [127–130]. Even on public lands, national forests with more empowered and active local political coalitions may be better funded to undertake processes like climate change vulnerability assessments. In light of the growing investment in public forests by private actors, relatively wealthier areas or more visible projects may be funded at the expense of places where ecosystems and livelihoods are more threatened by climate change [131]. This poses a future research question: who is likely to benefit from CDR forest policies in the USA, and who will experience hardship because of these shifts in forest management?

6. Conclusion

Forests will continue to be a key piece of climate mitigation efforts, especially as the emphasis on natural climate solutions grows. This form of CDR has its limitations in scope, however, as it lacks permanence and competes with other land uses. Forest-based CDR has the potential to be integrated with other CDR strategies (e.g. regulations and emissions caps), particularly those operating on larger spatial and temporal scales. Additionally, forest-based CDR cannot be viewed as a potential alternative to emissions reductions and attention must be paid to equity issues and trade-offs among ecosystem services, some of which may be critical to local livelihoods. Forest-based CDR must be examined critically because highlighting systemic challenges helps shape policies that are equitable, inclusive and more effective at mitigating climate change.

An array of policy tools will be necessary so that they are integrated with existing policies and governance approaches and comport with the policy design preferences of governments. Different tools are also needed at different levels to provide, for example, national standards and support, along with flexibility for more local policies. An array of tools is also needed to reach different CDR targets because of the complexity of forest types, feasible management

interventions, land ownership structures and objectives for forests. Challenges to shifting forest management toward a focus on CDR include integrating this new objective with existing practices, creating coherent policies that find synergies with other goals, incorporating uncertainties around measurement and verification, and working towards collaborative policy creation to create multiple beneficiaries.

There are key areas for future research in order to create equitable and effective forest-based CDR policies. Uncertainties cannot be eliminated but increased research into carbon measurement, tracking leakage and creating experimental designs that examine counterfactuals can enhance our understanding. Continual monitoring of the effects of forest-based CDR tools will also be necessary; for example, there is limited research on the experiences of landowners who actually participate in nascent US-based forestry offsets and much remains to be learned about the differential benefits of forest-based CDR policies within and across nation-states.

The future for forest-based CDR policy creation and existing policy implementation depends on the political will of leaders and pressures from constituents. Currently, in the USA the Trump administration has deprioritized addressing climate change, both generally and on forests. However, many US states, local governments, non-profit organizations and businesses are moving towards climate solutions, stepping in where the federal government has failed to act. Among private US landowners, offsets are likely to increase slightly (particularly among larger landowners) as programmes like the California Carbon Market grow, yet funding for incentive-based tools like forest reserve programmes will likely shrink based on recent trends. More influential factors on management are likely to be market demands (e.g. EU demand for wood pellets) and the increased need to manage for disturbances, both of which may additionally facilitate CDR, depending on the management strategy implemented. Internationally, voluntary markets continue to represent a limited effort but one that fills a key gap, while REDD+ expands in many economically developing countries but with substantial criticism. Finding real solutions to climate change will require a variety of policy mixes designed for different places, contexts and targets and with adequate information, capacity and funding for implementation.

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