Bringing albedo to the GHG market

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ABSTRACT
A global warming potential of albedo (GWPA) is proposed, that represents the carbon dioxide emissions equivalent to a 0.01 increase in albedo over 1 m² of horizontal surface. A survey of prior literature suggests GWPA ≈ 4.2 kgCO₂/m². Taking Los Angeles, CA as a test site for urban global warming mitigation actions, a residential “cool roof” project offers approximately seven times as much radiative forcing benefit from albedo change as from GHG reduction of energy efficiency; and a citywide increase to commercial building roof albedo offers radiative forcing benefit equivalent to the first 6½ years of all commercial sector GHG emission reductions proposed in the City of Los Angeles climate action plan. Discussion explores pathways and challenges to making albedo increases fungible with GHG reductions in GHG markets.

KEYWORDS
Albedo; radiative forcing; global warming potential; GWP; climate action plan; GHG market

The opportunity
Mitigation of global warming is rapidly becoming more urgent. Challenges associated with regulating carbon dioxide emissions at the global scale have increased attention to reducing short-lived greenhouse gases (GHGs) [1,2], and encouraged vigorous local government actions [3]. Local governments are creating ambitious climate action plans that set goals for reducing GHG emissions of the built environment. But GHG emissions are not the only way the built environment influences global climate, and local-scale climate action could include another important lever for reducing global warming: albedo management. City planners, architects, and structural engineers make choices, often without being aware of it, that strongly affect the degree to which shortwave solar radiation is reflected back into space rather than absorbed to become heat.

Albedo is directly correlated to the primary physical driver of global warming, radiative forcing. Changes to albedo produce instantaneous and nearly proportional changes to radiative forcing, so albedo management is by definition a promising tool for affecting global warming. Local governments’ regulatory and political access to albedo management is high, since local governments typically control building codes, approve building permits, own public land, and build roads. Furthermore, albedo projects can have very low implementation costs, beginning at the price of a can of paint.

It is my hypothesis that giving albedo management streamlined access to existing, GHG management policy tools will greatly accelerate albedo management’s contribution to global warming mitigation. Specifically, making albedo increases fungible with GHG reductions would provide access to the financial incentives provided by the now 20-year-old GHG reduction market. Below I propose a specific mechanism for albedo-GHG fungibility, the global warming potential of albedo, GWPA.

Proposed definition of GWPA
GHG markets utilize global warming potential (GWP) to normalize different GHGs in units of carbon dioxide equivalents (CO₂e). GWP was developed as a lubricant for fungibility between the chemically dissimilar GHGs intended for regulation under the Kyoto Protocol [4]. For better or worse, it has developed into the de facto underpinning of multi-gas GHG regulation, and now provides the inter-gas fungibility making possible the...
emphasized attention to short-lived gases in regulatory and voluntary GHG markets.

Aided by GWP, GHG mitigation policy has converged on a common trading unit of one metric ton of carbon dioxide equivalent (1.0 MgCO$_2$e). Albedo policy will also need to converge on a common trading unit. For purposes of discussion I propose this unit be a 0.01 albedo increase (brightening) over a surface area of 1.0 square meters (m$^2$). At least three other published articles on this topic have hypothesized the same policy unit in their discussions [5–7].

From the definition of the trading unit one can construct a formal definition of the global warming potential of albedo (GWPA): the radiative forcing of the albedo policy unit (0.01 brightening over 1 m$^2$), divided by the radiative forcing of the reference GHG pulse (1.0 kg CO$_2$), integrated over 100 years. In the nomenclature of the IPCC Fifth Assessment Report:

$$GWPA(H) = \frac{\int_0^H RF_{\Delta \alpha}(t)\,dt}{\int_0^H RF_{CO2}(t)\,dt}$$

where H is time horizon (100 years), $RF_{\Delta \alpha}(t)$ is radiative forcing due to a 0.01 brightening over 1 m$^2$ at time t, and $RF_{CO2}(t)$ is radiative forcing due to a 1 kg pulse of CO$_2$ at time t. This compares to the original expression defining GWP [8, p.711]:

$$GWP = \frac{\int_0^H RF(t)\,dt}{\int_0^H RF_{CO2}(t)\,dt}$$

where $RF(t)$ is radiative forcing due to a 1 kg pulse of greenhouse gas i at time t. Note that the value of GWPA will be negative since increases in GHGs and increases in albedo act in opposite directions on radiative forcing.

GWPA is unitless, since both the numerator and the denominator express radiative forcing per (identical) unit mass of the two gases being compared. GWPA however has units kgCO$_2$/m$^2$. This serves as a helpful reminder during policy application, that albedo projects folded into GHG regulatory schemas via GWPA are comparing radiative forcing of a physically fixed surface, to radiative forcing of a globally mixed gas. These two climate stressors will evaluate slightly differently in a global circulation model, and presumably impact global warming slightly differently in the real world.

**Likely range of numeric values of GWPA**

Values from five studies that attempt to cast the effect of albedo change in the built environment into CO$_2$ equivalents on a global-average basis, are summarized in Table 1. These five studies all provide independently computed values (or proxies) for GWPA.

The two studies lead-authored by Akbari [5,6] and the work of Menon et al. [7] report GWPA directly following the same definition used here. Campra et al. [9] is given as interpreted and cited by Akbari, Matthews & Seto [6]. Values from Muñoz & Campra [10] were computed by the author using exclusively parameters available in the published paper. The five studies estimate GWPA values ranging from $-2.55$ kgCO$_2$/m$^2$ to $-7.50$ kgCO$_2$/m$^2$ when integrating over a 100-year time horizon. The mean result among all five studies (with each study weighted equally) is $-4.17$ kgCO$_2$/m$^2$.

In addition to these studies suggesting a computable relationship between radiative forcing from albedo and from GHGs, a few peer-reviewed case studies are available as well, which are summarized in Table 2.

| Study | GWPA kgCO$_2$/m$^2$ |
|-------|----------------------|
| Akbari, Menon & Rosenfeld 2009 | $-2.55$ |
| Akbari, Matthews & Seto 2012 | $-6.50$ |
| Min | $-7.50$ |
| Menon et al 2010 | $-4.3$ |
| Muñoz & Campra 2010 | $-3.26$ |
| per-study average | $-4.17$ |

Table 1. Compiled values of GWPA reported in five published papers.

**CARBON MANAGEMENT**

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Mitigative value of urban albedo change compared to urban GHG reduction

So how powerful are the climate impacts of real-world albedo projects, versus real-world GHG projects? To provide a sense of the scale of global warming mitigation that can be offered by urban albedo projects I compute two comparisons. For consistency, both comparisons are made under the assumption of a location in Los Angeles County, California.

**Compared to the GHG reduction of a residential cool roof project**

Residential and commercial “cool roof” projects are typically justified by urban heat island mitigation and GHG reduction alone. Yet, the unaccounted albedo effect may provide more climate mitigation justification than the GHG reduction.

Levinson et al. [14] compute GHG reductions associated with residential cool roof projects as part of a large study of cool surfaces in California. Residential projects assume a 2,400 ft², two-story, single-family residence with an 18.4° slope roof having albedo 0.10. The authors offer results for three different home vintages, chosen to correlate with evolution of energy provisions in the California building code. For Los Angeles, the authors compute that an increase in roof albedo to 0.40 will produce a GHG reduction between 0.453 kgCO₂e/m²-yr and 1.051 kgCO₂e/m²-yr depending on home vintage. Normalizing to our standard unit of 0.01 brightening, and assuming a roof life of 25 years, the researchers’ results translate to a range of 0.378 kgCO₂e/m² to 0.876 kgCO₂e/m² of GHG reductions associated with 0.01 of roof brightening, over the life of the roof. The values of GWPₐ derived from literature, −2.55 kgCO₂/m² to −7.50 kgCO₂/m², have magnitudes about seven times larger than this.

**Compared to a municipal climate action plan as a whole**

The City of Los Angeles Climate Plan states a GHG reduction goal of climate neutrality by 2050, which includes building energy emissions dropping to zero [15]. As of 2017, GHG emissions of commercial sector buildings in Los Angeles were about 6.5 million tCO₂e annually through a combination of fossil fuel combustion and electricity consumption [16]. If Los Angeles follows a linear pathway beginning at the 2017 emissions level in 2020 and reaching zero in 2050, then commercial building GHG emissions will need to drop by an increment of 0.22 million tCO₂e per year.

Low-rise commercial buildings in Los Angeles present approximately 63 million square meters of roof area to the sky. If all of these were to gain an average of +20 trading units of albedo change, this translates to 5.3 million tCO₂e on a GWPₐ basis. That is equivalent to 6.5 years of cumulative reductions in energy-related emissions from Los Angeles’ entire commercial building sector, following the linear ramp GHG reduction schedule. Albedo actions appear to have the potential to contribute to a municipal climate action plan with an equal order of magnitude as GHG reductions.

**Sensitivity of GWPₐ to time**

The relationship between a metric like GWPₐ and time is complex [17]. Understanding and accounting for this complex relationship to time will be the principal challenge of creating policy that makes albedo increases fungible with GHG reductions. There are three domains of time-sensitivity: drift in project albedo, project duration, and decay of the CO₂ reference pulse.

**Drift in project albedo**

Over the course of a project’s lifetime, the albedo may change. In the case of cool roofs, the primary such change is due to weathering. Over time both degradation in the roofing material, and accumulation of dirt and detritus, can decrease the albedo. Maintenance and cleaning ameliorate this effect, but of course the timing and quality of the maintenance and cleaning events induce their own, poorly predictable variance over time.

**Project duration**

If albedo at a project site returns to its pre-project value, there is an instantaneous loss of the project’s induced change to radiative forcing. In

| study           | land use change type         | location         | in-situ GWPₐ kgCO₂/m² |
|-----------------|------------------------------|------------------|-----------------------|
| Cotana et al 2014 | building surface brightening | Tunisia          | −1.40 to −2.10        |
| VanCuren 2012   | cool roofs                  | California       | −0.99 to −1.52        |
| Xu et al 2020   | pavement brightening        | U.S. (various)   | −0.81 to −1.60        |
contrast, once a GHG emission has been avoided, the climate impact of the avoided emission persists through the time horizon $H$ to the extent the unavoi

ded GHG emission would have persisted through $H$.

The GWP$_A$ metric is only accurate to the extent that the albedo project lasts as long as the time horizon. Possible remedies for this limitation include:

- Shorten the GWP time horizon to a period commensurate with typical albedo project length;
- Compute project-specific GWP$_A$ values, that mathematically account for variable albedo within the time horizon$^3$;
- Use a standardized GWP$_A$ value, but prorate project climate credits according to the fraction of the time horizon covered; or
- Deploy policy changes that promise persistence of the albedo change throughout the time horizon.

Decay of the CO$_2$ reference pulse

The 1 kg CO$_2$ reference pulse decays between emission and the time horizon. This means that the reference radiative forcing is not a constant, so computation of GWP$_A$ can and should relate to the difference between the albedo project and the reference pulse’s radiative forcing over time (per Equation 1). This particular time effect does not need policy attention per se, but understanding it is critical to developing a physically meaningful mathematical formulation for GWP$_A$.

Sensitivity of GWP$_A$ to location & environment

The impact of albedo to radiative forcing is different, in differing local circumstances. Each of the following can and does have an effect$^4$:

- **Latitude.** Albedo changes at very high latitudes will have a smaller effect per unit surface area than at lower latitudes.
- **Aerosols/pollution.** Any substance that absorbs shortwave radiation between the Earth’s surface and the top of the atmosphere, reduces the climate impact of albedo changes.
- **Shading.** Trees, hillsides, neighbouring buildings, or other structures that cast shade on the treated surface will reduce the impact of albedo change.
- **Cloud cover.** Albedo changes in sunnier climates will have a greater relative effect.
- **Snow cover.** Climates that experience substantial snow cover each year will produce smaller effects from albedo changes in the built environment.
- **Surface orientation.** Albedo changes on non-horizontal surfaces require more sophisticated mathematical treatments of solar angle, and interact with the Latitude, Shading, and Snow Cover parameters.

Finally, besides the specific impacts to albedo change induced by the above six factors, there is also the general difference between global warming due to radiative forcing at a fixed portion of Earth’s surface, versus global warming due to radiative forcing of a globally mixed gas. This difference can only be evaluated with a general circulation model, which would present an insurmountable barrier for most municipal-scale albedo management projects. Hence, hybrid solutions will need to be developed that assign GWP$_A$ values balancing precision with accessibility. One solution might be, for example, to use general circulation models to compute a set of uncorrected GWP$_A$ values that account only for latitude, while specifying methodologies to correct for aerosols, shading, cloud cover, and snow cover.

Perceived policy barriers

In addition to technical hurdles, there are a few policy implementation concerns that will likely get raised if considering albedo projects for trading in GHG markets.

Computational complexity

Conventional, urban, climate mitigation focuses on GHGs of energy consumption. Albedo change projects have played a role in this conventional paradigm, insofar that altering the albedo of building surfaces can reduce space conditioning energy [14]. The complexity of assessing energy consumption changes using building energy models has led to a simplified policy response of adding minimum albedo prescriptions to some building codes and standards [18]. This history may produce an assumption that albedo change projects are too computationally complex (too burdened with transaction cost) to make sense in market-based solutions. But when albedo change is deployed for radiative forcing management rather than energy...
management, building energy modelling is no longer needed and the assumption of computational complexity is incorrect.

Additionality

Voluntary GHG reduction markets rely on each project’s demonstration of additionality for their environmental integrity [19]. Most additionality requirements include a legal test demonstrating absence of regulations that require the project. Ongoing interest in deploying albedo change both for energy management and for urban heat island mitigation [20] has motivated the inclusion of minimum roof albedo (and in one case, wall albedo) prescriptions to some building codes and municipal regulations [21].

Still, there remains enormous headroom for expanding the deployment of albedo change beyond regulatory requirements. In the United States, for example, only six states prescribe minimum rooftop albedo in state building codes, and then only for commercial structures1. Even when there is relevant building code, the minimum, three-year-aged solar reflectance5 is often specified at 0.55, leaving ample room for albedo projects that utilize the many commercially available roofing materials having solar reflectance much higher than this value6.

Market flooding

Strong prices for any commodity rely on scarcity. Would introducing albedo to GHG markets flood the markets to the point of making prices unacceptably low? In 2020 voluntary GHG offset markets traded a total of 188 million tCO₂e. [22] As computed earlier in this article, increasing all commercial rooftop albedo by 20 points for the entire city of Los Angeles produces a total of 5.3 million tCO₂e, equal in quantity to 2.8% of trading volume in one year. Reroofing an entire, large city in a single year is an absurd hypothesis; if such an extreme event would represent a 2.8% increment in trading volume then the slow roll-out of real albedo projects seems unlikely to be convulsive in the current market.

Discussion and conclusion

The conventional GWP metric is rife with well-documented methodological imperfections, the most notable of these being its sensitivity to time horizon. Though some authors have found these imperfections reason to question GWP as an appropriate basis for regulatory action [23], I find them to be encouraging rather than discouraging. Any proposed definition of GWPA will be rife with methodological imperfections too. But GWPA was good enough to enable the multi-gas GHG markets that are now enabling the productive focus on short-lived GHGs. Given the current escalation of the climate emergency, now is a time for creating a mechanism good enough to allow quick policy developments that add more albedo solutions to the climate stabilization toolbox.

In built environments albedo management can induce instantaneous reductions to radiative forcing, that are equal in scale to multiple years of conventional GHG management. As urgency builds to minimize global warming sooner rather than later, albedo management deserves consideration as part of the arsenal of tools available to do so. Testing my hypothesis that streamlining albedo project access to GHG markets would accelerate deployment of albedo projects, seems like it would be well-served by a two-pronged approach.

First, the academy must compare GHG and albedo impacts to global warming with more sophisticated models, and under a wider variety of geographic and environmental circumstances. Such studies would both corroborate (or revise) the strong effect I report here, and begin elucidating the geographic and temporal effects that can underpin acceptably precise evaluation of GWPA.

Second, GHG registries must pilot methodologies allowing albedo project developers to monetize CO₂-equivalents of albedo change, using provisional or conservative values of GWPA. Doing so will demonstrate that fungibility is possible, and greatly elevate the visibility of albedo as an important factor of global warming.

Academic efforts to quantify geographic and temporal effects will undoubtedly reveal uncertainty and variability in the value of GWPA. But there are well-documented uncertainties in the computation of conventional GWP as well. The linkage between albedo and GHGs won’t be scientifically perfect, but it can be good enough to ensure that we are unleashing every possible method to prevent dangerous anthropogenic interference with the climate system.

Notes

1. See supplemental online materials.
2. There are many other such case studies in the literature. The subject albedo change is almost always spatially variant, and it is rare for study
authors to report an area-weighted average albedo change. The three examples reported here are those in which an area-weighted average albedo change was available, allowing evaluation of the numerator in Equation (1).

3. This remedy can address the first type of time-dependence (albedo drift) as well.

4. Urban albedo changes strongly influence the local, urban heat island effect. However, changes to the urban heat island effect do not impact GWPA because urban air temperature has a negligible impact on reflected shortwave radiation. Though urban heat island reduction is a likely co-benefit of albedo management policy, it should be ignored in computation of GWPA.

5. In the building trades, albedo is discussed in the terminology of “solar reflectance.” Solar reflectance is defined by laboratory testing standards, while albedo is defined on a theoretical, energetic basis, so the two terms are not identical. However, they are closely related and are both unitless with identical ranges $0 \leq \alpha \leq 1$. For the purposes of this paper the two terms can be used interchangeably, but eventual albedo policy may include minor corrections from albedo as regulated by GWPA to solar reflectance as prescribed in material specifications.

6. As of May 14, 2022 the Cool Roof Rating Council Rated Roof Products Directory contained 508 products having $\alpha \geq 0.70$, of which 64 are products having $\alpha \geq 0.80$ [24].

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Data availability statement
The author confirms that the data supporting the findings of this study are available within the article and its supplementary materials.

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