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The Price of Snow: Albedo Valuation and a Case Study for Forest Management

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**Abstract**

Several climate frameworks have included the role of carbon storage in natural landscapes as a potential mechanism for climate change mitigation. This has resulted in an incentive to grow and maintain intact long-lived forest ecosystems. However, recent research has suggested that the influence of albedo-related radiative forcing can impart equal and in some cases greater magnitudes of climate mitigation compared to carbon storage in forests where snowfall is common and biomass is slow-growing. While several methodologies exist for relating albedo-associated radiative forcing to carbon storage for the analysis of the tradeoffs of these ecosystem services, they are varied, and they have yet to be contrasted in a case study with implications for future forest management. Here we utilize four methodologies for calculating a shadow price for albedo radiative forcing and apply the resulting eight prices to an ecological and economic forest model to examine the effects on optimal rotation periods on two different forest stands in the White Mountain National Forest in New Hampshire, USA. These pricing methodologies produce distinctly different shadow prices of albedo, varying from a high of 9.36×10^{-4} and a low of $1.75 \times 10^{-5} \text{ \$w}^{-1}\text{yr}^{-1}$ in the initial year, to a high of 0.019 and a low of $3.55 \times 10^{-4} \text{ \$w}^{-1}\text{yr}^{-1}$ in year 200 of the simulation. When implemented in the forest model, optimal rotation periods also varied considerably, from a low of 2 to a high of 107 years for a spruce-fir stand and from 35 to 80 years for a maple-beech-birch stand. Our results suggest that the choice of climate metrics and pricing methodologies for use with forest albedo alter albedo prices considerably, may substantially adjust optimal rotation period length, and therefore may have consequences with respect to forest land cover change.

1. Introduction**1.1. Background**

Carbon storage has become the focus of nearly all climate mitigation policies that involve modifications to natural landscapes, particularly forests (Canadell and Raupach 2008). However, it is well known that other properties of the land surface can have a strong influence on climate through biophysical interactions with the atmosphere (Marland *et al* 2003). Of these properties, surface albedo has received considerable attention (Anderson *et al* 2011), particularly in areas where snowfall is frequent. For example, several studies have considered surface albedo in the context

of the overall climate impact of forest biofuels (Bright *et al* 2011, 2012, Cherubini *et al* 2012a) and afforestation (Kirschbaum *et al* 2011).

Yet there remains very few cases in which albedo has been incorporated into an economic analysis of optimal land management (Sjolie *et al* 2013, Thompson *et al* 2009a, 2009b), whereas such analyses that focus on carbon storage are pervasive. This is despite the fact that the influence of albedo, just like carbon, can have considerable outcomes on the optimal management regime for climate (Bright *et al* 2014, 2012, Lutz and Howarth 2014) as well as the fact that managing for albedo can provide substantial climatic benefits that could be included in climate policies

(Thompson *et al* 2009a, 2009b, Anderson *et al* 2011, Zhao and Jackson 2014). The paucity of such studies can be attributed to the two-part difficulty in calculating the influence of albedo on climate change and then subsequently properly valuing it as a climate regulating ecosystem service.

Albedo-related radiative forcing varies quite substantially in terms of the efficacy at which it acts when compared to carbon dioxide as well as the time horizon in which it acts (Hansen 2005), and thus its dynamics are quite complex. One methodology that is generally used to roughly define the behavior of a non-carbon forcing for such analyses has been through the use of specialized metrics. Such metrics compare the impact of one type of climate forcing to a reference forcing, which is generally carbon dioxide (Reisinger *et al* 2010). Examples of these metrics include the global warming potential (GWP), which was the first widely implemented metric and has been utilized within the Kyoto Protocol. This metric relates forcing on the atmosphere of a gas of interest to that of a pulse emission of CO₂ (Shindell *et al* 2009). Criticism of the GWP (e.g. Fuglested *et al* 2003) led to the development of the global temperature potential (GTP) metric (Shine *et al* 2005) which, instead of focusing on time-integrated radiative forcing, examines the effect of emissions on subsequent changes in temperature. Both the GWP and GTP have an associated time horizon, which states the time period under which the examined forcing operates upon global climate. While several time horizons have been used (20, 100, and 500 years), the Kyoto Protocol has relied on a 100 year time horizon and subsequently that time horizon has proved to be the most widely adapted (Shine *et al* 2005).

Climate metrics are the most common method for relating albedo radiative forcing to carbon dioxide and therefore economic values, but this requires the construction of reliable shadow prices for carbon dioxide. These prices are generally based on combinations of modeling methods, values judgments, and societal risk tolerance (Howarth *et al* 2014). For instance, an Inter-agency Working Group across several agencies of the United States Federal Government utilized three different integrated assessment models to calculate the currently used social cost of carbon (IAWG 2010). Thus, by relating albedo to carbon through the use of metrics, it is possible to generate the shadow price of albedo radiative forcing for a stated shadow price of carbon. For instance, this approach has been taken in Sjølie *et al* (2013) which utilized Bright *et al* (2011) calculated relationship between albedo and carbon through the GWP. In addition to linking metrics to carbon shadow prices, several other methodologies for valuing albedo radiative forcing have been considered. Lutz and Howarth (2014) used the DICE integrated assessment model to derive the cost of climate damages from radiative forcing from the Earth's surface and then generate a shadow price for albedo. Euskirchen

et al (2013) tied the influence of albedo to terrestrial and atmospheric storage capacities of carbon and generated a shadow price based on previous carbon prices.

So far, many pieces of the overall process of valuing albedo radiative forcing have been examined in the literature (Bright *et al* 2012, Cherubini *et al* 2012a). However, an analysis of how these different valuation methodologies may influence albedo shadow prices has not been completed. Thus, there is a need to understand precisely how the use of the different climate metrics and pricing strategies, when applied to albedo, may have resultant effects on management of the land surface. This understanding is critically important in forested areas in high latitudes, where the tradeoffs amongst carbon and albedo are most dramatic (Betts 2000, Bright *et al* 2011, Zhao and Jackson 2014).

1.2. Aims and Scope

To address this need, we describe four methodologies for characterizing and valuing albedo radiative forcing and report their associated shadow prices. These methodologies are as follows:

(1) the GWP methodology (Cherubini *et al* 2012b), which estimates the climatic influence of albedo radiative forcing relative to CO₂ via the GWP metric;

(2) the GTP methodology (Shine *et al* 2005, Cherubini *et al* 2013), which is similar to the GWP method but uses the GTP metric instead;

(3) the methods of Euskirchen *et al* (2013), which uses a simple relationship between expected changes in radiative forcing per a doubling of CO₂ and subsequently applying that to albedo radiative forcing;

(4) and the DICE methodology (Lutz and Howarth 2014), which uses the integrated assessment model DICE-2007 (Nordhaus 2008) to calculate a shadow price for albedo radiative forcing independently of carbon dioxide.

We then present a case study applying these prices to the management of selected timber stands in the White Mountain National forest (WMNF), New Hampshire, USA. The WMNF is located in an area in which tradeoffs between climate regulating ecosystem services, notably carbon and albedo, can substantially alter optimal forest management practices, and thus was an appropriate testing ground (Lutz and Howarth 2014). Finally we address the questions: (1) what are the impacts of choosing these different prices and metrics on the optimal rotation period of several different forest types, and (2) how does the pricing methodology influence the total net present value of these forests with respect to timber, carbon, and albedo provisioning.

2. Methodology

2.1. Study site

The WMNF is located in the US states of New Hampshire and Maine and covers over 300 000 hectares. The WMNF predominantly consists of forest cover in an area that was historically logged and harvested in the 19th century and allowed to re-grow throughout much of the 20th century. The two main forest types within the WMNF are the sugar maple-beech-yellow birch forest (MBB), which covers 46% of the WMNF and is the most common hardwood forest type within New England, and the red spruce-balsam fir forest (SF), which covers 5% of the WMNF but is dominant at high elevations and on steep slopes (DeGraaf *et al* 1998). Generally, climate throughout the WMNF consists of summer highs in the low 30 s C and winter lows of -20 C, with snowfall averaging 150–180 cm yearly (Adams *et al* 2004).

We modeled individual stands of two main forest types within the WMNF and used forest growth, carbon storage, and daily albedo values from a variety of sources. Forest stand growth information were collected from the United States Forest Service Inventory and Analysis (FIA) database of forest plots from the WMNF (<http://www.fia.fs.fed.us/>) and carbon storage data from the US Department of Energy's Carbon On-Line Estimator 1605b reports (www.ncasi2.org/COLE/). Estimates of blue-sky albedo used to calculate radiative forcing followed the procedures used in Lutz and Howarth (2014) and Lutz *et al* (2015) which relied on a combination of Moderate Resolution Imaging Spectrometer (MODIS) albedo products MCD43A (Schaaf *et al* 2002) and MOD10A (Klein and Stroeve 2002) from 2002–2012 for a spruce-fir ($44^{\circ}10'44.75''\text{N}$, $71^{\circ}17'45.38''\text{W}$), maple-beech-birch ($43^{\circ}54'16.326''\text{N}$, $71^{\circ}26'9.9132''\text{W}$), and two nearby recently cleared sites. Details regarding the collection statistics are fully documented in Lutz and Howarth (2014). As in Lutz and Howarth (2014) we did not include variability in the albedo baseline as a result of forecasted changes to snowfall and albedo due to climate change.

2.2. Forest model

To simulate the flow of forest ecosystem services we used the Forest Albedo Carbon and Timber model (FACT), an updated version of the model created by Gutrich and Howarth (2007) and revised to include forest albedo (Lutz and Howarth 2014). FACT is a single-stand forest model that simulates annual incremental growth based on relationships between stand age and timber volume that are derived from forestry yield tables (Gutrich and Howarth 2007). Annual growth of timber volume is divided into saw timber and pole timber which is used to derive a total mix of forest products when harvest is triggered. Carbon storage within FACT stems from work by Van Kooten *et al* (1995) and is modeled in four different pools: live

biomass, dead and downed wood, soil, and wood products (figure 1). The simulation of these four pools is based on yield tables generated by the US Department of Energy (2004) and decay rates constructed by Heath *et al* (1996). Specific equations used within the FACT model for carbon and timber dynamics and their associated economic value can be found in Gutrich and Howarth (2007) and a table of parameters used to simulate WMNF forest types can be found on table 1. Details regarding the equations used in the FACT model can also be found in the supplemental material.

Simulating albedo for the forest stands within the FACT model utilized a set of physical equations relating the transfer of energy from the Sun to the land surface and back to the atmosphere, a relationship between stand age and reflectivity of the surface, and modeling work analyzing MODIS satellite albedo product data specific to the forest sites (Bright *et al* 2011, 2012, Cherubini *et al* 2012b, Lutz and Howarth 2014). As forest stands age, albedo decreases with time as canopy cover closes, until a saturation point is reached. Yearly changes in albedo are based on the assumption that as forests grow from bare ground, albedo decreases according to an exponential decay function, minimizing when the forest stand canopy is completely closed. Albedo change over time was calculated by using this decay function:

$$\varphi_a = ab^x \quad (1)$$

which is similar to (Cherubini *et al* 2012b), wherein φ_a is surface albedo, a is a scaling coefficient, and

$$b^x = \frac{\varphi_{\text{mature}} \left(\frac{1}{t_{\text{mature}} - 1} \right)}{\varphi_{\text{cleared}}} \quad (2)$$

where φ_{mature} is the average albedo for a mature forest, φ_{cleared} is the average albedo for a clear-cut area, and t_{mature} is the time in years from bare ground to complete canopy closure (figure 2). Calculation of the net shortwave radiative forcing from yearly changes in albedo was based on a methodology described in Bright *et al* (2012) and Cherubini *et al* (2012b) and used in Lutz and Howarth (2014). Detailed equations for these calculations can be found in the supplementary material.

One additional consideration made in the FACT model was the inclusion of mowing costs for short rotation periods. We implemented mowing costs that were triggered when a timber harvest was simulated, but when there was no timber volume of significant value present. This occurred in simulations where the rotation period was shorter than the parameter α_2 . Oehler (2003) estimated the costs for the maintenance of fields in the New England area to be between \$80 and 486 per hectare (2003). As such, we incurred a mowing cost that increased as the stand aged, reaching a maximum value of \$486 when the stand was $\alpha_2 - 1$ years old. We utilized the equation:

Table 1. Parameters and constants used in the FACT model simulations for this manuscript.

	Parameter	Maple-Beech-Birch	Spruce-Fir
α_0	Maximum timber volume ($\text{m}^3 \text{ha}^{-1}$)	397 ^a	590 ^a
α_1	Timber growth coefficient ($\% \text{yr}^{-1}$)	0.008 75 ^a	0.013 96 ^a
α_2	Minimum stand age with positive timber growth (years)	8.85 ^a	14.62 ^a
P_{pole}	Poletimber price in 2013 ($\$ \text{m}^{-3}$)	5.22 ^b	4.33 ^b
P_{saw}	Sawtimber price in 2013 ($\$ \text{m}^{-3}$)	40.26 ^b	42.38 ^b
β_0	Sawtimber share coefficient (%)	1.75 ^a	4.293 ^a
β_1	Sawtimber share coefficient (years)	6.622 ^a	606.87 ^a
β_2	Sawtimber share coefficient (%)	0.997 ^a	0.18 ^a
γ_0	Maximum carbon storage in live biomass (t ha^{-1})	143.53 ^c	169.9 ^c
γ_1	Live biomass growth coefficient ($\% \text{yr}^{-1}$)	0.017 ^c	0.018 ^c
$C_{\text{dead}}(0)$	Initial carbon storage in dead and downed wood (t ha^{-1})	41.1811 ^c	35.4 ^c
δ_0	Decay rate of dead and downed wood ($\% \text{yr}^{-1}$)	0.073 ^c	0.0178 ^c
δ_1	Formation coefficient for dead and downed wood	0.391 ^c	0.0266 ^c
δ_2	Formation coefficient for dead and downed wood	0.478 ^c	0.7619 ^c
C_{soil}	Soil carbon storage (t ha^{-1})	72 ^c	49 ^c
ϵ	Average carbon content of wood (t m^{-3})	0.327 ^c	0.255 ^c
ϵ_1	Carbon content of softwood pulpwood (t m^{-3})	0.3294 ^c	0.3294 ^c
ϵ_2	Carbon content of softwood sawlogs (t m^{-3})	0.2336 ^c	0.2336 ^c
ϵ_3	Carbon content of hardwood pulpwood (t m^{-3})	0.3566 ^c	0.3566 ^c
ϵ_4	Carbon content of hardwood sawlogs (t m^{-3})	0.3566 ^c	0.3566 ^c
h_1	% of harvest allocated to softwood sawlogs	0.1951 ^c	0.7581 ^c
h_2	% of harvest allocated to softwood pulpwood	0.0237 ^c	0.1068 ^c
h_3	% of harvest allocated to hardwood pulpwood	0.0053 ^c	—
h_4	% of harvest allocated to hardwood sawlogs	0.7428 ^c	0.1189 ^c
φ_{01}	Decay rate of softwood pulp products ($\% \text{yr}^{-1}$)	0.006 ^c	0.006 ^c
φ_{02}	Decay rate of softwood saw products ($\% \text{yr}^{-1}$)	0.0038 ^c	0.0038 ^c
φ_{03}	Decay rate of hardwood pulp products ($\% \text{yr}^{-1}$)	0.0062 ^c	0.0062 ^c
φ_{04}	Decay rate of hardwood saw products ($\% \text{yr}^{-1}$)	0.0042 ^c	0.0042 ^c
φ_{11}	% of wood carbon stored in softwood pulp products	0.237 ^c	0.237 ^c
φ_{12}	% of wood carbon stored in softwood saw products	0.298 ^c	0.298 ^c
φ_{13}	% of wood carbon stored in hardwood pulp products	0.227 ^c	0.227 ^c
φ_{14}	% of wood carbon stored in hardwood saw products	0.1873	0.187 ^c
α_{cleared}	Average cleared albedo	0.174 24 ^d	0.3036 ^d
α_{mature}	Average mature forest albedo	0.128 24 ^d	0.1563 ^d
a	Albedo decay function parameter	0.176 ^d	0.311 ^d
b	Albedo decay function parameter	0.993 ^d	0.977 ^d
L	Site latitude	43.91	44.18
Ta	Atmospheric Transmittance	0.854 ^e	0.854 ^e

^a FIA Datamart (<http://apps.fs.fed.us/fiadb-downloads/datamart.html>).

^b NHDRA (<http://www.revenue.nh.gov/mun-prop/property/stumpage-values.htm>).

^c Smith *et al* 2005 (<http://www.treearch.fs.fed.us/pubs/22954>).

^d Lutz *et al* 2015 (accepted manuscript).

^e Bright *et al* 2012 (<http://www.sciencedirect.com/science/article/pii/S0195925512000030>).

$$M_c = \begin{cases} LC + 0.835391 \left(\frac{s}{\alpha_2 - 1} \times HC \right) & s < \alpha_2 \\ 0 & s \geq \alpha_2 \end{cases} \quad (3)$$

where mowing costs were represented by M_c , which increased proportionately with stand age, s , to a maximum value at α_2 , and where LC and HC are the low and high, respectively, estimates of mowing cost per hectare according to Oehler (2003), adjusted for inflation.

2.3. Carbon and albedo prices

Shadow prices for annual carbon storage were generated in the DICE model for each year of the simulation

(Nordhaus 2008). The DICE-2007 model calculates the impact of carbon emissions on temperature and climate change, and subsequently calculates a price by measuring responding changes in social welfare through a damage function. Technically, the shadow price of carbon is the change in the value of the utility of consumption per unit of added carbon emissions, divided by the marginal utility of consumption (Nordhaus 2014). Mathematically, the social welfare (W) is a product of the instantaneous utility function for the time period (U), which is dependent on per capita consumption (c) and total labor input (L), and the social rate of time preference (R) (Nordhaus 2008):

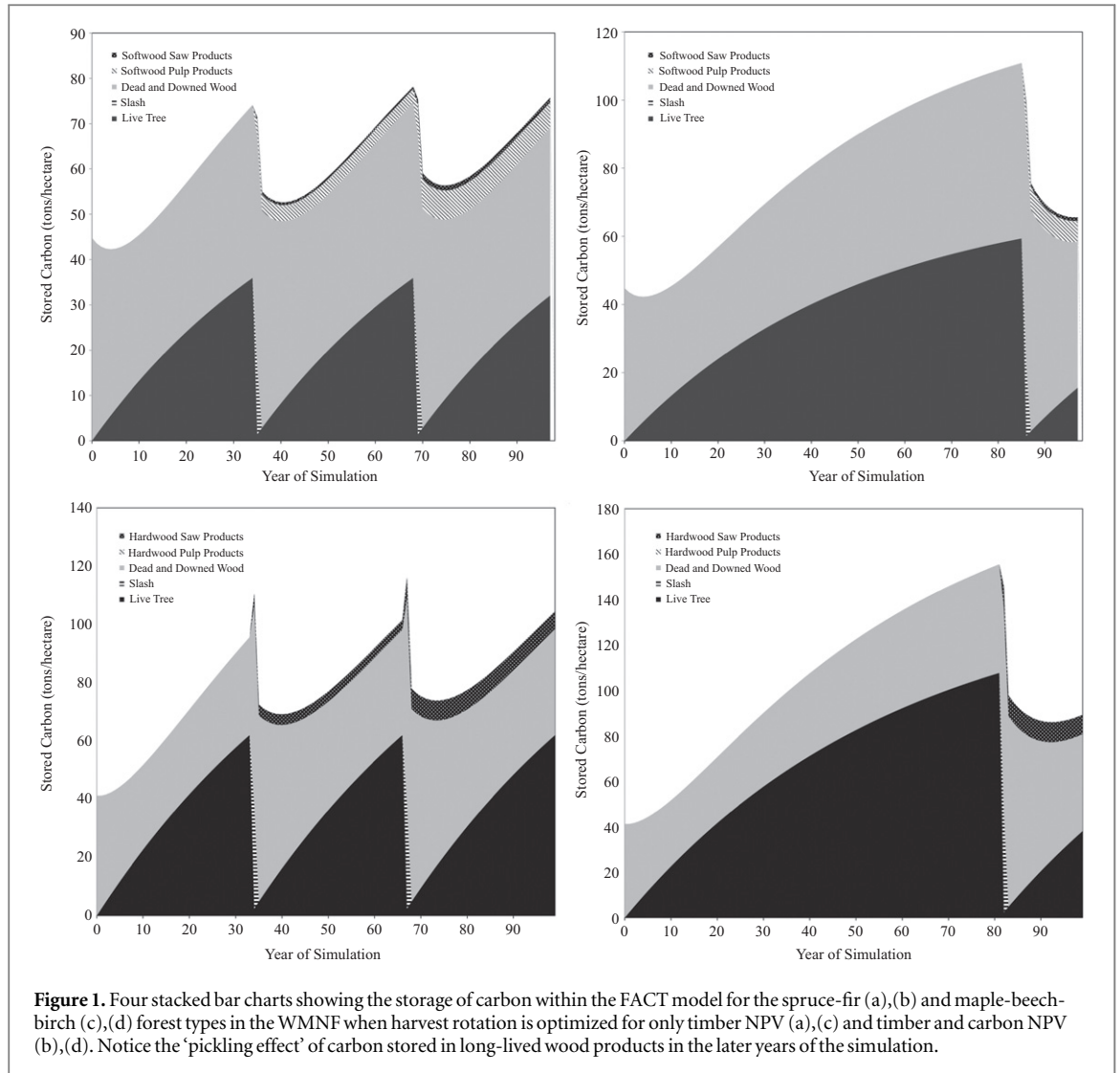


Figure 1. Four stacked bar charts showing the storage of carbon within the FACT model for the spruce-fir (a),(b) and maple-beech-birch (c),(d) forest types in the WMNF when harvest rotation is optimized for only timber NPV (a),(c) and timber and carbon NPV (b),(d). Notice the ‘pickling effect’ of carbon stored in long-lived wood products in the later years of the simulation.

$$W = \sum_{T_{\max}}^{t=1} U[c(t), L(t)]R(t). \quad (4)$$

Within the DICE model, once social welfare is calculated, a shadow price of a unit of carbon emissions, V_c , can be measured by estimating the change in social welfare (W) due to a one unit increase in carbon emissions, E , divided by the marginal utility of consumption (C):

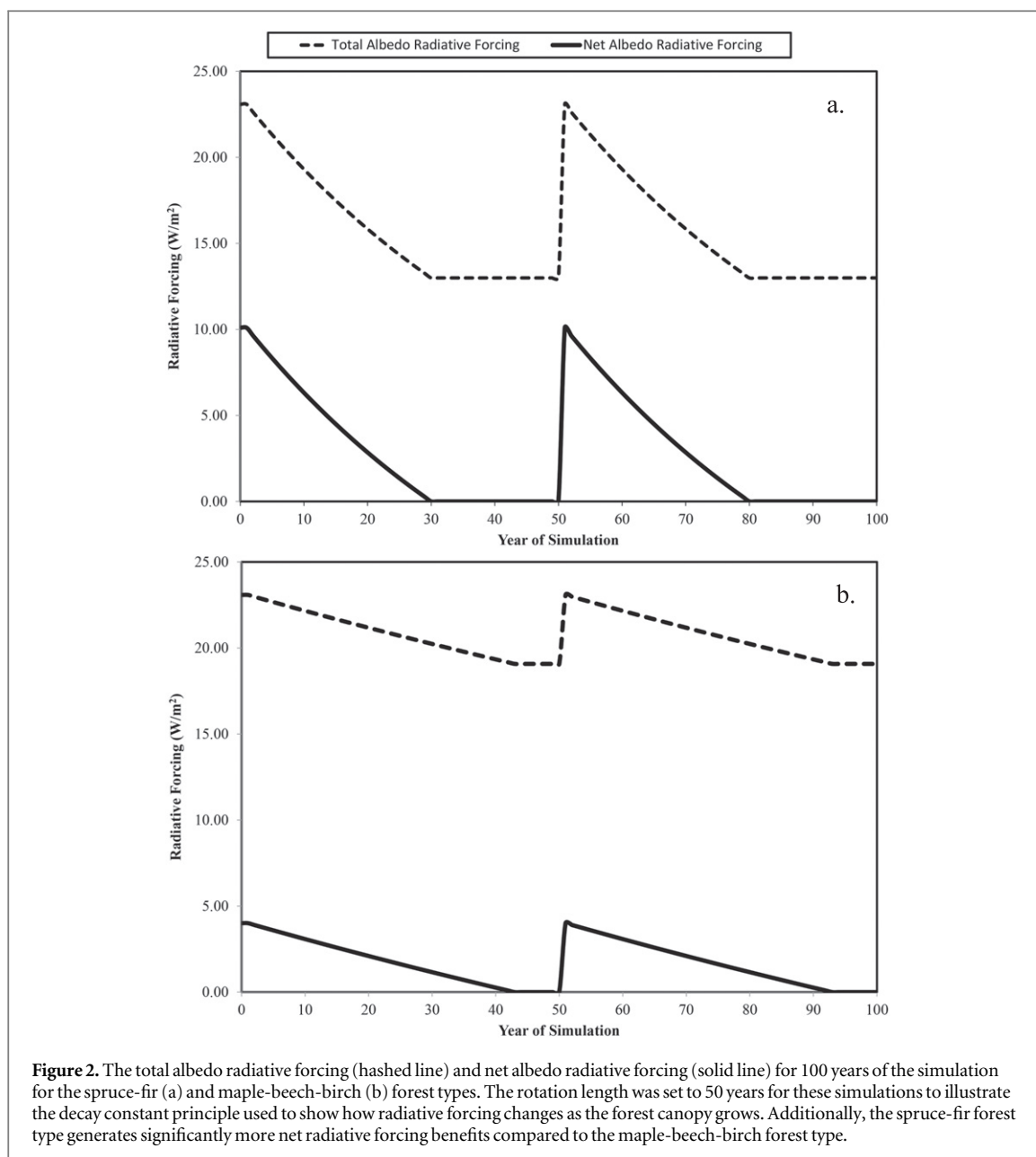
$$V_c(t) = \frac{[\partial W / \partial E(t)]}{[\partial W / \partial C(t)]}. \quad (5)$$

We relied on this methodology to calculate shadow prices for carbon for every simulation. The carbon price from DICE can be found in figure 3.

Calculation of the shadow prices of albedo varied based on the four methodologies outlined in section 1.2. Discrete steps used to make these calculations can be found in the supplementary material (available at stacks.iop.org/ERL/10/064013/mmedia). The first methodology for calculating the shadow price of albedo utilized components of the Global Warming Potential (GWP) metric to relate albedo radiative forcing for forcing from a pulse emission of carbon

dioxide, and then generated a shadow price as a function of the shadow price of carbon. This method divided the shadow price of carbon by the GWP of CO_2 as Cherubini *et al* (2012b) and then multiplied by conversion factors into units of CO_2 and metric tons according to values from the IPCC’s Fourth Assessment Reports. In order to reflect the differing climate efficacies between albedo and carbon dioxide, we utilized those efficacies reported by Hansen (2005). Furthermore, we followed Cherubini *et al* (2012b) and normalized the GWP of albedo to that of CO_2 for each stand by taking into account the carbon yield per hectare, a procedure used when considering climate metrics for forest ecosystems. This generated a $\text{GWP}_{\text{albedo}}$. We then converted the shadow price of carbon from DICE to a shadow price of albedo through the calculated $\text{GWP}_{\text{albedo}}$, taking care to convert units according to values from the IPCC’s Fourth Assessment Reports.

The second methodology for calculating a shadow price of albedo related the radiative forcing of albedo to that of carbon dioxide through the global temperature change potential climate metric (Shine *et al* 2005).



Similar to the GWP, the GTP is a metric which defines a relationship between two different types of forcings, however the GTP focuses on the relationship between how the overall surface temperature of the planet will respond to a pulse emission of the reference gas. The shadow price was calculated through a complex series of steps that related the influence of a change in global temperature at a time horizon by a unit of albedo radiative forcing to that of a pulse of carbon dioxide integrated through the same time horizon. As with the GWP methodology, we also utilized conversion factors to convert from kilograms of carbon dioxide to tons of carbon. Details for these calculations, including equations, can be found in the supplementary material and follow the methods of Cherubini *et al* (2013) and Boucher and Reddy (2008).

The third method of calculating a shadow price for albedo is based on the work of Euskirchen *et al* (2013).

In this methodology, Euskirchen *et al* convert albedo radiative forcing in W m^{-2} to carbon dioxide equivalents. This is done through the assumption that an increase in the carbon dioxide in the atmosphere to a concentration of 700 ppm will generate an increase in radiative forcing on the order of 4.0 W m^{-2} (2013), an assumption based on several estimates from general circulation models. This increased radiative forcing is related to carbon by assuming that terrestrial and oceanic carbon storage will double in size from measured levels at 350 ppm (Euskirchen *et al* 2013), yielding an increase in carbon storage per square meter of the planet of 1372 g C m^{-2} . By dividing this storage by the estimated radiative forcing per square meter, and then converting from C m^{-2} to carbon dioxide equivalents, one can convert between these two entities. Thus, an albedo price could be calculated by multiplying the forcing from albedo by this conversion

Table 2. Optimal rotation (years) and maximum NPV (\$) for the two different forest types under 8 different pricing scenarios. When an emphasis is placed on near-term forcing, the optimal rotation period approaches zero (GWP20, GWP 100, and GTP20 scenarios). Alternatively, using a longer time horizon for these climate metrics results in a significantly longer optimal rotation period.

		GWP 20	GWP 100	GWP 500	GTP 20	GTP 100	GTP 500	Euskirchen	
								<i>et al</i> 2013	DICE
Spruce-Fir	Optimal rotation (years)	2	7	102	4	104	107	15	15
	Maximum NPV (\$)	9156	3923	3417	5628	3325	3261	6000	5799
Maple-Beech-Birch	Optimal rotation (years)	35	68	76	51	79	80	55	43
	Maximum NPV (\$)	3686	2719	2504	3006	2462	2432	2870	3011

factor and the carbon price as calculated by the DICE model.

The fourth and final methodology for calculating a shadow price for albedo was based on the work of Lutz and Howarth (2014). This approach uses the DICE model to construct a shadow price for albedo that is independent of the shadow price for carbon. This method is similar to that of the calculation of the carbon shadow price, except that a change in social welfare, W , is calculated based on the influence of an incremental change in exogenous radiative forcing which influences a simplified two-level global climate model which then influences a damage function (Nordhaus 2014). Specifics regarding this method can be found in the supplementary material as well as in Lutz and Howarth (Lutz and Howarth 2014).

2.4. Model simulations

We simulated both the maple-beech-birch and spruce-fir forest stands in the WMNF with the FACT model for a period of 1000 years for a particular rotation period. The total net present value (NPV, including timber, carbon, and albedo benefits) for the stand was calculated and stored. This process was repeated for the rotation periods of 1 through 300 years and for each different shadow price of albedo. Using a grid search methodology, we identified the optimal rotation period for each forest type which yielded the greatest total NPV. We used a discount rate that was calculated in the DICE model (figure 3) which represents the general risk structure and returns of an average investment portfolio (Nordhaus and Sztorc 2013). The complete methods for the calculation of timber, carbon, and albedo NPV, can be found in the supplementary material.

3. Results

3.1. Albedo prices

The price of albedo, in $\$w^{-1}yr^{-1}$, varied quite substantially among the four methods for calculating shadow prices (figure 4). These prices in year 1 ranged from a high of 9.36×10^{-4} for the GWP method with a time horizon of 20 years to a low of $1.75 \times 10^{-5} \$w^{-1}yr^{-1}$ for the GTP method with a time horizon of 500 years. In year 100 of the

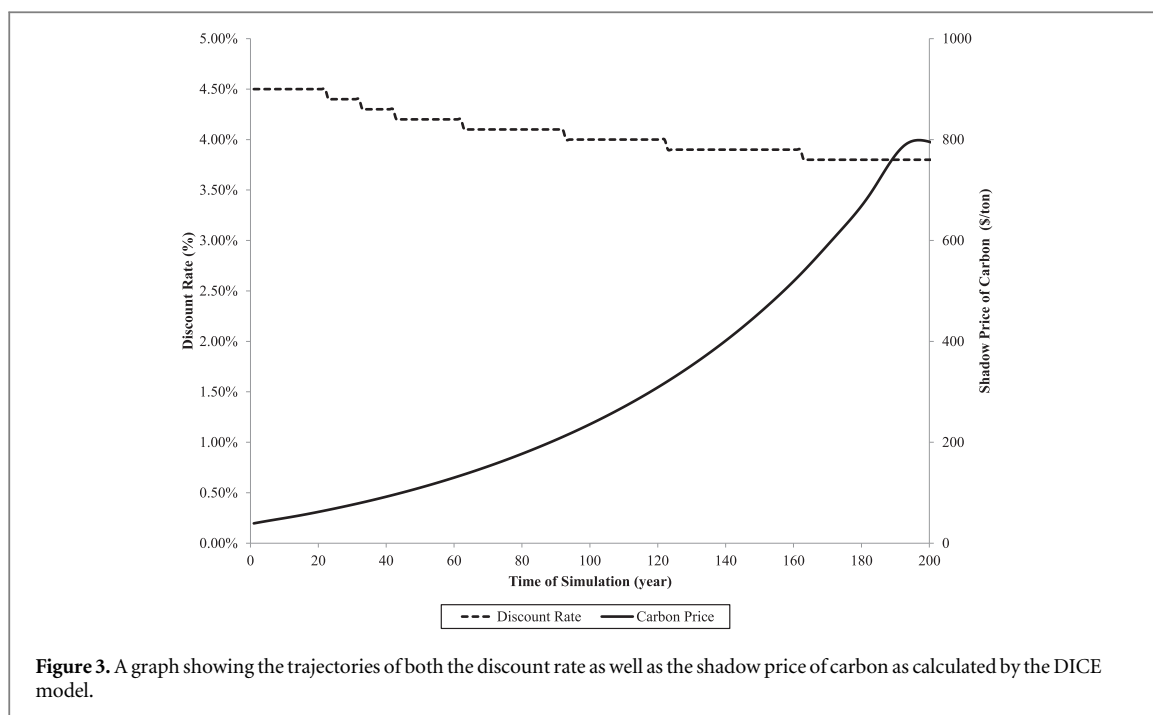
simulation prices ranged from a high of 5.62×10^{-3} for the GWP method with a time horizon of 20 years, to a low of $1.05 \times 10^{-4} \$w^{-1}yr^{-1}$ for the GTP method with a time horizon of 500 years. Most methods yielded a steady growth throughout the simulation as they were coupled to the shadow price of carbon; the DICE method, however, which was calculated independently of the shadow price of carbon, increased at a slightly faster rate over time. The GWP, GTP and Euskirchen *et al* methodologies all peaked in price near year 200 of the simulation, then maintained a steady price through the end of the 1000-year time period. The GWP and GTP pricing methods for a time horizon of 500 years generated shadow prices of albedo that were extremely low, never reaching above 0.0017 and 0.0004 $\$w^{-1}yr^{-1}$ at any time.

3.2. Optimal rotation periods

There was considerable variation amongst optimal rotation periods depending upon which pricing methodology was used to generate albedo revenues (table 2). In general, optimal rotations were shorter the higher the shadow price of albedo, particularly so when the time horizon was just 20 years (for the GWP and GTP methods). The spruce-fir forest type had shorter optimal rotation periods than the maple-beech-birch stand (for the DICE, Euskirchen, GWP20, and GTP20 methodologies), yet was equal to or longer for the 100 year time horizons for the GWP methodology and the 500 year time horizon for the GWP methodology. Despite the inclusion of mowing costs at short rotation periods, the optimal rotation period for the spruce-fir forest stand for the GWP and GTP methods for the 20 year time horizon was under 10 years, indicating the maintenance of a cleared pasture or field. Both the DICE and the Euskirchen *et al* methods yielded reasonable optimal rotation periods, although when the FACT model was run with only timber and carbon being considered, the rotation periods for all four of these methods was longer without albedo (245 for spruce-fir and 81 for maple-beech-birch respectively).

3.3. Total net present value

Pricing methodologies had a substantial effect on the overall net present value under optimal rotation



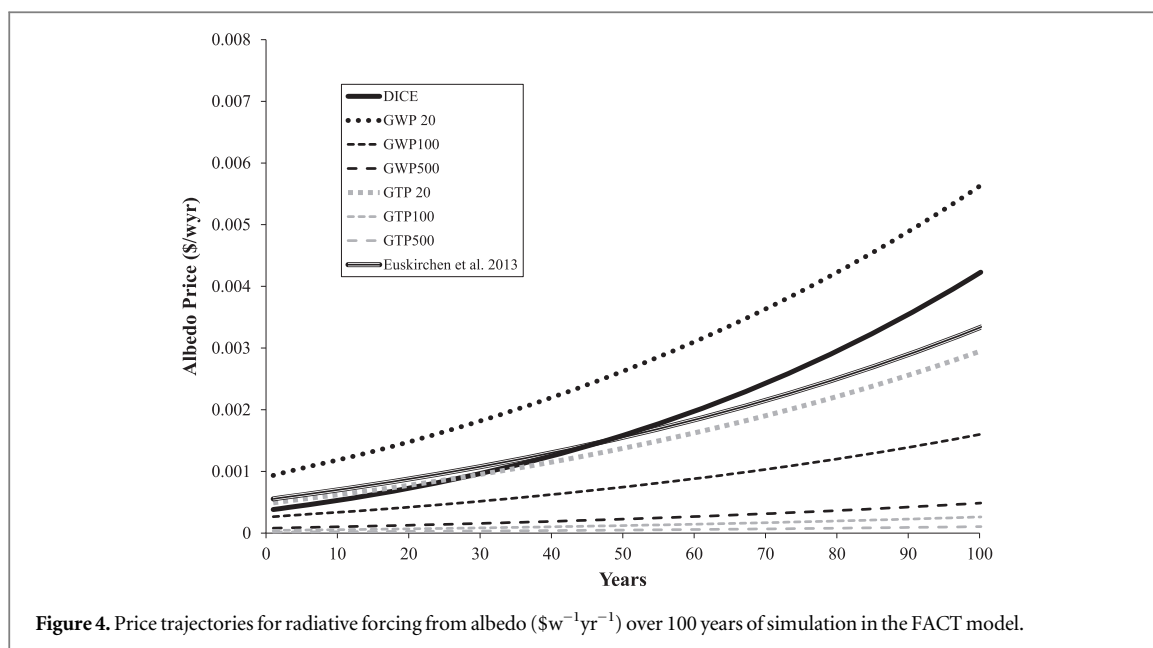
periods and markedly affected which ecosystem service provided the largest share of total NPV (figures 5 and 6). The total NPV was generally greater for the maple-beech-birch forest type than for the spruce-fir forest type, with the exceptions being for the 20 year time horizon GWP and GTP scenarios. The short time horizon (20 year) GWP and GTP scenarios yielded high albedo prices, which resulted in substantial albedo revenues in SF forests (\$12411 and \$13591 respectively). In no other scenario did albedo revenues reach higher than \$800, and in most cases, albedo revenues under optimal rotation were under \$150. In general, carbon revenues were greater than timber or albedo revenues, except in the aforementioned GWP and GTP 20 year time horizon scenarios. As a result, older forests had greater total NPVs due to their large stores of valuable carbon.

The contributions of timber, carbon, and albedo to total net present value at optimal rotation varied between spruce-fir and maple-beech-birch forest types. Since the spruce-fir stand had a low albedo when mature and did not generate valuable saw-timber, albedo was the dominant ecosystem service in four of the eight scenarios (figure 5). Maple-beech-birch forests, however, stored considerable quantities of carbon, produced valuable saw and pole-timber, and generated less albedo benefits when cut compared to when mature. Thus, carbon storage tended to dominate the balance of ecosystem services in these forests for seven of the eight scenarios (figure 6). Only when albedo was highly valued (the DICE, Euskirchen, GWP20 and GTP20 method) did albedo contribute substantially to the NPV of the maple-beech-birch stand.

4. Discussion

We found that each of the four pricing methodologies produced slightly different shadow prices for albedo. For instance, at year 100 of the simulation, the shadow price of albedo ranged from a low of $1.11 \times 10^{-4} \$w^{-1}y^{-1}$ to a high of $4.5 \times 10^{-3} \$w^{-1}y^{-1}$ between the GTP500 and GTP20 methods. In general, two patterns emerged. Firstly, for the GWP, GTP, and Euskirchen methods, which tied the shadow price of albedo to that of carbon, prices increased with time until the year 200 of the simulation, in which emissions control rates in the DICE model were implemented, which stopped the rise of the carbon price because the rate of increase of greenhouse gases in the atmosphere began to fall, and subsequently an incremental increase in carbon generated less severe damages. As a result, at this time the shadow price for albedo also ceased to rise sharply.

The second pattern found among the calculated shadow prices for albedo dealt with the time horizon in both the GWP and GTP methodologies. As the time horizon increased for each of these methods, the subsequent shadow price for albedo was reduced drastically. Both the GWP and GTP methods calculate the forcing of albedo over a particular time horizon, as compared to the time-integrated forcing of carbon dioxide (Shine *et al* 2005). By increasing the length of the time horizon, the impact of the forcing is integrated over a longer time period, and thus one unit of forcing has a less dramatic impact on climate. Since the 20-year time horizon had a more drastic impact on climate in the near term, the prices were substantially higher and had a more dramatic influence on optimal rotation period when used in the forest simulations.



Incorporating the various shadow prices for albedo into the FACT forest simulations generated substantial differences in optimal rotation period for both forest types. While the relationship between carbon prices and rotation periods has been a point of discussion in the context of forest management for several decades (Hoen and Solberg 1994), this is the first consideration of a variety of methods for calculating and including albedo radiative forcing. While greater prices for carbon tend to lead to longer harvest rotation periods as there is an economic incentive to store carbon (e.g. Chladná 2007), the opposite trend occurs when albedo is valued. The general practice of incorporating albedo as an ecosystem service into optimal rotation period length incentivizes shorter rotation periods (Thompson *et al* 2009a, 2009b, Lutz and Howarth 2014), which can counter-balance the incentive of carbon storage revenues.

Our findings align with this recent research that has examined the tradeoffs between carbon storage and albedo radiative forcing in the context of forestry. Sjølie *et al* (2013) used an intertemporal optimization model of the forest sector of Norway to examine the influence of a carbon/albedo tax and subsidy scheme on forest harvest throughout the country. When prices reached a rate of €100 per ton of CO₂e, forest harvest increased over 500% compared to a base case, primarily as a result of the subsidies associated with albedo (Sjølie *et al* 2013). Thompson *et al* 2009a, 2009b similarly examined the optimal rotation period of coastal forests in British Columbia when taxes and subsidies for carbon and albedo were applied and found that optimal rotations shortened compared to a carbon-only approach, however, their rotations never approached zero. Overall, this body of work corroborates with our results pointing out that the incorporation of

subsidies or incentives for albedo in forest policy may lead to strong incentives for quick and frequent harvest.

Three shadow prices of albedo resulted in an optimal rotation of less than 8 years, or a perpetual early-stage successional habitat. (In practice this would entail the maintenance of open fields.) Two of these stemmed from the use of the GWP and GTP climate metrics with short time horizons. The use of a short time horizon minimized the influence of carbon storage and maximized the influence of albedo on both radiative forcing, relevant for the calculation of GWP, and temperature change, which is used for the calculation of GTP. While snow albedo influences climate on a more rapid timescale than carbon dioxide (Hansen and Nazarenko 2004), this effect is multiplied in its influence on shorter rotation periods by selecting a short time horizon of 20 years. The selection of short time horizons for climate metrics has been the subject of discussion for other fast-acting greenhouse gases (Shindell *et al* 2009), yet studies examining the ramifications of these time horizons and subsequent changes in land cover are uncommon. Our results from the selected spruce-fir site indicate that the choice of a short time horizon for a climate metric in the valuation of albedo may lead to economic incentives for heavy forest harvest in cases of forests that receive heavy snowfall and grow slowly, even when costs for yearly mowing are taken into consideration. It is important to note that this is likely not typical of all spruce-fir stands across the state (Lutz *et al* 2015). This type of perpetual harvest may imperil critical forest ecosystem services which require a full canopy for generation. In the case of the WMNF, services such as recreational opportunities, habitat for forest-dwelling species, and sediment and nutrient retention would be altered by such a harvesting regime; thus, the

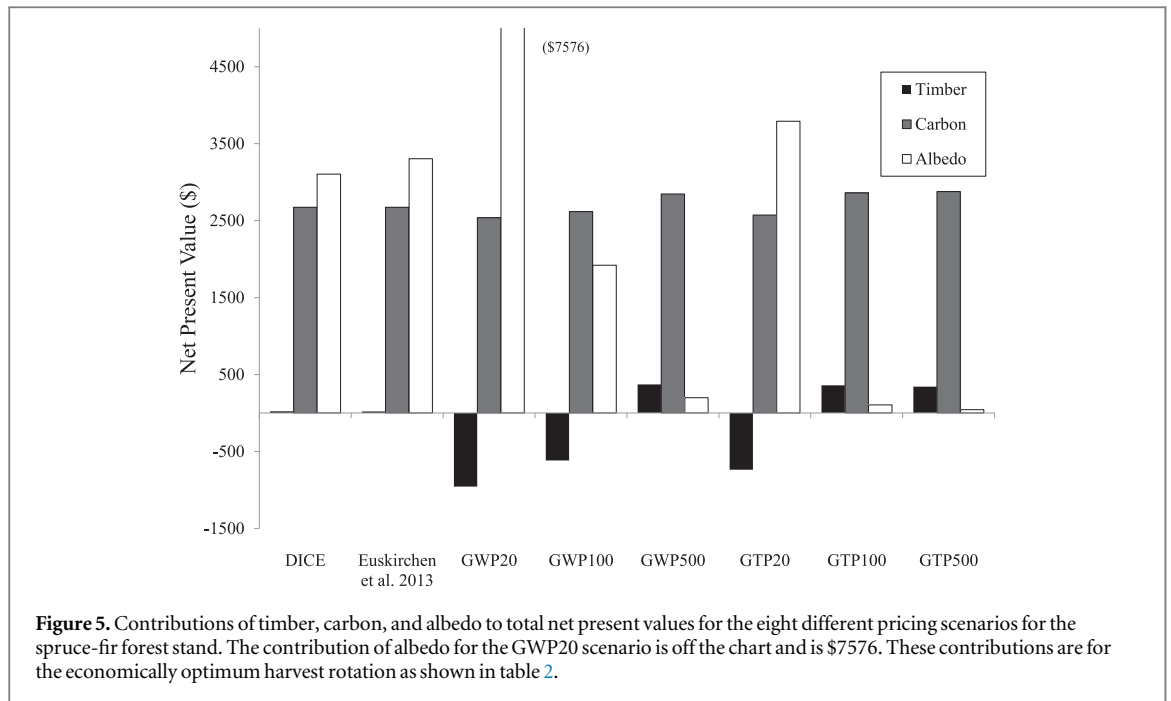


Figure 5. Contributions of timber, carbon, and albedo to total net present values for the eight different pricing scenarios for the spruce-fir forest stand. The contribution of albedo for the GWP20 scenario is off the chart and is \$7576. These contributions are for the economically optimum harvest rotation as shown in table 2.

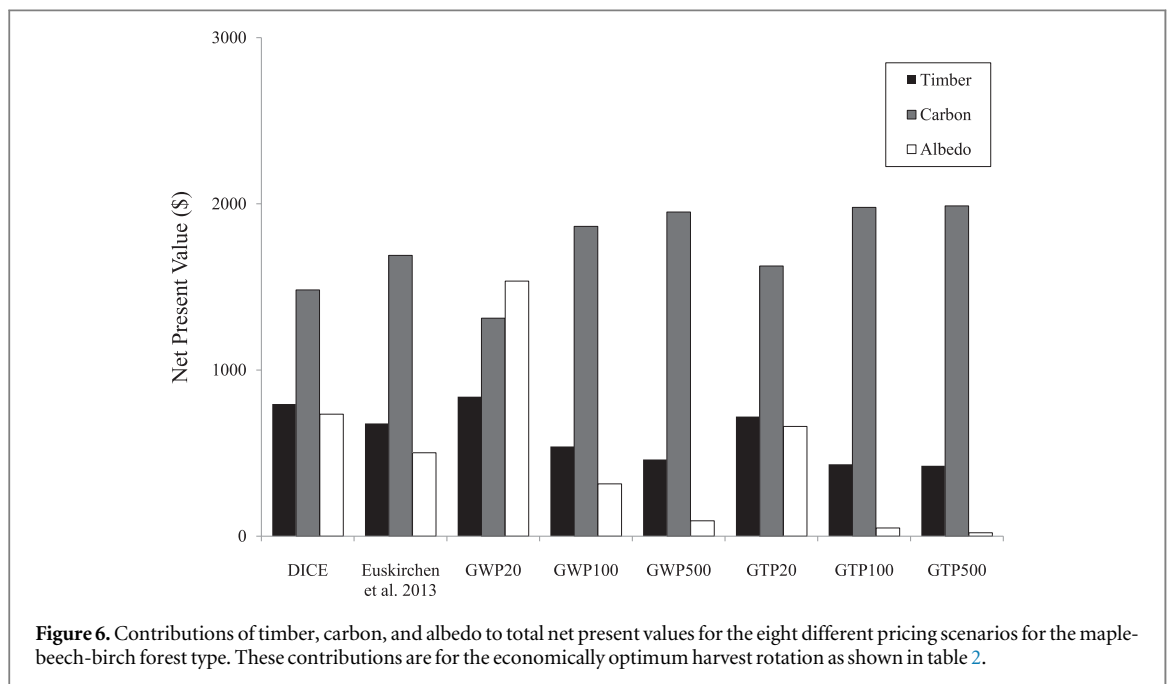


Figure 6. Contributions of timber, carbon, and albedo to total net present values for the eight different pricing scenarios for the maple-beech-birch forest type. These contributions are for the economically optimum harvest rotation as shown in table 2.

implementation of such pricing methodologies may have cascading and unintended consequences.

In addition to influencing the optimal rotation of the two simulated forest types, including the societal benefits of albedo into the net present value of forest increased the total potential stream of benefits substantially compared to a carbon and timber-only scenario. For instance, the net present value of albedo totals over \$200 per hectare for both forest types for the DICE and Euskirchen pricing methods. In the most extreme case, using the GWP20 and GTP20 pricing methods for the spruce-fir forest type, the additional net present value from albedo is greater than \$3500 per hectare. This additional

benefit is potentially important in that it makes managing for albedo comparable to alternative non-timber land uses in the region. D’Amato *et al* (2010) assessed the NPV of forested parcels in the Deerfield River Valley of Massachusetts and found that the total NPV per hectare to be \$4785 when land was managed for timber and enrolled in a tax reduction program for forested land owners, and \$10431 when the land was sold for a conservation easement. A second analysis of this region found the total NPV of a forested acre when left undisturbed to be left ‘wild’ for a conservation easement to be \$5577 (Catanzaro and Damery 2007). While these values undoubtedly deviate somewhat from that of our study area, this

comparison shows that including albedo as an ecosystem service under some pricing scenarios increases the total NPV markedly, such that an optimal management strategy for albedo compares with more conservation-focused land management strategies.

5. Conclusions

A growing body of research has concluded that a carbon-only approach to land-cover related climate change mitigation projects may in some cases be ineffective and possibly counteractive unless biophysical forcings are included as well (Thompson *et al* 2009, Bright *et al* 2011, 2012, 2014, Sjølie *et al* 2013, Lutz and Howarth 2014, Anderson *et al* 2011). However, very little has been written regarding how to appropriately price such biophysical forcings. This research investigated several of the most recent methodologies for calculating shadow prices for albedo radiative forcing and found vast differences between the price trajectories. Furthermore, we found that incorporating these prices in the context of forest management can lead to substantially different optimal methods of harvest. For instance, in our selected spruce-fir stand, which represents an extreme case wherein snow albedo outweighs carbon storage given the low rate of biomass growth, relating albedo radiative forcing to carbon dioxide equivalents using metrics with a short time horizon can generate a wide range of optimal rotation periods (105 years between the highest and lowest estimates). Thus, while incorporating albedo may be important to curtail afforestation projects which are ineffective from a climate perspective, depending on the shadow price associated with albedo, forests may be managed in a way deleterious to other important ecosystem services such as providing habitat for boreal species, water retention and nutrient cycling, and aesthetic and cultural values. It therefore must be realized that attributing a more full range of biophysical effects to forests for climate change mitigation may have unintended consequences due to a strong economic incentive for rapid harvest when radiative forcing shadow prices are high.

It is important to highlight that this study focused primarily on three forest-related ecosystem services and that a large number of other ecosystem services would need to be included for this study to be entirely robust. This caveat is common in research regarding modeling ecosystem service tradeoffs (Goldstein *et al* 2012). Therefore it is essential to view this research in the context of tradeoffs amongst these three services only and that additional values may alter optimal rotation periods substantially. Additionally, we highlight that there is still uncertainty in the scientific community regarding the overall impact of localized changes in radiative forcing from forest albedo and a change in

global temperature, and that although the use of efficiencies attempts to address this issue (Hansen 2005, Cherubini *et al* 2012a), additional coupled land-atmosphere modeling work is important in order to constrain our current estimates. Improvements on the representation of radiative transfer of surface albedo radiative forcing which consider multiple atmospheric layers would also improve this model considerably. Furthermore, including climate feedbacks into our analysis (i.e. changing snowpack or cloud cover with climate change) will also serve to strengthen our modeling results.

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