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REVIEW

Climate-Smart Forestry: Promise and risks for forests, society, and climate

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Abstract

Climate change is presenting a global challenge to society and ecosystems. This is changing long-standing methods to determine the values of forests to include their role in climate mitigation and adaptation, alongside traditional forest products and services. Forests have become increasingly important in climate change dialogues, beyond international climate negotiations, because of their framing as a Natural Climate Solution (NCS) or Nature-Based Solution (NBS). In turn, the term "Climate-Smart Forestry" (CSF) has recently entered the vernacular in myriad disciplines and decision-making circles espousing the linkage between forests and climate. This new emphasis on climate change in forestry has a wide range of interpretations and applications. This review finds that CSF remains loosely defined and inconsistently applied. Adding further confusion, it remains unclear how existing guidance on sustainable forest management (SFM) is relevant or might be enhanced to include CSF principles, including those that strive for demonstrable carbon benefits in terms of sequestration and storage. To contribute to a useful and shared understanding of CSF, this paper (1) assesses current definitions and framing of CSF, (2) explores CSF gaps and potential risks, (3) presents a new definition of CSF to expand and clarify CSF, and (4) explores sources of CSF evidence.

Introduction

For many millennia, forests have provided sustenance, materials, ecosystem services, and cultural values to human societies, who in turn have advanced various interventions to support these values. The long-standing roles of forests as providers are well documented [1–3]. Also documented is wide variation of culturally acceptable tradeoffs in protection, management, and material use of forests [4–6].

Climate change is presenting a global challenge to society and the forested ecosystems society relies on. This climate crisis, arising because of land use change and emissions from production and fossil fuels burning of, changing long-standing forest valuation to include climate mitigation and adaptation, alongside traditional forest products and services. In turn, forests have received scholarly recognition as a so-called "Natural Climate Solution" (NCS) or "Nature-Based Solution" (NBS), meaning society can address climate change through forestry

by reducing emissions from forest loss or by removing atmospheric greenhouse gases via photosynthesis and sequestration [7]. Previous NCS assessments have considered the potential of various land cover and management approaches in terms of opportunity scale (e.g., sequestration of million metric tons of CO_2e) and the costs of implementation. Assessments at international [7] and national levels [8, 9] point to currently- or potentially-forested lands as the dominant opportunity for nature-based climate change mitigation strategies.

Policy makers at various scales, from nation states to local governments, are considering and advancing forest and climate policies with broad implications for society and the environment. Forests have become increasingly important in international climate change dialogue, as seen in the Warsaw Agreement [10, 11], Paris Agreement [10, 12] and the recent COP26 Glasgow Leaders' Declaration on Forests and Land Use, which pledges to end and reverse deforestation by 2030 [13], and continued dialogue in COP27 on the role of market mechanisms to link emitters with forest nations via Article 6 [14]. These efforts are 'next steps' to the Kyoto Protocol and Clean Development Mechanism (CDM) [15]. These examples include Reducing Emissions from Deforestation and Degradation (REDD) investments and substantial international investments to measure, monitor, and promote change in global forest trends [16, 17].

In another context, various regulatory and voluntary markets using forest-based carbon credits have been initiated (e.g., European Union Emissions Trading System [18]), sputtered (e.g., Chicago Climate Exchange [19]), or gained traction (e.g., voluntary markets [20]) in the last two decades. Critiques of market-based activities are that they permit continued pollution [21], outsource mitigation activities, and are capitalistic measurement-intensive interventions. Some scholars [22] have further asserted that such attributes benefit only certain program participants, and that they are often the same actors responsible for global emissions. Regardless, forest carbon projects and innovative incentive programming continue to operate and grow, pointing to an increasing acceptance of mechanisms to finance GHG benefits of trees and forests.

The new emphasis on forest-based NCS has a wide range of interpretations and applications. Such divergent interpretations of forest connections with climate change adaptation and/or mitigation can conflict with one another and have already done so. For example, scholarly work has captured tensions between conservation versus utilization [23], issues with carbon commodification [24], and assertions that carbon credits are a form of 'greenwashing' [21]. Further, it brings an increasingly large assembly of policymakers, program designers, natural resource professionals, land managers, and private sector actors interested in developing, selling, buying, and assessing forest carbon credits. Attention to NCS in political, scholarly, public, and private sectors has dramatically altered forest management and sustainability framing in recent years, reshaping a long-standing dialogue about our relationship with trees and forests.

With a diversity of considerations, myriad actors are embracing a phrase that intends to capture a connection between forests, society, and climate: Climate-Smart Forestry (CSF). However, specific definitions for CSF vary widely, with some emphasizing sustainability [25] or economics [26], and others highlighting landscape carbon reserves [27] (see S1 Table for specific examples). As such, CSF is seemingly being applied to a wide swath of activities and interpreted uniquely by each audience, landowner type, and practice.

Considering the complexity of climate change and human relationships with forests, this paper questions whether the term CSF is adequately defined and if some CSF interpretations present new risks to the environment, society, and climate. This paper also seeks to enhance the emerging scholarly discussion on whether forest management can be sustainable without being 'climate smart' and if other forestry activities, including avoided conversion and restoration, are adequately recognized under the umbrella of CSF. To assess, we explore how different

actors are included or excluded in current CSF definitions and consider how other values for forests (e.g., biodiversity) relate to so-called 'climate-smart' outcomes.

To contribute to a useful and shared understanding of CSF, the authors have undertaken a literature review, qualitative assessment of documents, and statistical analysis of datasets from related studies. The results are presented in this paper, which (1) assesses current definitions and framing of CSF, (2) explores CSF gaps and potential risks, (3) presents a new definition of CSF to broaden intervention types and engage multiple scales of decision-makers, and (4) explores sources of evidence of CSF.

Current definitions and ideas in CSF, and their linkage to SFM

Use of the term CSF is rapidly increasing in usage in recent years and other examples can be seen across wide-ranging disciplines, from academia [28] to applied practice by policymakers [29–31], planners and builders [26], conservation NGOs [27], and certification body standards ([32]; see S1 Table for these examples and others). This section assesses current definitions of CSF (e.g., interpretations, applications, and principles) as found in current scientific reporting and literature, policymaking, and mainstream media.

Within academic literature, CSF has a range of definitions (see S2 Table). Consider that Web of Science searches for "carbon + forests" returned 132,532 results, "carbon + climate + forests" had 50,697 results, and "carbon + climate + forests + mitigation" returned 17,595 results. In contrast, as of January 2022, "Climate-Smart Forestry" returned just 18 results via Web of Science and Science Direct. Thus, despite a great body of scholarly work on topics intersecting carbon, forests, and climate, the term CSF is relatively new and has been minimally adopted and explored in scientific literature. Further demonstrating the limited scope, no CSF results are earlier than 2017, nearly all are European-focused (15 focused on Europe, 1 in sub-Saharan Africa, and 1 in the Pacific Northwest of the United States), and most pertain to industrial forest management (see, for example, [33])

One recent definition, [25, p 2] defines CSF with the following principles:

1. Increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services,
2. Enhancing human health and community resilience through adaptive forest management, and
3. Using wood resources sustainably to substitute for non-renewable, carbon-intensive materials.

With the word 'sustainable' explicit or implicit in most CSF applications, it is relevant to consider previous ideas about sustainable forestry, particularly Sustainable Forest Management (SFM). SFM is an approach, closely linked with the notion of 'sustainable development', that has been a central focus of forestry research since the 1980s and is well documented in scientific literature [34]. SFM has an emphasis on productive forest landscapes, or 'working' forests, thus denoting 'sustainable' in terms of sustained production and the ability to meet the needs of society now and into the future (see S3 Table for definitions relevant to this paper).

In recent years, while additional forest values (e.g., habitat provisioning) have received new emphasis in SFM [35], SFM still largely reflects industrialized, development-oriented framing. Scholars have critiqued SFM for not adequately encompassing socio-cultural values [35] and political ecologists have noted that industrial forestry generally includes utilitarian tactics that favor economic production above other values [36, 37]. Moreover, forestry, as a science, is dominated by ideas developed for and practiced in temperate forest ecosystems, with a focus

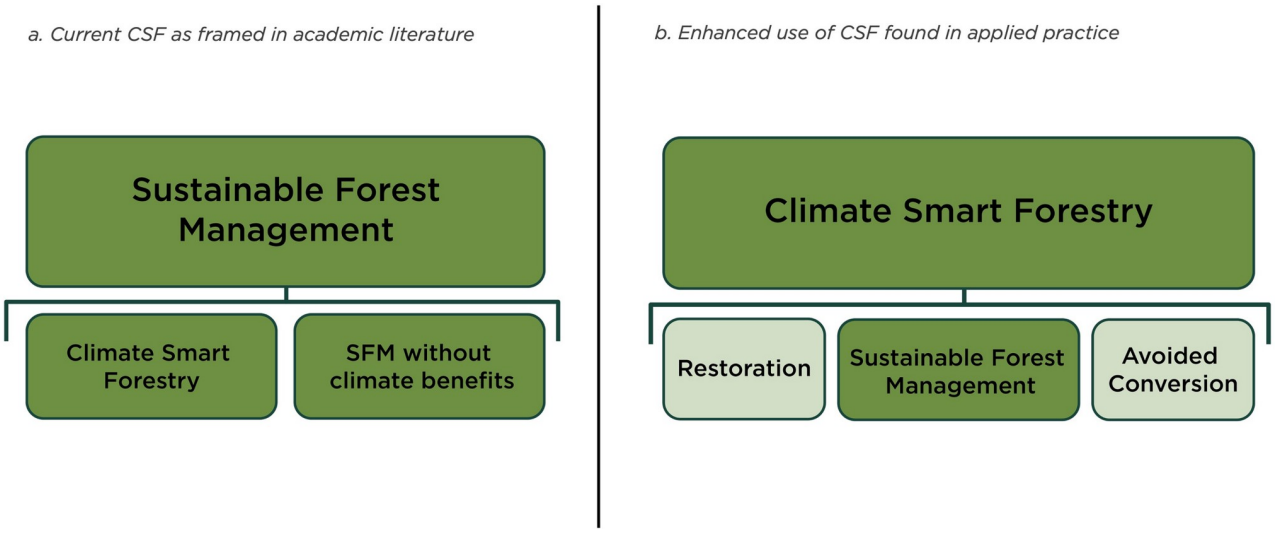

Fig 1. CSF theory examples in literature (a) and in applied practice (b).

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on timber over non-timber products [37]. Still, compared with conventional forest management, SFM is considered more interdisciplinary, inclusive, "less hierarchical", and more "socially accountable" [34, p 205].

Linking CSF and SFM, [28] suggest that CSF is a subset of SFM (Fig 1A), asserting that SFM can be advanced with climate considerations and that the resulting CSF is appropriate on myriad forested landscapes and use types. In their definition, CSF explicitly includes ecosystem services and acknowledges that climate change threatens production which would have previously been assumed under SFM practices alone, acknowledging that previous assurances may no longer be sufficient to ensure long-term outputs (e.g., due to drought or major disturbance). However, this definition implies that SFM can still be accomplished without climate benefits (Fig 1A) and overlooks forests or potentially forested lands that are not managed for productivity. Under an SFM framing (Fig 1A), CSF might be considered as an optional component of SFM. In contrast to *Current* CSF framing described here, this article introduces the *Enhanced* CSF framework (Fig 1B), where SFM is considered just one element of the forest-climate decision portfolio and is explored in more detail later in this paper.

Gaps and potential risks in current CSF

This section explores potential gaps and risks under a current framing of CSF that focuses only on forests managed for production by exploring 'science-practice gaps' and various risks to *Current* CSF framing. It addresses considerations for actors or actions represented in CSF manifestations and considers how bringing in underrepresented values for forests, like biodiversity preservation, or engaging rural communities could improve so-called 'climate-smart' outcomes.

Science–Practice gaps

Use of CSF and related terms, such as *Climate-Smart Forest Economy* [38] or *Climate-Smart Forest Products* [39], are emerging and seemingly rely on an assumption that CSF has been adequately defined and is well understood. This leads to the term being adopted and used colloquially, without critical examination and robust scientific rationale, constituting a 'science-practice gap'. Science, Technology, and Society (STS) scholars have undertaken work in

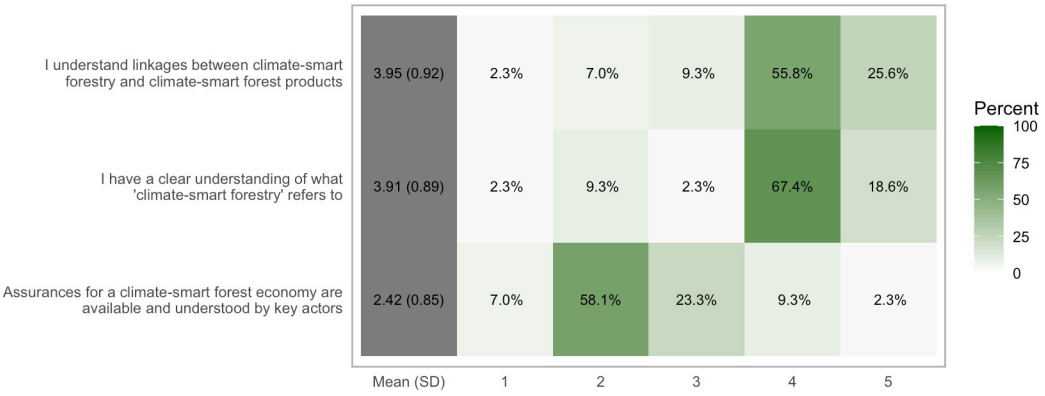

Fig 2. Survey responses from forest, forest product, conservation, and economic development organization professionals. Level of agreement: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral or I don't know, 4 = Agree, and 5 = Strongly Agree.

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myriad disciplines on such applied and data-driven science research-implementation gaps [40] or knowledge-action gaps [41]. With CSF, these manifest as challenges in interpreting and applying forestry (e.g., growth, carbon, biodiversity, health) and climate (e.g., forest-climate interactions) *sciences* to the *practice* and on-the-ground decision-making of CSF.

To explore perceptions of CSF, consider results from a recent survey distributed to a network of diverse professionals (based largely in North America and Europe) that are affiliated with or in the network of the Climate-Smart Forest Economy Program [42]. These professionals represent organizations that cross forestry, conservation, economic development, sustainability, building and construction. The survey assessed their understanding of CSF definitions and potential assurances for positive outcomes (Fig 2). When asked level of agreement with the statement "*I have a clear understanding of what CSF refers to*", 84% of respondents (n = 44) responded Agree or Strongly Agree. They demonstrated a similar level of agreement (81% responded Agree or Strongly Agree) with "*I understand linkages between CSF and climate-smart forest products*". However, only 26% of those participants agreed that *"Assurances for a climate-smart forest economy are available and understood by actors"*. These results show that the sampled professionals perceived an individual understanding but acknowledged a limited ability to provide adequate assurances to achieve CSF outcomes.

A different dataset derived from pre-course survey responses (n = 178) from domestic and international professionals participating in a United States university-level forest carbon training short course from 2019 to 2021 [43] presents further evidence (Fig 3). In this survey, 94% Agree or Strongly Agree that *"Forest carbon is becoming increasingly important in my profession"* (70% responding Strongly Agree). Interestingly, only 28% Agree or Strongly Agree with *"There is adequate knowledge of forest carbon amongst my colleagues"*. Note that 80% responded Strongly Agree that "*A better understanding of forest carbon will improve policy development and implementation"*. Despite this level of Agreement, decision-maker needs may not be clearly reflected in research and resulting material due to inadequate translation.

These data (Figs 2 and 3) can be interpreted as evidence of a 'science-practice gap' in CSF, by demonstrating gaps in forest carbon knowledge and CSF definitions, linkages, and assurances. This is not unique to CSF; STS scholars have found that "two-way knowledge flow between science and practice through joint knowledge-production/integration processes" is rare [40, p 93]. Considering the ongoing climate crisis coupled with the scale of investments in forest-based NCS, there is a pressing need for two-way knowledge flow to enhance science-

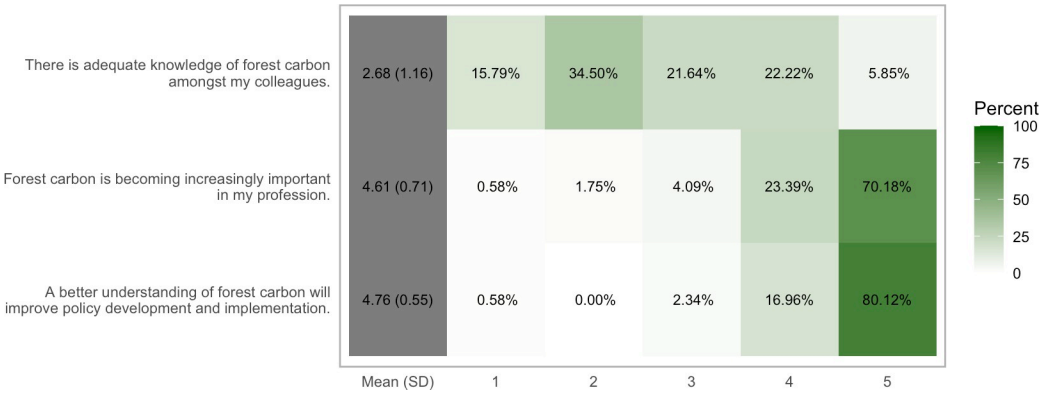

Fig 3. Data 2018–2021 pre-course participant questionnaire for understanding forest carbon management, MSU forest carbon and climate program. Level of agreement: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral or I don't know, 4 = Agree, and 5 = Strongly Agree.

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based CSF framing, metrics, and assessment. To overcome this and to ensure research is not overlooked by practitioners, [41, p 671] recommend making CSF research language:

1. Salient (relevant to decision-makers and readily accessible)
2. Credible (trustworthy, reliable, and sufficiently authoritative) and
3. Legitimate to both scientists and decision makers (developed via inclusive processes)

Risks of current CSF framing

This section explores a range of risks in *Current* CSF framing including (i) overly simplified relationships between carbon sequestration and forest management, (ii) emphasis on above-ground tree volume as forest carbon stocks, (iii) 'carbonization' of forest values, (iv) unintended social effects and unequal benefit distribution, (v) misinterpreting climate effects, and (vi) overlooking efficiency gains and economic misalignments.

Overly simplified relationships between carbon sequestration and forest management. Forest carbon storage is the outcome of complex, ecological processes. Oversimplifying carbon dynamics risks inadequately valuing late succession, primary, and/or old growth forests because of the misconception that sequestration diminishes rapidly or ceases altogether past the optimal harvest year, despite evidence that older trees and forests continue to sequester carbon at high rates well past this point [44, 45]. In fact, [44] uses the term 'financially mature' as a notable distinction from a presumably different biophysical threshold for reaching maturity (e.g., a substantial slowdown in annual growth), which may be over a hundred years later.

Forest management and public policy can strongly influence the sequestration process and some forestry systems may even emit carbon for a variety of reasons [46, 47]. While sequestration rates are generally higher in younger forests with more vigorous trees, old forests (of the same type), with larger trees, can have vastly more stored carbon. This has long generated debate within the scientific community in terms of resulted in a perceived tradeoff between maintaining carbon in older forests, with potentially declining sequestration, and conversion to younger forests, with potentially higher carbon sequestration rates [48–50].

As such, *Current* CSF literature framing may be appropriate for commercial forests but can leave out other important strategies linking forests and climate, such as avoiding deforestation or preventing reductions in forest complexity (e.g., biodiversity loss associated with conversions to monoculture plantations) [51]. Furthermore, many forests do not require

management to help them remain healthy and in a state of net carbon sequestration or long-term storage. In fact, many forest health problems today have been caused or made worse by human interference. Examples include fire suppression [52], disease in monoculture [53], and invasive species expansion post-harvest [54].

Management activities that disturb the forest result in biogenic carbon emissions [55]; nearby trees damaged during management may die, the disturbed litter pool increases decomposition, trees are felled for skid roads, equipment can cause deep soil ruts and loss of stored soil carbon, and there is a reduction of woody material being transferred to litter and dead material pools. Studies [56, 57] have estimated management-related losses of 30 ± 6% in forest floor carbon of temperate forests depending on species composition (among other factors). While wood products provide important biomaterials, scaling up production management in forests with currently low-impact or no management would result in immediate and near-term, and possibly long-term, losses to stored ecosystem carbon [56, 58]. This lower carbon persists for at least decades [59] and can contribute to a shifting-baseline syndrome, wherein the 'baseline' forest carbon levels used for reference are already much lower than historical conditions [60].

Losing large trees can have especially negative climate implications. Researchers have found that large-diameter trees "store disproportionally massive amounts of carbon and are a major driver of carbon cycle dynamics in forests worldwide" [61, p 1]. This study, using forest inventory data from over 3,300 plots to assess the role of large diameter trees (greater than 53 cm, diameter at breast height), found that such trees stored 42% of total aboveground carbon despite accounting for only 3% of trees in the inventory [61].

Emphasis on aboveground tree volume as forest carbon stocks. There are also multiple, distinct challenges with forest carbon measurement, particularly as they relate to *Current* CSF initiatives (e.g., forest carbon projects). One issue is that most forest carbon inventories focus on aboveground biomass as the principal data for measurement, reporting, and verification (MRV) of forest carbon stocks. It is convenient that inventories of forest merchantable stem volume can be correlated with forest carbon stocks, because this greatly increases data availability for estimating carbon sequestration through biomass expansion factor approaches (such systems have been employed in both the U.S. and Canadian national forest inventories; [62, 63]). However, such forest carbon estimates can be biased towards carbon in tree boles [64] and can minimize or leave out carbon pool estimates in other parts of the trees and forests, leading to bias in model predictions (e.g., tree crowns, see [65]).

One major issue is the use of forest volume inventories or timber yield curves as proxies for forest carbon accumulation; this has implications for how forests are measured in terms of understanding and pursuing carbon benefits. Forest carbon storage dynamics are more complex than timber growth and yield curves imply [61, 66]. Timber yield is often maximized in monospecific plantations, but studies have found that multi-species forests store more carbon overall, maintain high sequestration rates over time (avoiding boom/bust cycle), and store more carbon across other pools [67, 68]. Framing forest carbon dynamics in terms of timber growth and yield curves may give the false impression that plantation-style forests are ideal for carbon sequestration rates, but with underperforming results for net climate benefit. Consider that trees spend the first portion of their lives in lower productivity [67], so harvesting can return a stand to a very low period of productivity. On the other end of the life spectrum, forest trees accumulate high rates of carbon at later lifetime stages as, for example, an estimated 70–80% accumulated after tropical trees reach 70 years [69].

Constraints to measuring carbon in other pools (e.g., soil, litter, downed wood, belowground) is a significant barrier [70]. For example, only up to 50% of total tropical forest carbon is found in aboveground, living pools [56]. Forest soil carbon and root biomass are much

more difficult to quantify and remain a challenge in forest carbon measurements [71]. Some forest ecosystems have most of their carbon stored belowground; notably mangrove forests, which have been shown to have some of the highest carbon stores of any ecosystem worldwide [72, 73]. Aboveground carbon sequestration rates may be greater in highly productive plantation systems, but they may have lower total carbon storage than alternative forestry systems with lower above-ground sequestration rates (e.g., analog forestry systems versus teak plantations, see [68]). Another major challenge in forest carbon inventory comes from assumptions related to, or simply lack of data on, dead tree carbon stocks [74] and decay rates of dead material [71, 75].

Emerging science aims to better link other methods (e.g., remote sensing and tracking of fluxes through eddy covariance towers) that can enhance measurements and may be more appropriate in some cases and in other forest types [76]. Until such rates are quantified well, it will be difficult to determine more precisely the balance between carbon capture and emissions under different forest management scenarios.

'Carbonization' of forest values over resilience and biodiversit. Overemphasizing atmospheric carbon sequestration at the expense of other forest values has been called 'carbonization' of forest governance [77]. If CSF places a majority emphasis on carbon sequestration to mitigate climate change, there may be inadequate emphasis on adaptive mitigation strategies to ensure forests can respond to future climate trajectories. This may result in oversight of the peak ecological function necessary for forest resilience [78, 79]. While the CSF definition presented earlier [25]) includes 'adaptation', emphasis is largely placed on maintaining productivity and carbon storage levels.

Given the global biodiversity crisis co-occurring with the climate crisis, prioritizing carbon over biodiversity may have severe near and long-term consequences [80, 81]. Without a heavy emphasis on biodiversity in resilience, CSF can leave out the growing consensus around a need for diverse forests and to protect species richness. Notions of CSF currently do not appear to account for climate change effects on both floral and faunal diversity or intra-species genetic diversity [78, 82, 83]. Tree species diversity itself is centrally important in adaptation to maintain carbon stocks into the future [70].

Scholarly work has considered different management strategies that link carbon and biodiversity outcomes (see [84]). While some studies show clear linkages between increased carbon and biodiversity co-benefits, for example in tropical forest restoration [85], other studies point to key species benefits when aboveground carbon is lower. As an example, the Kirtland warbler in Michigan, USA jack pine (*Pinus banksiana*) forests, requires early succession habitat to thrive [86]. Other species require dense undisturbed or late succession forests, including many which we have more limited understanding (e.g., fungi, insects) of their unique roles in contributing to overall ecosystem function and resilience.

Researchers are finding carbon-focused conservation has limitations, as pursuing high carbon storage and habitat for specific species (e.g., birds or primates, see [87]) can still overlook overall biodiverse complexity [88]. This carries a risk for forests globally, as studies point to extended recovery times of species composition following a disturbance. For example, [87] showed that species requiring mature forests can still be absent from secondary forests 100 years later. The latter study goes on to assert that our understanding of secondary forest recovery is so limited it invalidates "any reliance upon the value of secondary forest for future conservation of tropical forest biodiversity" [87, p 28]. These results highlight risks of contributing to extinction for mature-forest dependent species by promoting management intensification in pursuit of higher sequestration rates, particularly with confounding stresses from a changing climate and the limited extent that mature forests have today.

Considering there is not a clear (e.g., linear) relation between carbon and biodiversity across different forest types [89], there is a pressing need to frame and assess biodiversity within CSF.

Unintended societal effects and unequal benefit distribution. CSF at scale implies substantial shifts in material use, investments, economics, and policies affecting land management, which will have wide-ranging societal impacts and creates the potential for unintended negative effects. *Current* CSF tends to emphasize large-scale opportunities, potentially overlooking smaller scale interventions (e.g., tree planting efforts, see [90]). Under a narrow framing of *Current* CSF, well-positioned beneficiaries (e.g., global investors and private companies) may stand to gain, while small landowners and Indigenous communities remain overlooked or even negatively affected by increasing pressure (e.g., timber production) or shifting values (e.g., monoculture) [21, 91]. Focusing mainly on commercially productive forests leaves out many potential actors or could create perverse incentives to develop more productive forests.

Moreover, *Current* CSF has a focus on complex, technical carbon stock measurements, which creates barriers for actors without training or sufficient resources to engage in complicated schemes [92–94]. Traditional ecological knowledge and cultural values may not be adequately embraced [95], and communities and rural actors likely perceive tradeoffs between livelihoods and biodiversity very differently than in industrialized outlooks [22, 96]. Because of this, not all such peoples are interested in advancing production-oriented forest management as defined in *Current* CSF framing. Despite optimistic views of far-reaching benefits for all [97], industry, investors, and governments are more likely to benefit as sophisticated participants and proponents of complex carbon schemes and global markets, an example of elite capture [21, 98].

The case of Indigenous people highlights how narrowly framed CSF risks overlooking best practices in justice and inclusion, by supporting entrenched systems of extraction, exploitation, and inequity. Roughly 1.5 billion Indigenous and rural peoples depend on forests for food and livelihoods, occupying approximately 28% of global land [81] and nearly 20% of global forests, with either formal or informal tenure rights [99]. Forests cover more than 80 percent of indigenous land area, totaling over 330 million hectares [100] of some of the most ecologically important, carbon rich biodiversity hotspots on Earth [81, 101]. Of these, 173 million hectares are considered "intact forests" meaning they have had little to no human modifications in the last 60–80 years [81]. Recent decades have seen an increased focus on indigenous and rural rights in relation to conservation and climate mitigation [91], which can be leveraged to reduce risk of CSF oversight.

The challenge of engaging rural landowners in CSF can be exemplified in data from a 2019 survey issued to farmland owners with over 100 years of consecutive ownership in the Kalamazoo River watershed in Michigan, USA (n = 116). Farm owners were asked questions about their land and if it could be leveraged to contribute to climate solutions (e.g., afforestation or forest restocking). The results were notable; 54% reported having marginal land (654 acres total) and 73% reported having fallow land (410 acres total) (Fig 4). Put together, this points to at least 1000 acres in one watershed, across 110 properties, as having potential for restoration with climate benefits. However, when participants shared their level of agreement with the statement "*Climate change influences my land management decisions*", only 16% responded Agree or Strongly Agree. Contrarily, 57% responded Agree or Strongly Agree with *"Environmental stewardship and beliefs influence my land management decisions"*. Finally, when asked level of agreement with the statement "*I would like to learn how my land can provide carbon sequestration*" the majority (41%) responded Neither Agree nor Disagree, indicating either disinterest or uncertainty. These data suggest that many rural landowners may not be ready to engage in or prioritize forest carbon but would be amenable to CSF activities framed as "environmental stewardship" or another culturally relevant term or phrase.

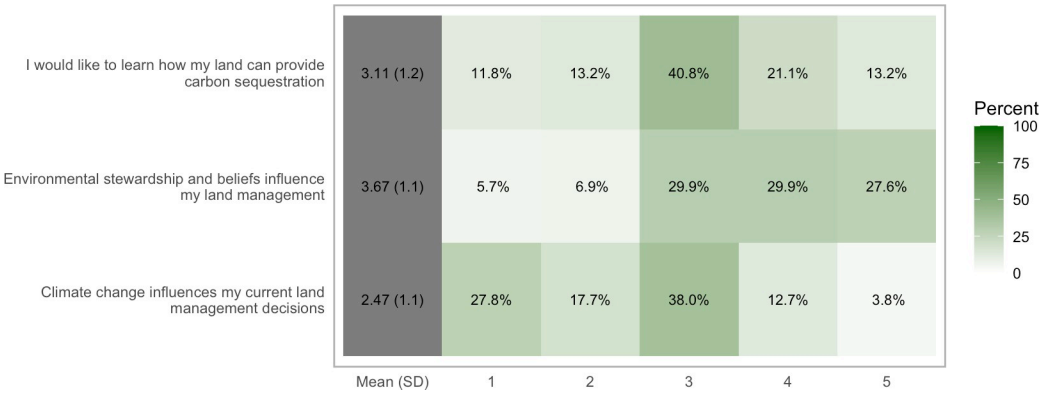

Fig 4. Survey response data by Michigan Kalamazoo watershed farmland owners (2019). Level of agreement: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral or I don't know, 4 = Agree, and 5 = Strongly Agree.

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Misinterpreting forest ecosystem management and climate effects. The emphasis on carbon sequestration as the dominant indicator of *Current* CSF brings in many potential misinterpretations in (1) non-carbon forest interactions with climate, (2) fossil fuel use in forestry operations and transportation, and (3) long-term and end-of-life carbon storage.

Non-carbon forest interactions with climate

Forest-climate effects are an area of active research and cannot be calculated from only biogenic carbon sequestration and emissions estimates. While the correlation between atmospheric CO_2 and global climate change is well documented [102], this does not fully explain forests' role in global temperature regulation. Forests generally have lower surface albedo (energy reflectance) and higher evapotranspiration (ET) compared to open land and non-tree vegetation due to the dark shade of the foliage. This reduced albedo can increase local warming, but this warming can be offset by increased ET. The precise connection is correlated with latitude; magnitudes and even effect direction on climate varies among tropical, temperate, and boreal forests [103]. These interactions complicate the carbon estimations, as recent research has found increased absorption of solar radiation creates localized warming that can outstrip the benefit of calculable increased carbon storage, for example by warming soil and increasing decomposition and release of soil carbon [104]. Because of these dynamics, climate benefits (e.g., local temperature, increased carbon storage) of interventions may have different effects based on forest type and geographic location. One study in Norway found net climate *warming* from increasing extent and quantity of high latitude mountain birch forests, even when considering the climate benefit of the additional stored carbon [105]. Comparatively, [106] explored temperature regulation and drought feedbacks ('savannization') in the Amazon basin linked to degradation, which points to prioritizing tropical forest protection over other forest-climate strategies.

Fossil fuel use in forestry operations and transportation

Fossil fuel use in forestry also undermines climate benefits calculated as part of harvested wood products (HWPs) in CSF. An established science, estimating carbon stored in HWPs requires robust life cycle analyses, including GHG emissions from production and shipping. A 2010 study estimated total yearly global emissions, considering both management and transport, to be 88.1 million metric tons CO_2e. Management-related emissions (36.9 million metric tons CO_2e) includes productivity interventions such as thinning as well as harvesting activities. Total transport-related forestry emissions were estimated to be over 50 million metric tons of CO_2e annually, with nearly 60 percent of these emissions associated with international trade [107]. Beyond this, fossil fuels are used in nearly all in-forest management activities including

thinning, harvest, and hauling to mills, suggesting a need for CSF strategies that reduce carbon emissions associated with forest management.

Long-term and end-of-life carbon storage

Materials from sustainably managed forests, or with low-intensity management, provide society with essential goods and have an important role in CSF. Carbon in wood products is estimated as stored carbon (based on wood density and carbon ratio estimates), embodied carbon (overall emissions using life-cycle analysis), and substitution effect (net benefit from replacing a more emissions-intensive material). Carbon in HWPs is stored if the material remains in its physical form. Buildings, furnishings, and infrastructure across the built environment hold carbon for the longest time when compared to other wood products.

Wood products are second only to concrete in US annual waste material production, producing 40.8 million tons of waste in 2018 [108]. At end of life, wood products are typically incinerated or landfilled. Once in landfills, HWPs release gas (approximately half methane, CH_4, and half CO_2 by volume) from decomposition of degradable organic carbon unless in strictly anaerobic conditions [107, 109]. To estimate stored carbon eventually reentering the atmosphere, IPCC provides a default value of 0.5 (50%) [110]; note that site-specific studies have reported much lower estimates (e.g., 0–3% in US landfills, [111]). However, conditions in anaerobic landfills vary globally, particularly as open dumps and incineration are still common waste management strategies in developing countries. Even in developed nations, CO_2 and CH_4 emissions from landfills are substantial (e.g., roughly 2% of annual GHG emissions in Europe) and undermine the carbon storage of HWPs in landfills [112]. Because of this, the HWP duration of use and end-of-life of need to be considered in CSF.

Overlooking efficiency gains and economic misalignments

Inefficiencies in harvesting, processing, and material transport can undercut climate benefits of CSF and reduce landscape carbon storage. The modern globalized economy creates new opportunities, as well as concerns, for timber and agroforestry commodities about large scale and rapid impacts on forested landscapes [113]. Global trade is rife with inefficiency and international trade has been linked to higher increased GHG emissions [114]; transporting materials globally that could be produced and used locally is a major source of emissions [81].

To pursue climate benefits under CSF, there are ample opportunities to alter traditional economic flows of goods and materials to better value and emphasize waste reduction and material re-use, extend residence time of forest-based material in circulation, and incentivize innovative carbon storage and HWP production in landscapes outside of traditional forest management (e.g., abandoned urban and peri-urban areas). Recycling and waste product utilization can also help meet demands of scaled applications (e.g., bioenergy, mass timber).

Data from the US EPA ([108]; see Table 1) estimated that only 17% of US wood (3.1 of 18.09 million tons) was re-used and recycled and 67% (12.15 million tons) ended up in a landfill in 2018. Note that such recycling is almost entirely from chipping wood used in transport and packaging (e.g., pallets), but it is unclear if the chips are re-used in new materials or go towards emissions (e.g., via decomposition or burning). Recycling of durable wood products (6.51 million tons of waste generated in 2018) remains "negligible" [108].

Table 1. 2018 US wood material data with estimated equivalent forest acreage (EPA 2020).

US estimate (2018)	Amount
Wood material produced (million tons)	18.09
Wood material landfilled (million tons)	12.15
Wood material recycled (million tons)	3.1
Approximate equivalent forest extent (estimating 100 tons per acre)	121,500 acres (49,169 hectares)

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Table 2. Estimate of avoided emissions with MSU campus wood material diversion program (in metric tons CO_2).

	Without MSU SWRI	With MSU SWRI
Biomass removed from campus	146.09	146.09
Biomass–Diverted to SWRI	0.00	- 68.66
Net biomass removed from campus	146.09	77.43
Emissions—Processing mulch	0.52	0.28
Emissions—IPF tree removal vehicles	27.17	27.17
Emissions—SWRI step truck	0.00	6.28
Emissions—SWRI sawmill	0.00	0.47
Emissions—SWRI wood lab	0.00	12.00
Total emissions	173.78	123.63
Total avoided emissions	0.00	**50.15**

https://doi.org/10.1371/journal.pclm.0000212.t002

Consider a hypothetical scenario to grasp the scale of this material (Table 1). Assuming an average US southeast softwood clear-cut produces 100 tons of wood material per acre (40.5 tons per hectare), one could estimate annual wood landfilled as equivalent to harvest of 121,500 acres (49,169 hectares) of such a forest. These figures demonstrate how wood in use now could support CSF by providing substantial source material that can minimize forest pressure in the case of increased demand for 'climate-smart' wood products.

A 2020 study from the Michigan State University campus assessed the carbon benefits of a wood material diversion (sustainable wood recovery initiative, or SWRI) program that uses trees felled on campus to create artisanal wood products (e.g., furniture and housewares) [115]. The analysis found that between 2015 and 2017, MSU SWRI reduced net CO_2 emissions from the MSU campus urban wood system by approximately 28.9%, diverting 68.66 metric tons of CO_2e in logs and securing 28.42 metric tons of CO_2e in final wood products, with 40.24 metric tons of CO_2e remained in storage. Without this intervention, removal of campus trees would have resulted in emissions of 173.78 metric tons of CO_2, whereas with the MSU SWRI, the system emitted 123.63 metric tons of CO_2, equating to total avoided emissions of approximately 50.15 metric tons CO_2 (see Table 2). While fossil fuel emissions from chipping diminished, overall energy used for processing increased, including a net increase in fossil fuel use. Despite some campus solar, energy is largely from natural gas, diesel, and gasoline, which reflect net additive emissions distinct from the biogenic carbon cycle stored in the wood.

While this case demonstrates the added value of storing biogenic carbon longer, the use of fossil fuels contributes a net increase in atmospheric carbon from pre-industrial times. Soon, it will be necessary to eliminate fossil fuels from a 'climate-smart' forest product system to improve the comparative scenarios of wood use.

Expanding and clarifying CSF

Enhanced CSF framework. This analysis finds there is ample opportunity to broaden the concept of CSF to a spectrum of activities currently underrepresented that will increase climate benefits as well as social and environmental co-benefits. Adding to [25] three pillars (see *Current definitions and ideas in CSF* above), a broader definition could explicitly include additional landscapes, forest types, and interventions with climate benefits. Here, we propose the following additions as two new pillars to create an '*Enhanced*' CSF definition:

4) Protecting natural places by avoiding loss of forests, intact forests, forest complexity, biodiversity, or connectivity, or conversion to higher management intensity;

5) Promote restoration of degraded landscapes, improved ecosystem function, and connectivity (e.g., through corridors)

To better understand the distinction between *Current* and *Enhanced* CSF framing, Fig 5 distinguishes activities that dominate *Current* CSF (dark green) from those on either end of the forest condition and type spectrum that are not adequately represented (light green). These *Enhanced* columns capture the new pillars presented above. Further, the left column, *Phases*, reflects assessment and implementation phases that have not yet been clearly defined for CSF. Phases 1–4 reflect those could be considered generally present in *Current* CSF framing. The addition of a new Phase 5 captures broader assessment and impacts of *Enhanced* CSF

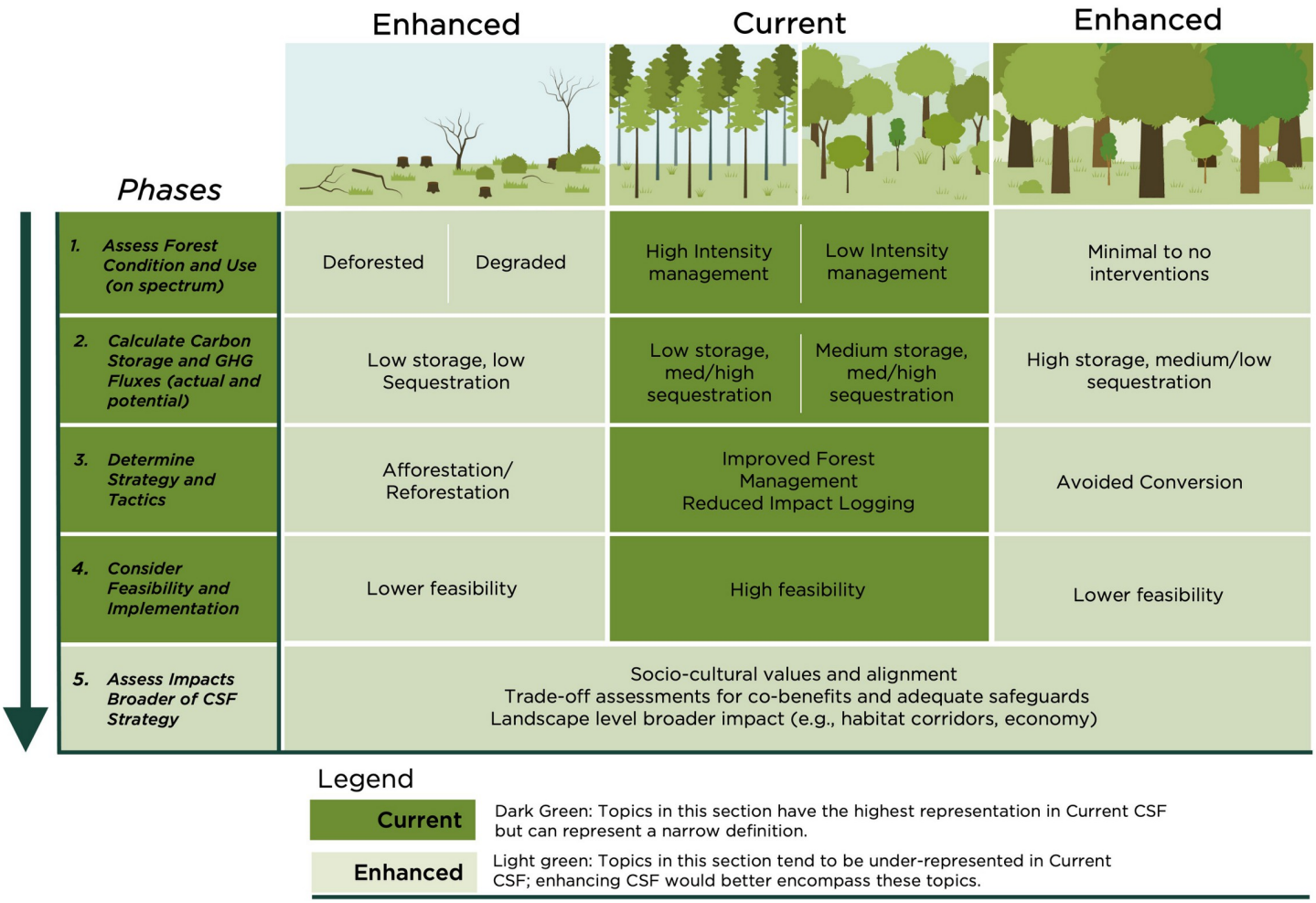

Fig 5. Planning and implementation phases of both *Current* CSF and proposed *Enhanced* CSF frameworks. This figure shows conceptual planning and implementation Phases (numbered 1–5) of both *Current* CSF and the *Enhanced* CSF proposed in this paper. The dark green center column indicates common features of *Current* CSF, particularly reflecting the emphasis on productive and managed forests in Improved Forest Management carbon projects. In Phase 1, *Enhanced* CSF, the light green columns on the right and left, encompass a broader spectrum of potential CSF landscapes from deforested or degraded (right, light green column) to minimal intervention, remote areas (left, light green column) than is seen in *Current* CSF alone (center, dark green column). After the landscape is assessed, GHG benefit (e.g., carbon storage and sequestration) is analyzed in Phase 2. Phase 3 includes a strategy assessment to achieve climate benefit, with tactics including reforestation and restoration (left, light green column), improved forest management (center, dark green column), and protection (right, light green column). Phase 4 captures feasibility challenges (e.g., finance, social license, additionality) that may be associated with each tactic; reflecting the high feasibility of *Current* CSF and the feasibility challenges facing *Enhanced* CSF. Phase 5, with the entire row in light green indicating it is a part of *Enhanced* CSF, reflects the increasingly dominant themes of landscape and biodiversity planning, inclusion, safeguards, and forest products that explicitly to link multiple scales and disciplines of actors that can be absent from *Current* CSF.

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currently absent from many strategies. Note that Phase 5 is increasingly discussed in CSF-related dialogues (e.g., climate-smart forest economies or mass timber) and we propose should have a role in a broader CSF definition.

Enhanced CSF components. The following sections explore key components of the *Enhanced* CSF framework presented above by highlighting details of the proposed *Phases* (see Fig 5, first column, for phase names).

1. Assess current forest condition and use (on a spectrum). CSF science would benefit from additional linkages across the spectrum of forest conditions and climate benefits to include these land and forest classifications as additional starting points to assess potential for CSF solutions. The *Current* CSF framework focuses on carbon in productive forests, including in most domestic US forest carbon projects and major international investments from development banks [116, 117]. However, as this review shows, there is a range of landscapes that could be included and promoted in CSF, including degraded areas, savannas, trees outside of forests, and intact areas with limited or no human interventions currently (e.g., remote tropical or boreal forests). These cover types are underrepresented in *Current* CSF literature but are relevant under *Enhanced* CSF framing. This aligns with several examples of colloquial usage (see Table 2, [117]) and makes for direct connections to REDD+ and restoration activities that are proven to provide highly impactful climate and carbon storage benefits.

2. Calculate carbon storage and GHG fluxes (Actual and Potential). CSF interventions must consider actual and potential greenhouse gas fluxes when considering benefits of wood use and stored carbon. There is an emerging emphasis on sequestration rates over carbon storage, which, as this paper explores, presents a narrow understanding of climate benefits compared to, for example, considering long-term resilience of forests and other treed landscapes. These oversights could undermine any carbon storage or sequestration by way of large-scale disturbance or die-off. On the other hand, *Enhanced* CSF principles can augment traditional forestry metrics by identifying and promoting additional indicators (e.g., tree longevity and biomass residency time) as part of CSF analysis to appraise multiple forest types more appropriately. These additional data will make it more likely that actors can adequately assess higher storage, lower productivity forests [56, 118, 119], as well as bring attention to maintaining large and secure carbon pools in place now [58].

Moreover, some forest carbon projects leave out carbon pools and GHGs considered 'not significant' or too difficult to assess, though some of them are potentially immensely important (e.g., such as forested peat soils, see [120]). While it may not be possible to adequately measure them now, their inclusion, event with default values, can provide important insights to support decision-making. Further, if CSF intends to make claims about carbon in the HWP pool, these calculations must be data-driven to avoid overestimating substitution benefit [121, 122] or underestimating emissions in forestry practices.

3. Determine strategy and tactics. While SFM focuses on forests managed for productivity, *Enhanced* CSF encompasses additional decisions for forested and potentially forested landscapes. An emphasis solely on 'productive', 'managed', or 'working' forests overlooks other opportunities for optimal climate benefits, particularly when planning at a landscape scale. Based on GHG information from Phase 2, an optimal mix of tactics can be determined that may include afforestation or reforestation, improved forest management (a type of SFM common in temperate carbon projects that pursues adjustments to practices to increase carbon storage on the landscape and in products) or Reduced Impact Logging (RIL), Avoided conversion of forested lands (including changes that result in loss of biodiversity or key species), or a combination of these.

Considering momentum on forest carbon projects and jurisdictional approaches, these methods and strategies could be explicitly linked in *Enhanced* CSF framing. Such interventions

Table 3. Examples sources of low feasibility scenarios in *Current* CSF framing.

Type	Example
Opportunity costs	High land value for commodity production overrides finances available for forest protection
Additionality	An inability to prove additionality (e.g., in the case of communally held remote tropical forests)
Carbon	Lower estimated sequestration rates despite immense carbon pools, (e.g., mature tropical Amazon)
	Low carbon return and high initial implementation costs for a period (e.g., for afforestation or reforestation)
Scale	Small scale intervention on a 20-acre parcel

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are well-documented in methodologies (e.g., Verra [123]), and access to a wider range of solutions can avoid potential pitfalls such as overlooking unique value of old or late succession forests, inappropriately prioritizing trees over prairies, or promoting more intense or even commercial forest management in communal forests with no history or interest in that activity. Further, if HWPs are part of the CSF strategy mix, it is essential to pursue efficiency for optimal climate benefits. CSF strategies could include identifying cascading value for wood materials to increase emphasis on long-lived products, reuse, and recycling.

4. Consideration of feasibility and implementation. Forest carbon projects typically have a feasibility stage that includes assessment of carbon stocks and fluxes, carbon market access, technical capacity, governance and management, and financial considerations (e.g., opportunity, inventory, and monitoring costs). *Current* CSF, particularly efforts that alter production management regimes (Improved Forest Management, or IFM), are highly feasible and have become the dominant source of carbon credits. For example, in the United States around 50% of projects on the Verra registry [123] and 87% on California ARB [117] are IFM projects. On the other hand, activities can be considered lower feasibility for a range of reasons, including high value of alternative land uses (known as opportunity costs), an inability to prove additionality, lower estimated sequestration rates, and scale of intervention (e.g., smaller parcels) (see Table 3).

CSF should include considerations beyond implementation costs and additionality to create more inclusive incentive structures. Carbon schemes that require evidence of deforestation risk to claim additionality or offer low payments to rural actors to protect forests, can undervalue stored carbon. For example, a major Peruvian conservation program, National Program for the Conservation of Forests (PNCB in Spanish), pays Indigenous communities 10 soles—approximately 3USD—per hectare, even in areas of demonstrably high risk [124] and of well-documented high-biodiversity ecological value [125].

Inclusive CSF interventions could benefit more actors by being easy to understand and with low barriers to entry (e.g., cost and knowledge). Increasingly, programs that provide *Enhanced* CSF benefits are reaching additional actors with programs that are comprehensible and with reasonable requirements (e.g., short time commitments). The Peruvian PNCB, discussed previously, performs well in this aspect, requiring commitments of only 5 years and presents the program in a simpler framing (avoiding forest conversion) and avoids technical carbon knowledge. Similarly, the US-based Family Forest Carbon Program offers shorter timeframes when compared to traditional carbon projects and compensates landowners for undertaking and committing to specific practices, like removing invasive species or allowing their forests to increase in maturity [126].

Key aspects of feasibility are social dimensions, like governance, participation, and inclusion of grievance mechanisms. [127] pointed out that policies should focus on how to ensure meaningful participation of local users in developing forest management and protection plans

[128]. Considering the example programs above, these tactics are helping overcome social barriers and increase feasibility that will be essential to scale and incentivize robust and diverse CSF interventions.

5. Assess broader impacts of CSF strategy

Enhanced CSF does not occur only at the parcel level. Instead, parcel-level initiatives are considered as component tactics of strategies to produce optimum outcomes at a landscape scale. This requires considerations like balancing production with protection and connecting natural areas as a restoration strategy.

Considering how and where to distribute benefits efficiently and equitably will be the central challenge going forward if CSF-oriented climate finance continues to arrive in forests globally [129]. Tactics should include horizontal (lateral) and vertical (top down or bottom up) benefit distribution across actors from forest decision-makers to wood users in built environments [130].

Multiple levels of governance and incentives require integrated approaches to sustainable land use, which will underpin CSF implementation. Further, multiple scales of government reporting (e.g., national level commitments in UNFCCC Nationally Determined Contributions (NDCs), jurisdictional approaches by sub-national actors) indicate different levels of uncertainty and possibilities for interventions. There remain opportunities to improve linkages between carbon stocks with landscape scale planning and management, to ensure carbon pool levels are maintained. Because of the wide range of possible actors in *Enhanced* CSF, it is becoming increasingly imperative and yet difficult to merge and layer this information in ways that neither inflate nor overlook benefits; or push increased sequestration at the detriment of stored carbon, communities, or other ecosystem services or forest inhabitants. Finally, efforts should strengthen incorporation of social and environmental safeguards (limiting negative consequences) in CSF, including unique approaches to eliminating harm (e.g., biodiversity loss) and increasing co-benefits across scales like local or regional economies and watersheds.

Sources of evidence of CSF

As shown in this analysis, *Enhanced* CSF reflects a complex interdisciplinary realm, crossing guidance and metrics for carbon storage and sequestration, biodiversity, sustainability, governance, and development. Dialogue on CSF can include wide ranging expertise, from architects to foresters to development organizations. Currently, there are substantial limitations in assuring sustainability in global forest management and product use, and it is unclear if or how available assurances can adequately assess and communicate CSF principles in an efficient and robust manner [93]. Further, the range of actors and decision-makers engaging in CSF makes it challenging to work across existing frameworks to safeguard against negative consequences.

The determination of whether forestry is 'climate smart' is a multistage process; the phases described here (Fig 5) represent a conceptualization of that process. Stacking and layering CSF methods and assurances will be necessary to assess these impacts; requiring the ability to translate data and methodologies for parcel level certifications, forest carbon projects, jurisdictional areas, and along the chain of custody for wood products. As many of these actors have good practice guidance or requirements in place, this section explores potential CSF additional metrics and assurances as well as additional sources of guidance useful for clarifying CSF and points of initiation for additional growth going forward.

Established implementation science

Scientific information can shape behavior through various processes of '*implementation science*'. In forestry, these can include regulations, voluntary guidelines, extension and knowledge transfer, evaluation frameworks, and professional organizations. Such examples of implementation

science act as a translator between research and practitioner communities, i.e., overcoming the science-practice gap. As climate change becomes an increasing and persistent threat to society and forests, there are efforts to rapidly expand previous evaluation sustainable forestry frameworks (e.g., sustainable management Certification, Criteria and Indicators, Laws and Policies, Nationally Determined Contributions), Trade agreements, Best Management Practices) with new initiatives (e.g., Climate Smart Forest Economy Program, jurisdictional approaches). There have been relevant scholarly efforts assessing SFM criteria and indicators to identify which indicators are applicable for CSF, in a largely managed forest context [28, 131]. *Monitoring*, Reporting, and Verification (MRV*)* is the science of metrics and indicators for forest carbon and other GHG measurements. As a well-established approach in line with national commitments, direct linkages to the emerging theories around CSF have not yet been made clear, though they presumably match with a variety of measurement approaches related to carbon and forests. Considering the immense MRV efforts by nation-states and increasingly sub-state actors to establish MRV systems, there is increasingly ample data on landscape carbon stocks in above and below ground pools, and increasingly in soils. However, as this paper explores, carbon stocks alone are limited in their ability to frame climate benefits more broadly (e.g., climate "smartness") and MRV protocols might need to be *Enhanced* to include broader CSF principles.

Sustainable forest management certification, particularly for landowners, is a central interface to close the science-knowledge gap (see S3 Table for the language in the standard as well as other examples). However, in areas with weak governance and high levels of illegal activity, chain of custody can be nearly impossible to determine, limiting the power of existing assurances like certification. This means that promoting wood used from unknown origins can have major social and environmental impacts. Generally, certification and their implementing organizations provide not only guidance, but a two-way communication platform to engage and train rural decision-makers and utilize inclusive stakeholder engagement process to develop guidance. Straka and Khanal [132] describe how forest certification is a tool for knowledge transfer, and, as an example, the latest Sustainable Forestry Initiative (SFI) standard includes a new Objective titled "Climate Smart Forestry" [32].

Emerging implementation science

Implementation science can also strive to include participatory and mutually beneficial data collection and sharing efforts (e.g., community-based monitoring). Increasing value for communities to participate, value their role as protectors of resources. These established sources of implementation offer opportunities to add specific guidance and planning related to CSF to reach practitioners [133].

Unique methodologies can address risk and improve outcomes. Project level requirements (forest carbon projects) are well established and emerging guidance on climate-smart forest economies is forthcoming. At the nation-state level, National Safeguard Information Systems (SIS) include indicators like 'No Net Loss' of biodiversity (NNL), or even strive for a 'Net Gain' (NG) [134]. Additional methodologies to provide guidance for identifying areas that are ideal for restoration (e.g., where previous high carbon storage areas, boost habitat connectivity) remain underdeveloped and underemphasized.

Overall, more research and engagement work at assessing CSF, particularly a broader definition is needed to implement the principles across additional landscapes and scales.

Conclusion

Largescale application of the *Current* CSF framework could result in paltry or even undesirable outcomes for climate, biodiversity, and society. This review finds that, despite its increasing

use in professional and applied contexts, definitions and analysis of CSF are limited in the literature, reflecting a 'science-practice gap'. Our analysis reveals additional planning and implementation components are necessary to assess and ensure the degree to which forest interventions are in fact 'climate-smart', including broadening forest cover types, conditions, and climate interactions. To do so, this paper presents a framework with an *Enhanced* CSF definition to better link scholarly work in carbon, climate, communities, and forests which evolving interpretations of forest-based climate action. This expanded framework aims to support the translation of the theoretical CSF, defined by the researcher, into practice, with interventions that to engage rural and marginal actors, build local and regional economies, minimize waste, limit and eventually eliminate fossil fuels, and value diverse forest values (e.g., carbon storage alongside cultural values, habitat).

CSF diverges from SFM in the depth of existing research, eligible land and forest categories, and indicators needed for assessment. Still under-studied, scholarly work appears to generally indicate that CSF could be understood as a niche component of SFM [29], implying that there exists forest management that is sustainable but not considered 'climate-smart' (as in, there are no calculable carbon or GHG benefits) as well as leaving out potentially forested landscapes and intact areas that can be targeted for protection. This analysis offers a different conclusion, contending CSF is a broad umbrella under which to assess additional forested or potentially forested landscapes, particularly those that may not be managed primarily for timber. In this definition, SFM is only one element *under* the broad umbrella of CSF, which encompass a diversity of land management and conservation practices beyond carbon, but that are essential to adapting to climate, actively consider other species, and supporting resilient landscapes for multiple values in society.

CSF is being used broadly outside of academia, demonstrating a need to incorporate climate-oriented decision-making across many landscapes *including*–not excluding–protected lands, urban areas, and in restoration. This framing reaches multiple professional disciplines crossing forestry, development and planning, timber production, conservation, natural resource management, social sciences, and governing bodies. For CSF to reach its potential, it should include wood use as efficiently and for as long as possible, eliminate risk of perverse incentives to replace more natural landscapes with plantation forests, maintain or increase landscape-level carbon, improve inefficient wood use practices, and restore degraded lands. An *Enhanced* framing of CSF would reduce risks associated with applying production-oriented CSF too broadly–undesirable outcomes for environment and society–by drawing in the robust body of science on carbon, climate, forests, habitats, and social science (including participation, economics, justice, and diverse values of nature).

Future work will need to pursue improved methods to estimate and model forest carbon across pools, as well incorporate climate sensitivity, uncertainty assessments, and quantification of other ecosystem services (e.g., biodiversity, hydrologic processes). Building on best practices from across sustainable development and forestry disciplines, CSF requires inclusive dialogue to navigate this profound opportunity for radical revisioning of forestland decision-making, forest product use, conservation, transparency, economic indicators, inclusion, and benefit sharing.

Supporting information

S1 Table. Examples of Climate-Smart Forestry (CSF) in use by diverse actors [27, 29, 30, 32, 100, 137–142].
(DOCX)

S2 Table. Definitions of CSF in academic literature (as of early 2022) [25, 29, 131, 143, 144].
(DOCX)

S3 Table. Approaches and phrases related to CSF, defined [38, 39, 42, 135, 136, 145–147].
(DOCX)

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