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Integrating albedo offsets in reforestation decisions for climate change mitigation outcomes in 2050: A case study in the USA

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ABSTRACT

Reforestation is generally regarded as having the most substantial climate mitigation potential among a suite of available natural climate solutions which have focused almost exclusively on the benefits of carbon sequestration and storage. However, these reforestation studies have not accounted for the adverse warming impacts resulting from corresponding surface albedo change. A newly available dataset developed with albedo imagery from the Landsat 8 satellite analyzed at field plots from the United States (US) Forest Inventory and Analysis (FIA) program provides non-soil carbon stocks and corresponding carbon-equivalent albedo offsets for 30 distinct forest-type groups indexed by 10-year age bins. In this case study we leverage this new dataset in concert with FIA species distribution data to investigate reforestation scenario planning based on joint carbon-albedo estimates (non-soil carbon stock less a carbon-equivalent albedo offset) instead of just carbon storage estimates alone. Specifically, our analysis informs managers interested in planting optimal forest-type groups for climate change mitigation outcomes approaching the year 2050. We assist in one of the most fundamental steps in any reforestation project: deciding which forest type or tree species mix to plant. We present our results as forest-type group recommendations within 64,000 hectare hexagons as a means to offer localized guidance and to examine the spatial patterns of albedo impacts across the conterminous US. We found that albedo offsets were most impactful on decisions in the Northeastern regions of the US, where optimizing for joint carbon-albedo in the next 25-years implies planting deciduous forest-type groups (Maple/beech/birch) instead of otherwise carbon-optimal coniferous forest-type groups (White/red/jack pine). Although the consideration of albedo did not alter 25-year tree planting decisions in most of the US, it did reduce the expected climate benefit of reforestation in general. We provide a standalone application that ranks all forest-type groups detected by FIA within a given hexagon, allowing managers to evaluate alternatives in light of site-specific constraints. This paper describes a replicable case study for incorporating albedo offsets in reforestation plans. Similar analyses may be performed anywhere Landsat albedo data are available over adequate measurements of forest carbon stocks.

Recommendations:

- Albedo impacts on 25-year tree planting decisions are concentrated in the Northeastern regions of the United States, where considering albedo offsets together with carbon stocks implies planting the Maple/beech/birch forest-type group in place of the otherwise carbon-optimal White/red/jack pine group.
- Our reforestation support application allows managers to explore localized forest-type group rankings on the basis of joint carbon-albedo benefits.
- Fine-resolution albedo data, which is not currently a standard data product, provides more comprehensive support for reforestation projects intended to mitigate global climate change.

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1. Introduction

The Intergovernmental Panel on Climate Change recommends that the global community achieves net-zero CO_2 emissions by 2050 to limit warming to ≤ 1.5 °C (IPCC, 2023; COP, 2015); as we approach this time horizon, there is increased interest in sustaining or increasing carbon storage in the land sector. It is likely that land managers are already aware of the carbon storage and sequestration benefits associated with the establishment and growth of forests (Griscom et al., 2017; Fargione et al., 2018). However, there is evidence that other geophysical variables, like surface albedo, will offset some of this mitigation potential (Shukla et al., 2019; Williams et al., 2021; Hasler et al., 2024; Lutz and Howarth, 2014). Within the conterminous United States (CONUS), recent advancements provide the ability to jointly consider the carbon benefits of reforestation with the countervailing effects of corresponding surface albedo change (Healey et al., In review), which generally function as a warming factor. In this case study, we leverage the joint carbon-albedo data (non-soil carbon stock less a carbon-equivalent albedo offset) born out of these advancements to support managers in decisions regarding which species mix or forest-type group to plant for maximum climate change mitigation potential. We describe the general geographic patterns of albedo impacts on 25-year (2050) tree planting decisions across CONUS and offer localized guidance by way of a downloadable application for land managers interested in making data driven tree planting decisions.

Natural climate solutions (NCS), a set of practices for manipulating natural systems to reduce the concentration of atmospheric greenhouse gases (GHG), have emerged as some of the most mature, well-established, and cost-effective strategies for mitigating global climate change (Griscom et al., 2017). Among the suite of documented NCS, reforestation has been estimated to offer the largest mitigation potential both globally (10,124 Tg CO_2 e $year^{-1}$; Griscom et al. (2017)) and within the United States (US; 307 Tg CO_2 e $year^{-1}$; Fargione et al. (2018)). The opportunity within the US is especially clear; Domke et al. (2020) reported that there are roughly 33 Mha of productive forestland classified as nonstocked (0%–9% tree cover) or poorly stocked (10%–34% tree cover), and Haase et al. (2022) reported a national capacity to plant ~1.4 billion seedlings per year. The large-scale expansion of the area of trees actively removing CO_2 from the atmosphere may offer numerous co-benefits and services, including increased availability of drinking water and enhanced biodiversity (Law et al., 2018).

International agreements, market mechanisms, and governmental policies are now in place to incentivize reforestation. Internationally, at the highest level, the United Nations Framework Convention on Climate Change and the Paris Climate Agreement (COP, 2015) explicitly support reforestation efforts through REDD+ (Corbera and Schroeder, 2011; Duchelle et al., 2018). Non-governmental organizations like the International Union for the Conservation of Nature and a consortium of conservation organizations (World Wildlife Fund, World Conservation Society, and BirdLife International) have launched the Bonn challenge (Verdone and Seidl, 2017) and the Trillion Trees program respectively. The former aims to restore 350 million hectares of degraded and deforested landscapes by 2030, and the latter supports forest restoration and tree planting generally. Within the US, at the federal level, the National Forest Management Act orders prompt reforestation, the REPLANT act mandates removing the reforestation backlog on national forest lands by 2031 and removes a 30 million US dollar cap on the Reforestation Trust Fund, and the Executive Order On Strengthening the Nation's Forest, Communities, and Local Economies (EO 14072) requires agency-specific reforestation targets by 2030 (Nave et al., 2018; Balloffet and Dumroese, 2022). At the state-level, several governments have produced climate action plans of their own, many of which aim to offset GHG emissions through forest restoration and tree planting (USCA, 2023; Lamb et al., 2021). In the private sector, the California cap and trade program (California Air Resources Board, 2024) and several voluntary carbon markets (American Carbon Registry, 2019; Verra, 2024; Climate Action Reserve, 2019) provide mechanisms for directing financial compensation to reforestation projects.

The reported benefit of, and subsequent momentum behind, reforestation as a climate change mitigation tool is almost entirely founded on potential for carbon storage and sequestration alone. However, it has been recognized by climate conventions (COP, 2015; Shukla et al., 2019) and recent studies (Hasler et al., 2024; Rohatyn et al., 2022; Williams et al., 2021; Mykleby et al., 2017; Lutz and Howarth, 2014; Bonan, 2008) that the changes in surface albedo corresponding with forest establishment and growth can result in a forcing of the planet's energy balance. Specifically, forests have lower albedo than most alternative land uses and therefore reduce the solar energy reflected into space. Healey et al. (In review) used newly available albedo retrievals (Erb et al., 2022; Wang et al., 2016; Shuai et al., 2011) from Landsat 8 together with measurements made by the US Forest Inventory and Analysis (FIA) program to quantify, in carbon-equivalent units, warming associated with the albedo evolution of different forest types and ages. Using albedo and carbon impacts measured across FIA's plot network, Healey et al. (In review) estimated that roughly half of the non-soil carbon benefits of US' forests are offset by albedo impacts.

Estimates of mean carbon stocks and albedo impacts supporting both Healey et al. (In review) and the current study are available from Healey and Yang (2023). Estimates in that dataset are grouped both by FIA's 30 forest-type groups and by 10-year age bins. In some forest types, Healey and Yang (2023) provide albedo impacts and carbon stocks for forests that are over 200 years old. Ongoing climatic and atmospheric changes prevent us from using such estimates to predict long-range impacts of trees planted today (related limitations are discussed more extensively in Section 3.3). In this study, however, we do use current carbon stocks and albedo offsets as a data-driven way to evaluate near-term (circa-2050) reforestation decisions. Projections of albedo-mitigated carbon benefits in this timeframe are motivated by pending net-zero emissions commitments targeting that year (Lamb et al. (2021); COP (2015); EO 14072).

In the context of providing managers with guidance regarding the 2050 benefits associated with reforestation efforts occurring now, our primary goal was to identify regions of the US where the optimal forest-type group for carbon storage is different than the optimal group when appropriate carbon-equivalent albedo offsets are applied. We use forest-type group co-occurrence in 64,000 hectare hexagons to define local species alternatives, and map regions where different species groups provide the best carbon vs. joint carbon-albedo outcome for the 20–30 year-old age bin. Recognizing that this broad-scale assessment does not account for site-specific factors like topography or other silvicultural considerations like fire resistance or merchantability, we also provide a standalone application that ranks all forest-type groups within each hexagon on the basis of joint carbon-albedo and aims to empower managers to leverage this information within the context of their unique understanding of site-specific constraints. In general, this case-study outlines a replicable approach for incorporating albedo offsets in tree planting decisions for climate change mitigation projects. Extension of this approach beyond the US is discussed below.

2. Data and methods

2.1. The Forest Inventory and Analysis database

The Forest Inventory and Analysis (FIA) program within the United States (US) Department of Agriculture Forest Service (USFS) maintains a nationwide network of permanent inventory plots arranged in a quasi-systematic hexagonal grid with a sample density of one plot for every ~2,400 ha (Bechtold and Patterson, 2005). The inventory records land uses, and within forested plots collects measurements of live and dead trees, litter, downed wood, and soil, as well as observations of stand-age and classifications into 30 forest-type groups. These measurements are later translated into estimates of biomass and carbon for five distinct pools (aboveground and belowground biomass, deadwood, litter, soil), are made available in a public relational database (Gray et al., 2012), and ultimately provide the basis for national forest carbon accounting (Woodall et al., 2015; Domke et al., 2023).

2.2. Joint carbon-albedo estimates by forest-type and age groups

Healey et al. (In review) applied standard FIA estimation methods to develop tables of non-soil carbon storage for the Inventory's 30 distinct forest-type groups, indexed by 10-year age bins. Although FIA has recently transitioned to using a new system of allometric models to convert granular measurements (e.g. diameter, height) to tree-level estimates of biomass and carbon (Westfall et al., 2024), Healey et al. (In review) obtained estimates based on the component-ratio-method (Woodall et al., 2011) which was the national standard at that time. Corresponding carbon-equivalent albedo impacts were identified for each type-by-age group using FIA's condition-level expansion factors for weights. Albedo impact for every FIA plot was determined by the annualized albedo difference, assessed through 4 years of Landsat albedo measurements (Erb et al., 2022), between the plot and its ten nearest non-forest plots. Monthly albedo differences were converted to monthly radiative forcings through the use of a radiative kernel (Bright and O'Halloran, 2019), and annualized radiative forcings were converted to carbon-equivalent units (Bright et al., 2016). All forested plots across CONUS were used to develop estimates for each age-by-type bin; in this way, the chronosequences of joint carbon-albedo estimates represent the national average of relationships between age and joint carbon-albedo for each forest-type group. Refer to Healey et al. (In review) for methodological details and Healey and Yang (2023) for resulting forest-type group-specific carbon stocks and albedo impacts.

2.3. Spatial patterns of albedo impacts on tree planting decisions

Treating the conterminous US (CONUS) as a case study for integrating albedo offsets into climate-aware forest planting decisions, we used a CONUS-wide hexagonal tessellation of 64,000 ha hexagons to explore spatial patterns of albedo impacts on tree planting decisions (White et al., 1992). These hexagons, which are sometimes used for fine-resolution analysis of the FIA database (Menlove and Healey, 2020), each contain ~27 FIA plots. Within each hexagon we identified the set of forest-type groups present in the most recent panel of inventories from each state (Bechtold and Patterson, 2005), and ranked each forest-type group at the 20–30 year-old bin (25 years represents the mid-point of this bin) on the basis of both joint carbon-albedo benefits (non-soil carbon stock less a carbon-equivalent albedo offset) and non-soil carbon storage estimated from the nationwide sample of forested plots (Section 2.2). We then computed the difference in 25-year joint carbon-albedo benefit between the joint carbon-albedo optimal forest-type group and the non-soil carbon optimal group to understand the impact (in units of megagrams per hectare [Mg ha^{-1}]) of only considering projected carbon stocks in the species selection process. To highlight regional patterns, we summarized hexagon-level results within USFS National Forest System regions (USFS, 2024). All spatial analyses were conducted with the sf package (Pebesma and Bivand, 2023; Pebesma, 2018) in the R programming language (R. Core Team, 2024).

2.4. Supporting managers through localized guidance

We developed a standalone application using the shiny and electron frameworks to support managers interested in making data-driven tree planting decisions (Chang et al., 2024; R. Core Team, 2024; Open J.S. Foundation). The application allows users to select a hexagon from a CONUS-wide map and subsequently exposes the full set of forest-type groups within the selected hexagon. The application ranks this set of forest-type groups based on 25-year joint carbon-albedo estimates and displays corresponding estimates of non-soil carbon storage, carbon-equivalent albedo offsets, joint carbon-albedo benefits, and associated uncertainties. Additionally, we present 100-year chronosequences (10-year bins) for each attribute (carbon, albedo offsets, joint carbon-albedo) across the same set of forest-type groups to offer insight into the temporal consistency of our recommendations.

3. Results and discussion

3.1. Regional concentration of albedo impacts

The following results explore how the consideration of albedo impacts jointly with carbon storage can affect the decision space of managers intending to generate climate change mitigation benefits with the stands they manage. We focus on a 25-year time horizon because of the importance of 2050 commitments (COP (2015); Lamb et al. (2021); EO 14072) and because global change limits our ability to project longer-term impacts (Section 3.3) using current carbon stocks and albedo impacts estimated by Healey et al. (In review). The majority of differences between 25-year carbon-optimal forest-type groups and joint carbon-albedo-optimal forest-type groups were concentrated in the Eastern region (USFS, 2024). In that region, > 50% of hexagons yielded a different forest type selection when carbon storage was appropriately offset by albedo impacts (Fig. 1). Roughly 26% of these differences, or ~14% of all hexagons in the region, indicate that the Maple/beech/birch forest-type group (MBB) should be planted instead of carbon optimal White/red/jack pine group (WRJP). Although 25-year carbon stocks are larger for the WJRP forest-type group (WRJP: 47.82, ± 3.27; MBB 38.65, ± 2.14), pine forests develop dense evergreen canopies yielding substantially larger carbon-equivalent albedo offsets (WRJP: 42.74, 1 SE interval [37.35, 48.12]; MBB: 11.89, 1 SE interval [7.88, 15.9]; Healey and Yang (2023)). As a result, planting MBB would yield an additional 21.7 Mg ha^{-1} of joint carbon-albedo benefits in 25 years relative to planting WRJP (Fig. 1 B). Although the consideration of albedo did not yield a different forest-type group relative to the carbon-optimal group in much of the US (Fig. 1), it did (and sometimes greatly) reduce the expected 25-year climate benefit of reforestation in general. Along these lines, Healey et al. (In review) estimated that roughly half of the non-soil carbon benefits of United States' (US) forests are offset by albedo impacts.

The concentration of 25-year albedo impacts in the Eastern region may be of particular interest given the Regional Greenhouse Gas Initiative (RGGI) that links 10 Eastern region states (11 including Virginia in the Southern region) in an emissions cap and trade program (Lamb et al., 2021). Forest carbon is not explicitly traded in the RGGI marketplace, however, all RGGI states have developed climate change mitigation planning documents guiding their GHG reduction efforts. All such documents describe the importance of forests and trees relative to strengthening statewide carbon sinks, and four such documents explicitly mention afforestation or reforestation as a specific strategy (Lamb et al., 2021).

Although we have presented planting MBB instead of WRJP forests as a simple, stark choice, site-specific conditions will govern the respective suitability and long-term success of each of these forest-type groups (see Section 3.2 for discussion on decision support in light of local context). Further, silvicultural practices that promote the establishment, health, and vigor of these two groups are distinct. MBB forests are suited to well-drained, fine-textured soils rich in calcium while WRJP forests are suited to coarse-textured, excessively drained outwash soils or eskers where hardwood trees are not competitive (Seymour, 1995). With the exception of birches, which will regenerate following clear cuts provided an adequate seed source, hardwoods within MBB forests regenerate best under partial shade, thus favoring the shelterwood method for regeneration (Seymour, 1995). This may present challenges

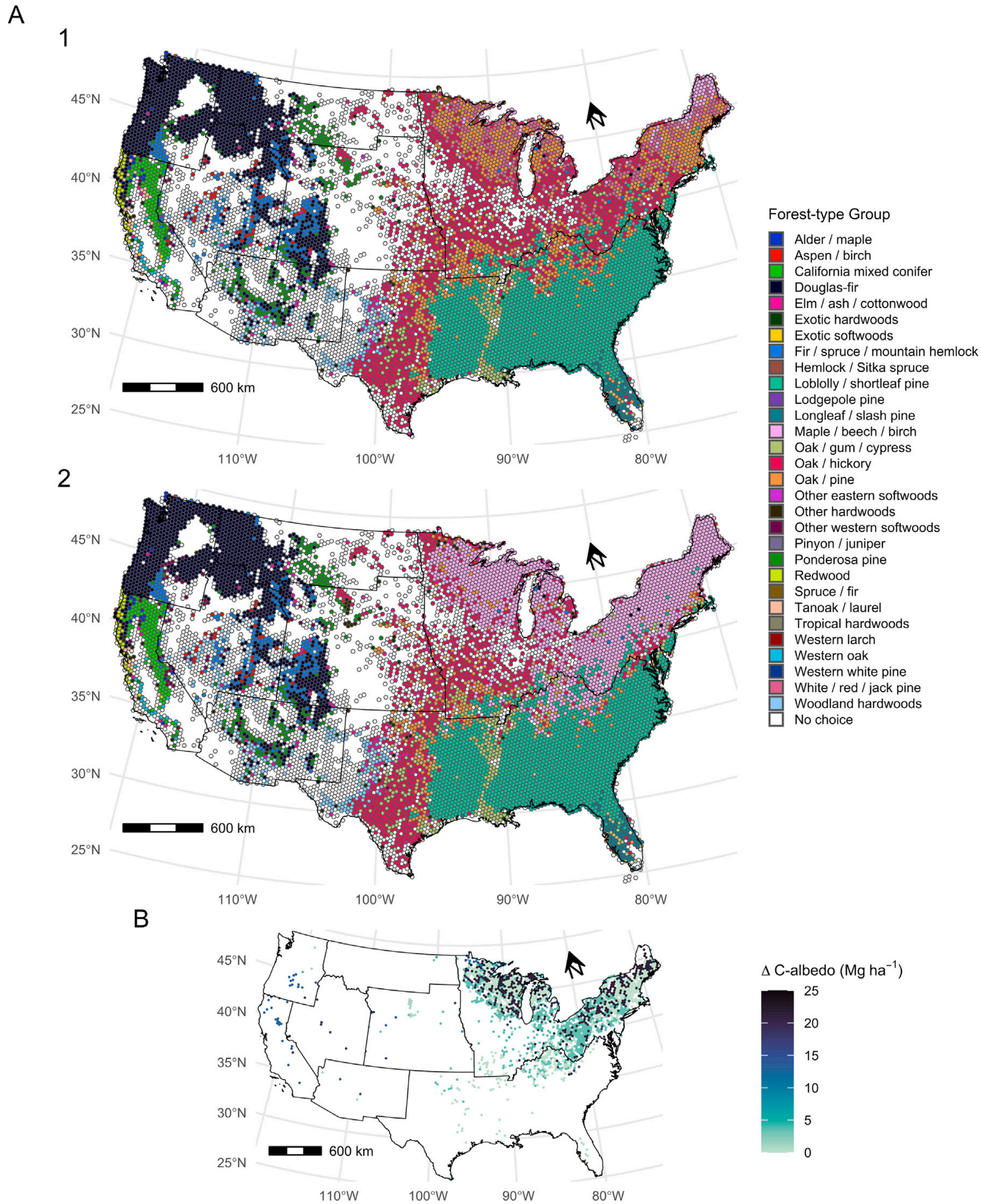

Fig. 1. Forest-type group recommendations (A) and opportunities (B) for a 25-year time horizon (2050). (A1) Forest-type groups to maximize non-soil carbon stocks. (A2) Forest-type groups to maximize joint carbon-albedo benefit. 'No choice' describes conditions where there was only one forest-type group present in the FIA inventory for a given hexagon. (B) Separation in joint carbon-albedo between the optimal forest-type group for joint carbon-albedo and the optimal forest-type group for non-soil carbon stocks. Hexagons were left blank where optimal forest-type groups (joint carbon-albedo, carbon) matched or when only one forest-type group was present in the FIA database ("No choice"). USFS National Forest System regions outlined in black.

in cases where tree planting projects target abandoned agricultural lands and adequate shading cannot be supplied to support regeneration of desired species (Xie et al., 2024; Mahoney et al., 2022; USDA National Agricultural Statistics Service, 2019). Conversely, areas with partial tree cover, like the millions of hectares of understocked timberland (<35% tree cover) across the Eastern region (Domke et al., 2020), may be prime candidates for planting MBB with limited investment in site preparation. It is worth noting that as soil fertility declines on MBB suitable sites, and where deer browse pressure is substantial (American beech [*Fagus grandifolio* Ehrh.] is not a preference), American beech may become important (Seymour, 1995). However, American beech are highly susceptible to beech bark disease and the emergent beach leaf disease, greatly diminishing the productivity of beech-dominant stands (Cale et al., 2017; Ewing et al., 2018).

In much of the western US there is no decision space available for managers to consider alternative forest-type groups for planting (Table

Table 1
Summary statistics grouped by USFS National Forest System region describing hexagons where there is only one forest-type group present in the FIA database, thus indicating no decision space. n refers to hexagons counts. '% Mode' computed relative to 'n No Choice'.

	All			Mode		
USFS Region	n Total	n No Choice	% No Choice	Mode Forest-type Group	n Mode	% Mode
Pacific Southwest Region	465	153	32.90	Western oak	81	52.94
Northern Region	526	151	28.71	Ponderosa pine	38	25.17
Pacific Northwest Region	543	62	11.42	Other western softwoods	35	56.45
Southwestern Region	717	401	55.93	Pinyon/juniper	256	63.84
Intermountain Region	758	319	42.08	Pinyon/juniper	274	85.89
Rocky Mountain Region	895	351	39.22	Elm/ash/cottonwood	95	27.07
Eastern Region	2605	349	13.40	Oak/hickory	216	61.89
Southern Region	3376	392	11.61	Woodland hardwoods	229	58.42
CONUS	**9885**	**2178**	**22.03**		**1224**	**56.20**

1; "No choice" in Fig. 1). The FIA sample identified just one forest-type group in 39%, 49% and 56% of all hexagons in the Rocky Mountain, Intermountain, and Southwestern regions respectively (Table 1). In the Intermountain and Southwestern regions in particular, the pinyon juniper forest-type is most often the only option (>63% of "No choice" hexagons). This forest-type accumulates carbon slowly and as a result yields increasingly net-negative joint-C albedo with age (Healey and Yang, 2023; Healey et al., In review). Assuming finite resources to support reforestation efforts nationally, it therefore may be prudent to prioritize regions with a wider variety of forest-type options to ensure favorable joint carbon-albedo outcomes.

3.2. Relevant considerations for managers

Given the density of the FIA-sample, we limited the resolution of our recommendations to 64,000 hectare hexagons, but acknowledge that within-hexagon variation, site-level limiting factors, and competing project objectives may preclude managers from planting the recommended forest-type group across the entire hexagon. Further, the 25-year temporal horizon (2050) considered in this study, though meaningful from a policy and mitigation urgency perspective (IPCC (2023); Lamb et al. (2021); COP (2015); EO 14072), may not be paramount to all managers. In light of these considerations, we developed a downloadable application (Fig. 2; Johnson et al. (2024)) to facilitate the exploration of all FIA-identified forest-type groups within a given hexagon. This application provides a means to (a) examine the temporal consistency of our recommendations beyond the 2050 horizon (within the bounds of limitations described in Section 3.3), (b) identify the separation in joint carbon-albedo benefits between all available forest-type groups, and (c) identify the impact of albedo offsets on the set of forest-type groups most germane to a specific project or site. In the example provided in Fig. 2, it is clear that the Oak/hickory forest-type group offers only slightly lower joint carbon-albedo benefits than the optimal MBB forest-type group shown in Fig. 1 (Δ 3.64 Mg ha^{-1}). We intend for this tool to help managers, who have a better understanding of local values, constraints, and desired outcomes, to investigate the impacts of albedo offsets on tree planting decisions alongside other competing benefits and forest ecosystem services.

3.3. Limitations

The estimates of joint carbon-albedo benefits that support the recommendations presented in this study were made under climatic and atmospheric conditions that are unlikely to remain constant in the next 25 years. Specifically, the historical net primary productivity that produced the carbon stocks measured by FIA is already likely changing in many places. Energy-limited ecosystems may become water-limited (Denissen et al., 2022; Albright and Peterson, 2013), and suitable ranges for forest-type groups are likely to shift northward given a warmer climate (Woodall et al., 2009; Iverson et al., 2008). CO_2 fertilization may support increased forest growth rates, although enhanced growth is dependent on a corresponding increase in water use efficiency, and is ultimately regionally variable (Hogan et al., 2024; Charney et al., 2016). There is already evidence for significantly extended growing seasons in many places (Linderholm, 2006). Forest assisted migration or the general consideration of future climate-adapted species should be pursued in future iterations of this study/tool (Williams and Dumroese, 2013).

Ongoing snowpack changes (Krasting et al., 2013) will alter mean albedo values for each forest type. This will likely reduce the contrast of evergreen tree canopies and exposed ground surfaces in neighboring non-forest areas, and as a result, will reduce implied impacts due to forest-related changes to albedo. Moreover, the abovementioned uncertainty affecting future carbon storage rates will reduce the precision and representativeness of time-dependent carbon equivalence (Bright et al., 2016) calculated for the albedo impact of current forests (Bright et al., 2024). We limit our analysis of future impacts to only 25 years from now while acknowledging and emphasizing that ongoing global change reduces the value of using current climate impacts as a proxy for expected future climatic services, even in the near term.

Estimates of joint carbon-albedo supporting this study represent outcomes dependent on the national average of conditions within each forest-type and age bin. Various stand densities, soil types, groundcover vegetation assemblage, and effects of management, all factors likely to have substantial influence on both albedo and carbon outcomes (Hovi et al., 2016), are currently pooled within age-by-type groupings. For example, in much of the Southern region the coniferous Loblolly/shortleaf pine group (LSP) is optimal when considering either non-soil carbon storage or joint carbon-albedo (Fig. 2) despite broad-scale overlap in distribution with deciduous or mixed forest-type groups with smaller albedo offsets (e.g. Oak mixes). We speculate that intensive management of LSP for timber across the Southern US (Fox et al., 2007) boosts the national average of 25-year LSP carbon storage such that it overcomes substantial carbon-equivalent albedo offsets (34.22 Mg ha^{-1}). In short, we emphasize that the difference between true local joint carbon-albedo outcomes and the estimates supporting this study will scale with the difference between local conditions and the national average of conditions.

3.4. Applicability beyond the United States

This case-study is most directly applicable to regions with well-established forest inventory programs like national forest inventories (Tomppo et al., 2010; McRoberts et al., 2010), or other regional, continental, or global scale forest plot networks (Hubau et al., 2020; Davies et al., 2021; Schepaschenko et al., 2017; Metzger et al., 2019; ForestPlots.net et al., 2021; SEOSAW partnership, 2020; Cleverly et al., 2019; Sist et al., 2014; Labrière et al., 2022). Assuming such field

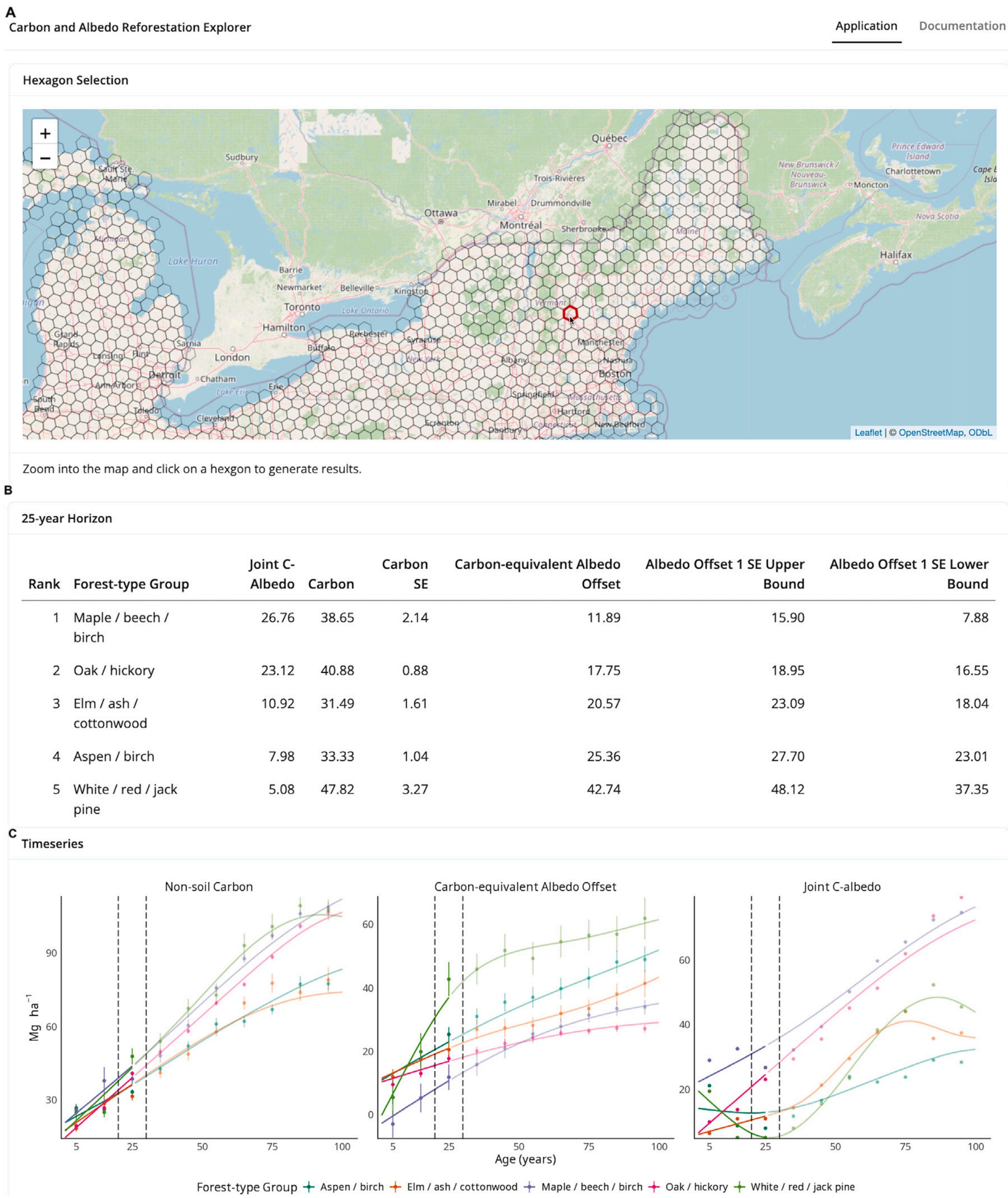

Fig. 2. A standalone application for reforestation decision support. (A) Point and click map selection with 64,000 hectare hexagon overlay. (B) Forest-type groups present within selected hexagon (options), ranked by 25-year joint carbon-albedo. (C) Chronosequences of non-soil carbon stocks, carbon-equivalent albedo offsets, and joint carbon-albedo for forest-type groups present within selected hexagon.

samples include estimates of biomass or carbon, and observations of stand age and forest type, then access to fine-resolution albedo imagery (Wang et al., 2016; Shuai et al., 2011; Erb et al., 2022; Bright and Ramtvedt, 2024) would be the only missing element to recreate forest-type-specific chronosequences of carbon and carbon-equivalent albedo offsets similar to those used here. The Landsat processing methods (Erb et al., 2022) behind the Healey and Yang (2023) dataset used in this study could be applied anywhere, and a systematic repository of albedo imagery would substantially broaden forest-climate perspectives (Radeloff et al., 2024).

In regions lacking adequate field inventory data (Labrière et al., 2022), other earth-observation (EO) data may provide an alternative. In particular, chronosequences of biomass have recently been developed using data from the National Aeronautics and Space Administration's Global Ecosystem Dynamics Investigation (GEDI) and Landsat-derived stand-age maps (Jha et al., 2024). This kind of approach could be augmented by co-registered albedo-imagery and satellite-derived forest-type maps (Hermosilla et al., 2024; Riemann et al., 2014; Wilson et al., 2012, 2013) to achieve the requisite chronosequences of joint carbon-albedo benefits partitioned by forest-type. Further, GEDI data in concert with NASA's Ice, Cloud, and land Elevation Satellite (ICESat−2) and European Space Agency's Climate Change Initiative have recently been used to create biomass density estimates for young secondary (< 20 years), old secondary (> 20 years), and primary forests, partitioned by IPCC defined global ecozones (Hunka et al., 2024). These age bins and ecozone delineations are much coarser than those used in this study, and substantial investments would be necessary both to develop corresponding carbon-equivalent albedo offsets and to translate these estimates into planting recommendations. However, the groundwork for broad-scale chronosequences of biomass and carbon has been established, the methods for producing fine-resolution albedo imagery are well-documented, and forest-type groups need not be the only way to partition the reforestation decision space.

4. Recommendations

Newly available data within the conterminous United States (US) has enabled reforestation planning based on joint carbon-albedo estimates instead of carbon storage estimates alone. Using this data we have demonstrated that albedo offsets at the 25-year time horizon are most impactful on tree planting decisions in the Northeastern regions of the US. Specifically, consideration of joint carbon-albedo impacts recommends planting the Maple/beech/birch forest-type group in place of the otherwise carbon optimal White/red/jack pine group to maximize 2050 climate change mitigation potential in this region. In general, and considering that the high-level geographical patterns highlighted in this case-study may not be most relevant to a specific project or site, we recommend that managers interested in making data-driven tree planting decisions explore the Healey and Yang (2023) data through our reforestation support application (Johnson et al., 2024). Finally, we highlight the value of fine-resolution albedo data products in this US-based case study and suggest that further production of such data would be needed for extension of our approach elsewhere.

CRediT authorship contribution statement

Lucas K. Johnson: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhiqiang Yang:** Writing – review & editing, Software, Methodology, Funding acquisition, Data curation, Conceptualization. **Angela Erb:** Software, Methodology, Funding acquisition. **Ryan M. Bright:** Writing – review & editing, Methodology, Funding acquisition. **Grant M. Domke:** Writing – review & editing, Methodology. **Tracey S. Frescino:** Software, Methodology. **Crystal B. Schaaf:** Writing – review & editing, Methodology, Funding acquisition. **Sean P. Healey:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

We have shared a link embedded in the Johnson et al. (2024) citation (also provided here: https://doi.org/10.5281/zenodo.14563711), to a downloadable application, archived on Zenodo, that supports the exploration of the data used in this study. Raw data are available from Healey and Yang (2023).

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