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REVIEW

Managing forests for carbon–Status of the forest carbon offset markets in the United States

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Abstract

Nature-based climate solutions are gaining international policy attention–with forests highlighted as a primary pathway for storing carbon. However, evaluations of additional carbon benefits and the permanence of forest carbon offset projects remain scarce. In response, we compiled a novel database to analyze trends in existing forest management projects from the two offset project registries (Climate Action Reserve and American Carbon Registry) who list, report, and verify forest carbon offsets in California's Compliance Offsets Program, part of the state's Cap-and-Trade Program. We found that improved forest management projects represent 96% of all credits from forestry projects and 80% of all offset credits to date and span a diverse set of forest management practices with different potential for carbon storage. Our results show that 26% of existing forest carbon offsets in the United States face the hazard of wildfire. From a policy perspective, these findings underscore the need for a robust framework to monitor and evaluate cumulative and future carbon benefits of forest-based offset projects, and for assessing the risk of reversal associated with each project.

Introduction

Nature-based climate solutions have recently gained attention in science and policy arenas as a way to offset carbon emissions arising from other industries [1, 2]. To date, more than 214,981,710 forest carbon offset credits (215 Tg CO_2e) have been issued through the California Air Resources Board's Compliance Offset Program [3]. The demand for carbon offsets from nature-based climate solutions is expected to continue to further increase as buyers prefer projects that demonstrate co-benefits beyond emission reductions (e.g., other ecosystem services beyond carbon and through voluntary purchases of carbon offsets) [4, 5]. In particular, carbon offset credits from forests have been in the spotlight. They are currently the primary type of projects in the global offset markets–globally traded forest-based offsets have increased by 159% between 2020 and 2021 [6]. In the United States, forest-based offsets represent 92% of offset credits issued in the Cap-and-Trade Program operated by the state of California [3, 7–

9]. Given this rise in investment, an assessment of the status of the Cap-and-Trade Program and voluntary offset market for the participating forest offset projects is urgently needed.

Forest carbon offset credits are being issued to projects that claim to store additional carbon relative to the status quo, including for avoided forest conversion, reforestation, and improved forest management. Improved forest management is the most common forest carbon offset project type in the United States [3, 10]. Improved forest management, defined in the market-context as any forest management activity that increases carbon stocks on forested land, is an umbrella term for many forms of forest management and silvicultural practices, ranging from thinning to selection harvesting (reviewed in [10]). These practices differ in their ability to store carbon relative to business-as-usual forest management and potentially differ from regional or local forest management practices [11, 12]. Evidence on the extent to which different improved forest management practices provide additional carbon benefits remains patchy, however [10, 13]. Most prior analyses of nature-based climate solutions from forest management only consider one form of management (extended rotations) [1, 14], yet a much broader array of practices is being implemented or considered on-the-ground (Table 1). As a result, the types of improved forest management projects that have been credited for offsets (Table 1) and their implications for carbon additionality–defined as the demonstrated effects on carbon sequestration in a forest by improved forest management–remain to be quantified and verified.

One major source of uncertainty regarding the long-term permanence of carbon offset credits is the potential for catastrophic wildfire [15–19]. Forest management could play a role in reducing or exacerbating these risks of carbon offset reversal from wildfire. For example, some practices, such as extending harvest rotations, have been featured as a nature-based climate solution pathway but may exacerbate the hazard of future carbon losses by retaining higher densities of aboveground biomass–some potential fuel for wildfires–longer in the landscape. In contrast, other practices such as thinning reduces fuel loads by removing flammable biomass from forested landscapes. Clearly, improved forest management practices can differ in their ability to reduce or increase risk of carbon loss from wildfires and the permanence of offsets. Therefore, an assessment of the suite of improved forest management practices being implemented, alongside wildfire hazards for offsets, is urgently needed.

In response, we have compiled a new database of forest management offsets from the only carbon offset market in the U.S. to address: 1) the type of forest management applied in existing forest carbon projects, and how it varies by ownership structure in these projects, and 2) the proportion of offsets that face potential reversal due to high or moderate risk from wildfire. For our final question, we focus on threats to current offset permanence from wildfire, rather than other disturbances, because it is the major disturbance on forestland in the Western United States where many of the forest carbon offset projects are located. Our analysis advances understanding of the status of forest carbon offset projects in the United States. Here, we offer new details on the types of improved forest management practices being implemented, and the potential wildfire hazard to forest offsets in the offset credit market. Doing so, we find that most analysis quantifying the role of improved forest management as a nature-based climate solution focus on extended rotations [1, 14], whereas most implemented projects do not, and that the most commonly certified practice is no management, which has significant implications for carbon offset reversal from wildfire and other large-scale disturbances in forests that climate change is further exacerbating.

Materials and methods

We review the status of forest carbon offsets, in terms of the types of forestry management practices listed, land ownership, the number and location of issued offset credits, and potential

Table 1. Forest management terminology used in project documentation for existing forest C offset projects, and the total forest carbon offsets issued (as of December 2020) per management practice/activity mentioned in project documentation. Note that some of the offset project documents mention multiple management practices and/or activities, so practices are not mutually exclusive and thus some offsets are listed multiple times in the table.

Management practice or activity	Definition	Projects mentioned one or more of these forest management terms	Total offsets issued	% of offsets issued
No management or no commercial harvest	No forest management or commercial harvest is applied.	No management, no commercial harvest, no harvest	62,721,277	34%
Uneven-aged management	Stands that have three or more age classes throughout the cutting cycle.	Extended rotations, retention harvesting, selection harvesting	65,983,843	36%
Even-aged management	Even-aged management comprises of a repetitive rotation cycle of distinct phases, including the regeneration, intermediate treatments (incl. thinning) and final harvesting.	Clearcut, clearcutting, even-aged management, even-aged stands, seed tree removal, two-aged management, extended rotations	29,521,224	16%
Retention	Harvesting method in which some structural elements are retained at the time of harvest, such as mature trees and dead wood to increase the structural complexity of the stand.	Basal area and diameter retention, canopy retention, greater retention, overstory retention, retain biomass, retain dead wood, retain dead wood and recruitment trees, retain dominant and co-dominant trees, retain harvestable stock, retain recruitment trees, retention harvesting to promote shade-intolerant species, retention of wildlife and recruitment trees, single tree retention, variable retention	87,817,348	47%
Selection harvest	Individual trees or smaller groups of trees are removed instead of all trees. Produces stands with several age-classes.	Group selection, hardwood control, hardwood release, improving species composition, increase standing and lying dead wood, old growth protection, release of well stocked conifer stands, rotation harvesting limited by basal area, selection cuts, selection for hardwoods and loblolly pine, single-tree selection, transition harvest	38,008,407	21%
Regeneration	Re-establishment of the forest stand, through natural (from existing seeds, samplings in the stand) or artificial regeneration (planting, direct seeding)	Natural regeneration, planted seedlings, planting, prescribed burns, reforestation/replanting, regeneration harvesting with reserves, rehabilitation, rehabilitation of understocked areas, replanting shelterwood, shelterwood regeneration, shelterwood system	17,777,969	10%
Pre-commercial thinning	Removal of specific trees or age-class of trees before trees reach merchantable size.	Pre-commercial thinning	2,245,671	1%
Other thinning	Removal of specific trees or age-class of trees to improve the growth or health of the remaining trees.	Commercial thinning, intermediate thinning, variable-density thinning	17,240,143	9%

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risk for reversal of these offsets due to wildfire. To do so, we compiled a novel database of all forestry projects from the two offset project registries participating in the only carbon market in the United States, California's Cap-and-Trade and Voluntary Offset programs. Climate Action Reserve (CAR) and American Carbon Registry (ACR) track offset projects and issue offset credits and are responsible for verifying and certifying emission reductions associated with offset projects.

Offset databases

In November 2020, we accessed, downloaded, and compiled the data from CAR and the ACR (see S1 Text). We examined all "Forest Carbon" projects from the CAR, and all "Improved Forest Management" (IFM) projects from the ACR. Information on the project ID, developer, name, owner, year registered and/or listed, status, Air Resources Board- status (i.e., inactive/active in the market), site location and number of offsets issued were retrieved directly from both registries. We collected information on management practices and project acreage from each forest offset project (Table 1; see S1 Text). Our analysis includes active offset projects that have received offset credits and includes completed projects but not planned (ARB-status

listed as proposed) or inactive projects (ARB-status listed as inactive). Practices were sorted into eight main categories based on the definitions from the Southwest Fire Science Consortium's silviculture terminology and the USDA Forest Services' reforestation glossary (see Table 1; see S1 Text). Per project, practices were not mutually exclusive, and some projects implemented multiple IFM practices.

Litter and soil carbon maps and wildfire hazard for existing forest projects

We overlaid project locations on maps of litter carbon and soil organic carbon (0–20 cm) data from Cao et. al. [20] and onto maps of aboveground carbon calculated from the USDA Forest Services' National Forest Inventory (FIA) data [21] using the 'rFIA' package v3.1 [22]. Aboveground carbon data was calculated from 'Plot' and 'Tree' tables from FIA data using the protocol recommended on the rFIA website [22]. The average aboveground carbon per tree in pounds was multiplied by trees per acre and divided by 2000 to result in tons of aboveground carbon per acre. Shapefiles for the maps used in Figs 3 and 5 were downloaded from the U.S. Census Bureau (U.S. Census Bureau, Cartography Boundary Shapefiles, 2018).

We overlaid forest offset project location data with Wildfire Hazard Potential (WHP) data, developed and published [in 2021] by the USDA Forest Service [23, 24]. WHP is determined based on spatial datasets of wildfire likelihood and intensity generated in the Large Fire Simulator program, as well as spatial information on fuels and vegetation data from LANDFIRE 2014, and point locations of past fires. WHP has 8 categories, out of which we used five ('very low', 'low', 'moderate', 'high', 'very high') considered appropriate for our analyses (categories 'unburnable', 'water' and 'undeveloped' were excluded). We used the mean categorical WHP for each county as a proxy for each offset project WHP. For projects in multiple counties, the county WHPs were averaged and each WHP-value, if a fraction, was rounded down. State WHP was used for projects that did not specify a county or that were in multiple states.

Results

We find that 92% of issued offsets by California Air Resources Board that are ARB-eligible (i.e., offset that are eligible to be traded in the market administered by California Air Resources Board) originate from forest carbon offset projects [3]. Furthermore, 96% of these forestry projects are considered improved forest management, while avoided conversion forest projects account for just 4% of the offsets issued. Improved forest management projects are heavily concentrated in the Western U.S.; 52% of forest offsets issued are from projects located in Alaska, California, Washington, and Oregon, with the first two states accounting for 40% of issued forest offset credits (Fig 1, S1 Table). Improved forest management projects received a total of 185,088,866 offset credits. Improved forest management projects represent 80% of all ARB-eligible credits issued–for all offset project types, not just forestry–by the two offset project registries, CAR and ACR (S1 Table).

Status of existing improved forest management offset projects

Forest management practices. Almost half of all projects mentioned using retention harvesting, whereas 34% of projects listed no management or no commercial management, 36% listed uneven-aged forest management practices in their project documentation, and 16% of projects used even-aged management practices (Table 1). Many projects listed multiple management strategies and therefore are counted in multiple categories for forest management (Table 1). Projects using no management or no commercial management of land accounted for 62,721,277 offset credits (Table 1, S1 and S2 Tables). Not all projects mentioned previous land use or history, but many had been managed for timber harvest (this was mentioned in the

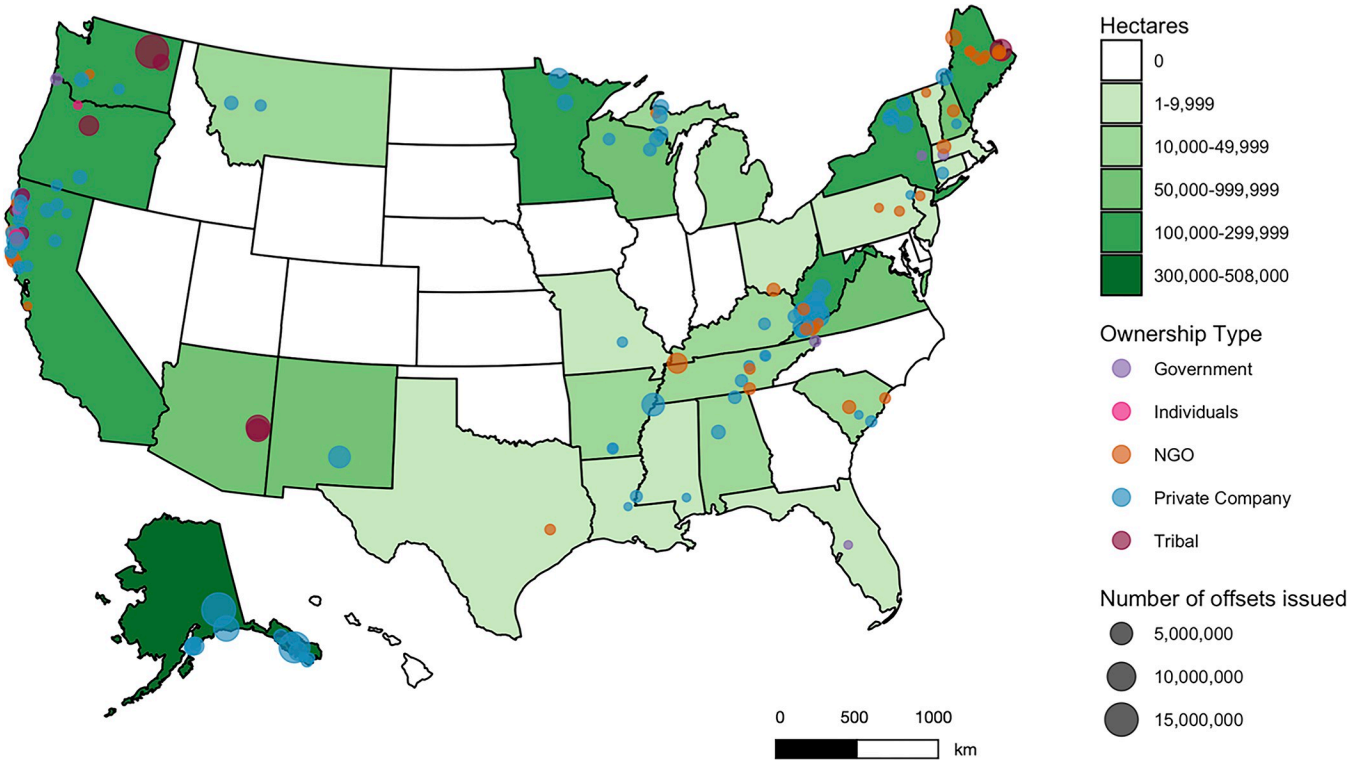

Fig 1. Locations of existing forest carbon offset projects (green, in hectares) in the United States and per ownership group (dots). Base map was drawn using R package 'usmap'.

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offset project documents). On average, these projects without management or commercial forest management received the most credits averaged per acre. From the projects that listed uneven-aged management, 1,056,534 acres were managed, at least in part, by selection harvesting. Some form of retention harvesting was practiced in 3,368,514 acres–in almost half of the projects. It is important to note that retention harvesting and selection harvest were listed as management practices in even-aged and uneven-aged forest management projects (Table 1). Further, per project, practices were not mutually exclusive, and some projects implemented multiple IFM practices.

Ownership. Companies owned 75% of forest carbon offset project area and received 69% of all offset credits issued (Fig 2, S2 Table); four projects owned by Alaska Native Regional Corporations received 17% of all private company offsets and comprised 12% of all private company acres. These four projects were not managed for large-scale, commercial forest harvest. Native American tribes owned comparatively few projects but owned the next largest amount of project land (15% of acres) and received 21% of offset credits. Non-governmental organizations owned 9% of offsets and 10% of project acres. Government organizations or municipalities owned few projects and acres but received over one million credits (0.6% of acres and offsets). Less than 0.3% and 0.7% of projects acres and offsets respectively were owned by individuals or universities combined. We found that most of the forest offset projects are owned by private companies (Fig 2, S2 Table). These projects had no management or no commercial harvest listed in almost half the projects, with one-third of the projects applying uneven-aged management.

Risk of carbon losses from wildfire. In the U.S., 1,100,485 project acres–or 19% of all forest project acres and 26% of forest project offset credits–occurred in areas of moderate wildfire

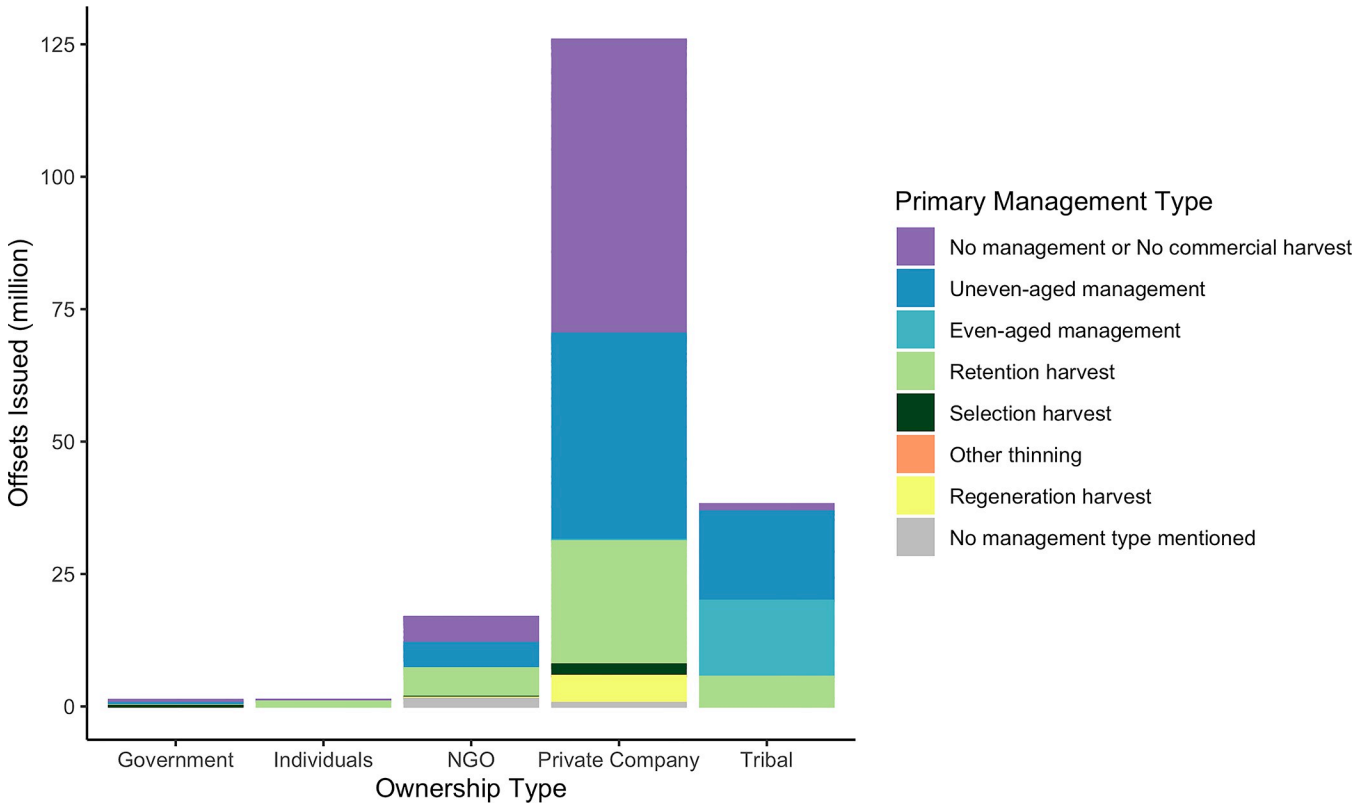

Fig 2. Forest carbon offsets issued per ownership group and forest management type. Table 1 defines the different types of forest management.

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hazard accounting for 48,683,288 of issued offset credits (28% of all improved forest management offset credits) (Fig 5). Out of these projects, 46 projects–representing 16% of all forest offset credits and 9% of all forest project acres in the country–are in California. These projects accounted for all of project acres and project credits in the state. Other moderate wildfire fire hazard projects were in Oregon (1 project, 4% of project acres and 68% of credits in the state), South Carolina (1 project, 14% of project acres, 20% of credits) and Washington (2 projects, 98% of project acres and 95% of offset credits). We find that improved forest management projects are often located in areas with high aboveground carbon densities, i.e., on productive forestland (Fig 2). Finally, due to the productive nature of these forestlands, these project locations have high soil organic carbon and litter carbon densities (Fig 4).

Discussion

Forest management as a nature-based climate solution has dominated the discourse on climate-focused land management. Analyzing existing forest carbon offset projects in the US, we find that forest-based offsets are the dominant offset type in the US market, and improved forest management projects account for 96% of forest offset credits and 80% of all offset credit issued by the offset project registries. Forest offset projects that list no management or no commercial harvest had received the highest number of offsets per acre, followed by retention and selection harvesting. In addition, we find that forest offset projects are indeed located on forestland with higher above- and belowground carbon densities (Figs 3 and 4), but also in areas of moderate wildfire hazard (Fig 5).

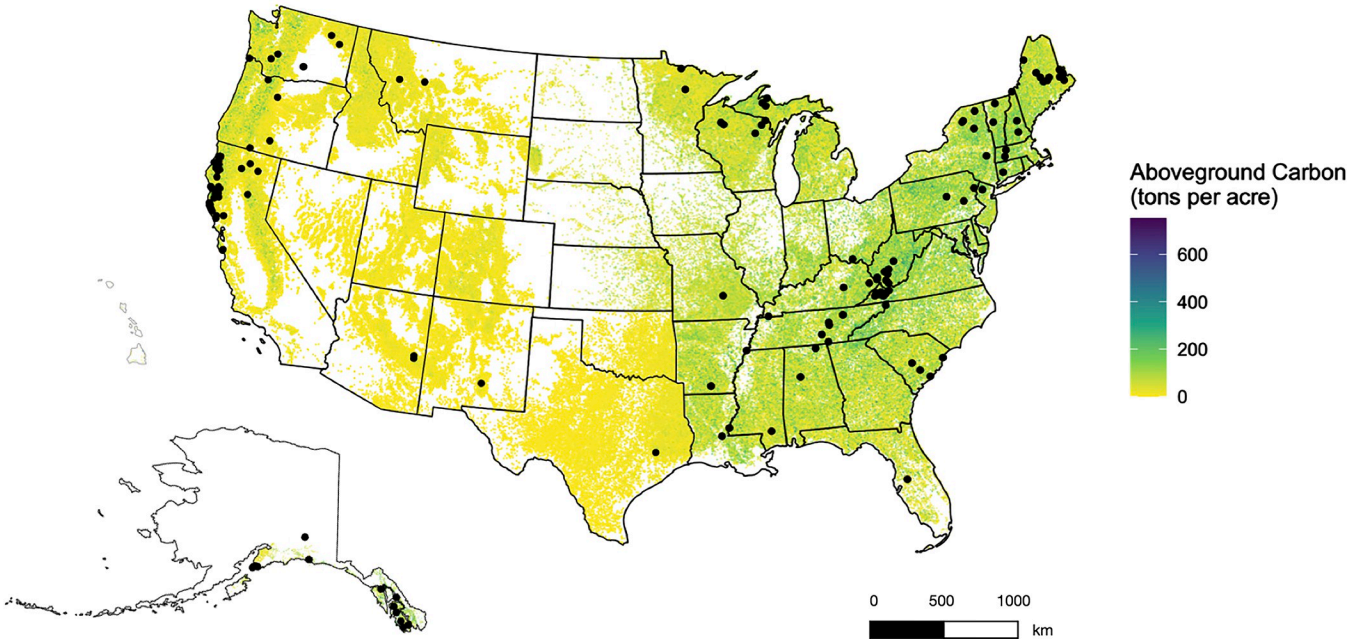

Fig 3. Map of aboveground carbon (US tons ac^{-1}) (n = 11,674,137) in the United States with locations of existing forest carbon offset projects in the United States and locations of (black dots). Aboveground carbon data was obtained from National Forest Inventory (NFI) plots maintained and measured by the Forest Inventory and Analysis (FIA) Program within the USDA Forest Service (n = the number of samples). Shapefiles for the census data (and base map) were downloaded from the U.S. Census Bureau (U.S. Census Bureau, Cartography Boundary Shapefiles, 2018). Base map was drawn using R package 'ggplot2'.

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Prior analyses on nature-based climate solutions from forest management have primarily focused on extending forest rotations as a nature-based solution pathway [1, 14]–most existing offset credit projects do not mention if extended rotations are being applied as part of 'no management or commercial harvest' (Fig 2). Indeed, while the market-level forest offset discourse has focused on extending rotations, we find little indication that lengthened rotations are applied in practice in these projects. Out of the 257 projects that we examined for this analysis, only 33 improved forest management projects mention extended rotation as a management tool in the project documentation. To that end, our analysis broadens the scope and definition of forest management practices that are considered effective and sustainable for managing forest carbon based on practices being certified on the ground in carbon offset markets (Table 1). This expanded view is important as ongoing improved forest management projects include a diverse suite of practices (Fig 2), not just extended rotations. From our analysis of improved forest management implemented on the ground, we also highlight several gaps and research needs for offsets and nature-based climate solutions from forest management.

Risk of reversal due to wildfire

Our analysis reveals that 26% of improved forest management projects are areas with moderate wildfire hazard (Fig 5). For wildfire specifically, the convergence of warming temperatures from climate change and expanded ignition pressure from people is increasing the number of large human-caused wildfires across the Western United States [25, 26]. As a result, under climate change wildfires could further threaten carbon offsets from forests across the US–not just in the flammable West. While our analysis did not find any existing projects with very high or high wildfire hazard potential we did, however, find a project in California with a high wildfire hazard potential, which had been issued 847,985 offset credits, but had been

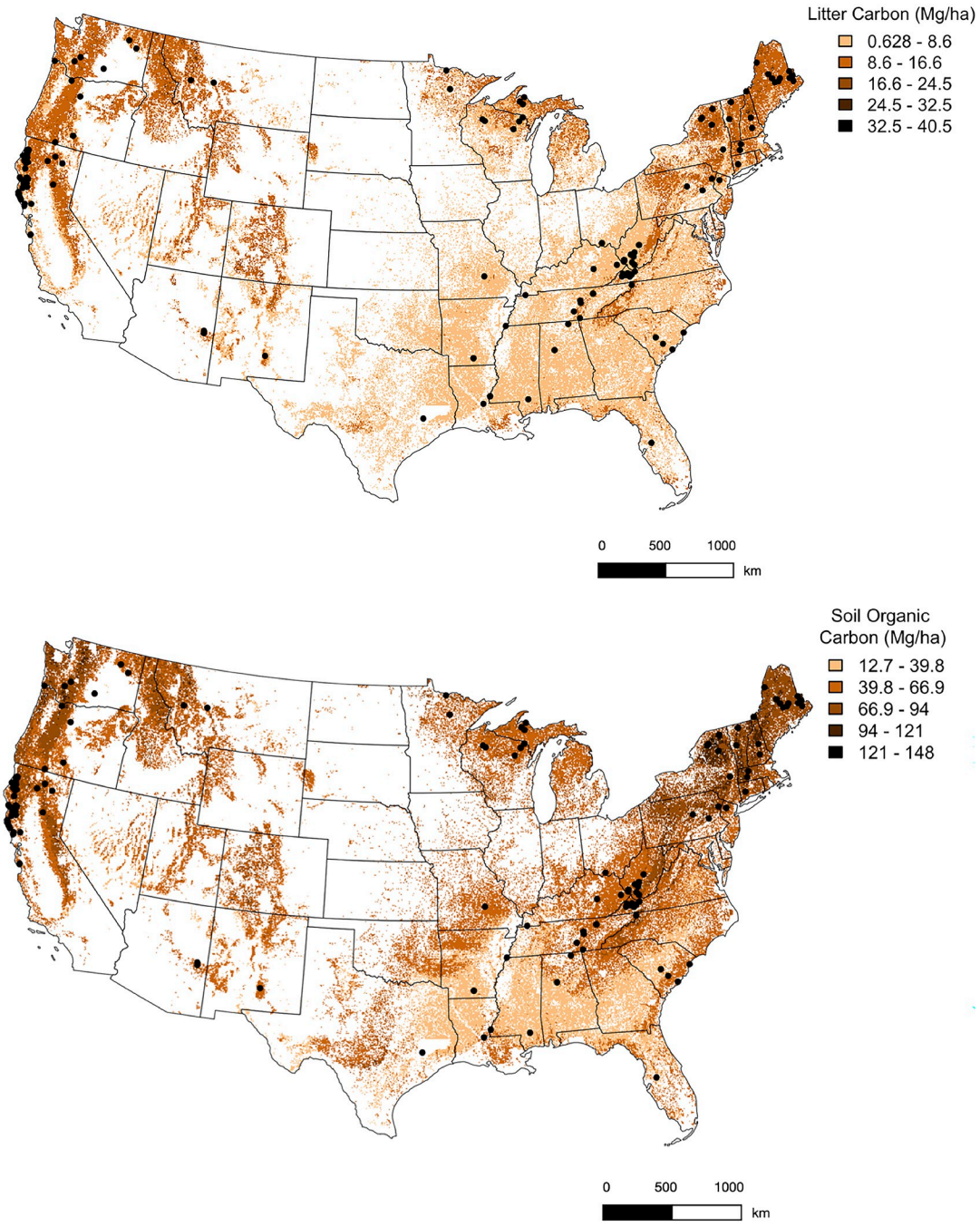

Fig 4. (A) Litter organic carbon (Mg ha^{-1}) (n = 3303) and (B) soil organic carbon (0–20 cm, Mg ha^{-1}) across continental United States and locations of existing forest carbon offset projects (black dots). Base maps for soil litter and carbon were obtained from Cao et al. (2019) and are published with permission from the copyright holder (CC BY 4.0, USDA Forest Service). Base map was drawn using R package 'ggplot2'.

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terminated in 2019 due to a wildfire. Increasing demand for forest based offset credits could also drive the expansion of projects further into fire-prone landscapes, where fuel conditions are further exacerbated by climate change driven changes, including unpresented drought [22–24].

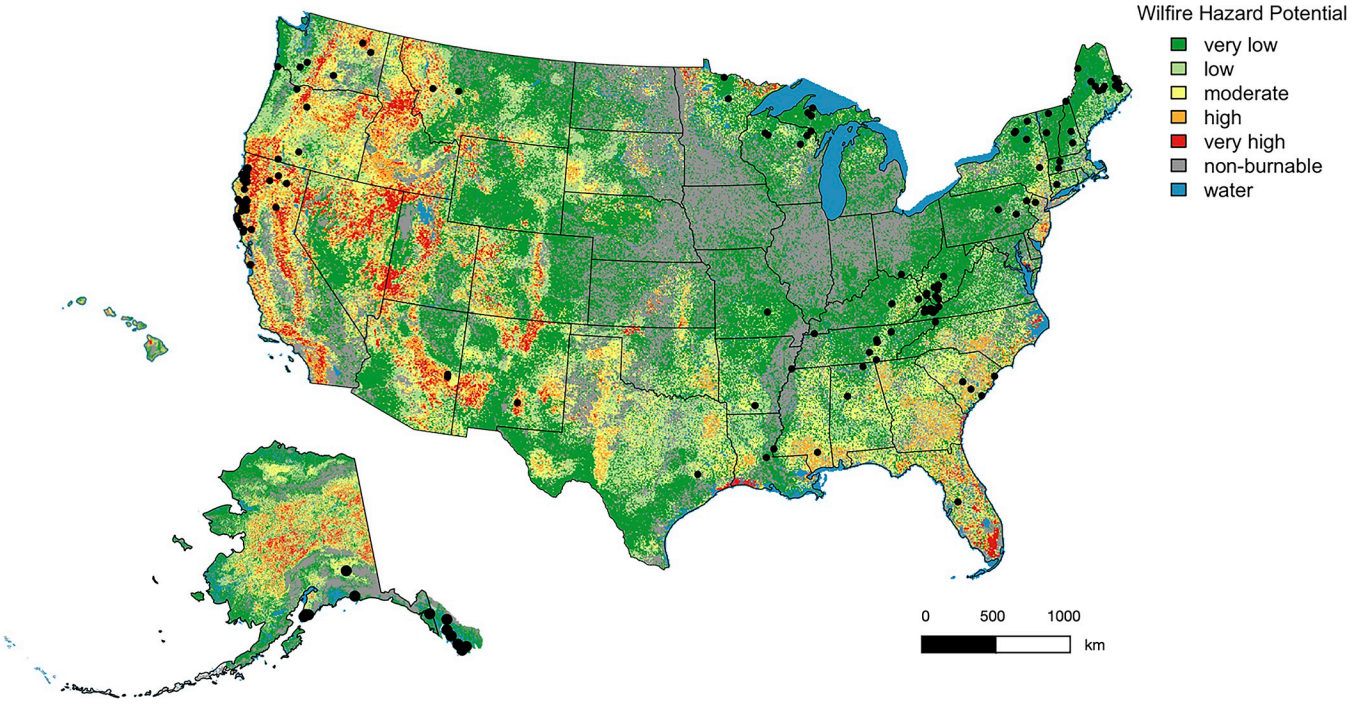

Fig 5. Wildfire Hazard Potential (WHP) in the United States and locations of existing forest carbon offsets projects (black dots) (estimate for each county's WHP is based on scale by Dillon et al., 2020). Shapefiles for the census data (and base map) were downloaded from the U.S. Census Bureau (U.S. Census Bureau, Cartography Boundary Shapefiles, 2018). WHP map layer data was retrieved from US Forest Service (Dillon and Gilbertson-Day 2020). Base map was drawn using R package 'ggplot2'.

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While low- and mixed-severity fires have historically been a natural phenomenon in the forested ecosystems of the Western United States, human influence (e.g., grazing, land conversion, urbanization, fire suppression) has resulted in exclusion of fires in the region [27, 28]. Decades of fire suppression have altered the structure and composition of many forests in the Western United States, some of which are now also facing compound disturbance effects of fire, bark beetles and drought [29]. In fire-suppressed forest stands, uncontrolled, high intensity wildfires are often severe in terms of their impact on aboveground carbon stocks [30]. Forest stands with high aboveground carbon densities tend to be more vulnerable to wildfires due to overstocking of flammable biomass following fire suppression. If a high-intensity fire was to occur, carbon losses from these stands could be significant. If left untreated for fuel, forestland can potentially release more CO_2 once they burn compared to thinned forests, as large catastrophic wildfires tend to consume all available biomass, including the litter layer and soil surface layers [16, 30].

These findings about CO_2 emissions from untreated (i.e., no fuel management) forestland with legacy of fire suppression have important implications for many forestry projects in the offset credit program. First, forest carbon offset projects are situated within areas of high above- and belowground carbon densities (Figs 3 and 4), suggesting that these forestlands have been excluded from fire or other large-scale disturbances in the recent past. Second, many locations had been previously managed for timber harvest thus indicating that the initial or project start aboveground carbon stocks were considerable. Finally, we find that a disproportionally large number of forest carbon offset project land (i.e., forestland) is untreated or not managed, whereas few explicitly use thinning or other types of fuel management practices. Thus, we anticipate an increasing risk to offsets from wildfire, and other climate-driven disturbances [31–34].

Guidelines for managing fuels on these forestlands participating in offset programs is urgently needed given the risks–particularly in California and across the Western U.S. states where wildfires are common. Only six existing forest offset projects in our database mentioned prescribed burning as a management practice and only one of these projects was in the West (in New Mexico). To that end, we recommend that improved forest management further expand its definition (reviewed by [10]) to include active fire and fuel management [30]. In addition, future markets from other sectors (e.g., agricultural crops) that face losses from events such as drought could provide some guidance for these emerging offset markets [35].

Finding a sustainable path for forest carbon offsets. In operational forestry, improved forest management is not well-defined, and the long-term carbon benefits of most of these practices remain to be tested [10, 11]. At the same time, markets are certifying forest offsets projects but offer limited accountability and transparency on additionality [13, 36, 37]. Further, large quantities of offset credits are awarded to projects at the start of the project (i.e., initial tracking period), particularly for improved forest management projects thus potentially disincentivizing future forest management activities [37, 38]. Currently, there are no policy instruments or regulations in the California offset credit market that focus on oversight and accountability of forest offset projects, and the governance for environmental integrity is focused on the development (i.e., the protocols) and start of the forest project [39]. The current mechanism of issuing, verifying, and accounting for forest carbon offsets has put into question the added carbon benefits of these projects [37].

Our analysis reveals that credited projects vary to a great degree in their disclosure about the planned or completed forest management activities for the project area. While several forest carbon offset projects provided detailed descriptions of the management objectives, and by extension forest management practices, many offered little detailed information on what type of management activities will take place and when. Going forward, a thorough and transparent planning and monitoring network for the forest practices applied in these projects, including retention harvest practices, would aid in determining the extent and scale of additional carbon benefits. Forming a new partnership between the entities involved with the carbon offset market, including the state of California, offset project registries, and finally, the forest research community, could assist in building a framework for assessing forest carbon offset opportunities on forestland in California and across the West.

Finally, we recommend future directions for research, partnerships, and policies around forest management offsets. While assessing the effectiveness of California's offset market to demonstrate significant carbon emission reductions is beyond the scope of this article, we call for substantial investments into oversight of credited and existing, and future forest offset projects, in line with recent articles [13, 36, 37]. Our results further highlight that a significant portion of existing forest carbon offsets face a risk of reversal through wildfire, including all the existing projects in California. Future research and partnerships could build a body of evidence for not only how these improved forest management strategies impact carbon, but also the extent to which they mitigate or exacerbate risk from disturbances such as wildfire [27, 40–43] and pest outbreaks [44]. For example, no active management could increase exposure to risk of catastrophic carbon losses, yet no management was the dominant practice in 34% of certified offset projects. In contrast, improved forest management strategies such as thinning reduce fuel loads but thinning only represented around 10% of credits (Table 1). Considering climate-driven disturbance risks, such as wildfire, in the forest offset protocol could increase the robustness of the offset credit program and help accurately determine the risk associated with each project. From a policy perspective, these results underscore that more sophisticated insurance mechanisms are needed for forest carbon offset losses and reversals, as well for the

validation of long-term carbon benefits from different types of forest management applied in these offset projects.

Supporting information

S1 Table. Forest carbon offsets issued per U.S. State (as of December 2020).
(DOCX)

S2 Table. Forest carbon offsets issued per ownership group and forest management listed for the offset project (as of November 2020).
(DOCX)

S1 Text. Methods: Additional details on review.
(DOCX)

S2 Text. Calculation of fire hazard and risk [of reversal] for offset projects.
(DOCX)

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Visualization: Lilli Kaarakka, Julia Rothey.

Writing – original draft: Lilli Kaarakka, Julia Rothey, Laura E. Dee.

Writing – review & editing: Lilli Kaarakka, Laura E. Dee.

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