





COMMENTARY

Carbon conundrums: Do United States' current carbon market baselines represent an undesirable ecological threshold?

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Forests are perhaps the most vital terrestrial carbon (C) pool in the United States providing the largest net offset to domestic fossil fuel emissions. In fact, reforestation and improved forest management show the greatest potential for climate change mitigation across terrestrial and aquatic ecosystems in the United States among a variety of proposed natural climate solutions (NCS; Fargione et al., 2018; Kaarakka et al., 2021), particularly when implementation costs are considered. As such, forest policy and management guidelines are increasingly framed through a lens of expanding and/or maximizing C storage/sequestration as policy makers and private entities alike seek net reductions or even net-zero status. To facilitate the attainment of such emission reduction targets, forest C offset markets have emerged, including the compliance market established by the California Air Resources Board (CARB), which incentivize landowners to increase C in their forests in exchange for payment. A key aspect for establishing eligibility for the CARB market is determining how a parcel's current and projected C stocks compare to regional "common practice" baselines. Landowners of forests with C stocks above these baselines receive initial C payments (effectively rewarding past C sequestration that contributed to that differential) while also committing to management strategies that will maintain stocks above the baseline over a 100-year period. However, these regional baselines may inadvertently represent ecological conditions—especially with regards to stem density—that are suboptimal for tree and forest health, especially under changing climatic conditions.

As recently noted by Anderson-Teixeira and Belair (2022), effective C programs should be based on the best available science,

and pitfalls including potential over-crediting due to the use of illogical ecological thresholds (e.g., Badgley et al., 2022) must be remediated. In particular, Anderson-Teixeira and Belair (2022) noted that scientists should help improve C accounting methodologies to enable more credible estimates of C mitigation potentials based on objective forest C baselines, which likely requires more rigorous assessments of forest C stocks and fluxes across both space and time. Beyond improving estimate credibility, there is a strong need to rectify incongruities between ecological conditions incentivized by C programs and maintaining key forest functions and attributes, including vulnerability to extreme climate and disturbance events (Hurteau et al., 2019), as well as wildlife habitat provisioning (e.g., Littlefield & D'Amato, 2022). For example, does maximizing forest C across the landscape now truly lead to long-term C stability (i.e., minimizing risks of future emissions) for future generations as global change accelerates? One simple yet effective method for improving C accounting methodologies is evaluating and re-calibrating the current ecological thresholds that effectively underpin the baselines used for determining project eligibility.

Carbon accounting methodologies, including CARB's, rely primarily on absolute and basic ecological metrics like total basal area (i.e., the average area occupied by tree stems) or C stocks with thresholds varying by ecological region (i.e., "supersections"), forest type, and site productivity (e.g., Kaarakka et al., 2021). Although these baselines reflect general conditions, they may ignore differences in forest developmental stage, biological potential for sequestration, and emission risks of natural disturbances that can be compounded by

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climate change. In contrast, more biophysically-relevant measures that can simultaneously account for stand development like relative density (RD) can guide management towards optimizing sequestration, while affording adaptability under changing conditions. Relative density, which is based on metabolic scaling theory (Enquist & Niklas, 2002), integrates tree size and density and thus expresses the degree to which a forest stand is “packed” with trees. Optimum RD levels reflect conditions that achieve full canopy closure, while minimizing competition between trees (and therefore tree mortality). Non-optimum RD levels may accelerate tree decline and mortality due to mechanisms that hinge on density (e.g., competition-induced moisture stress, insect invasion, and/or catastrophic fire spread). Recently, Woodall and Weiskittel (2021) highlighted current trends in RD across the United States and suggested that RD values have significantly increased in the last two decades, which have important implications for future management actions and climate adaptation, C sequestration, and mortality rates. In light of these trends, we must assess potential strengths of basing C thresholds on robust relative measures of forest attributes like RD that are strongly linked to ecological dynamics, in contrast to the absolute metrics C accounting methodologies often rely upon.

To compare these approaches, we summarized the range in rates of net forest C sequestration and its components, gross

growth and mortality, for forestlands across the United States using CARB (i.e., basal area) and RD thresholds. This was done using USDA Forest Service Forest Inventory and Analysis (FIA) Time 1 (1999–2012) and 2 (2013–2020) data from Woodall and Weiskittel (2021). We summarized these data by the “supersections” that inform CARB’s “common practice” baselines and calculated the following attributes over these two most recent inventory periods: (1) annual aboveground (AG) gross C sequestration based on growth of live, harvested, and ingrowth of trees greater than 2.54 cm diameter at breast height (dbh); (2) annual AG C mortality; and (3) annual AG net C sequestration, which is gross sequestration minus mortality. We compared how the relative frequency of these values differ when expressed per CARB (i.e., basal area) thresholds. For this analysis, the optimal RD was defined as being between 0.3 and 0.4 based on common application of this metric (e.g., Jack & Long, 1996). Total acreage of lands currently eligible for C market enrollment (i.e., private forest lands) in both Time 1 and 2 that met or exceeded current CARB basal area-informed baselines and our alternative RD-based approach were computed using FIA’s expansion factors for each plot.

Relative frequencies of components of net C sequestration across forest types and site conditions suggest that gross C sequestration rates are seemingly higher when aggregated by basal

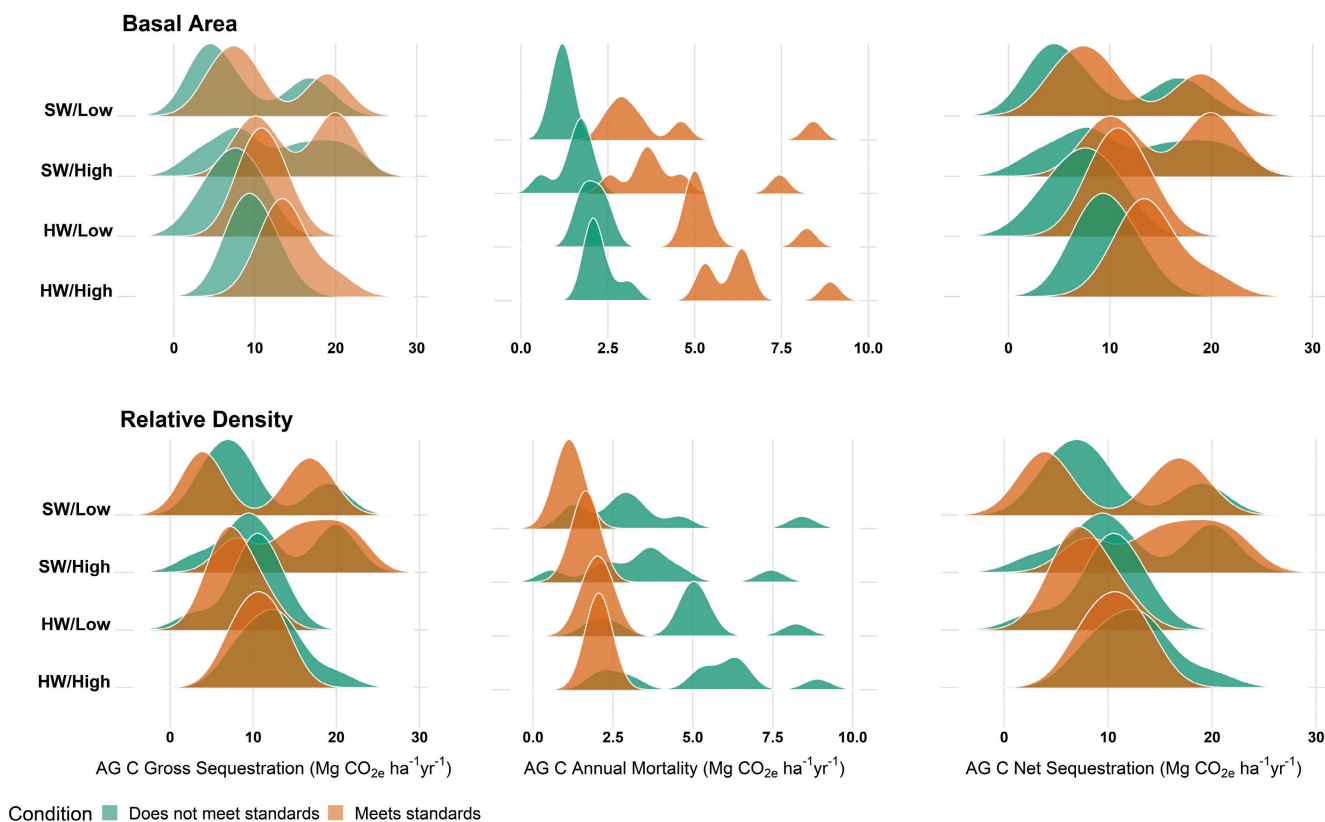


FIGURE 1 Relative frequency distribution of observed annual aboveground (AG) carbon (C) gross sequestration (left), mortality (middle), and net sequestration (right; $\text{Mg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$) summarized across supersections by forest type (Hardwood [HW] vs. Softwood [SW]) and site class (Low vs. High) based on approximately 130,000 remeasured USDA Forest Service Forest Inventory and Analysis plots across the United States. Top panels summarize conditions in plots that do and do not meet the California Air Resources Board standards based on total basal area, whereas bottom panels summarize conditions in plots falling inside and outside of optimum relative density levels

area-informed thresholds, but these forests also have greater levels of mortality such that net sequestration is similar between “below” and “exceeds” CARB standards (Figure 1). In other words, the apparent C benefits of exceeding the existing basal area-informed baselines are, in aggregate, negated and will likely decline with time given increased mortality trends. In contrast, delineating values based on optimal and suboptimal RD reveal a clear threshold above which C losses to mortality are greater, while net sequestration is similar to traditional baselines due to such losses. In an accounting framework, mortality represents current and future emissions (i.e., transfer to dead wood pools) with these risks compounded by wildfire potential in some systems, yet the mortality risks that are inherent to the inflated basal area-informed thresholds remain unaccounted for. Alternatively stated, current accounting methodologies based on the predominantly fully stocked and/or often overstocked forests following the intensive land-use changes in the 1800s–1900s (e.g., eastern agricultural abandonment and western wildfire suppression) belie the fact that density-dependent mortality reduces net sequestration rates of forests to levels comparable with rates achieved when RD values are informed by forest health objectives. The tradeoff of promulgating high-stocking of US forests for C objectives (i.e., C maximization), as current basal area-based thresholds do, rewards current conditions and historic sequestration without factoring in future vulnerability, which may manifest as increasing rates of live C transfer to dead pools (i.e., increased tree mortality) combined with higher risk of associated C loss to emissions due to accelerating decay and/or combustion.

In addition to the observed differences in net C sequestration based on the ecological threshold used, another striking difference between current standards and the use of optimum RD is the amount of US forestland area that satisfies either criteria (basal area-informed or RD), particularly given the shifts in forest RD observed by Woodall and Weiskittel (2021). Since 2012, forests have generally shifted to higher densities, which has effectively reduced the timberland area below the current CARB basal area standard from 39% to <24%. In contrast, the timberland area with an optimum RD has decreased from 11% to 4%, with approximately 83% of the current area above the optimum RD. This implies that nearly 14% of the current timberland area is below the optimum RD and could benefit from assisted natural regeneration or reforestation methods, which could greatly improve C sequestration across the US (e.g., Domke et al., 2020). For forests above the optimum RD, a variety of forest management strategies can be employed to reduce stand density and optimize C sequestration rates (i.e., C stability) (Karakka et al., 2021), while also affording a range of habitat conditions and/or addressing degradation concerns presented by invasive species, insects, or disease. Consequently, using the optimum RD as a guide allows for multiple management strategies to be used and multiple objectives to be achieved rather than solely focusing on increasing density like existing basal area-based C thresholds in essence require.

Overall, we simply ask, is the emerging Improved Forest Management (IFM) paradigm really improving forest conditions and supporting climate change mitigation in the long term? As our data suggests, IFM practices (as currently defined) inordinately focus

on maximizing C storage in the present at the potential expense of future provisioning, while achieving net C benefits no greater than forests with more optimal densities and reduced emission risks. Moreover, the uniformity and higher stocking that existing basal area-based methodologies compel us towards may undermine future provisioning of critical forest ecosystem services and habitat (e.g., water, wildlife; Littlefield and D'Amato (2022)). We suggest that IFM could be improved by adopting more biologically relevant yet flexible metrics like RD and expanding research into explicit consideration of C transfers among live to dead biomass pools, incorporating more robust assessments of tradeoffs across space/time, and considering the long-term sustainability of the practice in light of emission risks such as forest loss due to disturbances exceeding the historic range of variability and/or exceeding adaptive capacity. In short, are historic gains being credited with untenable thresholds that are not biophysically-informed at the expense of future, substantial emissions?

CONFLICT OF INTEREST

The authors declare no conflicts, financial or otherwise, that could be perceived as influencing the research described here.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in figshare at: <https://doi.org/10.6084/m9.figshare.19690936.v1>; <https://doi.org/10.6084/m9.figshare.19630119.v1>; <https://doi.org/10.6084/m9.figshare.19521970.v1>

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