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Projected surface radiative forcing due to 2000–2050 land-cover land-use albedo change over the eastern United States

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Satellite-derived contemporary land-cover land-use (LCLU) and albedo data and modeled future LCLU are used to study the impact of LCLU change from 2000 to 2050 on surface albedo and radiative forcing for 19 ecoregions in the eastern United States. The modeled 2000–2050 LCLU changes indicate a future decrease in both agriculture and forested land and an increase in developed land that induces ecoregion radiative forcings ranging from −0.175 to 0.432 W m^{-2} driven predominately by differences in the area and type of LCLU change. At the regional scale, these projected LCLU changes induce a net negative albedo decrease (−0.001) and a regional positive radiative forcing of 0.112 W m^{-2}. This overall positive forcing (i.e., warming) is almost 4 times greater than that estimated for documented 1973–2000 LCLU albedo change published in a previous study using the same methods.

Keywords: land-cover land-use change modeling; albedo change; surface radiative forcing; forecasting scenarios model; MODIS; Landsat

1. Introduction

Surface albedo affects the Earth's radiative energy balance by controlling how much incoming solar radiation is absorbed and reflected by the Earth's surface. The global averaged radiative forcing due to land-cover land-use (LCLU) albedo change since 1750 is estimated to be −0.25 W m^{-2} (Intergovernmental Panel on Climate Change (IPCC) 2007). However, the interactions between LCLU change, surface albedo, radiative forcing, and climate variability are poorly understood, reflecting that regionally the radiative forcing response to changes in surface albedo can be highly variable and difficulties in reliably parameterizing land–atmosphere interactions in surface and climate models (IPCC 2007; Matsui, Beltran-Przekurat, Pielke, Niyogi, and Coughenour 2007; Nair *et al*. 2007; Pitman *et al.* 2009; Menon, Akbari, Mahanama, Sednev, and Levinson 2010). A number

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of modeling studies considering past LCLU change and its impacts on climate have been undertaken (Betts 2001; Pielke *et al.* 2002; Kalnay and Cai 2003; Feddema *et al.* 2005; Davin, de Noblet-Ducoudré, and Friedlingstein 2007; Nuñez, Ciapessoni, Rolla, Kalnay, and Cai 2008; Pongratz, Raddatz, Reick, Esch, and Claussen 2009). In this article, we build on the approach of Barnes and Roy (2008, 2010) that used satellite-derived albedo, LCLU, snow, and incoming surface solar radiation data to compute surface radiative forcing estimates of 1973–2000 LCLU albedo change for the United States. Albedos for specific ecoregions were derived by summing the product of LCLU class areal proportions and LCLU class albedos; the surface radiative forcing was then derived as the product of the 1973–2000 LCLU albedo change and the incoming surface solar radiation (Barnes and Roy 2010).

In this article, we consider the surface radiative forcing of projected LCLU albedo change for one LCLU change scenario from 2000 to 2050 and only for the eastern United States as regionally this is where the greatest future LCLU changes within the conterminous United States (CONUS) are expected (Nowak and Walton 2005; White, Morzillo, and Alig 2009). Previously, we observed for the eastern United States a positive forcing of 0.030 W m^{-2} for 1973–2000 LCLU albedo change (Barnes and Roy 2010). In this article, we specifically seek to assess if this positive forcing (i.e., warming) will continue under projected future LCLU. It is well established that the prediction of LCLU is difficult, not least because statistical contemporary LCLU change trend data may not capture future changes in LCLU driving forces, such as socioeconomic, technological, and policy-related drivers acting at varying scales (Lambin 1997; Moss *et al.* 2010). Moreover, long-range (more than decadal) future LCLU can only be meaningfully considered when coupled with future climate (Seneviratne, Lüthi, Litschi, and Schär 2006). However, the two-way coupling between human LCLU-induced changes and a changing climate is poorly understood, and currently there is no integrated regional scale coupled climate–human LCLU change model that has sufficient resolution (spatial, temporal, or class nomenclature) to be meaningfully parameterized using regional moderate to high spatial resolution satellite data products. Consequently, in this study, we derive future 2050 LCLU using the FOREcasting SCEnarios (FORE-SCE) model, which uses contemporary LCLU information to project future LCLU using a semi-stochastic allocation procedure and a regional LCLU change scenario that does not explicitly include future climate change (Sohl and Sayler 2008).

2. Data

The United States Geological Survey (USGS) Land Cover Trends project is quantifying LCLU change across the CONUS using 1973–2000 Landsat satellite data (Loveland *et al.* 2002; Drummond and Loveland 2010). Landsat 10 km × 10 km or 20 km × 20 km subsets are classified by visual interpretation, inspection of aerial photography, and ground survey into 10 LCLU classes: water, developed, mechanically disturbed, mining, barren, forest, grass/shrub, agriculture, nonmechanically disturbed, and wetland. The Landsat subsets are selected using a stratified random sampling methodology within each of 84 contiguous ecoregions (Omernik 1987), with 10 km × 10 km or 20 km × 20 km subsets totaling 9–48 per ecoregion. From these, the ecoregion LCLU areal class proportions for 1973, 1980, 1986, 1992, and 2000 are estimated (Stehman, Sohl, and Loveland 2003). The ecoregion areal LCLU class proportions and classified Landsat subsets defined for 2000 are used in this study.

LCLU projection information for 2050 are provided by the FORE-SCE model which uses a spatially explicit modeling framework to produce scenario-based, 250 m LCLU maps (Sohl and Sayler 2008). The heritage of the FORE-SCE model is the Conversion of Land Use and Its Effects (CLUE) model which models future LCLU as a function of biophysical and human land-use driving forces and past and present LCLU conditions (Veldkamp and Fresco 1996). The eastern United States FORE-SCE scenario used in this study captures the likely decreasing distribution of forest and agricultural land and increasing urban development (Nowak and Walton 2005; Sohl and Sayler 2008; White *et al.* 2009; Drummond and Loveland 2010). Prescriptions for future LCLU classes are provided by ecoregion-based contemporary (1973–2000) LCLU change estimates derived from the USGS Land Cover Trends project data. The FORE-SCE model is initiated using a modified version of the 1992 National Land Cover Data (Vogelmann *et al.* 2001). LCLU class probability-of-occurrence surfaces are derived using logistic regression and individual patches of new LCLU are placed on the landscape in an annual iteration until the scenario prescriptions have been met. A more detailed description of the FORE-SCE model is provided by Sohl and Sayler (2008).

At the time of writing, 19 of the 84 CONUS ecoregions have both Land Cover Trends 2000 and FORE-SCE 2050-projected LCLU information generated, and these are used in this study. The 19 ecoregions encompass approximately 1.5 million km^2 of the eastern United States (Figure 1) and vary in area from 15,917 km^2 (Atlantic Coastal Pine Barrens, ecoregion 84) to 335,482 km^2 (Southeastern Plains, ecoregion 65).

Nine years (18 February 2000 to 31 March 2009) of Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5 Bidirectional Reflectance Distribution Function (BRDF)/Albedo 16-day 500 m product (Schaaf *et al.* 2002) were used to compute the median monthly broadband white-sky snow albedo and snow-free albedo for each of the 10 LCLU classes in each of the 19 ecoregions. The albedo values were derived at locations defined by the Landsat 2000 classified subsets. To ensure that the MODIS 500 m pixels contained only a single LCLU class, the boundaries of each LCLU class in each Landsat 2000 subset were morphologically eroded by 240 m (Serra 1982). Good-quality, full bidirectional reflectance distribution function inverted, nonfill albedo values (Schaaf *et al.* 2002) were then extracted at the remaining LCLU class centroids from the 9 years of MODIS albedo data starting after each Landsat subset 2000 acquisition date to 31 March 2009. A total of 8158 snow and 347,464 snow-free MODIS albedo values were extracted and used in this study.

The MODIS Collection 5 Global Monthly Average 0.05° Snow Cover product (Hall, Riggs, and Salomonson 2006; Hall and Riggs 2007) from January 2004 to December 2008 was used to estimate ecoregion snow cover. For each month, a representative ecoregion mean snow fraction (0–1) was derived as the mean of the 5-month values in the period 2004–2008; the ecoregion mean annual snow fraction was derived as mean of the 12 monthly values.

Monthly incoming surface solar radiation downwards (SSRD) provided in 2.5° × 2.5° cells were obtained and processed from the European Center for Medium-Range Weather Forecasts 40-year Reanalysis (ERA-40) data set (Allan, Ringer, Pamment, and Slingo 2004). Data from January 1973 to December 2000 were used to derive mean monthly SSRD climatology ($W\ m^{-2}$) for each ecoregion.

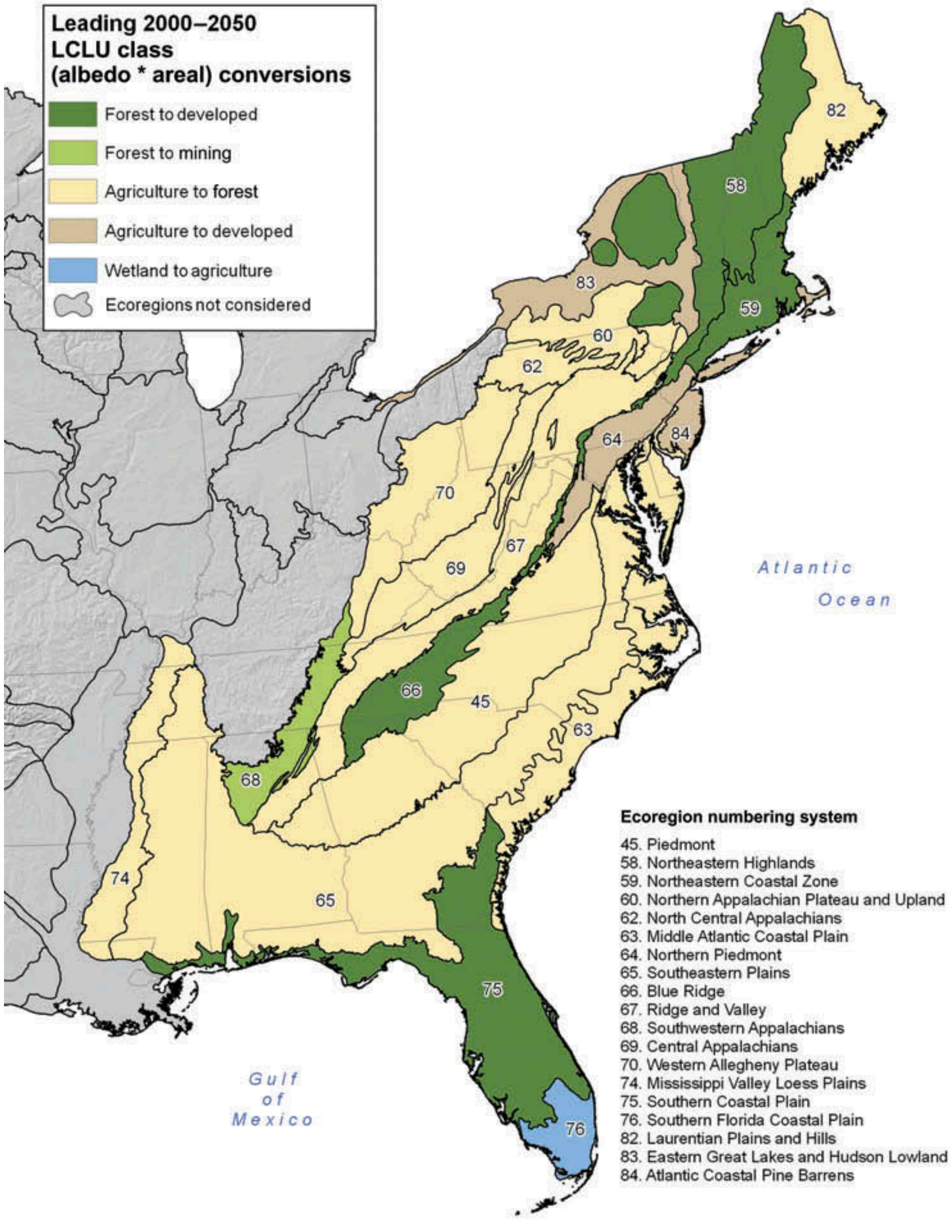

Figure 1. Leading projected LCLU class transitions due to albedo and areal LCLU change from 2000 to 2050 modeling snow conditions for the 19 eastern United States ecoregions (numbered and colored).
Note: LCLU, land cover land use.

3. Method

The method is based on that reported in Barnes and Roy (2010) but in this study using LCLU projection information for 2050 provided by the FORE-SCE model for the 19 eastern ecoregions. Ecoregion albedos are derived by summing the product of LCLU class areal proportions and LCLU class albedos, incorporating ecoregion snow fraction and LCLU class snow albedo. The surface radiative forcing is derived as the product of the 2000–2050 LCLU albedo change and the incoming surface solar radiation. Future climate change is not modeled – the 2050 incoming surface solar radiation and snow cover are set the same as that used for 2000 and future climate-induced LCLU changes are not captured in the FORE-SCE model.

The median snow and snow-free monthly albedo are computed from the 9 years of MODIS data for each LCLU class, ecoregion, and month as

$$\begin{aligned}\bar{\alpha}_{i,\text{ecoregion,month,snow}} &= \underset{9\text{ years}}{\mathit{median}}\left\{\text{snow albedo}_{i,\text{ecoregion,month}}\right\}\\ \bar{\alpha}_{i,\text{ecoregion,month,snow-free}} &= \underset{9\text{ years}}{\mathit{median}}\left\{\text{snow-free albedo}_{i,\text{ecoregion,month}}\right\}\end{aligned} \tag{1}$$

where $\bar{\alpha}_{i,\text{ecoregion,month,snow}}$ and $\bar{\alpha}_{i,\text{ecoregion,month,snow-free}}$ are the monthly median snow and snow-free monthly albedos for LCLU class i, respectively, in the ecoregion; and snow albedo and snow-free albedo are the snow and snow-free broadband white-sky MODIS 500 m albedo values. The impacts of any LCLU changes occurring during the 9-year period are assumed to be minimized by taking the median as [1] and because the LCLU class locations are defined from 9 to 48 subsets distributed across each ecoregion. The ecoregion monthly LCLU class albedos are computed (Roesch, Wild, Pinker, and Ohmura 2002; Barnes and Roy 2010) as follows:

$$\begin{aligned}\alpha_{i,\text{ecoregion,month}} = &\left(1 - f_{\text{snow,month,ecoregion}}\right)\bar{\alpha}_{i,\text{ecoregion,month,snow-free}}\\ &+ f_{\text{snow,month,ecoregion}} \times \bar{\alpha}_{i,\text{ecoregion,month,snow}}\end{aligned} \tag{2}$$

where $\alpha_{i,\text{ecoregion,month}}$ is the monthly albedo for LCLU class i; $\bar{\alpha}_{i,\text{ecoregion,month,snow}}$ and $\bar{\alpha}_{i,\text{ecoregion,month,snow-free}}$ are the median snow and snow-free monthly albedos for LCLU class i, respectively; and $f_{\text{snow,month,ecoregion}}$ is the ecoregion monthly MODIS snow fraction (0–1). The monthly LCLU class albedos for snow-free conditions in each ecoregion are computed by setting the ecoregion monthly snow fraction in Equation (2) to 0. The median rather than the mean monthly snow and snow-free albedos for each LCLU class is used as it is less sensitive to infrequent but anonymously low or high MODIS albedo values associated with residual cloud or shadow contamination.

Monthly albedo estimates for each ecoregion are computed independently for the LCLU class areal proportions in 2000 and 2050 (Barnes and Roy 2008, 2010) as

$$\alpha_{\text{ecoregion,month,year}} = \sum_{i=1}^{10}\left(p_{i,\text{ecoregion,year}} \times \alpha_{i,\text{ecoregion,month}}\right) \tag{3}$$

where year is 2000 or 2050, and for each LCLU class i, $p_{i,\text{ecoregion,year}}$ is either the LCLU class areal proportion in the ecoregion for the year 2000 defined by the Land Cover Trends project or for the year 2050 defined by the FORE-SCE projection model, and $\alpha_{i,\text{ecoregion,month}}$ is defined as in Equation (2). To help interpret our results the annual LCLU-induced albedo change from 2000 to 2050 is derived (Barnes and Roy 2010) as follows:

$$\Delta\alpha_{\text{ecoregion,annual}} = \frac{\sum_{\text{month}=1}^{12}\left(\alpha_{\text{ecoregion,month,2050}} - \alpha_{\text{ecoregion,month,2000}}\right)}{12} \tag{4}$$

where $\alpha_{\text{ecoregion,month,year}}$ is defined as in Equation (3).

The monthly surface radiative forcing (W m^{-2}) for each ecoregion due to LCLU albedo change from 2000 to 2050 is estimated (Jin and Roy 2005, Barnes and Roy 2008, 2010) as

$$\Delta F_{\text{ecoregion,month}} = -\bar{I}^{\downarrow}_{\text{ecoregion,month}} \left(\alpha_{\text{ecoregion,month,2050}} - \alpha_{\text{ecoregion,month,2000}}\right) \tag{5}$$

where $-\bar{I}^{\downarrow}_{\text{ecoregion,month}}$ is the ecoregion mean monthly incoming SSRD climatology (W m^{-2}), and $\alpha_{\text{ecoregion,month,2050}}$ and $\alpha_{\text{ecoregion,month,2000}}$ are the monthly ecoregion albedos for 2050 and 2000, respectively, defined as in Equation (3). The annual surface radiative forcing in each ecoregion, due to projected LCLU albedo change from 2000 to 2050, is computed as

$$\Delta F_{\text{ecoregion,annual}} = \frac{\sum_{\text{month}=1}^{12} \Delta F_{\text{ecoregion,month}}}{12} \tag{6}$$

where $\Delta F_{\text{ecoregion, month}}$ is defined by Equation (5).

Finally, an eastern United States scale net surface radiative forcing for the 19 ecoregions considered is estimated as

$$\Delta F_{\text{Eastern US,annual}} = \frac{\sum_{\text{ecoregion}=1}^{19} a_{\text{ecoregion}} \Delta F_{\text{ecoregion,annual}}}{\sum_{\text{ecoregion}=1}^{19} a_{\text{ecoregion}}} \tag{7}$$

where $a_{\text{ecoregion}}$ is the ecoregion area (km^2) and $\Delta F_{\text{ecoregion,annual}}$ is defined by Equation (6).

4. Results

Table 1 summarizes the MODIS broadband white-sky snow and snow-free albedos for the 10 LCLU classes derived from the 19 eastern ecoregion MODIS albedo data. These values are included to help interpret the LCLU class albedos only; they are not used in the forcing analysis. The albedo class values summarized in Table 1 are comparable to those described by other researchers and by Barnes and Roy (2010).

For the 19 eastern United States ecoregions, the dominant FORE-SCE LCLU changes from 2000 to 2050 are a net areal *increase* in developed land (4.4%) and a net *decrease* in both agricultural (2.5%) and forested land (2.1%) (Sohl and Sayler 2008). Table 2 summarizes these changes and other parameters used in this study, for the 19 ecoregions.

Figure 1 illustrates the leading projected LCLU class transitions that cause the greatest absolute change in albedo from 2000 to 2050 for each ecoregion. These leading LCLU class transitions do not always coincide with the leading transitions due only to LCLU areal change. This is because LCLU changes between classes with very different albedos may have a greater net albedo impact than more areally extensive changes between classes with similar albedos (Barnes and Roy 2008). For example, in the Mississippi Valley Loess Plains (ecoregion 74) the primary areal LCLU transition is from agriculture to developed land (Table 2, penultimate column), whereas the primary albedo (greatest absolute albedo change) transition is from agriculture to forest land (Figure 1 and Table 2, last column).

Table 1. Median snow-free and snow broadband white-sky albedos for each LCLU class computed over the 19 eastern United States ecoregions.

LCLU class	Eastern US snow-free albedo	Eastern US snow albedo
Water	0.0591	0.3576
Wetlands	0.1258	0.2993
Forest	0.1273	0.2543
Nonmechanically disturbed	0.1301	0.4323
Mechanically disturbed	0.1337	0.3121
Mining	0.1354	0.4374
Developed	0.1387	0.3284
Grassland/shrub	0.1438	0.3283
Agriculture	0.1574	0.5163
Barren	0.1938	0.4864

Notes: The LCLU classes are ranked in ascending snow-free albedo order. The LCLU class albedos are shown here for interpretive purposes only; they were not used in the described analysis. The albedos were computed for each class *i* from all the valid MODIS albedo samples for each month *m* (1, . . . , 12), ecoregion *e* (Figure 1), and year *y* (2000–2009) as follows:

$$\text{Eastern US}\ \alpha_i = \underset{12\ \text{months}}{median}\left\{\underset{19\ ecoregions}{median}\left\{\underset{9\ \text{years}}{median}\left\{\alpha_{i,m,e,y}\right\}\right\}\right\}$$

LCLU, land cover land use.

A total of 9 of the 19 ecoregions had a different leading LCLU transition when albedo and areal change were considered compared to considering LCLU areal change only.

The annual LCLU-induced albedo change from 2000 to 2050 (Equation (4)) is illustrated in Figure 2 and ranged from −0.0025 in the Northern Piedmont (ecoregion 64) due predominately to the transition of agriculture to developed, up to 0.0009 in the Southern Coastal Plain (ecoregion 75) due to forest loss. To illustrate the importance of these albedo changes, the mean annual incoming surface solar radiation for the 19 ecoregions is 177 W m^{-2} and a change in albedo of 0.0025 with this mean incoming solar radiation amount would induce a positive forcing of 0.442 W m^{-2}, which is nearly twice the global forcing estimates due to LCLU albedo change since 1750 (IPCC 2007).

Figure 3 illustrates the estimated annual surface radiative forcing due to the FORE-SCE-projected 2000–2050 LCLU albedo changes. About two-thirds of the ecoregions have a positive surface radiative forcing, but with no clear regional spatial pattern. The 19 ecoregion forcing estimates are highly correlated with the net 2000–2050 LCLU albedo change (−0.978) and only weakly correlated with the mean annual incoming surface solar radiation (0.269) and with the mean annual snow fraction (−0.259). The two ecoregions (Northern Piedmont (ecoregion 64) and the Southeastern Plains (ecoregion 65)) with the most positive radiative forcings have relatively high percentages of net 2000–2050 LCLU change (14.0–15.0%) and relatively high incoming solar radiation (177–195 W m^{-2}) and low mean annual snow fractions (0.002–0.037). The most positive surface radiative forcing (0.423 W m^{-2}) occurs in the Northern Piedmont (ecoregion 64) driven primarily by an extensive transition of agriculture to developed land. The most negative forcing (−0.175 W m^{-2}) occurs in the Southern Coastal Plain (ecoregion 75) due primarily to the transition of forest to developed land.

The surface radiative forcing results are mediated by snow cover and whether the LCLU transitions are between snow-hiding and snow-revealing LCLU classes (Betts 2001; Gibbard, Caldeira, Bala, Philips, and Wickett 2005; Barnes and Roy 2010). In six ecoregions the mean annual monthly snow fraction was greater than 0.1 and the absolute

Table 2. Estimated annual surface radiative forcing for the 19 eastern United States ecoregions and ecoregion summary statistics of the parameters used in this study.

Ecoregion name (ecoregion label)	Annual surface radiative forcing modeling snow (W m^{-2})	Annual surface radiative forcing assuming no snow (W m^{-2})	Mean annual monthly SSRD (W m^{-2})	Mean annual monthly snow fraction	2000–2050 LCLU change (%)	Annual surface albedo change (α_{2050}–α_{2000})	Leading 2000–2050 LCLU class transition by area only	Leading 2000–2050 LCLU transition by albedo and areal change
Northern Piedmont (64)	**0.423**	**0.409**	**177**	**0.037**	**14.0**	**−0.0025**	**Agriculture to developed**	**Agriculture to developed**
Southeastern Plains (65)	**0.300**	**0.298**	**195**	**0.002**	**15.0**	**−0.0015**	**Agriculture to forest**	**Agriculture to forest**
Mississippi Valley Loess Plains (74)	**0.258**	**0.256**	**194**	**0.002**	**14.0**	**−0.0013**	**Agriculture to developed**	**Agriculture to forest**
Southern Florida Coastal Plain (76)	0.256	0.256	202	0.000	3.0	−0.0012	Agriculture to developed	Wetland to agriculture
Eastern Great Lakes and Hudson Lowland (83)	0.222	0.164	157	0.181	8.0	−0.0017	Agriculture to developed	Agriculture to developed
Atlantic Coastal Pine Barrens (84)	0.196	0.188	180	0.040	9.0	−0.0011	Forest to developed	Agriculture to developed
Ridge and Valley (67)	0.092	0.086	176	0.033	9.0	−0.0005	Agriculture to forest	Agriculture to forest
Piedmont (45)	0.090	0.093	188	0.003	16.0	−0.0003	Forest to developed	Agriculture to forest
Western Allegheny Plateau (70)	0.084	0.077	169	0.030	5.0	−0.0005	Agriculture to forest	Agriculture to forest
Northern Appalachian Plateau and Upland (60)	0.077	0.051	160	0.150	3.0	−0.0006	Agriculture to forest	Agriculture to forest

Middle Atlantic Coastal Plain (63)	0.077	0.078	191	0.008	11.0	−0.0004	Forest to developed	Agriculture to forest
Southwestern Appalachians (68)	0.057	0.058	184	0.001	10.0	−0.0002	Forest to mining	Forest to mining
Northeastern Highlands (58)	0.030	0.033	155	0.284	5.0	−0.0001	Forest to mining disturbed	Forest to developed
Central Appalachians (69)	0.003	0.016	172	0.037	7.0	0.0001	Forest to mining	Agriculture to forest
Blue Ridge (66)	−0.003	−0.001	181	0.002	3.0	0.0001	Forest to developed	Forest to developed
Northeastern Coastal Zone (59)	−0.026	0.043	168	0.108	9.0	0.0005	Forest to developed	Forest to developed
North Central Appalachians (62)	**−0.030**	**−0.019**	**162**	**0.118**	**4.0**	**0.0002**	**Forest to mining disturbed**	**Agriculture to forest**
Laurentian Plains and Hills (82)	**−0.055**	**−0.010**	**154**	**0.303**	**6.0**	**0.0006**	**Forest to mining disturbed**	**Agriculture to forest**
Southern Coastal Plain (75)	**−0.175**	**−0.175**	**197**	**0.000**	**21.0**	**0.0009**	**Forest to developed**	**Forest to developed**

Notes: The ecoregions are ranked in descending surface radiative forcing order, with the three highest estimated annual positive and negative surface radiative forcing denoted in bold. SSRD, surface solar radiation downwards; LCLU, land cover land use.

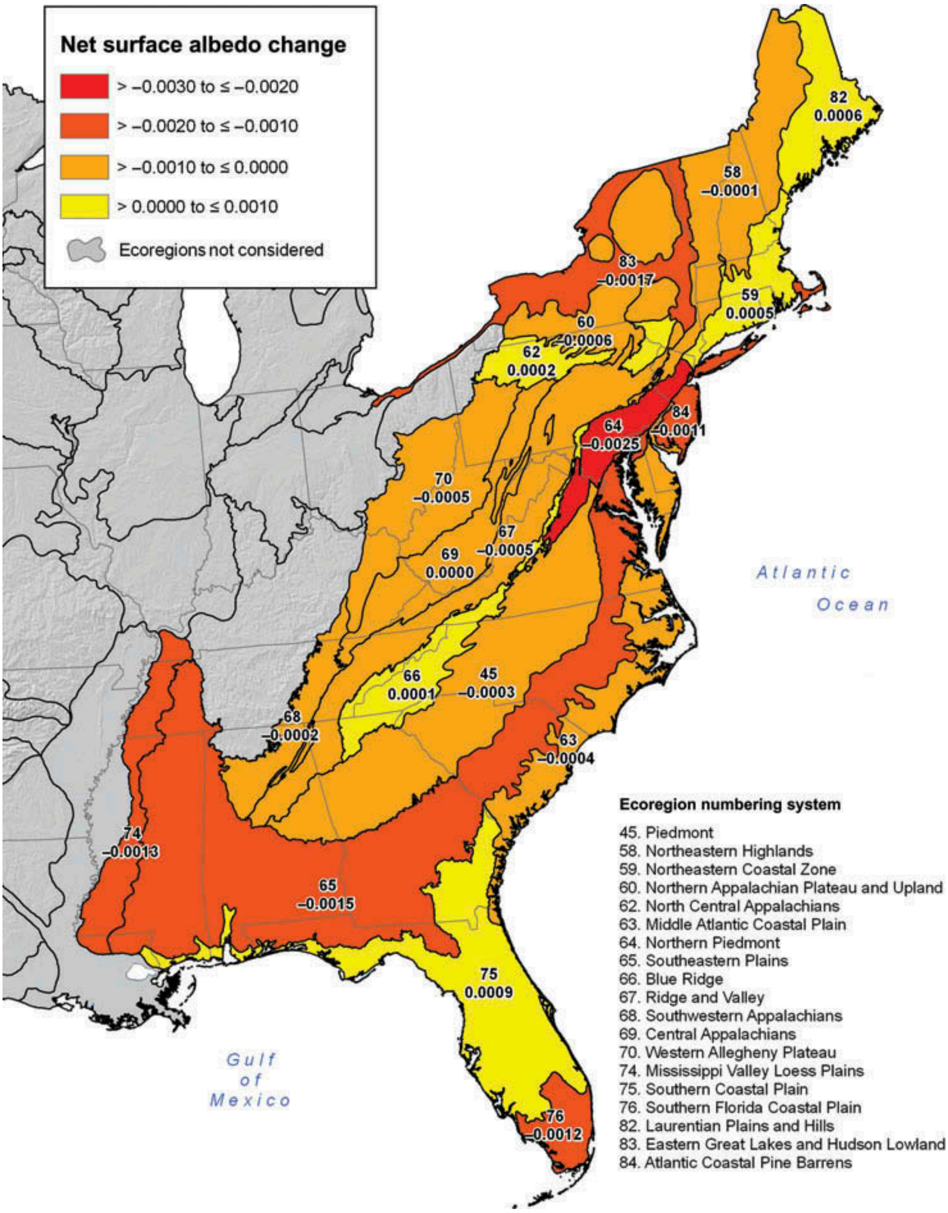

Figure 2. Estimated annual surface albedo change due to projected 2000–2050 LCLU change modeling snow conditions for the 19 eastern United States ecoregions.
Note: LCLU, land cover land use.

difference between the surface radiative forcing-estimated modeling snow (Table 2, column 2) and assuming snow-free conditions (Table 2, column 3) varied from 0.0002 to 0.0688 W m^{-2}. The greatest difference was in the Northeastern Coastal Zone (ecoregion 59, mean annual monthly snow fraction 0.108) which had the largest net 2000–2050 LCLU change (9.0%) of the six ecoregions and where the primary LCLU transitions were between forest (snow-hiding) and developed (snow-revealing) LCLU classes. As observed

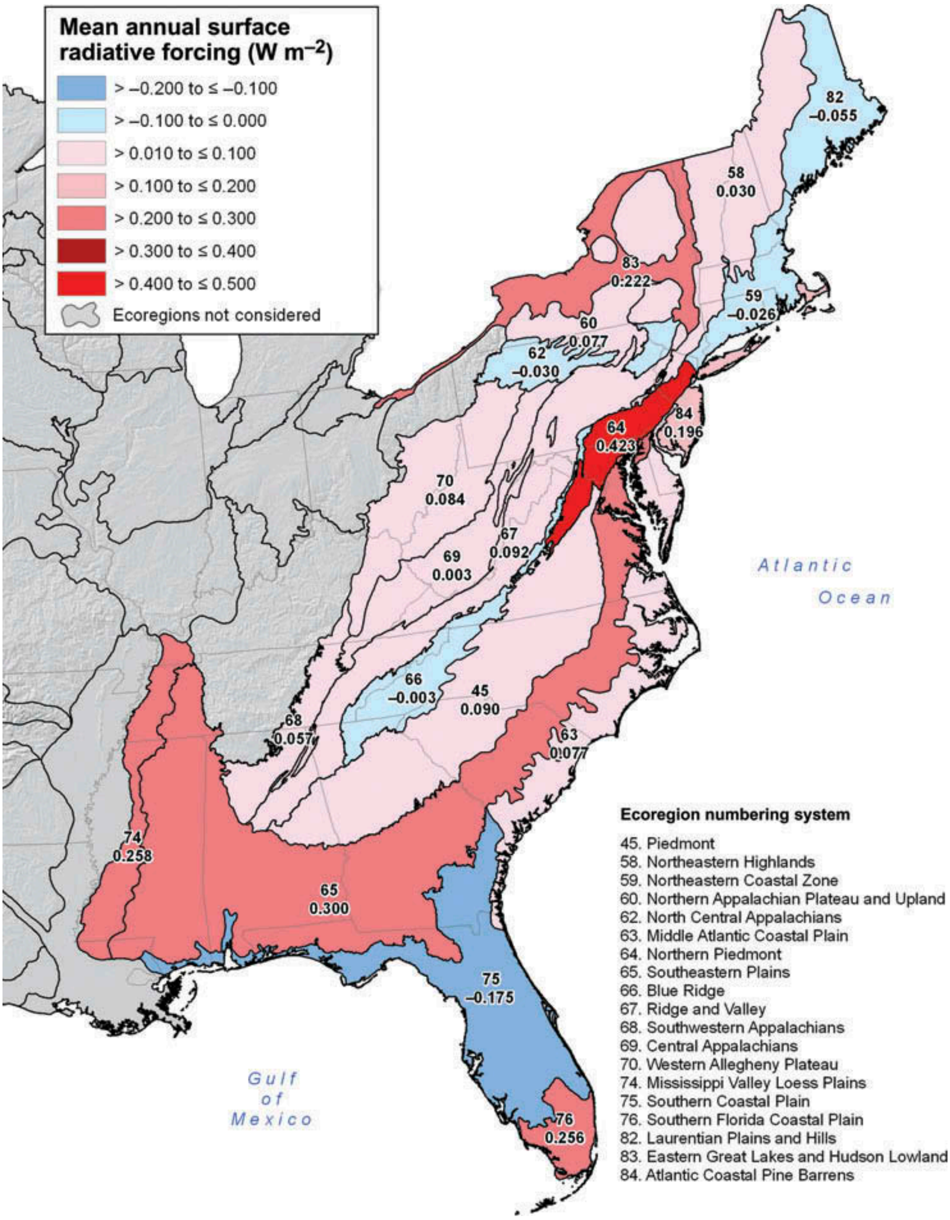

Figure 3. Estimated annual surface radiative forcing due to projected 2000–2050 LCLU albedo change modeling snow conditions for the 19 eastern United States ecoregions.
Note: LCLU, land cover land use.

by Barnes and Roy (2010), snow exacerbated both the negative and positive ecoregion forcings.

Although Betts (2001) established that snow has a significant land-cover-dependent albedo and radiative forcing effect, only about one-third of the 19 eastern United States ecoregions had significant mean annual snow cover. Therefore, the impact of snow at the regional scale was negligible, only changing the regional forcing estimate in the third decimal place when snow and snow-free conditions were modeled.

5. Conclusions

This article has demonstrated the utility of regional spatially and temporally explicit data to quantify the effects of potential LCLU albedo change on surface radiative forcing. The radiative forcing of FORE-SCE-projected 2000–2050 LCLU albedo change varies geographically in sign and magnitude, driven mainly by differences in the area and type of LCLU change across the eastern United States, with the most positive (0.423 W m^{-2}) and negative (-0.175 W m^{-2}) radiative forcings due primarily to the transition of agriculture to developed land and the transition of forest to developed land, respectively.

At the regional scale, the dominant FORE-SCE-projected LCLU changes are a net areal increase in developed land and a net decrease in agricultural and forested land. We estimate that these projected 2050 LCLU changes will induce a regional positive forcing of 0.112 W m^{-2}. This forcing is almost 4 times greater than the 0.030 W m^{-2} estimated using the same methods for 1973–2000 LCLU albedo change, driven primarily by the conversion of forest to mechanically disturbed and agriculture to forest lands (Barnes and Roy 2010). These future and contemporary LCLU albedo change positive forcing estimates contrast with an estimated cooling in the late nineteenth and early twentieth centuries in the eastern United States due to the initial anthropogenic conversion of forest to agriculture (Bonan 1999; Bounoua, DeFries, Collatz, Sellers, and Khan 2002).

In this work, only the direct impact of LCLU albedo change on the surface radiative energy balance was considered. Other biogeophysical and nonradiative feedbacks resulting from LCLU change may be important. For example, changes in LCLU can modify moisture budgets through changes in evaporation and the fluxes of latent and sensible heat, directly affecting precipitation and atmospheric circulation as well as temperature (Bounoua *et al.* 2002; Pielke *et al.* 2002; Davin *et al.* 2007; Findell, Shevliakova, Milly, and Stouffer 2007; Zhou, Dickinson, Tian, Vose, and Dai 2007; Pitman *et al.* 2009). In this study, future climate change is not modeled – the 2050 incoming surface solar radiation and snow cover were set the same as that used for 2000 and future climate-induced LCLU changes were not captured in the FORE-SCE model. Future climate is projected to change (IPCC 2007), but the two-way coupling between human LCLU-induced changes and a changing climate is currently poorly understood. Because future climate change is not included, the influence of LCLU change on surface albedo and radiative forcing can be isolated and understood. More detailed development of local and regional downscaled scenario-driven LCLU change studies and integration into ocean–atmosphere–surface models (Pielke *et al.* 2002; Davin *et al.* 2007) are needed to generate an envelope of spatially and temporally explicit future LCLU maps that will allow for more comprehensive forcing studies to provide more definitive conformation of the LCLU albedo positive forcing trend suggested by this research.

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References

Allan, R.P., Ringer, M.A., Pamment, J.A., and Slingo, A. (2004), "Simulation of the Earth's Radiation Budget by the European Centre for Medium-Range Weather Forecasts 40-Year Reanalysis (ERA40)," *Geophysical Research Letters*, 109, D18107.

Barnes, C.A., and Roy, D.P. (2008), "Radiative Forcing over the Conterminous United States Due to Contemporary Land Cover Land Use Albedo Change," *Geophysical Research Letters*, 35, L09706.

—— (2010), "Radiative Forcing over the Conterminous United States Due to Contemporary Land Cover Land Use Change and Sensitivity to Snow and Inter-annual Albedo Variability," *Journal of Geophysical Research*, 115, G04033.

Betts, R.A. (2001), "Biogeophysical Impacts of Land Use on Present-Day Climate: Near-Surface Temperature Change and Radiative Forcing," *Atmospheric Science Letters*, 2, 39–51.

Bonan, G.B. (1999), "Frost Followed the Plow: Impacts of Deforestation on the Climate of the United States," *Ecological Applications*, 9, 1305–1315.

Bounoua, L., DeFries, R., Collatz, G.J., Sellers, P., and Khan, H. (2002), "Effects of Land Cover Conversion on Surface Climate," *Climatic Change*, 52, 29–64.

Davin, E.L., de Noblet-Ducoudré, N., and Friedlingstein, P. (2007), "Impact of Land Cover Change on Surface Climate: Relevance of the Radiative Forcing Concept," *Geophysical Research Letters*, 34, L13702.

Drummond, M.A., and Loveland, T.R. (2010), "Land-Use Pressure and a Transition to Forest-Cover Loss in the Eastern United States," *BioScience*, 60, 286–298.

Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A., and Washington, W.M. (2005), "The Importance of Land-Cover Change in Simulating Future Climates," *Science*, 310, 1674–1678.

Findell, K.L., Shevliakova, E., Milly, P.C.D., and Stouffer, R.J. (2007), "Modeled Impact of Anthropogenic Land Cover Change on Climate," *Journal of Climate*, 20, 3621–3634.

Gibbard, S., Caldeira, K., Bala, G., Philips, T.J., and Wickett, M. (2005), "Climate Effects of Global Land Cover Change," *Geophysical Research Letters*, 32, L23705.

Hall, D.K., and Riggs, G.A. (2007), "Accuracy Assessment of the MODIS Snow-Cover Products," *Hydrological Processes*, 21, 1534–1547.

Hall, D.K., Riggs, G.A., and Salomonson, V.V. (2006), *Updated Monthly. MODIS/Terra Snow Cover Monthly L3 Global 0.05deg CMG V005 [Dates Used; January 2004 to December 2008]*, Boulder, CO: National Snow and Ice Data Center Digital Media.

Intergovernmental Panel on Climate Change (IPCC) (2007), Climate Change 2007: The Physical Science Basis, *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, New York: Cambridge University Press.

Jin, Y., and Roy, D.P. (2005), "Fire-Induced Albedo Change and its Radiative Forcing at the Surface in Northern Australia," *Geophysical Research Letters*, *32*, L13401, doi:10.1029/2005GL022822.

Kalnay, E., and Cai, M. (2003), "Impact of Urbanization and Land Use on Climate Change," *Nature*, 423, 528–531.

Lambin, E.F. (1997), "Modeling and Monitoring Land-Cover Change Processes in Tropical Regions," *Progress in Physical Geography*, 21, 375–393.

Loveland, T.R., Sohl, T.L., Stehman, S.V., Gallant, A.L., Sayler, K.L., and Napton, D.E. (2002), "A Strategy for Estimating the Rates of Recent United States Land Cover Changes," *Photogrammetric Engineering & Remote Sensing*, 68, 1091–1099.

Loveland, T.R., Gutman, G., Buford, M., Chatterjee, K., Justice, C., Rogers, C., Stokes, B., and Thomas, J. (2003), "Chapter 6: Land Use/Land Cover Change," in *Strategic Plan for the Climate Change Science Program*, ed. D.J. Dokken, Washington, DC: US Climate Change Science Program, pp. 118–134.

Matsui, T., Beltran-Przekurat, A., Pielke, Sr., R.A., Niyogi, D., and Coughenour, M. (2007), "Continental-Scale Multi-objective Calibration and Assessment of Colorado State University Unified Land Model. Part I: Surface Albedo," *Journal of Geophysical Research*, 112, G02028.

Menon, S., Akbari, H., Mahanama, S., Sednev, I., and Levinson, R. (2010), "Radiative Forcing and Temperature Response to Changes in Urban Albedos and Associated CO_2 Offsets," *Environmental Research Letters*, 5, 014005.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., and Wilbanks, T.J. (2010), "The Next Generation of Scenarios for Climate Change Research and Assessment," *Nature*, 463, 747–756.

Nair, U.S., Ray, D.K., Wang, J., Christopher, S.A., Lyons, T., Welch, R.M., and Pielke, Sr., R.A. (2007), "Observational Estimates of Radiative Forcing Due to Land Use Change in Southwest Australia," *Journal of Geophysical Research*, 112, D09117.

Nowak, D.J., and Walton, J.T. (2005), "Projected Urban Growth (2000–2050) and Its Estimated Impact on the U.S. Forest Resource," *Journal of Forestry*, 103, 383–389.

Nuñez, M.N., Ciapessoni, H.H., Rolla, A., Kalnay, E., and Cai, M. (2008), "Impact of Land Use and Precipitation Changes on Surface Temperature Trends in Argentina," *Journal of Geophysical Research*, 113, D06111.

Omernik, J.M. (1987), "Ecoregions of the Conterminous United States," *Annuals of the Association of American Geographers*, 77, 118–125.

Pielke, Sr., R.A., Marland, G., Betts, R.A., Chase, T.N., Eastman, J.L., Niles, J.O., Niyogi, D.D.S., and Running, S.W. (2002), "The Influence of Land Use Change and Landscape Dynamics on the Climate System: Relevance to Climate-Change Policy Beyond the Radiative Effect of Greenhouse Gases," *Philosophical Transactions of the Royal Society of London Series A – Mathematical Physical and Engineering Sciences*, 360, 1705–1719.

Pitman, A.J., de Noblet-Ducoudré, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Müller, C., Reick, C.H., Seneviratne, S.I., Strengers, B.J., and Voldoire, A. (2009), "Uncertainties in Climate Responses to Past Land Cover Change: First Results from the LUCID Intercomparison Study," *Geophysical Research Letters*, 36, L14814.

Pongratz, J., Raddatz, T., Reick, C.H., Esch, M., and Claussen, M. (2009), "Radiative Forcing from Anthropogenic Land Cover Change Since A.D. 800," *Geophysical Research Letters*, 36, L02709.

Roesch, A., Wild, M., Pinker, R., and Ohmura, A. (2002), "Comparison of Spectral Surface Albedos and Their Impact on the General Circulation Model Simulated Surface Climate," *Journal of Geophysical Research*, 107, 4221.

Schaaf, C.B., Gao, F., Strahler, A.H., Lucht, W., Li, X., Tsang, T., Strugnell, N.C., Zhang, X., Jin, Y., Muller, J.P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., d'Entremont, R., Hu, B., Liang, S., Privette, J.L., and Roy, D.P. (2002), "First Operational BRDF, Albedo and Nadir Reflectance Products from MODIS," *Remote Sensing of Environment*, 83, 135–148.

Seneviratne, S.I., Lüthi, D., Litschi, M., and Schär, C. (2006), "Land–Atmosphere Coupling and Climate Change in Europe," *Nature*, 443, 205–209.

Serra, J. (1982), *Image Analysis and Mathematical Morphology*, Orlando, FL: London Academic.

Sohl, T., and Sayler, K. (2008), "Using the FORE-SCE Model to Project Land-Cover Change in the Southeastern United States," *Ecological Modeling*, 219, 49–65.

Stehman, S.V., Sohl, T.L., and Loveland, T.R. (2003), "Statistical Sampling to Characterize Recent United States Land-Cover Change," *Remote Sensing of Environment*, 86 (4), 517–529.

Veldkamp, A., and Fresco, L.O. (1996), "CLUE: A Conceptual Model to Study the Conversion of Land Use and Its Effects," *Ecological Modeling*, 85, 253–270.

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., and Van Driel, J.N. (2001), "Completion of the 1990's National Land Cover Data Set for the Conterminous United States," *Photogrammetric Engineering & Remote Sensing*, 67, 650–662.

White, E.M., Morzillo, A.T., and Alig, R.J. (2009), "Past and Projected Rural Land Conversion in the U.S. at State, Regional, and National Levels," *Landscape and Urban Planning*, 89, 37–48.

Zhou, L., Dickinson, R.E., Tian, Y., Vose, R., and Dai, Y.J. (2007), "Impact of Vegetation Removal and Soil Aridation on Diurnal Temperature Range in a Semiarid Region – Application to the Sahel," *Proceedings of the National Academy of Sciences of the United States of America*, 104, 17937–17942.