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LETTER

Decreasing landscape carbon storage in western US forests with 2 °C of warming

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Abstract

Changing climate is altering the amount of carbon that can be sustained in forest ecosystems. Increasing heat and drought is already causing increased mortality and decreased regeneration in some locations. These changes have implications for landscape carbon storage with ongoing climate change. We used a climate analogs approach to project aboveground forest carbon density under +2 °C warming above pre-industrial climate for western US forests. We calculated analogs for current climate and under +2 °C warming and associated carbon density for each time period. We found that in most ecoregions, maximum carbon density values are projected to decline and the interquartile range of carbon density values is projected to narrow. Using mean carbon density values, we project a 796 Tg decline in landscape carbon storage across the western US. As tree mortality increases, the transition from live to dead carbon will increase fuel buildup and fire hazard in many ecosystems. Greater fire hazard and increased susceptibility to insects from drought could cause carbon density changes to occur more rapidly than our climate-only projections. This may have substantial implications for forest-based carbon offset projects.

1. Introduction

Climate and prevailing natural disturbance conditions determine the sustainable carbon density, or carbon carrying capacity, of a geographic location (Keith *et al* 2009). As heat and drought increase, tree mortality is increasing globally and restructuring the carbon stored in forest ecosystems, by transferring substantial amounts of live tree biomass to the dead pool (Allen *et al* 2015, Hammond *et al* 2022). Further, hot and dry conditions are reducing or eliminating tree regeneration in many locations (Pozner *et al* 2022, Davis *et al* 2023). When changing climate drives both adult and juvenile tree mortality, there is increased potential for reduced forest carbon density or change to a non-forest vegetation type with a lower carbon density. Determining where these changes are likely to occur is central to long-term planning for natural resource management and understanding the potential decline in forest contribution to climate regulation.

Although climate-driven conversions from forest to non-forest are likely to cause large changes in the carbon carrying capacity, shifts in forest type also influence carbon density (Thurner *et al* 2014). Even if the future climate at a given location can still support the same forest type, it may be in a less carbon dense condition (Hurteau *et al* 2024). Alternatively, forest assemblages of species that are more heat or drought tolerant can potentially replace species that are less so and maintain a similar carbon density. From a climate regulation perspective, the tree species and forest type are largely irrelevant, as long as the rate of carbon uptake, carbon density, and longevity are consistent, assuming no change in the surface reflectance (Hasler *et al* 2024).

Dynamic global vegetation models and forest landscape models are two approaches that are commonly used to understand how forest carbon dynamics are likely to change as a function of climate and disturbance. These different modeling approaches have yielded a range of projections in different western US ecosystems (Laflower *et al* 2016, Barros *et al* 2017, Keyser *et al* 2020, Hansen *et al* 2022, Turner *et al* 2022), which is to be expected given that most models were built for different purposes (Bugmann and Seidl 2022). While these models account for a range of traits and processes (e.g. dispersal, competition, etc), they require trade-offs to balance computational efficiency and fidelity to ecosystem processes. For example, the probability of post-fire tree seedling survival in the southwestern US varies as a function of topographic position and incoming solar radiation at relatively small scales (Marsh *et al* 2022a). Yet, incorporating this type of information in a forest landscape model requires simplifying relationships to operate at larger scales using predictor variables that are present in a model (Jung *et al* 2023). Alternatively, using spatial climate analogs to determine vegetation conditions that may occur under future climate based on vegetation conditions where that climate space currently exists offers a parsimonious alternative to simulating ecosystem processes (Yegorova *et al* 2025). The climate analogs approach has been used to forecast a wide range of ecosystem and socio-ecological state variables (Pugh *et al* 2016, Littlefield *et al* 2017, Fitzpatrick and Dunn 2019, Hoecker *et al* 2023).

In western US forests, disturbances, such as insects, drought, and fire, are rapidly changing the amount and distribution of forest cover and shifting the distribution of carbon stored within forests from the live pool to the dead pool (Anderegg *et al* 2015, Cohen *et al* 2016, Goodwin *et al* 2020). Ongoing warming and drying is already stressing western forests and disturbance size and severity are increasing (van Mantgem *et al* 2013, Westerling 2016, Crockett and Westerling 2018, Hammond *et al* 2022, Juang *et al* 2022). This pattern is projected to continue with additional warming and drying (Liang *et al* 2017, Parks *et al* 2025). The core of these drivers of forest change is ongoing climate change and the increasing frequency of extreme weather events (Allen *et al* 2015, McDowell *et al* 2020, Trugman *et al* 2021).

Given the role of climate in determining the carbon carrying capacity of a geographic location, we asked—how will +2 °C of increase in mean global temperature above pre-industrial levels alter the carbon density of forests throughout the western US? We used a spatial climate analogs approach to identify current locations that share climatic conditions projected for a focal location with +2 °C of warming. To enable us to project how warming would alter carbon density, we calculated current carbon density using interpolated forest inventory data (Riley *et al* 2016) and associated carbon density with current climate conditions. Our findings will be useful to land managers and policymakers interested in managing carbon to mitigate climate change.

2. Methods

We quantified changes in western US tree biomass between reference conditions (forest conditions in 2016, the vintage of the inventory data) and a +2 °C climate future by applying an analog impact model (Yegorova *et al* 2025), which examines where future climates are distributed today (i.e. climate analogs) to project impacts to ecological systems. We defined analogous climate locations using the reverse climate analog approach (i.e. backward analog, Dobrowski and Parks 2016, Dobrowski *et al* 2021). We then quantified the difference in carbon between each focal location (i.e. pixel) and the analog location under 2 °C (described in further detail below). We used climate data characterized by four key biophysical variables: mean maximum temperature of the warmest month (T_{max}), mean minimum temperature of the coldest month (T_{min}), mean annual actual evapotranspiration and mean annual climate water deficit . These variables are considered key determinants for ecosystem properties such as primary productivity, plant distributions, and disturbance regimes (Rosenzweig 1968, Mitchell *et al* 2016, Bouchard *et al* 2019). We used TerraClimate, a high-resolution global dataset of monthly climate and water balance variables (4 km), for both the reference period and +2 °C projection (Abatzoglou *et al* 2018). TerraClimate uses climatological normals from the WorldClim data set and interpolated meteorological data from CRU Ts4.0 and JRA55 (Abatzoglou *et al* 2018). The +2 °C projection data uses a pattern scaling approach that relies upon geographic patterns in climate that scale approximately linearly with changes in mean global temperature (Qin *et al* 2020). We used a 30 year baseline period of 1986–2015 to calculate the four climate variables for the reference period, which precedes the values of the reference period forest biomass. Given the range of our baseline period, climate variables already include some influence of anthropogenic warming. For the future climate condition, we used 2 °C above pre-industrial levels, which roughly corresponds to projected mid-21st century conditions (Friedlingstein *et al* 2014). We used the monthly data to calculate annual average values of the four climate variables for each time period.

We subdivided the western US study area prior to implementing the reverse analogs approach using 18 forested Bailey ecoregions where, at the regional scale, climate influences forest type and disturbance regimes (Bailey 1983, Hessburg *et al* 2019). We then used the TreeMap data product to provide carbon density for forested areas. The TreeMap product is an interpolated raster of US Forest Service Forest Inventory and Analysis (FIA) data, which assigns one FIA plot to each 30 m grid cell (Riley *et al* 2021). The FIA program is the official United States forest inventory. Each FIA plot represents 2400 ha and plots are measured every 5–10 years (Blackard and Patterson 2014). The plot structure uses a series of fixed radius plots to measure individual trees, and the FIA program uses national biomass estimators to produce aboveground biomass density values (Westfall *et al* 2024). The TreeMap product was developed by using random forest imputation to model relationships between LANDFIRE rasters of vegetation, biophysical condition, disturbance, and topography, and FIA plot data, and then uses those relationships to predict which measured FIA plot is the best match to each pixel. TreeMap 2016 imputed FIA plots to LANDFIRE version 2016 rasters. LANDFIRE version 2016 was developed using circa 2016 satellite imagery to map vegetation, biophysical condition, and disturbance. Therefore, TreeMap 2016, the version we used, is a gridded raster of FIA plots that best characterize circa 2016 conditions measured by satellite imagery. As part of the TreeMap validation process, the authors compared interpolated FIA data to a national vegetation cover map and report the mean cover of the pixels at FIA plot center was within 10% in 60.9% of cases (Riley *et al* 2022). The authors also calculated within-class agreement between vegetation attributes calculated from TreeMap-imputed FIA plots with those mapped by LANDFIRE, and found 97.7% agreement between TreeMap and LANDFIRE for forest cover, 99.6% agreement for forest height, and 94.8% agreement for vegetation group. We then aggregated the TreeMap 30 m aboveground carbon data to the 4 km scale of the TerraClimate data by calculating the mean carbon density of the 30 m TreeMap pixels within each 4 km TerraClimate pixel.

We calculated carbon analogs for both the reference condition and with +2 °C of warming to ensure the comparison between the two climate conditions was consistent (supplemental figure S1). We modeled reference period carbon from climate analogs instead of using the observed carbon from TreeMap to ensure a proper comparison to mid-century carbon projections. To identify climate analog locations, we used Mahalanobis distance (D), which is standardized by the Chi-square distribution, and calculated climate dissimilarity between focal cells and potential analog locations within a 500 km radius of each focal cell. Areas within adjacent ecoregions that were within 500 km of each focal cell were evaluated. First, we calculated the standardized Euclidean distance which is normalized by the local interannual climate variability and then we calculated the Mahalanobis distance. Second, we converted the Mahalanobis distance to percentiles of the Chi-square distribution to statistically evaluate the distance of each potential analog from the focal cell (Hamann *et al* 2015, Dobrowski *et al* 2021). After calculating climate dissimilarity within the search radius for each focal cell, we selected the top 100 analog candidates that had analogous conditions that most closely matched the focal cell (i.e. dissimilarity in climate (σ_{d}) < 2). We then used the top 100 cells to calculate mean biomass under the analog condition. To assess uncertainty in our estimates of biomass, we quantified analog agreement (Yegorova *et al* 2025) by calculating the median and upper and lower quartiles of the 100 candidate cells for both the reference and the analog condition (supplemental table S1). This approach for quantifying uncertainty follows Dobrowski *et al* (2021), except that Dobrowski *et al* (2021) was quantifying agreement across categorical response, whereas in this study we are quantifying agreement across a numerical response. If greater than 50% of the top 100 analog cells were non-forest, we assigned a carbon value of zero, functionally making it not applicable, because the TreeMap data product only includes forest data and our analysis was focused on trying to understand how forest carbon storage in the west would change with additional warming. When we did not locate an analog within the search area that currently supports forest vegetation, we assumed transition to a non-forest vegetation type. We used R version 4.3.3 for the analysis and plotting (R Core Team 2024).

To evaluate the performance of the analogs approach, we conducted a contemporary validation (Yegorova *et al* 2025) by plotting mean carbon density from the TreeMap data against the mean carbon density from the reference period analogs (figure 1). We found that the analog approach approximated the TreeMap data well, but it did underestimate locations with high carbon density. This is likely because they are less common and because high carbon density at these locations may be driven by factors that occur at a finer spatial scale than the 4 km climate data. Additionally, taking the average of the 100 analogs decreases the influence of extreme values.

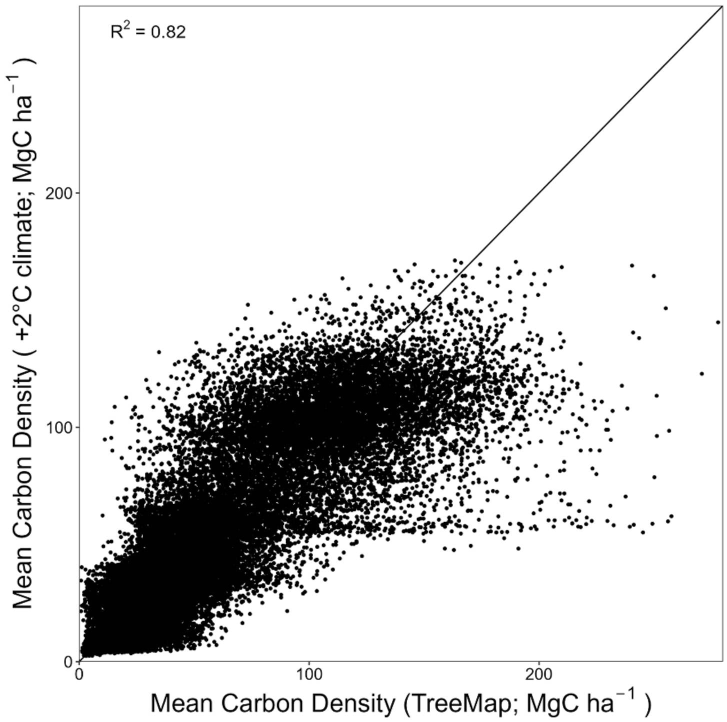

Figure 1. Mean carbon density calculated from TreeMap data plotted against mean carbon density for reference conditions using the analog approach. The line is 1:1.

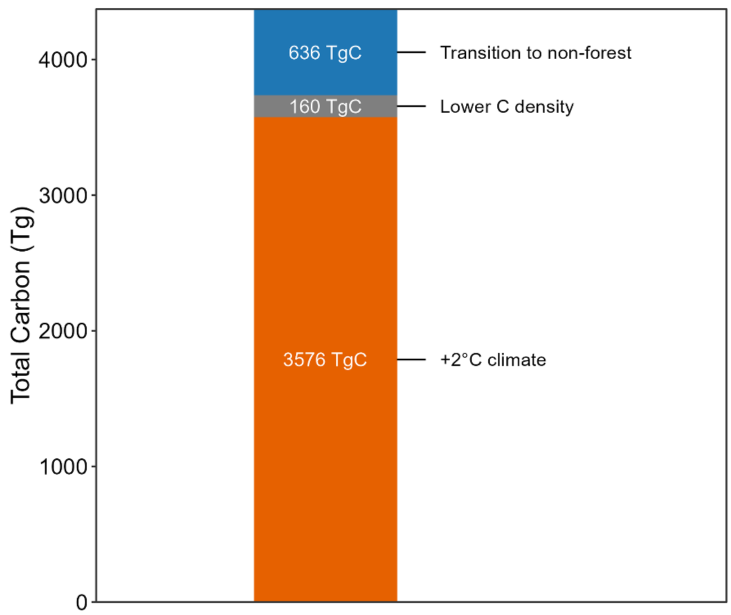

Figure 2. Change in aboveground carbon with reductions categorized as a reduction in carbon density or a transition from forest to non-forest from the reference period (2016) to the +2 °C climate. The total bar shows the total carbon for the reference period and the orange portion of the bar the total carbon in a +2 °C climate. The blue part of the bar shows the decrease from reference to +2 °C climate that is due to transition to non-forest and the gray portion of the bar that is due to lower carbon density.

3. Results

Our findings show that aboveground forest carbon storage is projected to decrease by 18% (796 Tg C) under +2 °C conditions (hereafter +2 °C climate) across the western US (figure 2). This was driven in part by forest carbon density decreases in the most carbon dense locations and by decreased total forest cover as areas that are marginally capable of supporting forests under reference conditions became climatically unsuitable (figures 2 and 3).

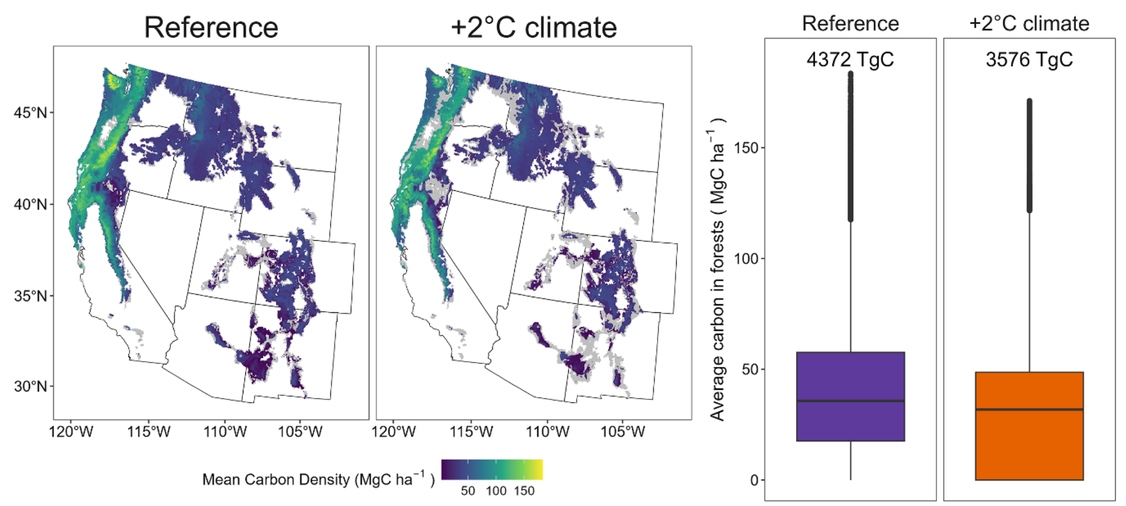

Figure 3. Aboveground carbon density across the western US for the reference period (2016) and under +2 °C climate (left) and carbon density distributions for both reference and +2 °C climate (right). Areas shaded in gray have no forest cover. Values above boxplots are total aboveground forest carbon storage for the western US.

Within some ecoregions, mean carbon density remained stable between reference and +2 °C climate conditions, with the differences in mean carbon density being driven primarily by reductions in the highest carbon density locations (supplemental table S1). For example, the Klamath Mountains ecoregion had the same total carbon storage (307 Gg C) for both reference and +2 °C climate conditions and the primary change was that the highest mean carbon density values were reduced under +2 °C climate conditions (figures 4 and 5). We saw a similar pattern in the Okanagan, which has a steep east-to-west elevation gradient. In the most carbon dense, high-elevation locations in the Okanagan, mean carbon density increased under +2 °C climate conditions, but because forest cover loss occurred at low elevations in the Okanagan, there was an overall decrease in total carbon storage (figures 4 and 5). The largest reductions in mean ecoregion carbon density occurred in locations with observed tree mortality from a mix of fire, insects, and drought (Fellows and Goulden 2012, Xu *et al* 2022) and we expect forest cover to decrease with +2 °C climate, such as the California South Coast ((Hope and Stow 1993, Baguskas *et al* 2014), figure 3). In some locations, such as the Utah High Plateaus ecoregion, forest cover loss is projected to be substantial, yet total carbon loss under +2 °C climate was relatively small (17 Tg C) because carbon density was low under current climate (figures 4 and 5). The greatest decreases in carbon density occurred in ecoregions that are either low latitude or have large elevation gradients, where +2 °C climate is outside the range of climatic conditions of any currently forested area.

4. Discussion

Leaf area is a key determinant of forest productivity at the individual tree and stand-scales, with water availability being an important regulator of leaf area (Whittaker 1970, Gholz *et al* 1990, Stephenson *et al* 2014, Trugman *et al* 2021). As the atmosphere warms and dries, seasonally dry ecosystems experience increased water stress that causes declines in productivity driven by slower growth and mortality (Trugman *et al* 2019, Hammond *et al* 2022). This direct climate-driven decrease in carbon carrying capacity is accompanied by increasing insect and fire caused mortality (Anderegg *et al* 2015, Juang *et al* 2022, Francis *et al* 2025). Our results demonstrate that a change in the prevailing climate conditions consistent with a +2 °C future could lead to lower total forest carbon storage across the western US. The primary driver of the decline in more carbon dense ecoregions was decreasing carbon density, while in less carbon dense ecoregions it was conversion to non-forest vegetation types occurring in locations that are currently warmer and drier, similar to results using an ecosystem modeling approach (Kodero *et al* 2024). While a western US-wide reduction of 796 Tg C of landscape carbon storage is small relative to human-caused emissions in the US (2022 = 6343 Tg CO2e), there are several factors that suggest a +2 °C future will be problematic for both forest carbon density and our use of forests to help mitigate fossil carbon emissions.

As we proceed toward a +2 °C future, ongoing warming and drying will increase over time and, with it, climate extremes (Fischer *et al* 2021). Our analogs approach to projecting forest carbon density uses a space for time substitution to determine how carbon density, or carbon carrying capacity,

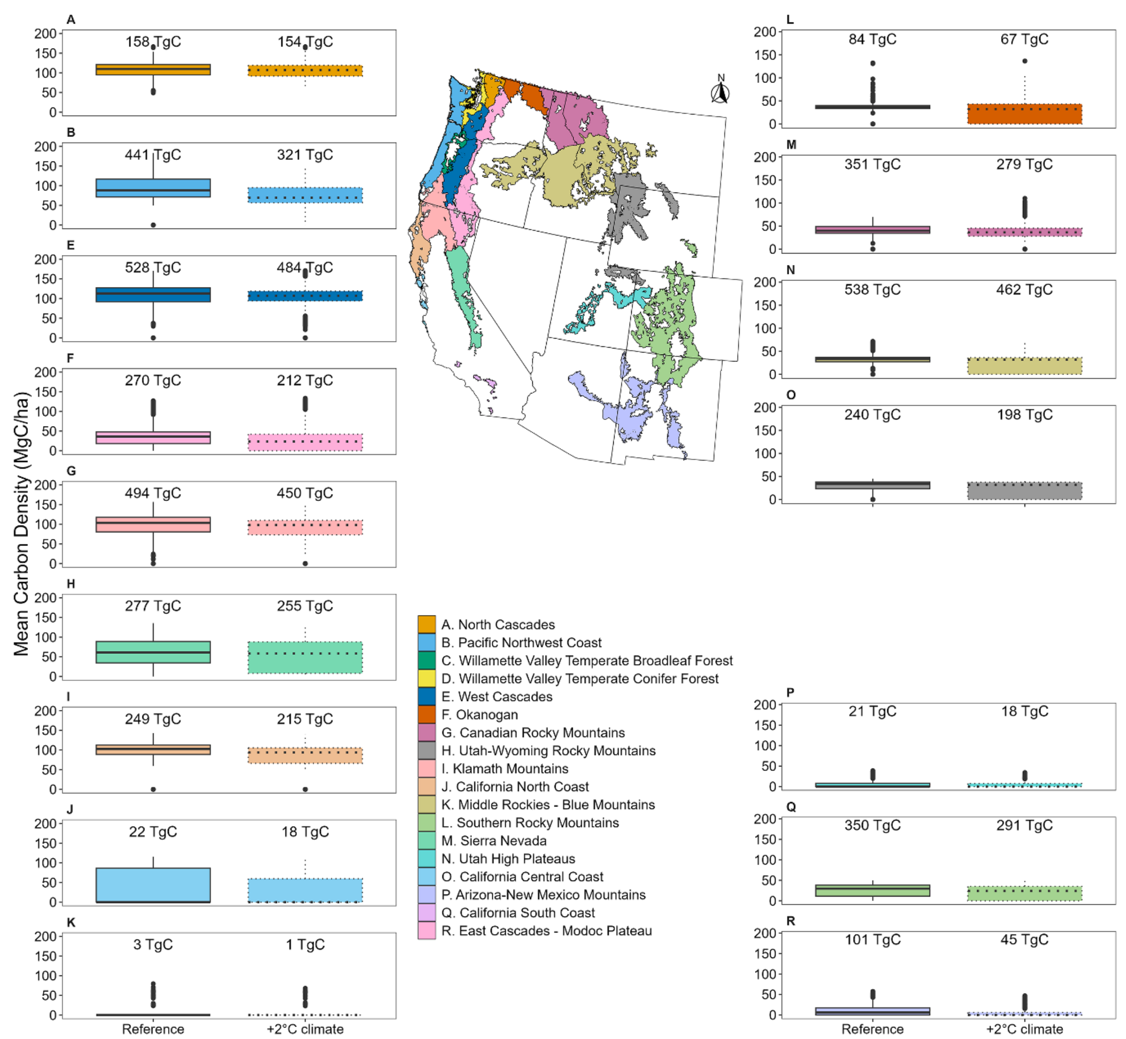

Figure 4. Distribution of mean carbon density by ecoregion under reference and +2 °C climate conditions. Values above boxplots are total aboveground forest carbon storage for the ecoregion for the reference period (left) and +2 °C climate (right).

will change. One of the limitations of this approach is that ecosystems are comprised of groups of species and their movement and establishment in a new location is a function of climate and biology. Dispersal distances vary by species and can limit movement, causing a lag in establishment or a mismatch between the location of sexually mature adults and the climate space where juveniles can establish (Liang *et al* 2017, Sharma *et al* 2022). Thus, there is a potential lag in ecosystem response with a changing climate at a given geographic location. Even when species are capable of moving to a location with a suitable climate, establishment and growth take time. These factors could lead to carbon density values being lower than the carbon carrying capacity for a prolonged period of time.

The impacts of increasing heat and drought on tree mortality and establishment is already being observed. Climate-driven mortality events have been documented in all forest biomes and are projected to increase with additional warming (Williams *et al* 2010, 2013, Hammond *et al* 2022). While heat and drought driven mortality events are likely to reduce carbon carrying capacity, tree regeneration failure in hot and dry locations is already a constraint on replacement (Rodman *et al* 2020, Davis *et al* 2023). Ongoing warming has the potential to reduce the realized niche for tree seedlings from that of adults or spatially shift the realized niche space beyond that of mature individuals (Liang *et al* 2017, Sharma *et al* 2022, Crockett and Hurteau 2024). Following germination or planting, susceptibility to heat and drought stress can kill seedlings (Davis *et al* 2019, Rank *et al* 2022, Marsh *et al* 2022a, Crockett and Hurteau 2024). There are opportunities to plant tree seedlings following mortality events and selecting planting sites based on suitable microclimate and assisted migration can increase planted seedling survival and forest establishment (Gray *et al* 2011, Marsh *et al* 2022a). Yet, climatic limitations to establishment mean that in some recently forested areas, the thermal environment may prevent tree seedling survival (Rank *et al* 2022, Marsh *et al* 2022a, 2022b, 2023).

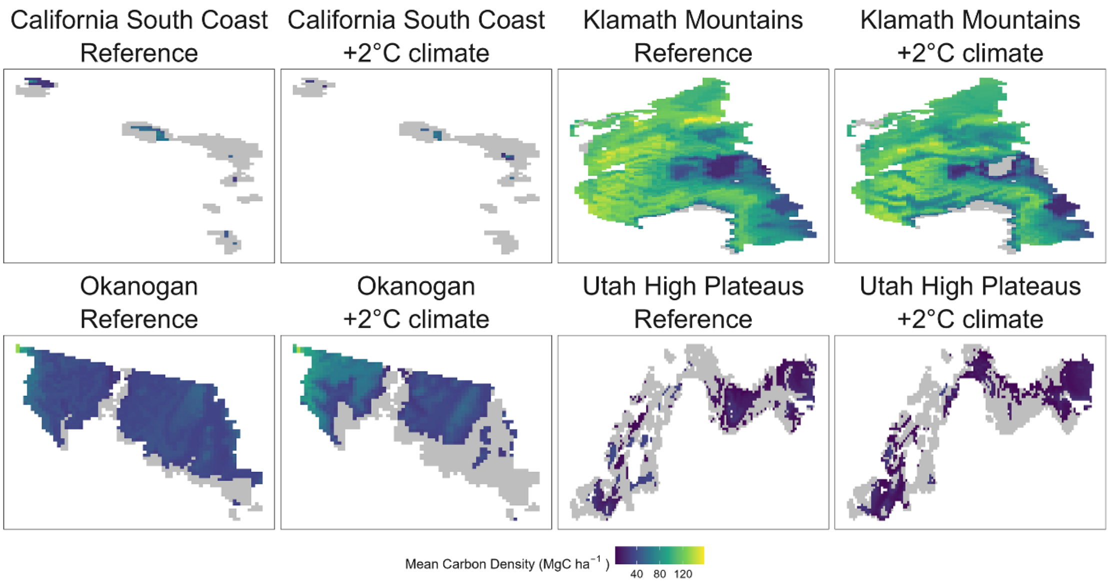

Figure 5. Mean carbon density for the California South Coast (reference 3 Tg C, +2 °C 1 Tg C), Klamath Mountains (reference 494 Tg C, +2 °C 450 Tg C), Okanogen (reference 84 Tg C, +2 °C 67 Tg C), and Utah High Plateaus (reference 21 Tg C, +2 °C 18 Tg C) ecoregions under reference conditions (left) and +2 °C climate (right). Gray pixels represent locations that are forested under current climate, but do not have an analog with forest cover under +2 °C climate.

Changing climate will likely lead to gradual changes in forest carbon density. However, the effects of prevailing climate on carbon carrying capacity do not occur in the absence of disturbance agents, which can catalyze acute changes in the carbon density of live trees. The TreeMap data we used implicitly includes the effects of insects, fire, and other disturbances on carbon density and these data are representative of forest conditions in 2016, which is prior to multiple large disturbance years. Disturbances such as fire and insect outbreaks are amplified by changing climatic conditions. Both extreme climatic events and widespread climate-driven disturbance can cause rapid vegetation change, which typically causes lower carbon density.

The probability of insect outbreaks and wildfire both increase with increased warming (Hoecker *et al* 2023, Francis *et al* 2025). Higher temperatures increase tree susceptibility to insect-induced mortality and increased mortality increases the proportion of dead biomass in the forest (Goodwin *et al* 2020, Howe *et al* 2021, Fettig *et al* 2022). These additional fuels are increasingly available to burn as higher temperatures increase atmospheric water demand (Goodwin *et al* 2021, Juang *et al* 2022). Both insect- and fire-induced mortality increase the proportion of dead aboveground biomass, a pool of carbon that will largely end up in the atmosphere either through decomposition or combustion which poses a risk to any remaining live trees if a fire occurs with high fuel loads present (Stephens *et al* 2022, Hurteau *et al* 2024). If the 796 Tg of live carbon that transitions to dead carbon in our projections were distributed evenly across forest land in the western US, that would be equivalent to 0.14 TJ ha^{-1} of energy stored in dead fuel, a substantial fire hazard. There is a potential feedback where compound disturbances cause tree mortality and reinforce transition from a forest to a non-forest vegetation type, which will further decrease landscape carbon storage (Liang and Hurteau 2023). Given that our study only included climate-driven changes in carbon density, our results likely underestimate landscape carbon storage under +2 °C of warming.

Our carbon analog approach to projecting forest carbon density in the western US with +2 °C of warming provides an approximation of the changes we can expect with additional climate change and should be considered in the context the limitations we have identified. The potential mismatch between climate and carbon carrying capacity is already evident in reference condition projections. Some areas that are currently forested are already experiencing climate conditions that have no forested analog (figure 2). Thus, there is a portion of the landscape where we are probably already committed to carbon and forest cover loss because the 2016 carbon density in TreeMap may be a reflection of climate conditions that pre-date our 1985–2015 reference period. Because of the differences in carbon density between the TreeMap data and the reference analog, the relatively small changes in median carbon density values across many ecoregions are in line with what we would expect, given the size and topographic variability of western US ecoregions is such that forest carbon density will remain relatively high. The reductions in the interquartile range and, particularly, the decrease in the highest density values are more problematic given ongoing efforts to monetize forest carbon storage to offset fossil carbon emissions.

Currently, forest carbon offset projects that are focused on increasing carbon density through improved forest management are typically located in productive locations to take advantage of disparities between the standing stock of carbon and the common practice baseline (Badgley *et al* 2022). Based on our results, +2 °C of warming is projected to decrease both the maximum and the upper quartile of carbon density across nearly all ecoregions within the western US. While these decreases may be in part an artifact of the analysis, if the carbon carrying capacity of locations with established carbon offset projects declines because of ongoing warming and drying, it would create significant financial exposure in both compliance and voluntary offset systems and, more importantly, it would mean organizations are claiming offsets that cannot be realized and further emphasizes the need for dynamic baselines which can account for changing climate (Anderegg *et al* 2022a, 2025, Sanders-DeMott *et al* 2025). The climate risk to forest offset projects in the western US is probably much larger than is currently accounted in project-specific risk assessments (Anderegg *et al* 2022b). Accurately quantifying the potential for carbon loss from offset project locations will also require projections of climate-driven disturbance and how different disturbances will impact carbon storage (Sanders-DeMott *et al* 2025).

Given the potential for the interaction of changing climate and disturbance to yield rapid changes in vegetation type and carbon density, our +2 °C climate estimate of carbon density likely represents a lower bound for change because it does not account for disturbances beyond those which had occurred by 2016. Further, our analog approach assumes species capable of occupying projected climatic conditions in a given location can disperse to that location, establish, and grow. In reality, we are predicted to reach +2 °C of warming by mid-century and there will likely be a lag in the dispersal and establishment of species that are climatically suitable for a given location. Given these factors, there is a strong possibility that western US landscapes experience a larger decline in carbon storage than climate-driven changes in carbon carrying capacity suggests. When considering how best to manage post-disturbance conditions, our results can serve as a climate adaptation tool whereby efforts to reestablish forest cover after disturbance are informed by future climatic conditions and managers can select species-specific physiological tolerances better suited to projected climate when identifying species for reforestation. Regardless of whether the objective is managing risk or recovery, climate-driven declines in carbon carrying capacity are likely to occur across western US forests and must be accounted for in decision making.

Data availability statement

The data and code that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5061/dryad.1g1jwsv9g.

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