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Enhanced observation of forest albedo reveals significant offsets to reported carbon benefits

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Abstract

Rapidly maturing frameworks for investing in and committing to mitigation of climate change through forest management have focused almost exclusively on the benefits of carbon sequestration, without accounting for collateral changes in geophysical factors such as surface albedo. Newly available 30m albedo retrievals derived from imagery acquired by the Landsat 8 satellite, analysed at 273,652 field plots monitored by the United States Forest Service, suggests that large areas of the U.S. Inter-Mountain West's forests have a net warming impact on the planet's surface energy balance. For the conterminous U.S. (CONUS), the impacts of albedo offset approximately half of the recognized non-soil forest carbon storage benefit. The emerging capacity to resolve albedo evolution at the scale of a large number of inventory plots also provides unprecedented empirical evidence that albedo impacts vary strongly as a function of both tree age and species group. This research highlights a correctable source of uncertainty in operational monitoring of forest-climate interactions, and it may temper expectations for forest establishment as a means of mitigating global climate change.

Keywords: albedo, forest carbon, Landsat, forest inventory

1. Introduction

Climate conventions acknowledge that albedo and other geophysical variables might impact the net climatic effect of managed forests (Jia *et al* 2019, COP 2015). Surface albedo is the fraction of incoming solar radiation that is reflected from the Earth's surface back into space. The relatively low albedo of tree canopies in relation to other land cover types can represent a global warming factor as more energy is introduced to the climate system instead of radiating into space. Work with land surface models (Bonan 2008, Mykleby *et al* 2017) and with modeled albedo values (Williams *et al* 2021, Hasler *et al* 2024, Rohatyn *et al* 2022) suggests that albedo changes occurring with the establishment and aging of forests may significantly offset benefits associated with forests' capture of atmospheric carbon in the form of biomass. However, while extensive systems have emerged for tracking forest carbon in the context of market- and treaty-based commitments (Nesha *et al* 2021, Espejo *et al* 2020, Hurtt *et al* 2022), operational consideration of albedo in those contexts has been hampered by limited capacity for empirical measurement.

We used newly available high-resolution albedo observations developed from Collection 1 Landsat 8 satellite imagery (Erb *et al* 2022, Roy *et al* 2014) to assess, at CONUS- and subnational-scales, how albedo changes associated with forested conditions across the United States affect the climate. Landsat's ground field of view (30 m) better matches the dimensions of most field inventory plots than previously available 500m products from MODIS (Wang *et al* 2014). We analysed three years of albedo data acquired over the footprints of 273,652 inventory plots maintained by the USDA Forest Service Forest Inventory and Analysis Program (FIA). FIA is the national forest inventory, and this analysis used the non-public "true" geographic plot coordinates, following the FIA Program's protocols to maintain plot confidentiality.

Surface albedo acquired September, 2016 to April, 2019 for each forested sample plot was compared to albedo measurements from the ten closest non-forest plots measured by the USDA Forest Service (mean distance = 18.75 km), with the difference calculated as an instantaneous radiative forcing (RF) (Bright and O'Halloran 2019a) that was then converted to a carbon-equivalent metric (TDEE, Time Dependent Emission Equivalent), hereafter called "albedo impact" (Bright *et al* 2016, Bright and Lund 2021). Inclusion of full-year albedo evolution was important for calculating albedo impact because dynamics outside of the growing season factor into difference between, for example, deciduous and evergreen forests, as discussed later. Use of FIA's sample falling outside of forest areas provided locally specific alternative non-forest albedo baselines, allowing direct comparison, in terms of impact on the planet's current energy balance, of the carbon storage and (generally) decreased albedo associated with forests measured across FIA's national forest inventory.

In addition to modifications to the surface albedo, forest cover perturbations are accompanied by sensible and latent heat flux perturbations which can result in atmospheric adjustments that moderate RF (Smith *et al* 2020, Hansen *et al* 2005, Sherwood *et al* 2015). However, the sign and magnitude of these adjustments are highly uncertain and climate model-dependent (Smith *et al* 2020, Richardson *et al* 2019). As others have done (Lutz *et al* 2016, Potter *et al* 2019, Graf *et al* 2023, Rohatyn *et al* 2022), we focused only upon the external forcing of albedo on the top-of-atmosphere energy budget.

Evaluating albedo impact at forest plot locations of known carbon storage, forest age, and forest (species) type allowed us to both: 1) assess the magnitude and dynamics of albedo change across complex landscapes, and; 2) demonstrate that it is practical to infer joint carbon-albedo climate impacts with straightforward estimates of uncertainty. As forest management is increasingly seen as a "natural climate solution" (Griscom *et al* 2017, Kaarakka *et al* 2021), it is important to know how investments in increased carbon storage might be offset by countervailing albedo dynamics.

2. Methods

2.1 Landsat albedo

Land surface albedo is a function of both the hemispherical incoming solar radiation and the outgoing hemispherical radiation reflected by the surface. The methodology originally presented by Shuai et al. (2011) and further developed by Wang et al. (2016) was applied to generate 30m albedo from Landsat 8's Operational Land Imager (OLI). This approach pairs Landsat Collection 1 30m surface reflectance values with the daily concurrent MODIS MCD43 V006 500m BRDF product to generate white-sky (assuming completely diffuse illumination) and black-sky (assuming completely direct illumination) albedos at 30m resolution (Wang *et al* 2018). To generate accurate forcing calculations, these atmosphere-free albedos were combined as a function of aerosol optical depth (AOD) to generate blue-sky or true albedos under specific illumination and atmospheric conditions. Given inclusion of snow-covered surfaces in this work, full-expression blue-sky albedo computations were used for all forcing calculations.

Landsat Collection 1 was used in this analysis because of known Collection 2 issues involving overcorrection of aerosol path radiance in Landsat 8-9 Surface Reflectance resulting in nonphysical values over bright surfaces (http://usgs.gov/landsat-missions/landsat-collection-2-known-issues). Given the sample-based nature of this assessment and the importance of albedo retrieval over snow, we could not simply drop plots with reflectance values outside the expected range. We therefore reverted to Collection 1 imagery.

This algorithm (Román *et al* 2010) was developed for the MODIS albedo products. It uses extensive modeling of atmospheric and illumination conditions within the MODTRAN radiative transfer model and specifically considers multiple scattering events shown to be particularly valuable in generating albedo under snow covered conditions. To implement the full-expression blue-sky albedo operationally, atmospheric aerosol optical depth values were retrieved from Terra and Aqua Aerosol Cloud Water Vapor Products (MOD08v06 and MYD08v06) at daily, eight day and monthly time steps (Platnick *et al* 2017). If no valid measurements were recorded on a daily timestep, the eight-day interval product and monthly products were queried. In cases where no valid AOD information could be retrieved, a universal climatology value of 0.2 was used. Blue sky albedo was produced for all cloud-free pixels over the entire Landsat 8 archive across the conterminous US from September, 2016 to April, 2019. The length of this 22-month period was judged necessary to provide an adequate sample of the rarer forest type/age group bins in every month. It included three winters, covering the months in which albedo acquisition is most affected by clouds in some regions. This Landsat albedo dataset is freely available from the authors.

2.2 Calculation of Time-Dependent Emission Equivalent for albedo effects

Determining the radiative forcing (RF) of forest as a land use in terms of both albedo and carbon storage depends upon quantifying the difference in energy flux between forested lands and comparable non-forest areas. For albedo forcing in this investigation, this involved the contrast between Landsat blue-sky albedo retrievals for a given forested inventory plot and mean retrievals from the ten nearest non-forest inventory plots. FIA maintains a network of inventory plots at a density of one plot per 2428 hectares across the U.S. (Bechtold and Patterson 2005); plots are allocated randomly and include both forested conditions and other land uses. FIA's definition of forest involves land being managed to allow tree growth above minimum thresholds of cover and height, regardless of whether those thresholds have yet been met.

Landsat does not measure albedo continuously; the mission uses a nominal 16-day repeat orbit, and it is common in many parts of the U.S. to lose up to 60% of an average image to cloud cover (Zhu *et al* 2018). We compensate for this by grouping albedo retrievals by the age (10-year bins) and forest type group (30 species assemblages) of observed forestland, as well as by month. The FIA sample used here contained 273,652 plots, and most of the forest type/age bin combinations used in this paper were represented by dozens if not hundreds of plots.

Figure 1 summarizes the process of leveraging Landsat albedo measurements across a large number of field plots of known forest type group and age to develop statistical estimates of albedo impact due to forested land use. This entailed:

1. The mean albedo measurement for a given plot in a given month was compared against the mean albedo retrieved at the nearest ten non-forest plots, producing a month-specific albedo difference value – or delta albedo ($\Delta\alpha = \alpha_F - \alpha_{NF}$);
2. Delta albedo in each month was used with location information and the CACK (CERES-based albedo change kernel) method (Bright and O'Halloran 2019) to quantify the shortwave radiative energy imbalance at the top of Earth's atmosphere due to the delta albedo. Output was a month-specific radiative forcing (RF) due to delta albedo for the plot;
3. The mean RF among all plots in each forest type/age group was determined for each month, using plot weights based upon published expansion factors consistent with FIA's sample design. Month-specific

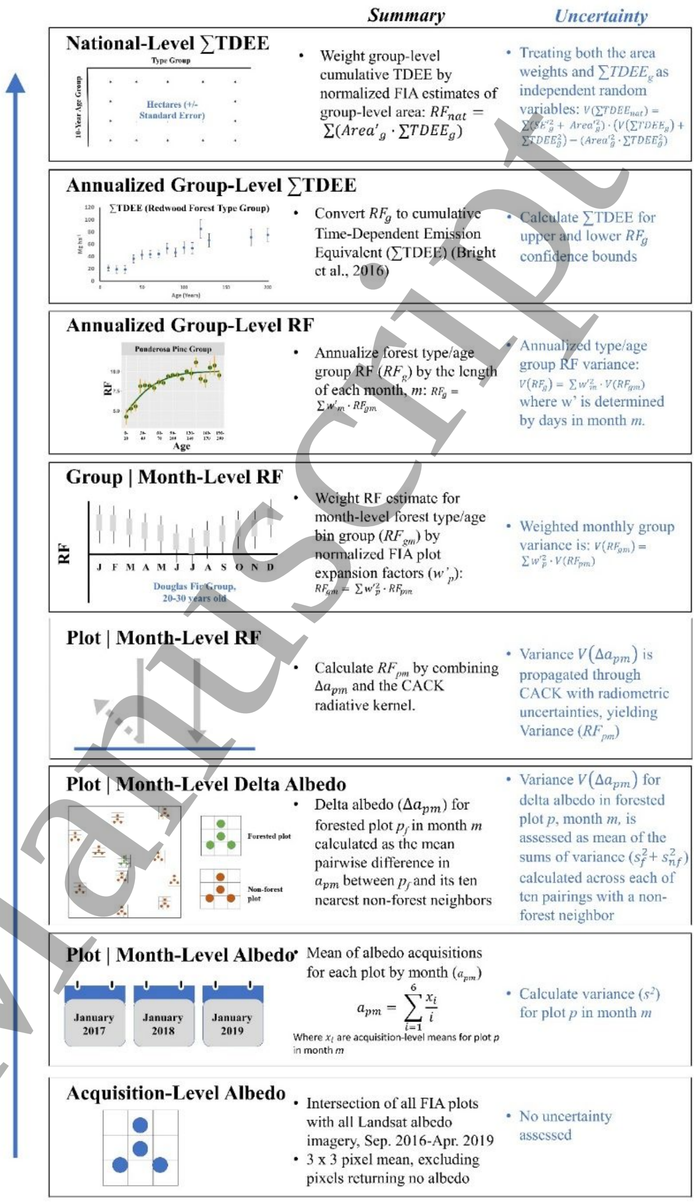

Figure 1. *Calculation and error propagation for carbon-equivalent albedo impacts, as quantified by the temporally accumulated time-dependent emission equivalent (∑TDEE; Bright et al., 2016). Estimation of mean ∑TDEE, in Mg ha*$^{-1}$*, for the country begins with retrieval of Landsat blue-sky albedo on both forested and non-forested FIA plots, followed by determining plot-level albedo differences from neighbouring non-forest plots, plot-wise conversion to RF through the CACK monthly radiative kernel, grouping plot-level RF values by month and age/forest type group, conversion to ∑TDEE and finally, making a CONUS-level estimate weighted by the FIA-estimated area of age/forest type group (table S1).*

values were then annualized by forest type/age group;

4. Time Dependent Emission Equivalent (TDEE) was calculated for the annualized RF time series (with age as a proxy for time) and accumulated over all age bins (∑TDEE) (Bright and Lund 2021, Bright *et al* 2016);
5. The weighted average albedo impact for both all forests in the conterminous U.S. as well as for more than 12,000 640-km^2 hexagons covering the contiguous US was calculated using weights derived from the relative areas estimated by FIA (Frescino *et al* 2015) for each forest type/age group (see table S1).

It should be noted that while only cloud-free Landsat albedo values were used in the calculation of delta albedo, locally realistic impacts of clouds on incoming radiation were applied through CACK.

TDEE yields a time series of CO2-equivalent emission or removal pulses that generate a time-dependent radiative forcing scenario that exactly matches that which is induced by our time-dependent albedo change scenarios. In our case, the latter is determined for each species by chronosequencing the differences between the mean albedos in each 10-yr age bin and that of the non-forested reference plots. To compare to the average carbon stock for any given age bin, the TDEE time series is then summed across the antecedent time steps (age bins) and the units are converted from kg-CO2-equivalent./m^2 to t C-equivalent/ha. Details of the TDEE metric are provided in Bright et al. (2016) and evaluated against other CO2-eq. metrics, including time-agnostic measures, in Bright & Lund (2021).

Uncertainties were propagated throughout this process, encompassing: the variance of albedo observations at the plot level; variance in delta albedo calculated for each plot in relation to each of its ten nearest non-forest neighbors; uncertainties related to the RF of a given delta albedo value from CACK; variance of RF values within a given bin; and the standard error of FIA area estimates used to weight forest type/age-specific RFs for a region of interest. Figure 1 traces these calculations.

Some FIA plots span boundaries separating different land uses, forest types, or age cohorts. These multiple-condition plots were omitted from albedo forcing calculations because Landsat albedo measurements could not be unambiguously assigned to particular conditions. Only plots measured since 2014 were used, and any plots disturbed (e.g., fire, harvest) between plot measurement and albedo acquisition, according to national disturbance maps (Healey *et al* 2018), were omitted. This left a total of 77,925 forested plots and 195,727 non-forest plots.

The spatial dimensions of FIA plots align with a 3x3 window of 30-m Landsat pixels. The spatial matching of FIA field plots to Landsat albedo data in figure 1 occurred whenever at least one clear albedo retrieval was available from the 9-pixel window centered over the plot; 2.9 million plot-level retrievals (9-pixel means) were collected over forested plots and 8.4 million retrievals were collected over non-forest plots.

2.3 Forest carbon storage

Mean forest carbon storage was calculated for each forest type / age bin, as well as for every hexagon and for the entire country, as a function of the biomass measured by FIA in all pools (including aboveground and belowground biomass, dead wood, litter) except soil organic carbon. Soil carbon is a significant pool both within and outside of forests, but FIA does not measure it outside of forests, so it was excluded from this analysis. The most recent measurements (up to August, 2021) of biomass on the forested conditions of all FIA plots were compiled using methods consistent with US national greenhouse gas reporting (Woodall *et al* 2015). Weighted average estimates of biomass density were made for the forest type/age groups mentioned above. Weights were determined by FIA condition-level expansion factors. In practice, these factors are adjusted by FIA for non-response at the state level. This introduced a small degree of imprecision to within-bin weights, as weighting operations treated expansion factors from different states interchangeably.

Unlike the albedo analysis, which could only unambiguously use plots representing a single condition, carbon analysis used all available plots. Estimates of the variance of the mean used sample-based expansion factors given for each plot as well as information about the fractional distribution of each plot among different forested condition.

2.4 Sensitivity of fractional albedo offset to disturbance and afforestation rates

Our CONUS-level estimation of carbon storage and carbon emission equivalents due to delta albedo, as described above, had two primary operations: 1) estimation of the mean by forest type and age group (fig S1); and 2) integration of those means with estimates of the distribution of US forests by type and age group (table S1). We explored the sensitivity of the net CONUS joint carbon/albedo impact to different rates of disturbance and afforestation by modifying the forest area distribution used in the second operation.

We created simple 30-year projections where, similar to methods used for national timber projections (Wear and Coulston 2019), we altered age distributions to reflect monotonic age increases for undisturbed forests and variable probabilities of stand-replacing change. Specifically, we simulated alternative changes to the stand-replacing disturbance rate (from 100% increase to 100% decrease) simultaneously with different levels of immediate afforestation (zero to 30 million ha). At ten, twenty, and thirty years into the future under each scenario, we generated a different realization of the type/age group area distribution in table S1 and recalculated a CONUS net RF.

With each time step, the area in hectares of the 0-10 year age group was simulated according to the scenario's defining change in disturbance rate. For example, a 50% increase in disturbance was represented by an 50% increase of the area of 0-10 year old forest, a rate of turnover held constant for the three time steps of the simulation. While disturbances can differentially affect forest ages and types in complex ways (McDowell *et al* 2020), we simplistically applied uniform probabilities of disturbance to each age group such that the area added to the 0-10 year age group was drawn proportionally from the other age groups at each time step. We left non-stocked forest areas (approximately 3% of the current distribution) constant throughout all simulations.

Each individual simulation also involved, for a given level of disturbance (above), establishment of 0-30 million ha (in 200,000-ha intervals) of new forest in the Oak-Hickory forest type group. The maximum area of simulated afforestation was 30 million hectares, approximately 12% of the current area of forests in the contiguous United States. To be clear, this involved simulating an increase in the area of the country's forestland, representing land use transition from other class such as agriculture or rangeland to forest. The Oak-Hickory type group was chosen because of its wide spatial distribution and its relatively high observed carbon storage relative to albedo impact. The appropriate amount of area was added to the current 0-10 year age bin, and that cohort advanced through the age groups (subject to disturbance losses as described above) through successive decades. Evidence of this kind of afforestation event can be found in actual age distributions measured by FIA (Healey and Menlove 2019). A total of 3171 simulations were run for each of three decadal time steps (10% disturbance rate change intervals from 100% decrease to 100% increase, and 0-30 million hectares of afforestation 200,000-hectare intervals). Each simulation of joint afforestation level and change in disturbance rate produced a mean carbon storage and ∑TDEE, from which a fraction of carbon benefits offset by albedo effects was calculated. A heat map interpolation technique was used to display results across scenarios all disturbance and afforestation scenarios.

3. Results and Discussion

Mean carbon and carbon-equivalent albedo impacts measured on the national plot network maintained by the USDA Forest Service Forest Inventory and Analysis Program (FIA) were summarized by 10-year age bins for each of FIA's 30 forest type (species) groups (fig. S1; (Healey and Yang 2023)). Uncertainties were obtained as summarized in figure 1.

The albedo contrast between forests and paired nearby non-forest areas represented a warming factor (positive carbon-equivalent value in figures 2A and S1) in nearly every age group / forest type combination. Albedo impacts in deciduous forest type groups (blue spatial distributions in figures 2B and S1), which expose bright sub-canopy surface elements (snow, exposed soil/litter) outside of the growing season, were generally lower than the impacts of evergreen forests (red distributions). Forest types common in mountainous and high-latitude areas (see above-referenced distribution maps) generally exhibited larger albedo impacts, as snow cover can accentuate the albedo difference between forests and areas without trees (Jin *et al* 2002). These dynamics are evident in the strong albedo impacts of Lodgepole Pine forests, which form dense, evergreen canopies in snowy alpine areas, compared for instance to deciduous-dominated Oak-Hickory forests, common in more mesic areas (figure 2).

To our knowledge, this is the first broad-scale empirical study to quantify albedo impact dynamics as forests age beyond initial stages of post-disturbance recovery. Hasler et al. (2024) used modelled albedo values to calculate locally representative transitions between forest and different non-forest land use classes, but did not address those transitions as a function of stand development. Using more empirical albedo retrievals and with access to detailed tree list information, we found albedo impacts to vary dynamically with age and across specific forest type groups, keeping up with or surpassing the impact of carbon storage in some groups (figure 3). Figure 3a suggests that while albedo impact remains relatively stable as a function of age in some forest type groups, it continues to grow in others (see also fig. S1). The current descriptive analysis does not suggest an ecological mechanism for the observed differences, although changing species mixes across age bins within the same type group may play a role, as may shifting understory composition and variable self-thinning dynamics.

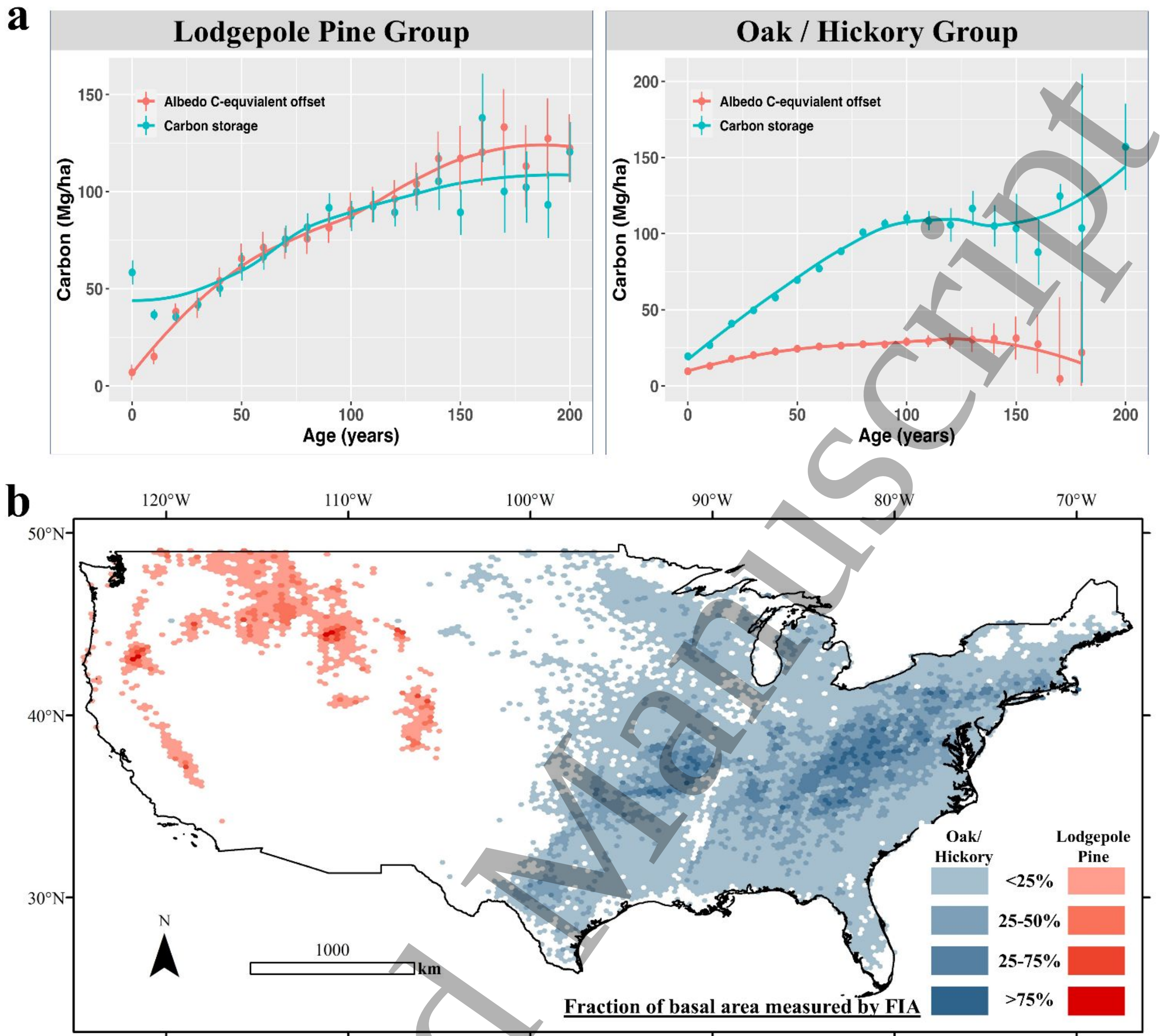

Figure 2. *Comparison of carbon and carbon-equivalent albedo impacts derived from independent sample plots in two widely distributed FIA forest type groups: Lodgepole Pine and Oak Hickory. Measurements made at the location of FIA forest plots were used to create estimates (with 95% confidence intervals) for each 10-year age group (Fig. 1a). Estimates are linked with a LOESS line for clarity. While albedo effects largely negate carbon storage benefits in Lodgepole Pine forests, they represent a more minor offset that decreases with age in Oak-Hickory forests. Occurrence of these forest type groups in FIA's sample is mapped as a fraction of all basal area in figure 2b.*

The age profile of how albedo offsets carbon storage is highly relevant for the timeline of benefits expected from efforts to mitigate climate change by way of afforestation (Lutz *et al* 2016). For example, while approximately 78% of the carbon storage benefit of Oak/Gum/Cypress forests 10 years after establishment is offset by albedo impacts, that fraction falls to 31% after 100 years (figure 3). Lodgepole pine exhibits the opposite trend (41% at 10 years vs. 103% at 100 years; figure 3). The attractiveness of planting these species would vary substantially if an afforestation project were targeting mitigation in the 2030s vs the 2120s.

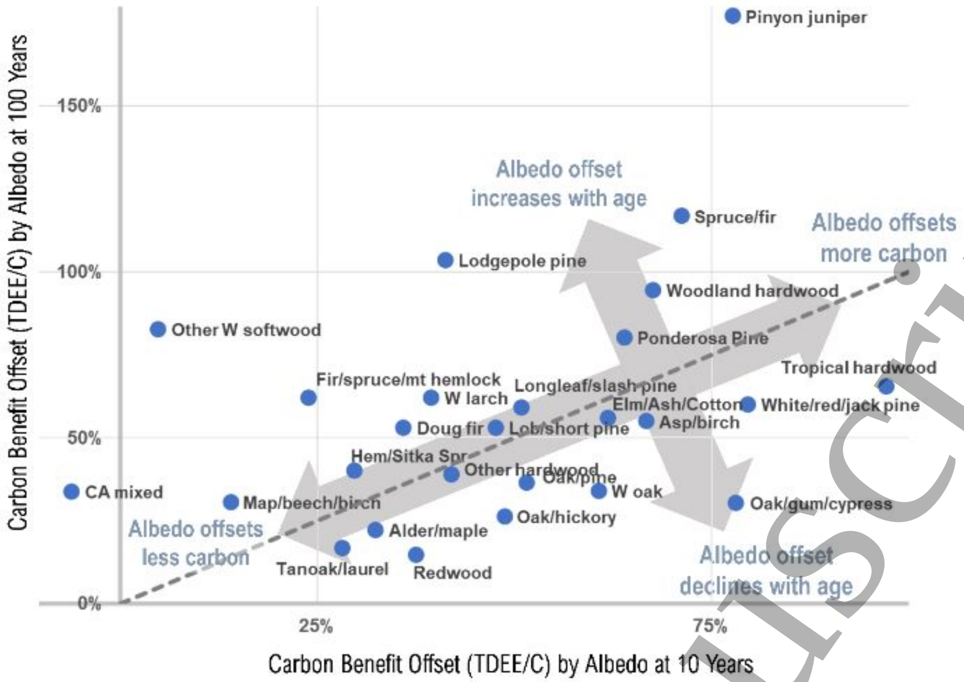

Figure 3. *Change in albedo impacts as stands age from 10 to 100 years old, expressed as a fraction of carbon storage by FIA forest type group. Forest planting and protection projects vary in the timeline of expected carbon benefits. This study shows that the intensity of albedo (offset) impacts likewise varies as forests age. The dashed line indicates stable offset fraction from 10 to 100 years of age; perpendicular to that axis are forest type for which the relative impact of albedo either increases (above the line) or decreases (below) through the first century of stand development.*

However, climatic impacts are dynamic, and the mean radiative forcing associated with existing 50-year old forests, for example, are not necessarily predictive of impacts of newly planted forests 50 years into the future. In addition to global change factors that may alter carbon storage rates (e.g., variation in growing season length, uptake by oceans, and evolving atmospheric composition), changes affecting albedo impact trends, such as decreased snow residency and altered radiative transfer dynamics, are also likely.

A CONUS-scale estimate of mean albedo impact of US forests was made by weighting the age-by-type group estimates in figure S1 by FIA estimates of the areas of those combinations (table S1). The mean carbon-equivalent albedo impact of US forestland (excluding Alaska and Hawaii) was 35.44 ± 0.17 Mg ha^{-1}, compared to mean estimated carbon storage in all non-soil pools of 71.67 ± 0.36 Mg ha^{-1}. Albedo impacts, quantified as we describe in terms of external forcing of the top-of-atmosphere energy budget, thus offset approximately half of the country's forest carbon storage benefit.

Strong regional patterns emerge (figure 4) when joint carbon-albedo impacts are mapped according to the ages and types of forests measured by FIA within 640-km^2 hexagons sometimes used by the inventory for high-resolution analysis (Menlove and Healey 2020). While albedo impacts below 40% of carbon storage are common in the mid-Atlantic and West Coast regions, many of the forests in the drier interior parts of the country vary from net neutral to exhibiting strong joint net warming. This is consistent with recent findings that global dryland forests have limited climate change mitigation potential due to albedo (Rohatyn et al., 2022).

Sensitivity analysis showed that neither intensive afforestation efforts nor variation of average distrubance rates would substantially affect the national fraction of carbon storage offset by albedo impacts (figure 5). While both factors have strong potential to affect gross future carbon storage and net climatic benefit, no simulated scenario caused the fraction of carbon storage offset by albedo impacts to vary outside of the range of 48-50% (figure 5). For instance, the simulated net carbon-equivalent climate impact (carbon storage minus albedo offset) of CONUS forests after 30-years between a scenario of 50% disturbance decrease and afforestation of 6.8 million hectares compared to a 50% disturbance increase with no afforestation is approximately 1800 teragrams. Despite this difference, the ratio of albedo impact to carbon storage plotted in fig.5 for these two scenarios (48.9% and 49.3% respectively) is nearly identical to the current percentage offset we estimate for CONUS (49.5%). Thus, while forest management in the U.S. has large climate mitigation potential, a CONUS-scale offset factor of about 50% is likely to remain appropriate for the foreseeable future.

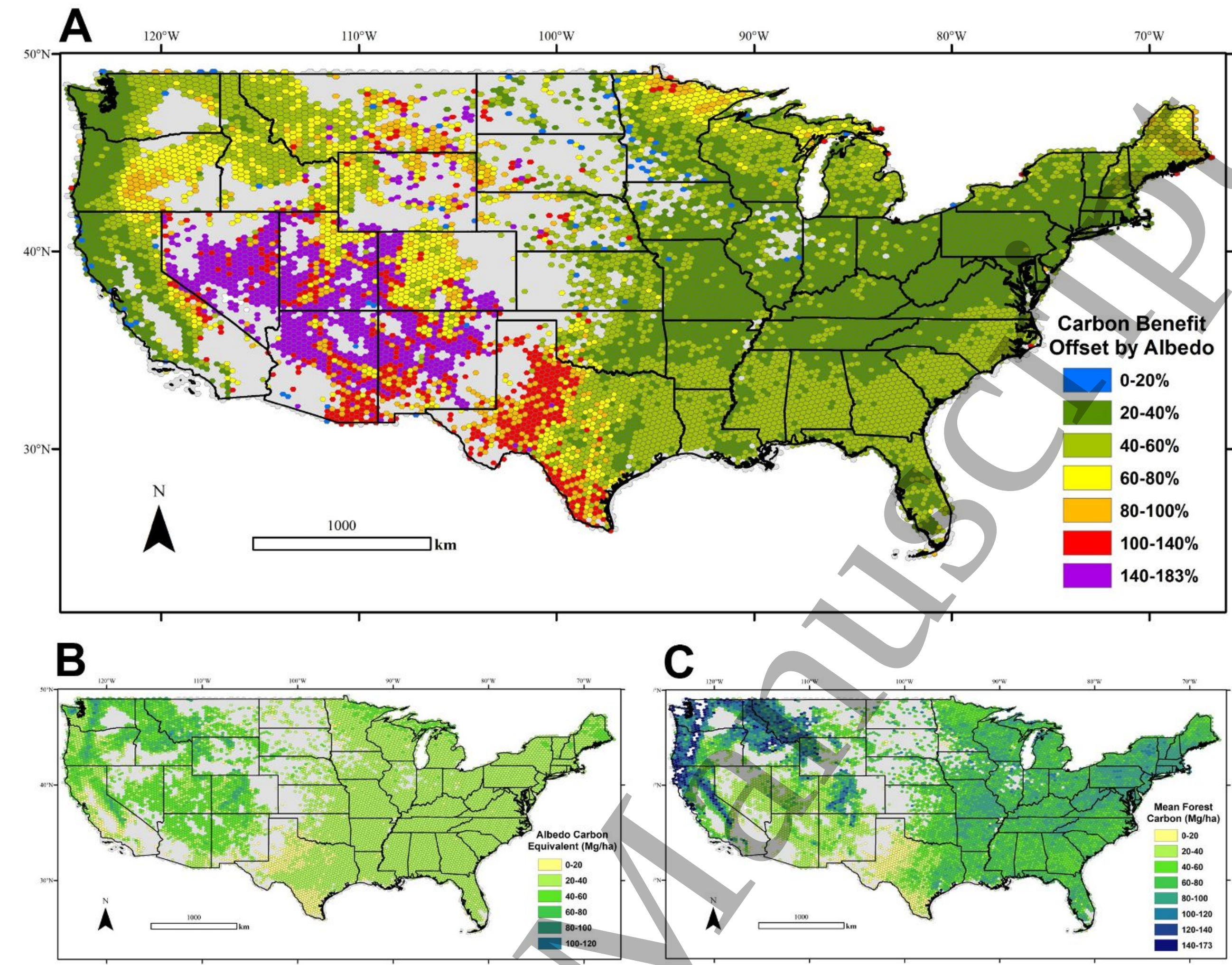

***Figure 4**. Average albedo impact expressed as a percent offset of forest carbon storage (figure 4a), calculated from the ratio of TDEE (figure 4b) to total non-soil carbon storage (figure 4c). Values greater than 100% indicate that forests exert a net warming impact with respect to joint albedo/carbon factors. Estimates are evaluated within 640-km2 hexagons, using carbon and albedo impacts displayed in figure S1, weighted by per-hexagon FIA estimates of forest type group and age group distributions. Regional patterns diverge substantially from the CONUS-level estimate of mean offset (0.494 ± 0.005).*

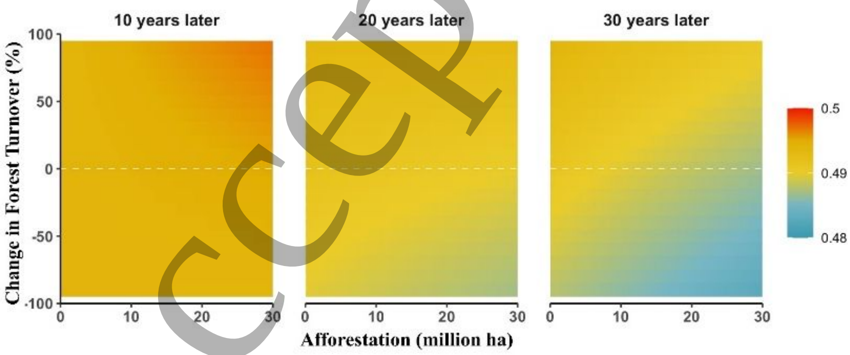

***Figure 5.** Sensitivity of albedo impacts as a fraction of non-soil carbon storage to simulated changes in the disturbance rate (Y axis) and increasing levels of afforestation using the Oak-Hickory forest type group (X axis). Colors represent the range of the CONUS-level ratio of ∑TDEE to non-soil carbon storage across simulations.*

4. Conclusion

As the global consequences of climate change become more urgent, and as alternative mitigation approaches emerge in the form of renewable energy (IPCC 2011, Ivanova *et al* 2020, Espejo *et al* 2020), industrial carbon capture (Tian *et al* 2018), and improved agricultural practices (Mosier *et al* 1998), it is important to clearly understand the effectiveness of forest management as an investment in climate change mitigation. The joint carbon-albedo dynamics we document show that forest as a land use results in warming in some areas, and that accounting systems which ignore albedo are likely to systematically overstate forest climate benefits. This has profound implications for Paris-aligned carbon budgets and for markets intended to generate forest carbon-based offsets for emissions in other sectors. Intact, resilient forests provide unparalleled, irreplaceable services in areas such as biodiversity (Betts *et al* 2017) and drinking water (Liu *et al* 2021). However, further diligence regarding albedo, and possibly other biophysical processes, may be needed to reduce what this study shows to be a large uncertainty in forest benefits related to global climate change.

It should be noted that this study of US forests gives little insight into the tropical ecosystems where many international efforts related to reducing emissions from deforestation are focused (Fuss *et al* 2021, Mackey *et al* 2020). Sample numbers in the Tropical Hardwood group (figure S1) were small, and radiative transfer in the tropics differs considerably from the latitudes studied here (Zhang *et al* 2004). However, simple assessments of joint carbon-albedo forest impacts should be possible, globally, using albedo retrievals from both Landsat (Radeloff *et al* 2024) and the Copernicus Sentinel-2 instruments (Roujean *et al* 2019, Lin *et al* 2022, Bright and Ramtvedt 2024) along with high-quality biomass measurements from sources such as NASA's GEDI mission (Dubayah *et al* 2020, Duncanson *et al* 2022).

Our sensitivity analysis showed that the CONUS-scale fraction of forest carbon benefit offset by albedo impacts storage (0.494 ± 0.005) is unlikely to change over the next few decades, even if management actions are taken to plant trees and control rates of natural disturbance. Nevertheless, both the disturbance rate (Birdsey *et al* 2019) and strategic tree planting (Kaarakka *et al* 2021) remain important management levers affecting the gross amount of carbon removed from the atmosphere and therefore overall climate change mitigation potential. Figures 2 and 4 highlight that not all forest carbon storage is created equal; geographic and forest type considerations can greatly influence the degree to which any amount of biomass is offset by albedo dynamics.

Having comprehensive, high-resolution albedo observations over time was critical to our analysis and will be important in any movement toward practical global albedo monitoring. Forest conditions vary over short distances (Franklin and Van Pelt 2004), and resolving albedo evolution at the scale of most inventory plots (approximately 0.1 ha) is crucial for detecting factors that cause forest albedo to change. Land use is likewise granular (Barnes and Roy 2008), and to the degree that previous past use of coarse-resolution imagery conflated albedo of forest and non-forest conditions, assessed albedo contrasts and impacts may have been biased downward.

Considering only carbon in international agreements or in afforestation projects may result in sub-optimal or even counter-productive outcomes with respect to limiting climate change (Luyssaert *et al* 2018). While it remains difficult to systematically monitor forest impact on some geophysical processes, such as transpiration (Tan *et al* 2019), surface roughness (Winckler *et al* 2019), and production of biogenic volatile organic compounds and subsequent formation of secondary organic aerosols (Claeys *et al* 2004), our study of albedo suggests that the impact of physical processes may vary acutely with forest condition and may be significant in relation to carbon storage benefits. This is relevant context for frameworks oriented around natural climate change solutions, suggesting the need for broader climate impacts to be considered.

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[see separate file Supplementary_files_Healeyetal.pdf for table S1 and figure S1]

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