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LETTER

What do we know about the albedo effect of afforestation and reforestation? A systematic synthesis of the scientific literature

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Abstract

Carbon dioxide removal (CDR) will play a crucial role in mitigating climate change and achieving net zero CO_2 emissions. As one technique of the CDR portfolio, afforestation and reforestation (A/R) is heavily relied on in both climate change mitigation scenarios and policy strategies. However, beyond CO_2 sequestration, A/R can have side effects that may affect its effectiveness in drawing global temperatures down, which is the ultimate aim of CDR. In our study, we focus on A/R's impact on the Earth's albedo. Here, we provide the first systematic overview of the albedo effect. We review and synthesize the existing evidence in the scientific literature and analyze patterns of the albedo effect. The results show a heterogeneous literature landscape with large areas of underrepresentation. Our collected data shows a reduced albedo in almost all cases, and different temperature responses on different scales. Considering the data heterogeneity and availability, our research findings show that more detailed research is needed to comprehensively assess the albedo impact of A/R and consider fine-grained site-specific factors such as topography.

1. Introduction

Large-scale carbon dioxide removal (CDR) from the atmosphere is an essential measure to reach net zero CO_2 emissions and achieve the temperature goal of the Paris Agreement. As global CO_2 emissions are still increasing, overshooting the temperature goal of the Paris agreement is becoming more likely (Dhakal *et al* 2022, Schleussner *et al* 2023, Friedlingstein *et al* 2024, Bevacqua *et al* 2025, Cannon 2025). The need for CDR—in addition to rapid emission reductions—is growing.

Most climate change mitigation scenarios and national strategies to reduce CO_2 emissions rely on afforestation and reforestation (A/R) as a crucial instrument to scale up CDR deployment (Rogelj *et al* 2018, Byers *et al* 2022, Dooley *et al* 2024, Gidden *et al* 2024, Lamb *et al* 2024). A/R is a well-established method with a high technology readiness level and scalability, low public opposition, and significant potential for co-benefits (Lomax *et al* 2015, Geden *et al* 2024, Moustakis *et al* 2024, Prütz *et al* 2024). To date, A/R represents approximately 85% of CDR that has been deployed, mainly in North America, Europe, and East Asia (Pongratz *et al* 2024).

Similar to other CDR methods, A/R has side effects (Fuss *et al* 2018, Prütz *et al* 2024). Some can have implications for its effectiveness in reducing the global temperature, such as biogeochemical (e.g. changing greenhouse gas fluxes) and biogeophysical effects, e.g. changes in evapotranspiration or albedo (Pongratz *et al* 2021). Here, we specifically focus on the effect on the Earth's albedo (biogeophysical) and the effect of CDR (biogeochemical). Since the albedo determines the amount of solar radiation that is absorbed by the Earth's atmosphere and surface, it plays a crucial role in the Earth's energy budget and temperature (Otterman 1977, Stephens *et al* 2015, Kumar *et al* 2021). Similarly, the CO_2 concentration of the atmosphere is a crucial determinant of the global temperature (IPCC 2018).

Although an altered albedo occurs on a local level, it has a non-local temperature effect as well (Bala *et al* 2007, Betts 2000). CDR in contrast has a non-local temperature effect only (Pongratz *et al* 2021). All non-local effects together determine the effectiveness of

A/R to reduce the global temperature. The temperature can not only be affected on the non-local level, but also on the local (Bright *et al* 2015). Depending on a range of factors, these effects may counterbalance each other (Anderson *et al* 2011, Bright *et al* 2020). The non-local temperature reduction achieved through CDR can be weakened through an altered albedo. Under specific conditions, the albedo effect can even (temporarily) offset the CDR effect of A/R, and lead to a (temporary) net warming effect of A/R (Bonan 2008, Anderson *et al* 2011, Bright *et al* 2015, Bright and Lund 2021, Mace *et al* 2021). As the albedo remains relatively stable once the forest has matured, but the carbon stock continues to increase, the effects may change over time, and the potentially offsetting albedo effect may decrease. At the same time, the local temperature can still be significantly reduced, as the driving factors (e.g. evapotranspiration) are mainly non-radiative (Bright *et al* 2015). While this range of effects on different levels is important for the overall impact of A/R, we only focus on the albedo effect.

It is crucial to consider the albedo effect when estimating A/R's potential for CDR. Despite this, it is not yet a regular component of assessments of the implementation of A/R for climate change mitigation (Forster *et al* 2021, Walker *et al* 2022, Hasler *et al* 2024). Current assessments often stay broad and assume that the albedo effect intensifies poleward, or even overlook the albedo effect altogether (Smith *et al* 2016, Canadell *et al* 2021, Nabuurs *et al* 2022). Additionally, the accounting for albedo in carbon crediting protocols used in the voluntary carbon market is lacking (Riley *et al* 2025). However, quantifying the CDR equivalent effect of albedo change remains challenging. Bright and Lund (2021) reviewed such approaches that use radiative forcing but could only emphasize the variety of existing concepts, such as global warming potential, time-dependent emission equivalence, or emission equivalence of shortwave forcing. Several metrics exist, but none has prevailed yet, and the authors highlight the need for better approaches to quantify the CDR equivalent effect of albedo change (Bright and Lund 2021).

In this study, we used methods of evidence synthesis and meta-analysis. We first looked at the data availability and then reviewed and analyzed the collected evidence. To our knowledge, this work is the first systematic review of the literature on the albedo effect of A/R.

2. Methods

2.1. Search strategy

We followed a systematic search approach to comprehensively collect, screen, and select the available evidence, and then coded, synthesized, and analyzed the collected data (figure 1). First, we identified 334 studies through the literature database *Scopus* using a search query (see SI 1) that has been developed and tested following Lück *et al* (2025). The cutoff date for the literature search was July 24th, 2024. After two rounds of screening and coding, we included 55 peer-reviewed studies (table SI 1). The selection followed strict inclusion and exclusion criteria which are detailed in table SI 2.

After screening and selection, the papers were coded according to a coding scheme consisting of three context categories and five thematic categories (figure 2). We coded the scope of both the studies themselves (local, regional, global) and the related temperature changes (local and non-local). As not all studies included this level of detail, the categorization was done to the authors' interpretation in some cases. Additionally, we coded both the mean net temperature change, caused by all types of factors as well as the isolated temperature change only attributable to the altered albedo, where possible.

2.2. Data aggregation

We aggregated the collected data to increase comparability. Following the format in which data on albedo change is most often presented in the literature, we aggregated our data to relative numbers showing the change of albedo and temperature compared to the study specific baseline, i.e. adjacent area without A/R, time series (before vs after), or scenario design. Temperature changes are being differentiated for land surface temperature and near surface air temperature (e.g. 2 m air temperature). Both temperature types respond differently to A/R. Generally, A/R has a larger impact on the surface temperature than it has on the near surface air temperature (Li *et al* 2025). We further distinguish between local and non-local temperature effects. Local temperature effects may be caused by predominantly non-radiative biogeophysical factors, such as evapotranspiration (Bright *et al* 2015). The non-local temperature is mainly driven by radiative biogeophysical and biogeochemical factors and is the main target of CDR (Bright *et al* 2015, Pongratz *et al* 2021).

Additionally, we created latitudinal bands of 15° from North to South and allocated our effect sizes[3] to the respective band where possible, either according to coordinates given in the studies, or based on manual allocation using study locations presented in the literature. As coding spatial data in our coding scheme was beyond the scope of this work, we only coded non-spatial data. We collected 395 non-spatial quantitative effect sizes, and four non-spatial qualitative effect sizes. In our analysis on study-level, e.g. to analyze the data availability (Chapter 3.1), we include all studies (qualitative and quantitative, spatial and non-spatial). When reviewing the data, e.g. in

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[3] One effect size is one data point. One study can have one or (often) more effect sizes. For example, a study analyzing the albedo effect for every season would have four effect sizes.

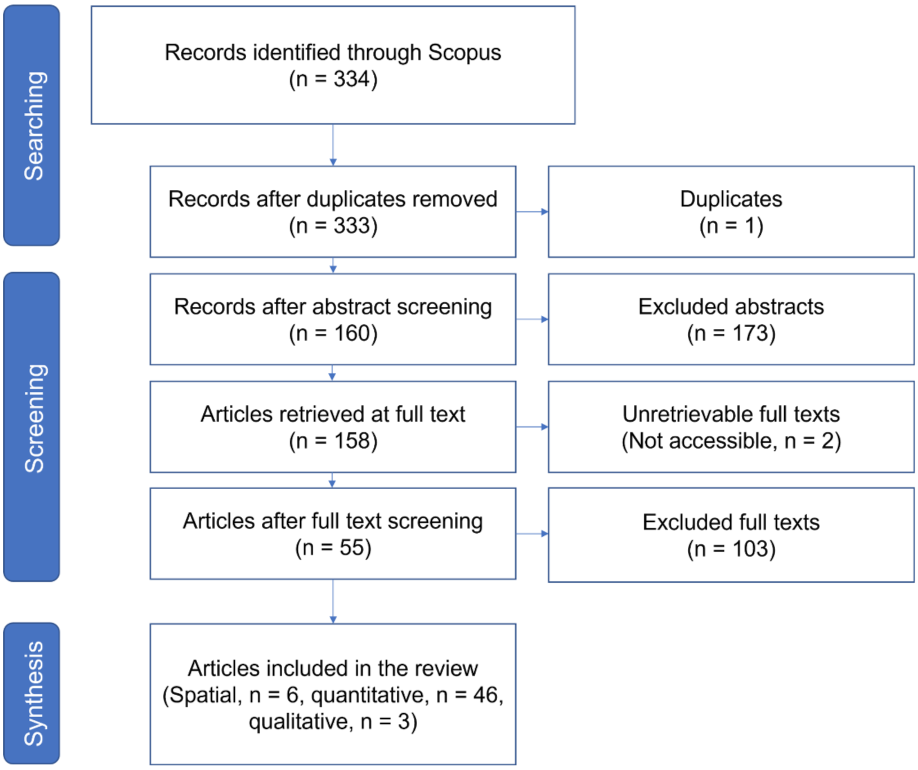

Figure 1. Flow diagram of the workflow of this study ranging from literature identification to synthesis. Reproduced from (Haddaway *et al* 2018). CC BY 4.0.

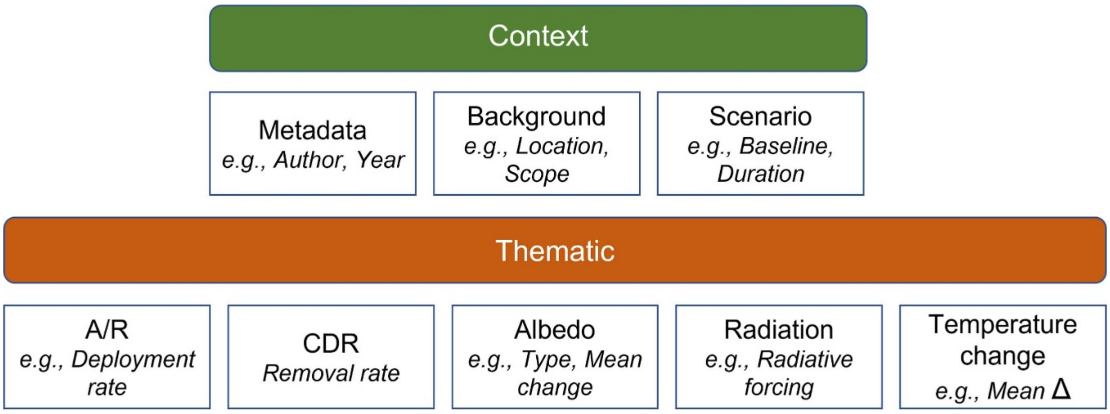

Figure 2. Overview of the coding scheme used in this study.

Chapter 3.2, we focus on non-spatial quantitative effect sizes.

We also used a linear mixed effects model to estimate the influence of the different predictor variables on the albedo effect compared to a specific reference level. Due to the limited data availability, we only show the results in the SI. There, the model shows what further results could look like with a stronger evidence base.

3. Results

We first show an overview of the distribution of effect sizes, and the variables and methods used to estimate these (Chapter 3.1). Both study level and effect sizes level are shown. Next, we review the albedo effect and the related temperature changes in Chapter 3.2.

3.1. Data availability

Geographically, the existing evidence is unevenly distributed across latitudes, countries and continents (figure 3). We find that most of the data is from the northern hemisphere, while there is very few evidence for the southern hemisphere. Both studies and effect sizes show a large accumulation in China, while the rest of Asia shows almost no evidence. Additionally, we find a reasonable number of studies and effect sizes in Europe, and no country-specific evidence

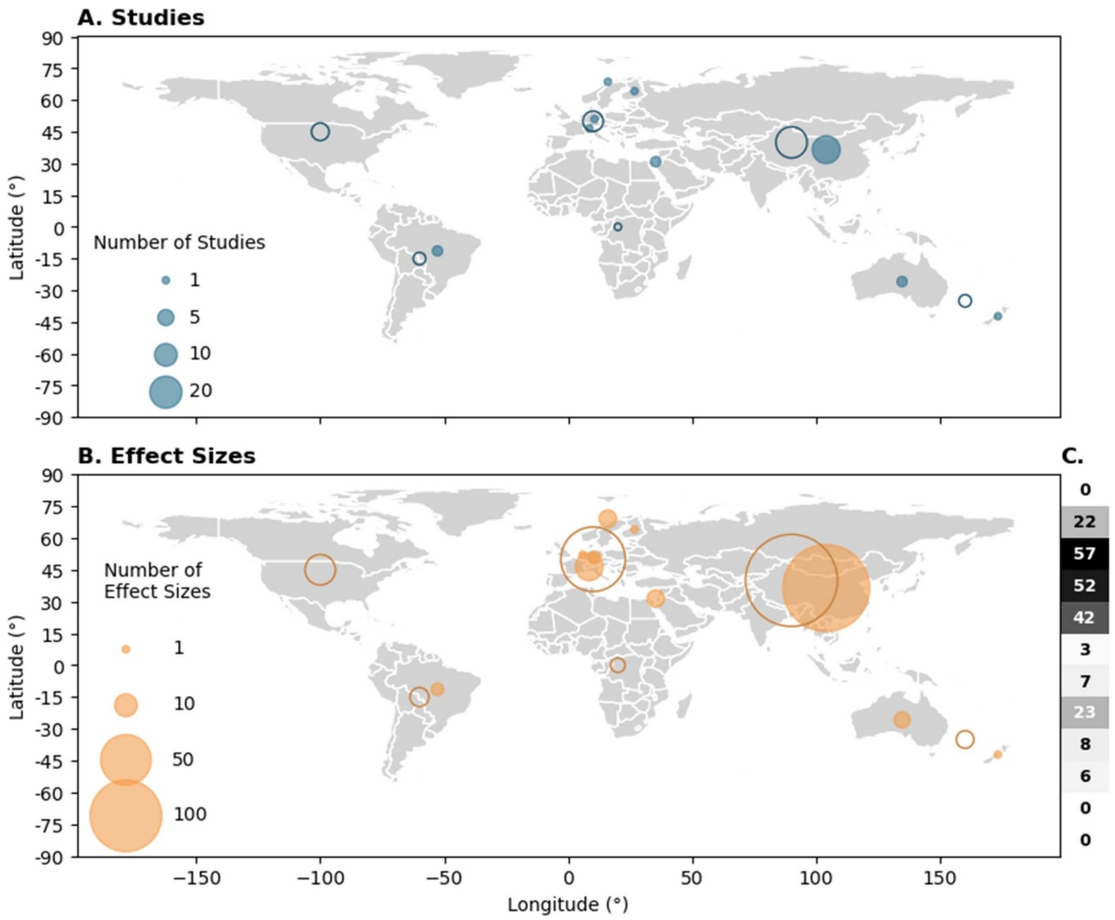

Figure 3. Geographic distribution of country- and continent-specific studies and effect sizes. In Panel (A), filled circles show country specific studies ($n = 26$), and unfilled circles show continent specific studies ($n = 40$). In Panel (B), filled circles show country specific effect sizes ($n = 188$), and unfilled circles show continent specific effect sizes ($n = 281$). In Panel (C), boxes show effect sizes per 15° latitudinal bands ($n = 206$).

from North America. Along latitudes, we find the highest numbers of effect sizes between 15° N and 60° N, confirming the patterns described above. In addition, we find 15 studies and 134 effect sizes with a scope larger than continental. These either focus on the entire globe or on specific intercontinental regions (e.g. the northern hemisphere) and are likely to also cover continents that are missing focused effect sizes.

Figure 4 shows the availability of data by five thematic categories (Panel (A)), pre-defined classification schemes (Panel (B) and Panel (C)), and shows details of the methodologies used in the studies (Panel (D) and Panel (E)). We find large numbers of studies and effect sizes for both, albedo data and temperature data, while only few studies provide information on A/R (e.g. tree species), or CDR (e.g. CDR rates). While most studies include data on the overall temperature change, only few studies show the isolated albedo induced temperature change. Although almost half of the studies include some data about radiation, the variety of radiation variables (e.g. net radiation, radiative forcing) is remarkable and prevents further analysis. Confirming the geographic pattern identified above, we find most effect sizes for temperate climate zones (using the Köppen–Geiger climate zones) and forest types. While we collected 37 effect sizes in arid climate, and 32 effect sizes in cold climate, almost no evidence in polar ($n = 5$), and tropical climate ($n = 2$) is available. The FAO forest types show a similar pattern, with only few effect sizes from boreal and tropical forests. Minor differences between these two variables may come from different classification schemes used.

The existing evidence consists of studies using modeling ($n = 39$), remote sensing ($n = 20$), and field observations ($n = 7$) as methods. With the rising attention on topography related variables (Hasler *et al* 2024), we also show the inclusion of three specific variables, namely elevation, slope, and aspect. Additionally, we recorded studies generally including topography without further differentiation. We find that only very few studies actively consider topography, especially with regards to the slope and the aspect. Although we only considered information given in the studies, some models and remote sensing products may include topography variables that have not been mentioned in the studies. However, the

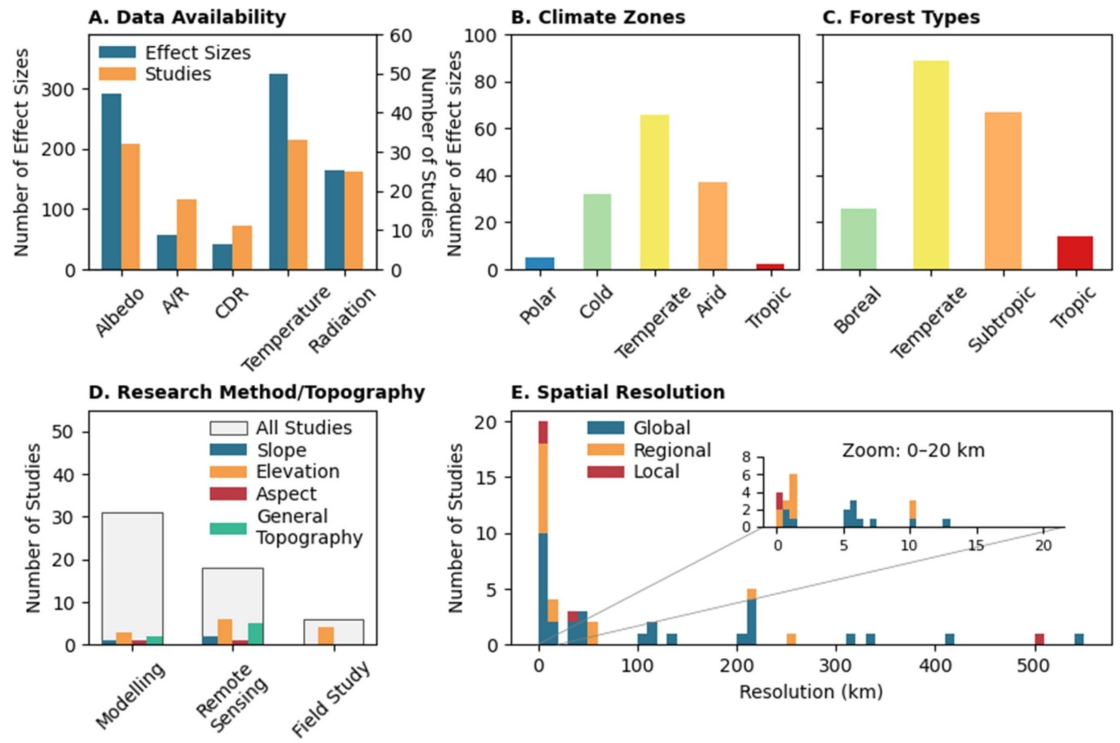

Figure 4. Data availability by studies and effect sizes (Panel (A)), number of effect sizes in pre-defined classification schemes of climate zones (Panel (B)) and forest types (Panel (C)). Panel (D) shows the research method used and the number of studies including topography related variables per research method. Panel (E) shows the spatial resolution used and the study scope.

resolutions used indicate that a detailed representation of topography is often not possible. Resolutions used vary from 30 m to 5.5° (∼550 km), while most studies have a spatial resolution of 50 km and less. Zooming in into this section shows that seven studies use a resolution of less than one kilometer, with four of them using less than 500 m. However, none of the latter is global, and only three global studies use a resolution of less than 5 km.

3.2. Review of albedo and temperature data

We collected 291 non-spatial effect sizes that include quantitative information on the mean albedo change. The mean value is −0.052. Figure 5 shows the mean albedo change by latitudinal bands for those effect sizes that are attributable to a 15° latitudinal band. We find a negative albedo change, i.e. a decrease, for all regions. In the northern hemisphere, where the density of effect sizes is the highest, we find a weakening albedo effect towards the Equator. No such pattern can be observed for the southern hemisphere, where only few effect sizes are available. However, and notably, the effect sizes between 15° and 30° south show a mean albedo change of −0.04, while the mean albedo change between 15° and 30° north is only −0.005, likely caused by the uneven distribution of effect sizes and individual study designs.

Next, we review the mean net temperature change following afforestation. Since reducing the overall temperature is the target of CDR, we show the results in figure 6—although this is not only attributable to albedo change but all sorts of effects, including biogeophysical, such as the albedo effect, and biogeochemical effects, e.g. CDR. We distinguish between local and non-local temperature change, referring to the scope and place of the temperature change. Our gathered data shows significant differences between scopes. Local temperature changes have a range of almost 12 °C, while non-local temperature changes range from −2 °C to 0.7 °C. Local temperature values show a strong mean temperature decrease, although some values show increases. In contrast, the majority of non-local temperature values are positive, with a mean value of 0.07 °C. The heterogeneous geographic distribution of our effect sizes does not allow to generalize this result. Effect sizes that report non-local temperature changes do not necessarily consider A/R for the whole globe, but can also restrict their A/R to a certain area to estimate the non-local temperature effect. Positive values may therefore come from A/R at higher latitudes, for example. We additionally differentiate between land surface temperature and near surface air temperature. The notable difference between land surface and near surface air temperature is around 0.15 °C–0.2 °C for both scopes. Land surface temperature shows a greater decrease on the local level. On the non-local level, land surface temperature values show a reduction, while near surface air temperature values show a warming.

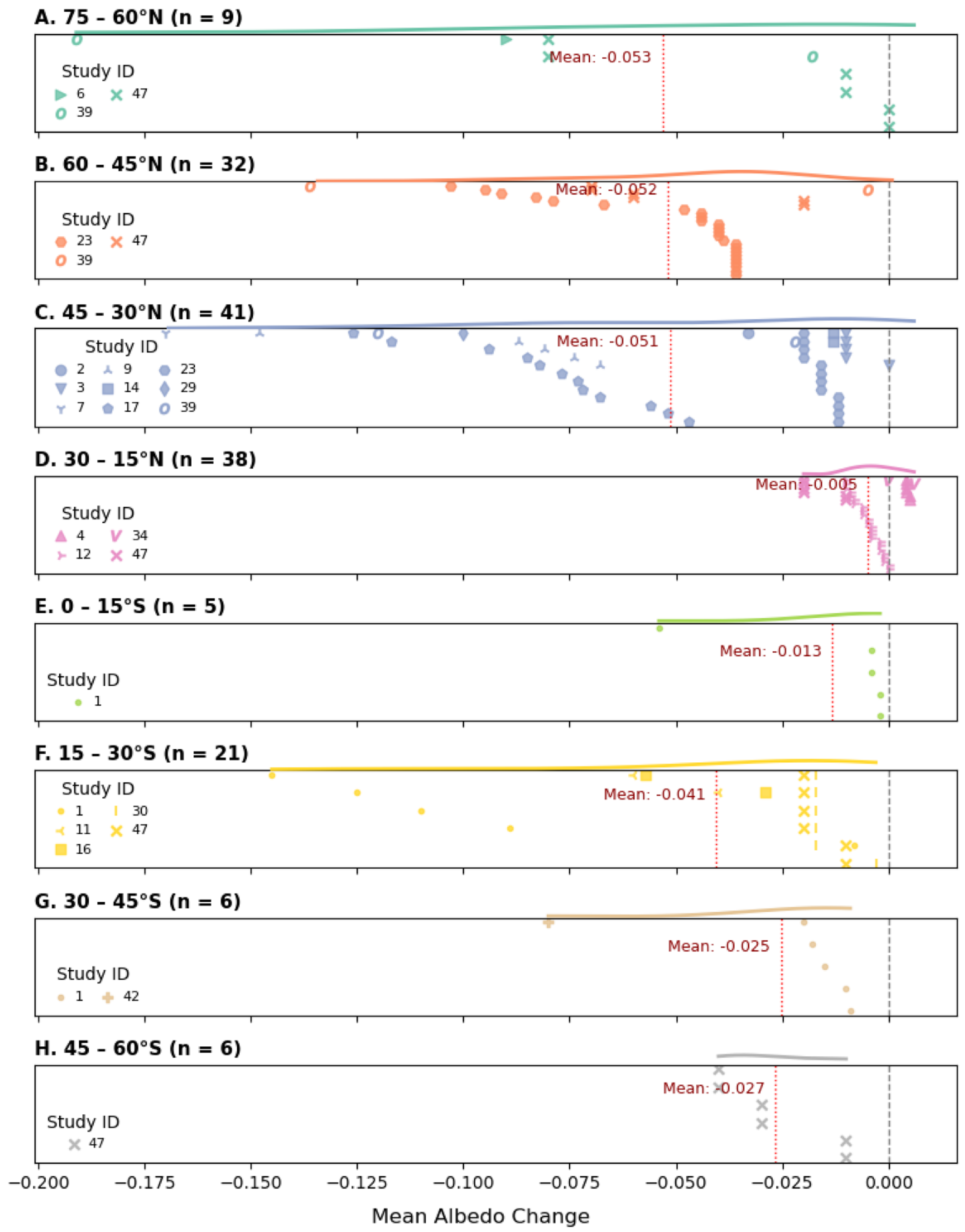

Figure 5. Mean albedo change per 15° latitudinal band and effect size (in total, $n = 158$). The individual dots represent effect sizes, n shows the number of effect sizes per box. The symbols show the respective study as shown in the bottom left of each box. The red dashed vertical line represents the mean value per box. The horizontal line shows the kernel density estimation per box. This figure only includes studies and effect sizes which include quantitative data on albedo change through A/R.

Figure 6 shows that large differences may exist between studies, scopes, and approaches, e.g. considering the land surface temperature or the near surface air temperature. While some studies only report positive values, others only show negative values—highlighting the importance of location and other factors already discussed in our study.

Focusing on the albedo effect, we also coded the isolated temperature changes attributable to albedo and CDR wherever possible. Figure 7 shows effect sizes with isolated temperature change induced by albedo or CDR, and their mean net temperature change, as well as the scope of the temperature. The majority of effect sizes show a temperature increase caused by albedo change. More than half of the mean net temperature change values, as well as their mean value, is still negative, i.e. other effects offset the albedo effect. However, temperature values are most

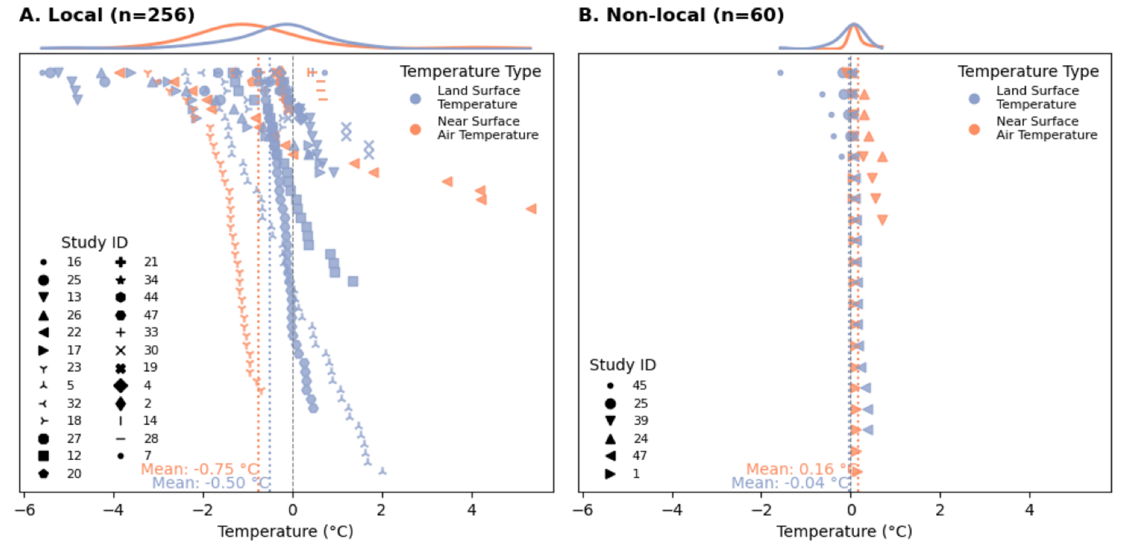

Figure 6. Mean net temperature change through A/R in °C per scope (in total, $n = 316$). The data visualized here shows the mean net temperature change, i.e. through various biogeochemical and biogeophysical factors, including albedo change and CDR. The orange dashed vertical line represents the mean value of near surface air temperature per box and the blue dashed vertical line shows the mean value of land surface temperature per box. The horizontal line shows kernel density estimation per box. The scope is here defined as the place where the temperature change is estimated for.

often only reported for local temperature changes. The few non-local temperature values all also show a net cooling effect, albeit a warming albedo effect. As the scope is less relevant for albedo change, it becomes considerably relevant that the isolated albedo effect on the temperature could theoretically (when disregarding other factors) lead to a warming of 4 °C, and can be up to 6 °C higher than the net value. Still, there is an overall scarcity of disaggregated data on isolated temperature effects, especially CDR-induced temperature change.

Overall, the data reviewed in our study shows a strong cooling effect of A/R on the local level, but a slight warming effect of A/R on the non-local level. Given the heterogeneity and low availability of data, these findings cannot be generalized.

4. Discussion

This study provides the first systematic review of the scientific literature on the albedo effect of A/R. Our findings are generally in accordance with previous studies, but underpinned by a more comprehensive body of evidence. Emphasizing the systematic synthesis approach, which is novel to this topic, we highlight that the generally assumed pattern of the albedo effect is based on a rather low data availability and, thus, generalizing the distribution and dimension of the albedo effect must be done carefully. Previous review studies on A/R (and its side effects) show similar literature patterns, e.g. a large concentration of studies in the northern hemisphere and especially China (Prütz *et al* 2024, Lück *et al* 2025).

We observe extremely low data availability for regions with some of the world's largest forests, such as South America, central Africa, and south-east Asia. The scarcity of research in areas, where A/R is considered a particularly suitable approach to mitigate climate change (Griscom *et al* 2017, Walker *et al* 2022), is noteworthy, although research on some of these areas might be published in languages other than English. Considering the general certainty of our and previous studies that the albedo effect in subtropical and tropical areas is relatively weak, i.e. the cooling climate impact of CDR dominates,—this is not alarming. Global studies add to the representation of these regions, but often rely on resolutions that are not able to capture fine-grained differences in topography or land cover (Hasler *et al* 2024). Recently, attention on the albedo effect has grown and the need for more detailed assessments has been expressed (Bright *et al* 2015, Davin *et al* 2020, Hasler *et al* 2024, Huang *et al* 2024). A special focus in these studies is on the inclusion of fine-grained topography, especially slope and aspect. It may be questioned whether a global scope is capable of this. For example, Hasler *et al* (2024) consider their spatial resolution of 500 m as not capable to capture the comprehensive topography including aspect and slope—although this is the highest resolution of global studies included in our work. As these factors become increasingly relevant poleward, because of the angle of the incoming solar radiation, it is extremely relevant to further study the influence of topography in regions that have previously been considered as not appropriate for A/R. For example, topography might allow effective deployment of A/R on north-facing slopes in the northern latitudes, but not on south-facing slopes, as

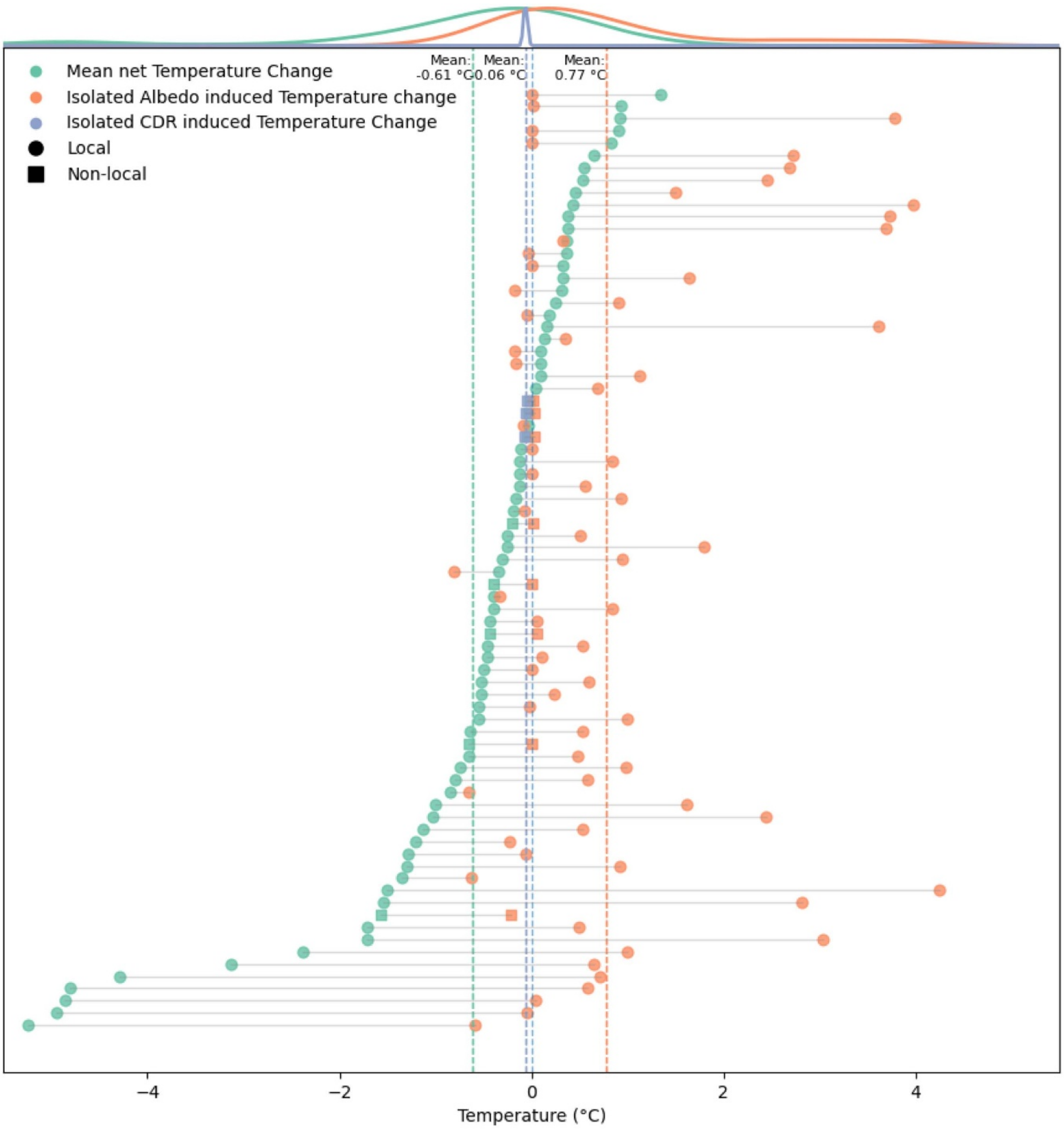

Figure 7. Isolated temperature change driven by albedo or CDR ($n = 77$). One horizontal line represents one effect size, differentiated between albedo induced temperature change, CDR induced temperature change, and mean net temperature change. The shape of the marker indicates the scope of the temperature. The vertical lines show the respective mean value, the horizontal lines at the top show the respective kernel density estimation.

the amount of incoming sunlight differs significantly (Hasler *et al* 2024).

While there is moderate to high evidence and agreement on the albedo effect in flat areas with low topographical variation, there is low evidence for areas with high topographical variation, particularly in the boreal and polar regions. Thus, we must be careful when generalizing latitudinal trends of the albedo effect and their implications for CDR's effectiveness, as more drivers that have not yet been comprehensively studied shape its dimension.

The literature shows surprisingly little information on the actual implementation of A/R, such as tree type or density. However, there are studies arguing that A/R's characteristics can have a significant impact on the albedo effect, such as species composition, or ground vegetation (Lukeš *et al* 2013, Matthies and Valsta 2016, Ramtvedt *et al* 2021). Besides general classification of forest types, more research is needed to assess the impact of more detailed forestry and tree variables. Considering these variables could potentially weaken the albedo effect under some conditions, and therefore increase the efficiency of A/R for CDR.

Lastly, the existing evidence on the albedo effect of A/R rarely includes data on actual CDR rates. The albedo effect is often presented in relation to temperature changes, but its impact on CDR is rarely investigated and a connection to CDR's effectiveness is rarely made. Where this connection is drawn, it is most often related to local temperature effects (figure 7), while CDR is targeted at the non-local temperature. As previously mentioned, approaches to quantify the CO_2-equivalence of albedo change exist, but are challenging (Bright and Lund 2021). Although some studies use such approaches (Bright *et al* 2020), they are generally rarely used. Some studies alternatively use concepts such as a break even time to estimate when the (increasing) effect of CDR is overcoming the (relatively stable) albedo effect (Bright *et al* 2020, Rohatyn *et al* 2021, 2023).

While discussing the effectiveness of A/R as a CDR method, it is important to consider the various other implications that A/R may come with. Even with a (temporary) global warming effect, A/R may cool the local climate through non-radiative effects, and can have a positive effect for biodiversity (depending on local and A/R conditions, the effect on biodiversity can also be negative), the air quality, or the water cycle (Prütz *et al* 2024). This highlights the role of A/R in climate change adaptation, even if under specific conditions the dominance of the albedo effect over the biogeochemical effect could prevent its use for climate change mitigation.

We conclude that existing analyses of the albedo effect often stay too broad to provide a detailed and fine-grained assessment of A/R's impact on albedo. The widespread assumption of the geographic differences of the albedo effect is often oversimplified and the actual albedo effect depends on a wide range of factors and site-specific conditions. This makes concrete statements and assumptions on the albedo effect difficult, as well as the inclusion of the albedo effect in more general research on A/R as a CDR method, especially in integrated assessment modeling studies (Rouhette *et al* 2024). The oversimplified subtraction of a specific fraction across regions does not do justice to the complexity of the albedo effect. Considering the albedo effect of A/R (among others) when discussing it as a CDR approach is essential to decrease the risk of overestimating A/R's effectiveness for climate change mitigation, and avoid misleading reliance on A/R as a CDR methodology, especially as it is heavily featured in national strategies. Furthermore, A/R plays a major role in the voluntary carbon market (Smith *et al* 2024) and carbon crediting protocols need a scientific foundation to accurately integrate the albedo effect into their accounting schemes.

4.1. Limitations

We see two main limitations of our work. First, finding a suitable approach to include six studies which provided their data only in spatial form was beyond the scope of our study. Similarly, we only included the non-spatial data of studies that present their results in spatial and non-spatial format. This may have led to a certain degree of underrepresentation of some areas, although we find that the resolutions used and factors considered may not always be capable to comprehensively account for the albedo effect. More place-specific research on the albedo effect that considers the local context as well as non-local temperature effects is necessary.

Second, the low availability and heterogeneity of data might have reduced the robustness of our results. We believe it is important to flag this, especially given the widespread assumptions that the albedo effect increases poleward. We show that this is only underpinned by a limited foundation of (non-spatial) data. Aggregation of the heterogeneous data was necessary to ensure comparability, despite reducing the level of detail. In addition, we did not consider more in-depth variables, such as surface roughness, ground vegetation, or snow, with the latter being reflected by the seasonality. Such variables were rarely reported in the literature, although their relevance for the albedo effect has been shown. While our study shows the general trend in the literature, it also highlights the need for more research on the albedo effect.

4.2. Outlook

Our work highlights the importance of fine-grained, location specific and detailed research on the albedo effect with a comprehensive consideration of a broad set of factors, including topography. Tropical, boreal and polar regions show a significant underrepresentation in the existing literature and a missing consideration of topographic factors, which in fact play an even bigger role poleward. Temperature estimations are often made for the local level, while research on the albedo effect must also consider the non-local temperature. Future assessments and studies of this topic must consider fine-grained data on aspect and slope, especially in boreal and polar regions. Additionally, analyses of the albedo effect of A/R must include more data on actual CDR rates and must use measures to estimate the net CDR efficiency more often.

5. Conclusion

We show that A/R decreases the Earth's albedo in almost all of the reviewed effect sizes. Although an altered albedo can increase global temperatures and thus have significant impacts on the efficiency of A/R as a CDR strategy, we argue that A/R remains a suitable approach for both, climate change mitigation and adaptation in most parts of the world. However, comprehensive and fine-grained research is needed to further assess the albedo effect and its implications for the non-local temperature of location-specific A/R.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary data 1 available at: https://doi.org/10.1088/1748-9326/ae608b/data1.

Supplementary data 2 available at: https://doi.org/10.1088/1748-9326/ae608b/data2.

Supplementary data 3 available at: https://doi.org/10.1088/1748-9326/ae608b/data3.

Supplementary data 4 available at: https://doi.org/10.1088/1748-9326/ae608b/data4.

Supplementary data 5 available at: https://doi.org/10.1088/1748-9326/ae608b/data5.

Supplementary data 6 available at: https://doi.org/10.1088/1748-9326/ae608b/data6.

Supplementary data 7 available at: https://doi.org/10.1088/1748-9326/ae608b/data7.

Supplementary data 8 available at: https://doi.org/10.1088/1748-9326/ae608b/data8.

Supplementary data 9 available at: https://doi.org/10.1088/1748-9326/ae608b/data9.

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Conceptualization (equal), Supervision (equal), Writing – review & editing (equal)

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