2010

United States Land Cover Land Use Change, Albedo and Radiative Forcing: Past and Potential Climate Implications

Christopher A. Barnes
South Dakota State University

UNITED STATES LAND COVER LAND USE CHANGE, ALBEDO AND RADIATIVE FORCING: PAST AND POTENTIAL CLIMATE IMPLICATIONS

By

CHRISTOPHER A. BARNES

A dissertation submitted in partial fulfillment of the requirements for the

Doctor of Philosophy

Major in Geospatial Science and Engineering

South Dakota State University

2010

UNITED STATES LAND COVER LAND USE CHANGE, ALBEDO

AND RADIATIVE FORCING: PAST AND POTENTIAL CLIMATE IMPLICATIONS

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this dissertation does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Dr. David Roy
Dissertation Advisor Date:

Dr. Matthew Hansen
Co-Director, GIScCE Date:

Dr. Tom Loveland
Co-Director, GIScCE Date:

Acknowledgements

I realize that it is impossible to adequately express my sincere appreciation to all those people who have been involved in enabling me to reach such a significant academic achievement. Rather than try, I will focus on a small collection of people and agencies that deserve recognition.

An appropriate starting point is NASA for the Earth System Science Fellowship that I won competitively in 2006. Without this prestigious award I would never have been able to accomplish this academic achievement. I would also like to thank the USGS Earth Resources and Observation and Science (EROS) Center for employing me and providing me with the opportunity to pursue my doctorate degree.

Special and heartfelt thanks are due to my doctoral advisor, Dr David Roy. My successful completion of a doctoral degree in Remote Sensing Geography is because of Dr Roy. He spent considerable time yelling at me, making constructive comments, asking relevant questions, and offering worthy advice. You are a very talented man, with a tremendous gift of applying remote sensing solutions to terrestrial monitoring. You are a terrific teacher, and I count you as a valued friend.

Clearly, my doctoral committee deserves my thanks for their willingness to work with me and provide their critical perspectives on my research. I wish to extend my sincere gratitude to Drs. Tom Loveland, Matthew Hansen, Kevin Gallo and Carol Cumber.

Lastly, I wish to thank my parents, Christine and William, my sister Louise and my partner Jen for providing me with the strength, words of encouragement and belief in myself to succeed. Without them none of this would have been possible. I love you all. Thank you.

ABSTRACT

UNITED STATES LAND COVER LAND USE CHANGE, ALBEDO AND RADIATIVE FORCING: PAST AND POTENTIAL CLIMATE IMPLICATIONS

Christopher A. Barnes

December 2010

Land Cover Land Use (LCLU) change affects Earth surface properties including albedo that impose a radiative forcing on the climate. Recent spatially explicit satellite derived contemporary LCLU, albedo, and projected LCLU data are used to study the impact of LCLU change from 1973 to 2000, and from 2000 to 2050, on albedo and surface radiative forcing for the conterminous United States. Four research hypotheses concerned with past and potential future climate implications of LCLU change are addressed.

The research described in this dissertation makes an important contribution to advancing understanding of the role of LCLU change on the climate system, which the *Intergovernmental Panel on Climate Change* [2007] currently describes as having a low to medium level of scientific understanding. This research explicitly addresses the recommendation made by the U.S. National Research Council (NRC) Radiative Forcing Effects of Climate Change report, for regional studies to better understand climatic responses to LCLU change [*NRC*, 2005]. This dissertation research has, to date, resulted in one published, one in press and one submitted paper.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER 1

INTRODUCTION

1.1 Conceptual Overview: Changing Land Cover Land Use, Albedo and Resulting Radiative Forcing

The impact of land cover land use (LCLU) change on regional and global climate is of considerable concern as population and development pressures continue to mount [*Ramaswamy et al.,* 2001]. A large portion of the Earth's surface has already been modified for croplands, pasture land, forest harvesting, and urban and industrial development. Almost 35% of the Earth's land surface (nearly 55 million km^2) has been directly converted to human-dominated systems [*Ramankutty and Foley,* 1999], while extensive areas are heavily influenced by human activities [*Klein Goldewijk,* 2001]. LCLU changes affect the Earth's physical surface properties, including albedo, and are well established as imposing a radiative forcing on the climate system [*Sagan et al*. 1979; *Hansen et al*., 1998; *Intergovernmental Panel on Climate Change*, 2007]. Surface radiative forcing is the 'instantaneous change in radiative flux at the Earth's surface measured in watts per meter square (Wm^{-2}) [*Hansen et al.,* 1997] and is distinct from top of atmosphere radiative forcing, which is the change in the net irradiance at the troposphere after allowing for stratospheric temperatures to re-adjust to equilibrium [*IPCC,* 2007]. A *positive* surface radiative forcing warms the Earth's surface, while a *negative* forcing cools the surface.

Surface albedo affects the Earth's radiative budget by controlling how much incoming solar radiation is absorbed and reflected by the Earth's surface. The *IPCC* [2007] defines climate change as, "*a statistically significant variation in either the mean state of the climate or its variability…".* It is thought that LCLU change during the twentieth century has induced a net cooling effect on mid latitude climate [*Gibbard et al.,* 2005] and globally has resulted in a surface radiative forcing of approximately -0.25 Wm^{-2} [*IPCC*, 2007]. However, the level of scientific understanding associated with the interaction between LCLU change, albedo, radiative forcing and climate variability is low to medium [*IPCC*, 2007], and reflects the complexity and uncertainty of assessing this human induced climate forcing agent.

Surface albedo is defined as the fraction of incident incoming solar radiation that is reflected (0-1); many general circulation models require both visible (0.4–0.7 μm) and near-infrared (0.7–5.0 μm) albedo, whereas surface energy balance and radiative forcing studies, such as this research, use broadband shortwave (0.25–5.0 μm) albedo [*Liang et al.,* 1999]. Bare soil has a shortwave albedo of 0.25 - 0.45 depending on the type and mositure of the soil, whereas live vegetated surfaces typically have low shortwave albedo, 0.15 - 0.30, due to their photosynthetic properties [*Pielke and Avissar*, 1990; *Jin et al.,* 2002; *Zhou et al.,* 2003]. The albedo of snow cover, especially fresh, deep snow, has a high shortwave albedo of 0.70 - 0.95 [*Myhre and Myhre,* 2003; *Gao et al.,* 2005].

To compute the radiative forcing at the Earth's surface due to surface albedo change, the downwards incoming surface solar radiation (Wm^{-2}) is multiplied by the change in surface albedo between the two time periods under consideration [*Jin and Roy*, 2005; *Myhre et al.,* 2005; *Randerson et al.,* 2006]. Small changes in albedo can have a significant warming or cooling effect. *Wielicki et al*. (2005) noted that the "*global average incident surface solar radiation downwards is ~341* Wm^{-2}*, so that a change in surface albedo of 0.01 represents a global energy balance change of 3.4* Wm^{-2}*, similar in magnitude to the impact of doubling carbon dioxide in the atmosphere*".

1.2 Research Hypotheses

The goal of this research is to study and quantify contemporary LCLU change on albedo and radiative forcing in order to examine past and potential future climate implications of human land surface activity. The following four research hypotheses are addressed:

#1. Over the last 30 years LCLU change across the CONUS has led to a mean net positive albedo increase and a consequent albedo-related cooling.

#2. Radiative forcing due to LCLU albedo change is greater than that due to inter-annual albedo variability.

#3. Current rates of LCLU change imply future net albedo increases and associated albedo-related cooling effects.

#4. There are large regional disparities in LCLU change, consequently large regional disparities in albedo change and radiative forcing will modify the outcomes of hypotheses #1, #2 and #3 at the regional scale.

Whether research hypothesis #1 is true is an open research issue. Certainly *Houghton et al.* [2001] and *Govindasamy et al*. [2001] suggest that human land surface activities on a regional scale have caused an increase in surface albedo and a subsequent net cooling due to albedo change. However, in the conterminous United States (CONUS) there are differences, for example, in the southeastern U.S. 2.1 million acres of cropland were converted to forest from 1973 to 2000 [*Loveland et al.,* 2002]. Forests generally have lower albedo than cropland and so arable to forest conversion may have resulted in a decrease in surface albedo, and thus a net albedo-related warming in the southeastern U.S. Similarly, *Hale et al*. [2008] observed negligible but not insignificant increases in minima and maxima near-surface temperatures due to arable to forest conversion across the Eastern U.S. Further still, the effect of albedo change may be accentuated in snow prone regions, as open land can become completely snow-covered and hence highly reflective, while forest canopies may remain exposed above the snow [*Betts*, 2000].

Research hypothesis #2 posits the important question that radiative forcing of anthropogenic LCLU albedo changes are greater than the radiative forcing not due to LCLU albedo change but due to inter-annual albedo variability. Albedo varies because of factors including land management practices, vegetation phenology, soil moisture changes, land degradation e.g., due to sustained overuse, and changes in snow cover [*Gao et al.,* 2004; *Gao et al.,* 2005]. The inter-annual variability of albedo is usually lower than seasonal albedo variability [*Wang et al*., 2004*, Matsui et al.,* 2007], and failure to adequately prescribe seasonal variations may significantly bias LCLU change forcing estimates [*Nair et al.,* 2007]. The veracity of hypothesis #2 is likely to vary regionally as the type and phenology of vegetation, and so albedo, varies across the CONUS.

Research hypothesis #3 follows on from hypothesis #1 and will be considered using projected future LCLU scenarios. This hypothesis is worthy of interest as it is unclear even what contemporary LCLU change rates imply are and it is unknown what they suggest for the future.

Research hypothesis #4 will be addressed by considering the previous three hypotheses and comparing their results among ecoregions. Across the CONUS it is likely that there is no single profile of LCLU change, rather there are varying pulses affected by clusters of change agents [*Loveland et al.,* 2002, *Brown et al.,* 2005]. This argues strongly for a regional based analysis approach as continental averages may mask regional differences.

1.3 Significance of the Research

The research responds to the recent recommendation made by the U.S. National Research Council (NRC) for regional forcing studies to better understand climatic responses to LCLU albedo change [*NRC*, 2005]. The interaction between LCLU change, albedo, radiative forcing and climate variability is poorly understood. The *Intergovernmental Panel on Climate Change* [2007] currently describes the role of LCLU change on the climate system as having a low to medium level of scientific understanding. Studies have been limited due to uncertainties in LCLU change and albedo data [*IPCC,* 2007; *Myhre and Myhre,* 2003]. Albedo data for different land cover types are available from a variety of surface and space borne sources but have large published variability [*Oleson et al.,* 2003; *Zhou et al.,* 2003; *Roesch et al.,* 2004; *Wang et al.,* 2004; *Gao et al.,* 2005], and inter-annual albedo variability [*Moody et al.,* 2005] has not been considered. Until recently, there have been no LCLU data that capture decadal scale changes over large areas that have been defined in a reliable or systematic manner. For these reasons, previous studies of LCLU radiative forcing have necessarily only considered hypothetical LCLU change scenarios using representative albedo values [*Betts* 2000; *Bala et al.*, 2007]. These *scenario* driven studies, although useful, cannot reliably capture LCLU change and albedo effects, especially when it is considered that the impact of albedo change depends on both the type and spatial extent of LCLU change, and the spatial averaging of opposite signs of LCLU change may under represent LCLU contributions over large areas [*Pielke et al.,* 2002; *Kleidon,* 2006]. Satellite driven studies have been undertaken using spatially and/or temporary explicit albedo retrievals but have not considered contemporary LCLU change [*Jin and Roy*, 2005; *Myhre et al.,* 2005; *Randerson et al.,* 2006]. The recent advent of spatially and temporally explicit satellite derived albedo [*Schaaf et al.,* 2002] and systematically sampled LCLU data [*Loveland et al.,* 2002] offer the opportunity for real advances to quantify, and begin to understand the drivers of LCLU change related radiative forcing.

1.4 Summary of Chapters

Chapter 2 expands the conceptual review described above through a review of: (*i*) historical trends in mean global surface temperature changes, (*ii*) the establishment of an international scientific organization tasked to determine the significance of human activities on Earth surface climate processes, (*iii*) LCLU change across the conterminous United States, (*iv*) research to predict future LCLU, (v) the effects of LCLU albedo change on the climate system and, (*vi*) the concepts of climate and radiative forcings.

Chapter 3 addresses research hypotheses #1 and #4, and describes the processing methodology developed to quantify the surface radiative forcing of contemporary LCLU albedo change (1973 to 2000) not including snow effects, for an area equivalent to 43% of the CONUS. This chapter was published in the *Journal of Geophysical Research Letters* (impact factor 3.2).

Chapter 4 addresses research hypotheses #2, and describes the sensitivity of the forcing estimates to inter-annual albedo variations not associated with LCLU change. This chapter also provides a revised estimate of the previous chapters CONUS surface radiative forcing estimate by considering a greater area, 69% of the CONUS, and by improving the representation of the LCLU class albedos. This was achieved by incorporating spatially and temporally explicit snow albedo and snow fraction data. This chapter has been accepted for publication in the *Journal of Geophysical Research Biogeosciences* (impact factor 3.1).

Chapter 5 addresses research hypotheses #3 and #4, and demonstrates the utility of regional spatially and temporally explicit data to quantify the effects of projected 2050 LCLU albedo change on surface radiative forcing for the Eastern United States. This chapter has been submitted for publication to the *Journal of Environmental Research Letters*.

Chapter 6 summarizes the research hypotheses findings and provides a synthesis of the results. In addition, recommendations for future research are presented with an emphasis on improvements to datasets used to study LCLU albedo change climate forcing effects, integration of the forcing results into climate models and, the need to place the dissertation research into a global context.

1.5 References

Bala, G., K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire, and A. Mirin (2007), Combined climate and carbon-cycle effects of large-scale deforestation, Proc. *Natl. Acad. Sci.,* USA. 104: 6550–6555.

Betts, R. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature,* 408, 187-190.

Brown, D. G., K. M. Johnson, T. R. Loveland, and D. M. Theobald (2005), Rural land use trends in the conterminous United States, 1950– 2000, Ecol. Appl., 15, 1851– 1863.

Gao, F., C. B. Schaaf, A. H. Strahler, A. Roesch, W. Lucht, and R. Dickinson (2005), MODIS bidirectional reflectance distribution function and albedo Climate Modeling Grid products and the variability of albedo for major global vegetation types, *J. Geophys. Res*., 110, D01104, doi:10.1029/2004JD005190.

Gibbard, S., K. Caldeira, G. Bala, T.J. Philips, and M. Wickett (2005), Climate effects of global land cover change, *Geophys. Res. Lett*., *32*, L23705, doi:10.1029/2005GL024550.

Govindasamy, B., P.B. Duffy, and K. Calderia (2001), Land use changes and Northern Hemisphere cooling, *Geophys. Res. Let.*, 28, 291-294.

Hale, R.C., **K.P. Gallo, and T.R. Loveland** (2008), Influences of specific land use/land cover conversions on climatological normals of near-surface temperature, *J. Geophys. Res.*, 113, D14113, doi:10.1029/2007JD009548.

Hansen, J., M. Sato, and R. Ruedy (1997), Radiative forcing and climate response, *J. Geophys. Res.*, *102*(D6), 6831–6864.

Hansen, J., M., Sato, A. Lacis, R. Ruedy, I. Tegen, and E. Matthews (1998), Climate forcings in the Industrial Era, *Proced. Nat. Acad. Sci.*, 95, 12753-12758.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson Eds., (2001), *Climate Change 2001: The Scientific Basics.* Cambridge University Press, 881pp.

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*, edited by S. Solomon *et al.,* Cambridge Univ. Press, New York.

Jin, Y. and D.P. Roy, (2005), Fire-induced albedo change and its radiative forcing at the surface in northern Australia, *Geophys. Res. Let.*, 32*,* L13401, doi:10.1029/2005GL022822.

Kleidon, A (2006), The climate sensitivity to human appropriation of vegetation productivity and its thermodynamic characterization, *Global Planet Change*, 54:109–127.

Klein Goldewijk, K (2001), Estimating global land use change over the past 300 years: the HYDE database, *Global Biogeochem. Cycles,* 15, 417-433.

Liang, S., A.H. Strahler, and C. Walthall (1999), Retrieval of Land Surface Albedo from Satellite Observations: A Simulation Study, *Journal of Applied Meteorology,* 38. 6:712–725.

Loveland, T.R., T.L. Sohl, S.V. Stehman, A.L. Gallant, K.L. Sayler, and D.E. Napton (2002), A Strategy for Estimating the Rates of Recent United States Land Cover Changes, *Photo. Engin. Rem. Sens.*, 68. 1091-1099.

Matsui, T., A. Beltran-Przekurat, R.A. Pielke Sr., D. Niyogi, and M. Coughenour (2007), Continental-scale multi-objective calibration and assessment of Colorado State University Unified Land Model. Part I: Surface albedo. *J. Geophys. Res,* 112, G02028, doi:10.1029/2006JG000229.

Moody, E. G., **M.D. King, S. Platnick, C.B. Schaaf, and F. Gao** (2005), Spatially complete global spectral surface albedos: Value-added datasets derived from Terra MODIS land products, *IEEE Trans. Geo. Rem. Sens.,* 43. 144-158.

Myhre, G. and A. Myhre (2003), Uncertainties in radiative forcing due to surface albedo changes caused by land-use changes, *American Meteorological Society,* 16. 1511-1524.

Myhre, G., **M. Kvalevag, and C. Schaaf** (2005), Radiative Forcing due to human vegetation change based on MODIS surface albedo data, *Geophys. Res. Lett.,* 32, L21410, doi:10.1029/2005GL024004.

National Research Council (NRC) (2005), *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, National Academic Press, Washington, D.C.

Nair, U.S., D.K. Ray, J. Wang, S.A Christopher, T. Lyons, R.M. Welch, and R.A. Pielke Sr. (2007), Observational estimates of radiative forcing due to land use change in southwest Australia. *J. Geophys. Res.,* 112, D09117, doi:10.1029/2006JD007505.

Oleson, K.W., G. B. Bonan, C. B. Schaaf, F. Gao, Y. Jin, and A. H. Strahler (2003), Assessment of global climate model land surface albedo using MODIS data, *Geophys. Res. Lett.,* 30(8), 1443, doi:10.1029/2002GL016749.

Pielke, R.A. **and R. Avissar** (1990), Influence of Landscape Structure on Local and Regional Climate, *Landscape Ecology*, 4:2/3, 133-155.

Pielke, R.A., **G. Marland, R.A. Betts, T.N. Chase, J.L. Eastman, J.O. Niles, D.S. Niyogi, and S.W. Running** (2002), The influence of land-use change and landscape dynamics on the climate system - relevance to climate change policy beyond the radioactive effect of greenhouse gases, *Phil. Trans. R. Soc. Lond. A.,* 360: 1705–1719.

Pielke, R.A. (2008), A broader view of the role of humans in the climate system**.** *Physics Today*, 61, 11: 54-55.

Ramankutty, N., and J.A. Foley (1999), Estimating historical changes in global land cover: croplands from 1700 to 1992, *Global Biogeochem. Cycles*, 14: 997–1027.

Ramaswamy, V., **O. Boucher, J. Haigh, D. Hauglustaine, J. Haywood, G. Myhre, T. Nakajima, G.Y. Shi, S. Solomon, R. Betts, R. Charlson, C. Chuang, J.S. Daniel, A. Del Genio, R. van Dorland, J. Feichter, J. Fuglestvedt, P.M. de F. Forster, S.J. Ghan, A. Jones, J.T. Kiehl, D. Koch, C. Land, J. Lean, U. Lohmann, K. Minschwaner, J.E. Penner, D.L. Roberts, H. Rodhe, G.J. Roelofs, L.D. Rotstayn, T.L. Schneider, U. Schumann, S.E. Schwartz, M.D. Schwarzkopf, K.P. Shine, S. Smith, D.S. Stevenson, F. Stordal, I. Tegen, Y. Zhang** (2001), Radiative forcing of climate change, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, pp 350-416, Cambridge University Press, Cambridge, U.K.

Randerson, J. T.,**H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, C. S. Zender** (2006), The impact of boreal forest fire on climate warming, *Science*, 314: 1130–1132.

Sagan, C., O.B. Toon, J.B. Pollack (1979), Anthropogenic albedo changes and the Earth's climate, *Science*, 206, 1363-1368.

Schaaf, C. B., F. Gao, A. H. Strahler, W. Lucht, X. Li, T. Tsang, N. C. Strugnell, X. Zhang, Y. Jin, J.P. Muller, P. Lewis, M. Barnsley, P. Hobson, M. Disney, G. Roberts, M.

Dunderdale, C. Doll, R. d'Entremont, B. Hu, S. Liang, and J. L. Privette, and D. P. Roy (2002), First Operational BRDF, Albedo and Nadir Reflectance Products from MODIS, *Remote Sens. Environ.*, *83*, 135-148.

Sohl, T., and K. Sayler (2008), Using the FORE-SCE model to project land-cover change in the southeastern United States, *Ecological Modeling*, 219:49-65.

Wang, Z., X. Zeng, M. Barlage, R. E. Dickinson, F. Gao, and C. Schaaf (2004), Using MODIS BRDF and Albedo Data to Evaluate Global Model Land Surface Albedo, *J. Hydrometeorl*., 5, 3-14.

Wielicki, B., T. Wong, N. Loeb, P. Minnis, K. Priestley, R. Kandel (2005), Changes in earth's Albedo Measured by Satellite, *Science*, 308: 825.

Zhou, L., R. E. Dickinson, Y. Tian, X. Zeng, Y. Dai, Z.-L. Yang, C. B. Schaaf, F. Gao, Y. Jin, A. Strahler, R. B. Myneni, H. Yu, W. Wu, and M. Shaikh (2003), Comparison of seasonal and spatial variations of albedos from Moderate-Resolution Imaging Spectroradiometer (MODIS) and Common Land Model, *J. Geophys. Res.*, 108(D15), 4488, doi:10.1029/2002JD003326.

CHAPTER 2

RESEARCH BACKGROUND

2.1 Introduction

The Earth's climate system has changed many times during the planet's history, with events ranging from ice ages to long periods of warmth [*National Research Council* (NRC), 2005]. Historically, natural factors such as volcanic eruptions, changes in the Earth's orbit, and the amount of energy released from the Sun have affected the Earth's climate system. However, since the start of the Industrial Revolution (about 1750), the burning of fossil fuels such as coal and oil, and global deforestation has influenced the concentration of greenhouse gases (i.e., carbon dioxide, methane and nitrous oxide) significantly in the Earth's atmosphere [*Hansen et al.,* 2007]. As the concentration of greenhouse gases in the atmosphere has continued to rise, the temperature of the Earth has become warmer. According to the National Oceanic and Atmospheric Administration (NOAA) the 2000 to 2009 decade was the warmest on record, with an average global surface temperature of 0.54°C (0.96°F) above the twentieth century average, and significantly greater than the 1990 to 1999 value of 0.36°C (0.65°F) [*NOAA,* 2010]. A warming trend has been confidently attributed to the effect of increasing human-made greenhouse gases [*Hansen et al.*, 2007], and has been linked to more extreme weather conditions, such as intense floods and droughts, heavier and more frequent storms, and a possible increase in the frequency and intensity of the El Niño Southern Oscillation [*IPCC*, 2007].

2.2 The Intergovernmental Panel on Climate Change (IPCC)

Climate change is a complex issue with highly politicized environmental and socio-economic consequences. The World Metrological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988, "*to provide an objective source of information about the causes of climate change*" [*IPCC*, 2007]. The IPCC does not conduct any research, rather, its role is "*to assess on a comprehensive, objective, open and transparent basis the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation*" [*IPCC*, 2007]. The IPCC has provided assessment reports at regular intervals since its establishment, which are used by policymakers and scientific experts as standard works of reference. The findings of the first IPCC report in 1990 were instrumental in leading the United Nations framework Convention on Climate Change (UNFCCC) in the Rio de Janeiro Summit in 1992, and continues to be a major source of information for the development of the UNFCCC and Kyoto Protocol [*IPCC*, 2007].

The *IPCC* [2007] reports that "*climate change may be due to natural internal processes or external forcings, or to persistent human changes in the composition of the atmosphere or in land cover and land use*".

2.3 Land Cover and Land Use Change

Land cover is defined as "*the biophysical state of the earth's surface and immediate subsurface and includes natural vegetation, crops, and human structures that cover the land surface*" [*Turner II et al.,* 1995]. Examples of land cover include forest, grasslands, and wetlands. *Land use* implies "*both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation*" [*Turner II et al.,* 1995]. For example, 'grass' is a *land cover* class, whereas pasture and recreational parks are *land uses* of grass.

The term *land cover land use change* is used to describe the effects of human influence on the land surface including activities such as irrigation, urbanization, deforestation, desertification, reforestation, grazing of domesticated animals and dryland farming [*Lambin and Geist,* 2006]. Although humans have continually shaped the Earth's landscape for centuries, LCLU change has only been recognized as a key driving force of climate change within the past three decades [*Sagan et al.,* 1979; *Bryant et al.,* 1990; *Pielke et al.,* 1998; *Stohlgren et al.,* 1998; *Betts* 2000; *Ramaswamy et al.,* 2001; *Turner II* 2001; *Nair et al.,* 2003; *NRC,* 2005; *Betts et al.,* 2007; *IPCC*, 2007, *Wichansky et al.,* 2008]. Depending on the nature and type of the LCLU change activity it can influence the regional climate by altering the Earth's surface albedo, surface roughness[1], leaf area index, fractional vegetation cover, soil moisture and fluxes and storage of carbon and other types of nutrients [*Betts*, 2001; *Claussen et al*., 2001]. These changes

[1] Surface roughness describes the degree to which surface atmospheric motion is influenced by vegetation and man made structures such as high density urban centers. Typically high density urban centers cause more atmospheric turbidity than large homogeneous areas of vegetation.

can affect surface air temperatures, atmospheric boundary conditions, cloud formation, and precipitation, which can in turn influence surface weather and climate across a range of spatial and temporal scales [*Pielke*, 2001; *Kabat et al.,* 2004]. Many studies have revealed the extent to which land surface changes have affected local and regional climates, and it is increasingly clear that some changes in the land surface can have significant impacts on the climate system in distant parts of the Earth [*Pielke and Avissar*, 1990; *Handerson-Sellers*, 1995; *Lynn et al.,* 1995; *Claussen et al.,* 2001; *Pielke*, 2001; *Kabat et al.,* 2004] and are described in terms of *teleconnections* [*NRC*, 2005]. For example, it is established that changes in forest cover in the Amazon Basin affect the flux of moisture into the atmosphere, regional convection and precipitation [*Lean and Warrilow*, 1989; *Baidya Roy and Avissar*, 2002] but recent research has shown consequences beyond the Amazon Basin, *Werth and Avissar* [2002] found that U.S. Midwest spring and summer precipitation is reduced due to Amazonia deforestation.

2.4 Land Cover Land Use Change across the Conterminous United States

The land surface of the conterminous United States (CONUS) covers approximately eight million square miles, and has experienced extensive LCLU change since the arrival of settlers in the early 1500s [*Williams*, 1989; *Whitney*, 1994]. The first major land cover transformation was the clearing of the eastern forest for wood products and agriculture, which steadily progressed westwards across the Appalachians into the Ohio and upper Mississippi River basins. By the 1840s, agriculture had peaked in the northeast and many abandoned farm fields and pasturelands were in the process of forest regeneration. The Homestead Act of 1862 (where 160 acres of government land were given free to those people settling and cultivating it for at least five years) led to well established agriculture in the Great Plains in the late-1800s [*Hart,* 2003]. The late 1800s to early 1900s saw intensive commercial logging of old-growth forests in the Great Lakes and Pacific Northwestern states, followed by mechanized logging of southern pine forests [*Hart,* 2003]. In 1902, the government passed the Reclamation Act of 1902 to provide irrigation resources to small farmers, which further encouraged the agricultural development of the Midwest [*Lambin and Geist,* 2006]. The early 20th century saw the abandonment of croplands and regrowth of forests in the Eastern U.S., which was in part due to competition from more fertile regions of the Midwest, and also due to competing demands on land within the east from rapid population growth and urban expansion [*Strack et al.,* 2008]. Between the 1930s and 1950s, the government sponsored large irrigation projects in the west that led to the subsequent agricultural development of California and other western states [*Ramankutty and Foley,* 1999].

As the research in this dissertation is concerned with LCLU change from the 1970s to present, and from the present to 2050, only contemporary and future LCLU is considered in the remainder of this section.

Over the last 30 years the population of the CONUS has increased by more than 50% [*U.S. Census Bureau,* 2010], while agricultural land use has been in decline [*Drummond and Loveland,* 2010] and the rates of forest harvesting [*Pinder et al.,* 1999] and exurban sprawl have been accelerating [*Brown et al.,* 2005; *Steyaert and Knox,* 2008]. From 1982 to 2003 the amount of agricultural acreage declined by about 12%, while in the same period, the area of developed land increased by 48% [*White et al.,* 2009]. The resulting transition of agricultural land to native grasses was concentrated in the Great Plains region and has been attributed primarily to the 1985 Farm Bill that established the Conservation Reserve Program (CRP) [*Johnson and Maxwell,* 2001]. This voluntary program offered financial incentives for farmers to retire environmentally sensitive agricultural land to native grasses or trees, usually for ten years in duration. The most extensive CRP transitions of agriculture to grassland have been in the Missouri and Souris-Red-Rainy/Upper Mississippi river basins. In the intensely agricultural Central Valley of California, croplands have expanded even though urban growth is consuming significant tracts of land [*Sleeter et al.,* 2010]. Changes in western region forests have been driven in part by international timber markets, conservation of habitat for endangered species, and management of federal forest lands [*Daniels*, 2005]. Although forest logging-related activity declined in the west between 1992 and 2000 [*Sleeter,* 2008], forest loss has increased in recent years as a result of natural disturbances such as fire [*Westerling et al.,* 2006] and insect outbreaks [*Logan et al.,* 2003], which is predicted to continue with future climate change [*Bachelet et al.,* 2003; *Hicke et al.,* 2006]. In the southeast large scale tree planting operations has occurred on former agricultural land, primarily due to economic opportunities associated with wood and pulp demands, and because of CRP's economic incentives [*Drummond and Loveland,* 2010]. The landscape of the CONUS continues to become more fragmented because of continued residential urban expansion, and changes in forest, agriculture and grasslands. However, there is no single profile of contemporary LCLU change across the CONUS, rather, there are varying pulses affected by clusters of change agents [*Loveland et al*., 2002]. Continued development of LCLU information is needed, especially given that CONUS LCLU conversion is expected to continue [*White et al.,* 2009].

2.5 Modeling Future Land Cover Land Use Change

Nowak and Walton [2005] projected that 5.3% (118,000 km^2) of non-urban forest land will be subsumed by urban growth by 2050, with the greatest impacts in Southern and Eastern U.S. forests. This type of future LCLU information is needed in support of water quality and availability, land use planning, biodiversity, carbon balances, and climate change studies [e.g., *Pielke et al.,* 2002; *Baidya Roy et al.,* 2003; *Foley et al.,* 2005; *Lambin and Geist,* 2006; *Sohl and Sayler,* 2008]. Projecting future LCLU is complex and difficult. Scenarios are increasingly used to provide plausible descriptions of what potentially could happen on the landscape as a result of different often related but sometimes antagonistic drivers including socioeconomic, political, technological and environmental factors, and emissions of greenhouse gases and aerosols [*Riahi et al.,* 2010]. *Parker et al.* [2002] state that if scenarios are to provide modeling tools for policy makers, they need to move away from abstract, generative LCLU change scenarios to more realistic, descriptive scenarios based on real-world data and processes. A key difficulty is establishing linkages between socioeconomic, political, technological and biophysical drivers of change with changes in LCLU [*Gutman et al.,* 2004; *Rindfuss et al.,* 2004; *Verburg*, 2006]. Although the IPCC has used a series of Standardized Reference Emissions Scenarios (SRES) as a central component of its work in assessing likely future climate, they decided in 2006 not to commission another set of SRES, leaving new scenario development to the research community [*Moss et al.,* 2010]. Given this new opportunity, the research community selected from the published literature a set of Representative Concentration Pathways (RCPs) to map a broad range of climate outcomes. The RCPs could provide a starting point for new and wide-ranging research to yield valuable insights into the interaction of human-induced climate processes and are recommended to be included in future LCLU radiative forcing studies [*Moss et al.,* 2010]. A perfect representation of all the factors that influence LCLU change is impossible to achieve in any single scenario [*Sohl and Sayler,* 2008; *Verburg et al.,* 2008], and instead many scenarios are needed and their ensemble effects considered.

2.6 Concept of Climate Forcings

Factors that perturb the Earth's climate system are described in terms of forcings, usually measured in watts per meter square (Wm^{-2}), and their feedbacks. A climate forcing is defined by the *NRC* [2005] as "*an energy imbalance imposed on the climate system either externally or by human activities*". Climate forcings can be natural processes (i.e., changes in solar energy output, volcanic emissions) or due to human activities (i.e., LCLU change, emission of greenhouse gases and aerosols). A climate feedback is an internal climate process that amplifies or dampens the climate responses to a specific forcing. For example, as rising concentrations of greenhouse gases warm the Earth's system, snow and ice begin to melt to reveal darker land and water surfaces that absorb more of the Sun's energy, causing more warming, which causes more melting, and so on, in a self-reinforcing cycle. This feedback loop, known as the 'ice-albedo feedback', is one of many that may amplify the warming caused by rising levels of greenhouse gases [*Bony et al.,* 2006].

The 2005 NRC Radiative Forcing Effects of Climate Change report recommended the broadening of the climate change debate to include LCLU change processes as an important climate forcing. The current *IPCC* [2007] report on the radiative forcing of long lived greenhouse gasses is thought to be too focused and limiting and does not address the diverse effects of human disturbances on the climate system e.g., the role LCLU change effects are not included. A broadening in its perspective is suggested as overdue [*Pielke and Niyogi*, 2008]. The findings of the *NRC* [2005] report state the following:

"Regional variations in radiative forcing may have important regional and global climatic implications that are not resolved by the concept of global mean radiative forcing. Tropospheric aerosols and landscape changes have particularly heterogeneous forcings. To date, there have been only limited studies of regional radiative forcing and response… Improving societally relevant projections of regional climate impacts will require a better understanding of the magnitudes of regional forcings and the associated climate responses" (*NRC,* 2005).

Clearly, the above statement identifies the importance of LCLU change in the climate system.

2.7 Concept of Radiative Forcing

Climate forcings are subdivided into *direct radiative forcings*, *indirect radiative forcings*, and *non-radiative forcings*. The *IPCC* [2007] defines these terms as follows: *direct radiative forcings* directly affect the radiative budget of the Earth i.e., increased carbon dioxide (CO_2) absorbs and emits infrared radiation. Direct radiative forcings may be due to a change in concentration of radiatively active gases, a change in solar radiation reaching the Earth, or changes in surface albedo. *Indirect radiative forcings* create an energy imbalance by first altering the climate system components (e.g., the precipitation efficiency of clouds due to aerosols), which then almost immediately lead to changes in radiative fluxes. *Non-radiative forcings* create an energy imbalance that does not directly involve radiation, an example being the increased evapotranspiration flux due to agricultural irrigation. The radiative forcing concept provides a framework for investigating how the Earth's energy budget can be modified, and for quantifying the modifications and their potential impacts in terms of surface temperature response [*NRC*, 2005]. A surface radiative forcing effect is defined as the '*instantaneous change in radiative flux at the surface*' [*Hansen et al.,* 1997] and is distinct from top of atmosphere (TOA) radiative forcing, which is defined as '*the change in the net irradiance at the troposphere after allowing for stratospheric temperatures to re-adjust to equilibrium*' [*IPCC*, 2007]. This radiative forcing concept arose from early studies of climate response to changes in solar insolation and CO_2, using simple radiative-convective models [*Manabe and Strickler*, 1964; *Manabe and Wetherald*, 1967]. A *positive radiative forcing* warms the Earth's surface, while a *negative radiative forcing* causes surface cooling.

Figure 2-1 illustrates the magnitude of several important global mean radiative forcings as estimated in the most recent synthesis report of the *IPCC* [2007], from 1750 to 2005 due to a range of climate perturbations, including green house gases, ozone, land use, aerosols, aviation effects on clouds and solar irradiance. The largest positive forcing (i.e., warming) in Figure 2-1 is from the increase of well-mixed greenhouse gases (CO_2, nitrous oxide (N_2O), methane (CH_4), and chlorofluorocarbons (CFCs)) and amounted to an estimated 2.4 Wm^{-2} between the years 1750 and 2000. Among the long lived greenhouse gases, CO_2 increases have caused the largest forcing since pre-industrial times. Tropospheric ozone increases have also contributed to warming, while stratospheric ozone decreases have contributed to cooling [*NRC*, 2005]. Aerosol particles also influence radiative forcing directly through scattering and absorption of solar and infrared radiation in the atmosphere. Some aerosols cause a positive forcing while others cause a negative forcing. The direct radiative forcing summed over all aerosol types is negative. However, of the forcings illustrated in Figure 2-1, the radiative impact of aerosols has the greatest uncertainty, and if the actual negative forcing from aerosols were at the high end (most negative) of the uncertainty range, then it could potentially offset all of the positive forcing due to long lived greenhouse gases [*Boucher and Haywood*, 2001].

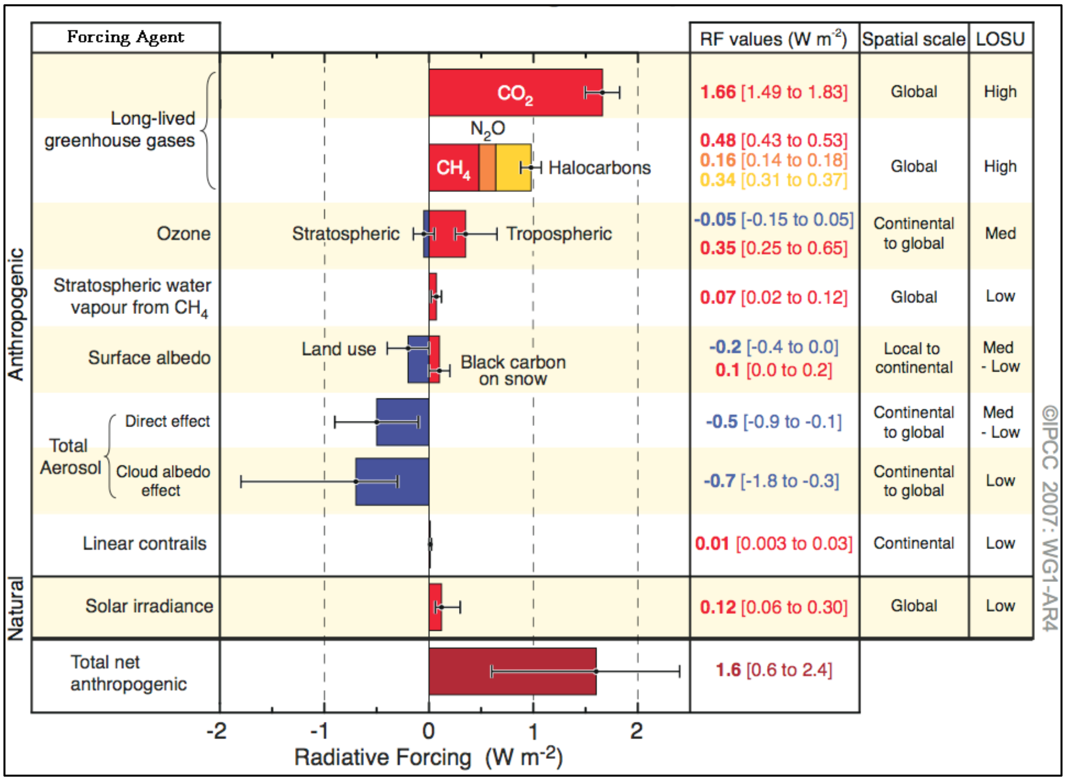

Figure 2-1. Summary of the principal components of the radiative forcing of climate change in watts per meter square (Wm^{-2}), the typical geographical extent of forcing, and the currently assessed level of scientific understanding (LOSU). The values represent the forcings in 2005 since pre-industrial times (1750). These radiative forcing result from one or more factors that affect climate and are associated with human activities or natural processes. Human activities have cause significant changes in long-lived greenhouse gases, ozone, water vapor, surface albedo, aerosols and contrails. Positive forcings lead to warming of the climate and negative forcings lead to a cooling.

Although Figure 2-1 has been widely used in scientific and policy communities, it does have some important limitations. For example, there is no information about the timescales over which each of the forcings is active; it does not provide information about regional variation in radiative forcing; there is no consistency to indicate the forcing associated with specific sources (e.g. coal, gas, agricultural practices); and nor does it include the effect of non-radiative forcings, priorities all recommended in the 2005 NRC report [*NRC*, 2005]. The timeline adopted by the IPCC in initiating the 2007 assessment report did not allow for recently published papers and reports to be properly considered. Thus, the recommendations from the 2005 NRC report received little representation in the current IPCC assessment. It is not known if this would be modified for the next assessment [*Pielke and Niyogi*, 2008].

2.8 Land Cover Land Use Surface Albedo Change Direct Radiative Forcing

Land cover land use (LCLU) surface albedo change is defined by the *IPCC* [2007] as a direct surface radiative forcing, as the radiative budget of the Earth is directly affected when a LCLU surface albedo change occurs. For clarity, and for the remainder of this dissertation, LCLU surface albedo change direct radiative forcing will be referred to more simply as *surface radiative forcing*.

Albedo is defined as the fraction of incident radiation which is reflected at the Earth's surface [*Roesch et al.,* 2002], and plays a key role in the surface-atmosphere interaction [*Liang et al.,* 1999]. LCLU albedo change is thought to provide a dominant influence on mid and high latitude climate change [*Betts,* 2001; *Bounoua et al.,* 2002]. The albedo of human landscapes can be very different from that of potential natural vegetation (i.e., vegetation that would exist without the influence of humans). Humans have altered the Earth's surface albedo, primarily through changes in croplands, pastures and forests [*Ramankutty and Foley*, 1999]. The albedo of agriculture or cropland is typically greater than that of forest because the greater leaf area of forest canopies and multiple reflections within the canopy result in a higher fraction of incident radiation being absorbed [*Román et al.,* 2009]. Consequently, the higher surface albedo of agriculture or cropland typically results in more reflection of sunlight, cooling surface air temperatures comparatively greater than forest. This LCLU difference forcing effect is particularly accentuated when snow is present, because open land can become entirely snow-covered and hence highly reflective, while forest can remain exposed above the snow [*Harding and Pomeroy,* 1996; *Betts,* 2000; *Hall et al.,* 2006].

It is thought that LCLU change during the twentieth century has induced a net cooling effect on mid latitude climate [*Oleson et al.,* 2004; *Gibbard et al.,* 2005] and globally has resulted in a climate forcing of approximately -0.25 $Wm^{-2} \pm 0.25$ Wm^{-2} due to surface albedo change [*IPCC*, 2007]. These estimates compare with global climate forcing estimates from the increase in atmospheric CO_2 of 1.66 $Wm^{-2} \pm 0.17$ Wm^{-2} [*IPCC,* 2007]. However, climate forcing impacts due to human LCLU change have been limited due to uncertainties in LCLU change and albedo data [*IPCC*, 2007]. Albedo data for different land cover types are available from a variety of sources but have a large published variability [*Oleson et al.,* 2003; *Zhou et al.,* 2003; *Roesch et al.,* 2004; *Wang et al.,* 2004; *Gao et al.,* 2005], and intra-annual and inter-annual albedo variability [Wang *et al.,* 2004; *Moody et al*., 2005] are not usually captured by such data. There has been no extensive LCLU change data that captures change over large areas defined in a reliable or systematic manner. For these reasons, previous studies have been primarily based on hypothetically modeled LCLU change scenarios. For example, *Bala et al.* [2007] simulated a net cooling influence with large scale global deforestation. *Brovkin et al.* [2006] estimated the global mean radiative forcing since 1750 to be –0.15 Wm^{-2}, considering only cropland changes. Hansen *et al.* [2005] also considered only cropland changes and simulated the radiative forcing since 1750 to be –0.15 Wm^{-2}. *Betts* [2000] simulated a positive radiative forcing as a result of forestation of agricultural land in northern hemisphere temperate and boreal forested regions. The forcing ranged from 3 Wm^{-2} in temperate regions to over 20 Wm^{-2} in the boreal forests and was highly sensitive to the presence of snow.

Other studies have estimated the radiative forcing at present day relative to potential natural vegetation and include: *Govindasamy et al.* [2001] –0.08 Wm^{-2}, *Myhre et al.* [2005], *Friedl et al.* [2002] and *Schaaf et al.* [2002] –0.09 Wm^{-2}. These scenario and model driven studies, although useful, cannot reliably capture LCLU change and albedo effects especially when it is considered that the impact of albedo change depends on both the type and the spatial extent of LCLU change [*Pielke et al.,* 2002; *Kleidon*, 2006]. Satellite driven studies have been undertaken using spatially and/or temporally explicit albedo retrievals but have not considered contemporary LCLU change [*Jin and Roy*, 2005; *Myhre et al.,* 2005; *Randerson et al.,* 2006]. However, the recent advent of spatially and temporally explicit satellite derived albedo and land cover data sets offer the opportunity for real advances in understanding surface LCLU albedo and changes in radiative forcing.

2.9 References

Bachelet, D., R. P. Neilson, T. Hickler, R. J. Drapek, J. M. Lenihan, M. T. Sykes, B. Smith, S. Sitch, and K. Thonicke (2003), Simulating past and future dynamics of natural ecosystems in the United States, *Global Biogeochem. Cycles*, 17(2), 1045, doi:10.1029/2001GB001508.

Baidya Roy, S., and R. Avissar (2000), Scales of response of the convective boundary layer to land surface heterogeneity, *Geophys. Res.,* 27: 533-536.

Baidya Roy, S., and R. Avissar (2002), Impact of land use/land cover change on regional hydrometeorology in Amazonia, *J. Geophys. Res.*, 107(D20), 8037, doi:10.1029/2000JD000266.

Baidya Roy, S., G. C. Hurrt, C. P. Weaver, and S. W. Pacala (2003), Impact of historical land cover change on the July climate of the United States, *J. Geophys. Res.,* 108(D24), 4793, doi:10.1029/2003JD003565.

Bala, G., K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire, and A. Mirin (2007), Combined climate and carbon-cycle effects of large-scale deforestation, *Proc. Natl. Acad. Sci.,* U.S.A., 104: 6550–6555.

Barrett, T. M., D. Gatziolis, J. S. Fried, and K. L. Waddell (2006), Sudden oak death in California: What is the potential? *Journal of Forestry*, 104:61–64.

Betts, R.A. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature,* 408: 187-190.

Betts, R. A. (2001), Biogeophysical impacts of land use on present-day climate: near-surface temperature change and radiative forcing, *Atmos. Sci Lett.,* 2: 39-51, doi:10.1006/asle.2001.0023.

Betts, R.A., P.D. Falloon, K.K. Goldewijk, and N. Ramankutty (2007), Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change, *Agric. For. Meteorol*., 142: 216-233.

Bony, S., R. Colman, V.M. Kattsov, R.P. Allan, C.S. Bretherton, J.-L. Dufresne, A. Hall, S. Hallegatte, M.M. Holland, W. Ingram, D.A. Randall, D.J. Soden, G. Tselioudis, and M.J. Webb (2006), How well do we understand and evaluate climate change feedback processes?, *J. Climate*, 19, 3445-3482.

Boucher, O. and J. Haywood (2001), On summing the components of radiative forcing of climate change, *Clim. Dyn.*, 18:297-302.

Bounoua, L., R, DeFries, G.J. Collatz, P. Sellers, and H. Khan (2002), Effects of land cover conversion on surface climate, *Clim. Chg.*, *52*, 29-64.

Brown, D. G., K. M. Johnson, T. R. Loveland, and D. M. Theobald (2005), Rural land use trends in the conterminous United States, 1950– 2000, Ecol. Appl., 15, 1851– 1863.

Brovkin, V., M. Claussen, E. Driesschaert, T. Fichefet, D. Kicklighter, M.F. Loutre, H.D. Matthews, N. Ramankutty, M. Schaeffer, and A. Sokolov (2006), Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity, *Clim. Dyn.,* 26(6): 587-600.

Bryant, N. A., L.F. Johnson, A.J. Brazel, R.C. Balling, C.F. Hutchinson, L.R. Beck (1990), Measuring the effect of overgrazing in the Sonoran Desert, *Clim. Ch.,* 17**:** 243–264.

Claussen, M., V. Brovkin, and A. Ganopolski (2001), Biogeophysical Versus Biogeochemical Feedbacks of Large-Scale Land Cover Change, *Geophys. Res. Lett.,* 28(6): 1011–1014.

Daniels, J. M. (2005), The rise and fall of the Pacific Northwest log export market, *Technical report PNW-GTR-624*, U.S. Department of Agriculture, U.S. Forest Service, general.

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

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, P.K. Snyer (2005), Global consequences of land use, *Science,* 22, 570–574.

Friedl, M.A., D. K. McIver, J. C. F. Hodges, X. Y. Zhang, D. Muchoney, A. H. Strahler, C. E. Woodcocka, S. Gopal, A. Schneider, A. Cooper, A. Baccini, F. Gao and C. Schaaf (2002), Global land cover mapping from MODIS: algorithms and early results, *Remote Sens. Environ.*, 83: 287–302.

Gao, F., C. B. Schaaf, A. H. Strahler, A. Roesch, W. Lucht, and R. Dickinson (2005), MODIS bidirectional reflectance distribution function and albedo Climate

Modeling Grid products and the variability of albedo for major global vegetation types, *J. Geophys. Res.,* 110, D01104, doi:10.1029/2004JD005190.

Gibbard, S., K. Caldeira, G. Bala, T.J. Philips, and M. Wickett (2005), Climate effects of global land cover change, *Geophys. Res. Lett*., *32*, L23705, doi:10.1029/2005GL024550.

Govindasamy, B., P.B. Duffy, and K. Caldeira (2001), Land use changes and Northern Hemisphere cooling, *Geophys. Res. Lett*., 28(2): 291–294.

Gutman, G., R. Defries, S. Devers, E. Kasischke, L. Giglio, C. Justice, S. Prince, D. Roy, G. Sun, J. Townshend, S. Goetz, and C. Jantz (2004), *Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface*, Kluwer Academic Publishers, Dordrecht.

Hall, D. K., G.A. Riggs, and V.V. Salomonson (2006), updated monthly. MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG V005, [Dates used; January 2004 to December 2008]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Handerson-Sellers, A. (1995), *Human effects on climate through the large-scale impacts of land-use change. In: Future Climates of the World: A Modelling Perspective. World Survey of Climatology*, vol 16. Elsevier, Amsterdam.

Hansen, J., *et al.,* (2005), Efficacy of climate forcings, *J. Geophys. Res*., 110, D18104, doi:10.1029/2005JD005776.

Hansen, J., M. Sato, R. Ruedy, P. Kharecha, A. Lacis, R. Miller, L. Nazarenko, K. Lo, G. A. Schmidt, G. Russell, I. Aleinov, S. Bauer, E. Baum, B. Cairns,

V. Canuto, M. Chandler, Y. Cheng, A. Cohen, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, J. Jonas, M. Kelley, N. Y. Kiang, D. Koch, G. Labow, J. Lerner, S. Menon, T. Novakov, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, R. Schmunk, D. Shindell, P. Stone, S. Sun, D. Streets, N. Tausnev, D. Thresher, N. Unger, M. Yao, and S. Zhang (2007), Dangerous human-made interference with climate: A GISS modelE study, *Atmos. Chem. Phys*., 7: 2287-2312.

Harding, R. J. and J. W. Pomeroy (1996), The energy balance of the winter boreal landscape, *J. Clim*., 9, 2778-2787.

Hart, J. F. (2003), *The Changing Scale of American Agriculture*, University of Virginia Press, 320pp.

Hicke, J. A., J. A. Logan, J. Powell, and D. S. Ojima (2006), Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States, *J. Geophys. Res.*, 111, G02019, doi:10.1029/2005JG000101.

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*, edited by S. Solomon *et al.,* 996pp., Cambridge Univ. Press, New York.

Jackson, R.B., J.T. Randerson, J.G. Canadell, R.G. Anderson, R. Avissar, D. D. Baldocchi, G.B. Bonan, K. Caldeira, N.S. Diffenbaugh, C.B. Field, B.A. Hungate, E.G. Jobbágy, L.M. Kueppers, M.D. Nosetto and D.E .Pataki

(2008), Protecting Climate with Forests, *Environ. Res. Lett.,* 3, doi:10.1088/1748-9326/3/4/044006.

Jin, Y., and D.P. Roy (2005), Fire-induced albedo change and its radiative forcing at the surface in northern Australia, *Geophys. Res. Lett.,* 32, L13401, Doi:10.1029/2005GL022822.

Johnson, J. and B. Maxwell (2001), The role of the Conservation Reserve Program in controlling rural residential development*. J. Rural Stud.,* 17, 323-332.

Kabat, P., M. Claussen, P. A. Dirmeyer, J. H. C. Gash, L. Bravo de Guenni, M. Meybeck, R. Pielke Sr., C. J. Vörösmarty, R. W. A. Hutjes, and S. Lütkemeier, eds. (2004), Vegetation, Water, Humans and the Climate—A New Perspective on an Interactive System. Berlin: Springer Verlag.

Kalnay, E., and M. Cai (2003), Impact of urbanization and land use on climate change, *Nature,* 423, 528–531.

Kinloch, B. B. (2003), White pine blister rust in North America: past and prognosis, *Phytopathology,* 93:1044–1047.

Kleidon, A. (2006), The climate sensitivity to human appropriation of vegetation productivity and its thermodynamic characterization, *Global Planet. Change*, 54: 109–127.

Lambin, E.F., and H.J. Geist (Eds) (2006), *Land-Use and Land-Cover Change. Local Processes and Global Impacts*, The IGBP Series, Springer-Verlag, Berlin, 222pp.

Lawton, R.O., U.S. Nair, R.A. Pielke, and R.M. Welch (2001), Climatic Impact of Tropical Lowland Deforestation on Nearby Montane Cloud Forests, *Science,* 294: 584-587.

Lean, J., and D.A. Warrilow (1989), Simulation of the regional climatic impact of Amazon deforestation, *Nature,* 342: 411-413.

Liang, S., **Strahler, A.H. and Walthall, C.** (1999), Retrieval of Land Surface Albedo from Satellite Observations: A Simulation Study, *Journal of Applied Meteorology.* 38. 6:712–725.

Logan, J., J. Regniere, and J. A. Powell (2003), Assessing the impacts of global warming on forest pest dynamics, *Frontiers in Ecology and the Environment,* 1:130–137.

Loveland, T. R., T.L. Sohl, S.V. Stehman, A.L. Gallant, K.L. Sayler, and D.E. Napton (2002), A strategy for estimating the rates of recent United States land-cover changes, *Photogramm. Eng. Rem. S.,* 68(10):1091-1099.

Loveland, T. R., and W. Acevedo (2010), Land cover change in the Eastern United States. In *Status and Trends of Eastern United States Land Cover*, ed. W. Acevedo and P. J. Jellison. U.S. Geological Survey Professional Paper, in press.

Lynn, B.H., D. Rind, and R. Avissar (1995), The importance of subgrid-scale Mesoscale circulations generated by landscape heterogeneity in general circulation models (GCMs), *J. Clim.,* 8: 191-205.

Manabe, S., and R.F. Strickler (1964), Thermal equilibrium of the atmosphere with a convective adjustment, *J. Atmospheric Sciences,* 21(4): 361-385.

Manabe, S., and R. Wetherald (1967), Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *J. Atmospheric Sciences,* 24: 241-259.

Moody, E. G., M.D. King, S. Platnick, C.B. Schaaf, F. Gao (2005), Spatially complete global spectral surface albedos: Value-added datasets derived from Terra MODIS land products, *IEEE Transactions on Geoscience and Remote Sensing,* 43: 144-158.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S.Emori, M. Kainuma, T. Kram, G.A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant and T.J. Wilbanks (2010), The next generation of scenarios for climate change research and assessment, *Nature*, 463, 747-756, doi:10.1038/nature08823.

Myhre, G., M. Kvalevag, and C. Schaaf (2005), Radiative Forcing due to human vegetation change based on MODIS surface albedo data, *Geophys. Res. Lett*., 32, L21410, doi:10.1029/2005GL024004.

Nair, U. S., R.O. Lawton, R.M. Welch, and R.A. Pielke (2003), Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of cumulus cloud field characteristics to lowland deforestation, *J. Geophys. Res.*, *108*(D7), 4206, doi:10.1029/2001JD001135.

National Research Council (NRC) (2005), *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, National Academic Press, Washington, D.C.207pp.

National Oceanic and Atmospheric Administration (NOAA) (2010), http://www.ncdc.noaa.gov/oa/climate/globalwarming.html, Last accessed 14th September 2010.

Nowak, D.J., J.T. Walton, (2005), Projected urban growth (2000–2050) and its estimated impact on the U.S. forest resource, *J. Forestry*, 103 (8), 383–389.

Oleson, K.W., G. B. Bonan, C. B. Schaaf, F. Gao, Y. Jin, and A. H. Strahler (2003), Assessment of global climate model land surface albedo using MODIS data, *Geophys. Res. Lett.,* 30(8), 1443, doi:10.1029/2002GL016749.

Oleson, K., G. Bonan, S. Levis, and M. Vertenstein (2004), Effects of land use change on North American climate: impact of surface datasets and model biogeophysics, *Clim. Dyn.,* 23: 117-132.

Parker, D.C, Berger T, Manson SM (eds) (2002), Agent-based models of land-use and land-cover change. Report and Review of an International Workshop October 4-7, 2001, Irvine, California, USA.

Pielke, R.A. and R. Avissar (1990). Influence of landscape structure on local and regional climate, *Landscape Ecol*., 4 (2-3): 133-155.

Pielke, R.A., R. Avissar, M. Raupach, H. Dolman, X. Zeng, and S. Denning (1998), Interactions between the atmosphere and terrestrial ecosystems: Influence on weather and climate, *Global Change Biology*, 4: 461-475.

Pielke, R. A. (2001), Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall, *Rev. Geophys.*, 39: 151-177.

Pielke, R.A., G. Marland, R.A. Betts, T.N. Chase, J.L. Eastman, J.O. Niles, D.S. Niyogi, and S.W. Running (2002), The influence of land-use change and landscape dynamics on the climate system - relevance to climate change policy beyond the radioactive effect of greenhouse gases, *Phil. Trans. R. Soc. Lond. A.,* 360**:** 1705–1719.

Pielke, R.A., and D. Niyogi (2008), The role of landscape processes within the climate system. In: Otto, J.C. and R. Dikaum, Eds., Landform - Structure, Evolution, Process Control: Proceedings of the International Symposium on Landforms organised by the Research Training Group 437. Lecture Notes in Earth Sciences, Springer, Vol. 115, doi:10.1007/978-3-540-75761-0_5.

Pinder, J.E. III., T.E. Rea, and D.E. Funsch (1999), Deforestation, reforestation and forest fragmentation on the upper coastal plain of South Carolina and Georgia. *American Midland Naturalist,* 142: 213–228.

Ramankutty, N., and J.A. Foley (1999), Estimating historical changes in global land cover: croplands from 1700 to 1992, *Global Biogeochem. Cycles*, 14: 997–1027.

Ramaswamy, V., **O. Boucher, J. Haigh, D. Hauglustaine, J. Haywood, G. Myhre, T. Nakajima, G.Y. Shi, S. Solomon, R. Betts, R. Charlson, C. Chuang, J.S. Daniel, A. Del Genio, R. van Dorland, J. Feichter, J. Fuglestvedt, P.M. de F. Forster, S.J. Ghan, A. Jones, J.T. Kiehl, D. Koch, C. Land, J. Lean, U. Lohmann, K. Minschwaner, J.E. Penner, D.L. Roberts, H. Rodhe, G.J. Roelofs, L.D. Rotstayn, T.L. Schneider, U. Schumann, S.E. Schwartz, M.D. Schwarzkopf, K.P. Shine, S. Smith, D.S. Stevenson, F. Stordal, I. Tegen, Y. Zhang** (2001), Radiative forcing of climate change, in *Climate Change 2001: The Scientific Basis. Contribution of Working*

Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp 350-416, Cambridge University Press, Cambridge, U.K.

Randerson, J. T.,H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, C. S. Zender (2006), The impact of boreal forest fire on climate warming, *Science*, 314: 1130–1132.

Riahi, K., A. Gruebler, and N. Nakicenovic (2007), Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change,* 74, 887–935.

Rindfuss, R. S.Walsh, V. Mishra, J. Fox, G. Dolcemasscolo (2004), Linking household and remotely sensed data: Methodological and practical problems, in *People and the Environment; Approaches for Linking Household and Community Surveys to Remote Sensing GIS* edited by Fox, J., R. Rindfuss, S. Walsh and V. Mishra, pp.1-29, Kluwer Academic Publishers, Massachusetts, Boston.

Roesch, A., M. Wild, R. Pinker, and A. Ohmura (2002), Comparison of spectral surface albedos and their impact on the general circulation model simulated surface climate, *J. Geophys. Res.,* 107(D14), 4221, doi:10.1029/2001JD000809.

Roesch, A., C. Schaaf, and F. Gao (2004), Use of Moderate-Resolution Imaging Spectroradiometer bidirectional reflectance distribution function products to enhance simulated surface albedos, *J. Geophys. Res.,* 109, D12105, doi:10.1029/2004JD004552.

Román, M. O., C. B. Schaaf, P. Lewis, F. Gao, G. P. Anderson, J. L. Privette, A. H. Strahler, C. E. Woodcock, and M. Barnsley (2009), The MODIS (Collection V005) BRDF/albedo product: Assessment of spatial representativeness over forested landscapes, *Remote Sens. Environ.*, 113, 2476-2498.

Sagan, C., O.B. Toon, and B. Pollack (1979), Anthropogenic Changes and the Earth's Climate, *Science*, 206, 1363-1368.

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

Sleeter, B. M. (2008), Late 20th century land change in the Central California Valley Ecoregion, *The California Geographer*, 48:27-60.

Sohl, T., and K. Sayler (2008), Using the FORE-SCE model to project land-cover change in the southeastern United States, *Ecological Modeling*, 219:49-65.

Steyaert, L.T., and R.G. Knox (2008), Reconstructed historical land cover and biophysical parameters for studies of land-atmosphere interactions within the eastern United States*, J. Geophys. Res.,* 113, D02101, doi:10.1029/2006JD008277.

Stohlgren, T.J., T.N. Chase, R.A. Pielke, T.G.F. Kittel, J.S. Baron (1998), Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas, *Global Change Biology,* 4 (5), 495–504 doi:10.1046/j.1365-2486.1998.t01-1-00182.x.

Strack, J. E., R. A. Pielke Sr., L. T. Steyaert, and R. G. Knox (2008), Sensitivity of June near-surface temperatures and precipitation in the eastern United States to historical land cover changes since European settlement, *Water Resour. Res.*, 44, W11401, doi:10.1029/2007WR006546.

Turner II, B.L., D.L. Skole, S. Sanderson, G. Fischer, L. Fresco, and R. Leemans (1995), Land-Use and Land-Cover Change: Science/Research Plan. IGBP Report No. 35 and HDP Report No. 7. 132 pp.

Turner II, B. L. (2001), Land-Use and Land-Cover Change: Advances in 1.5 Decades of Sustained International Research, *GAIA-Ecological Perspectives in Science, Humanities, and Economics,* 10: 269-272.

United States Census Bureau (2010), http://www.census.gov/popest/estimates.html, Last Accessed 26th October 2010.

Verburg, P.H. (2006), Simulating feedbacks in land use and land cover change models. *Landscape Ecol.,* 21:1171–1183.

Verburg, P.H., B. Eickhout, H. van Meijl (2008), A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *Ann,. Reg,. Sci.,* 42:57–77.

Wang, Z., X. Zeng, M. Barlage, R. E. Dickinson, F. Gao, and C. Schaaf (2004), Using MODIS BRDF and Albedo Data to Evaluate Global Model Land Surface Albedo, *J. Hydrometeorl*., 5, 3-14.

Werth, D., and R. Avissar (2002), The local and global effects of Amazon deforestation, *J. Geophys. Res.,* 107 (D20), 8087, doi:10.1029/2001JD000717.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006). Warming and earlier spring increase western US forest wildfire activity, *Science*, 313:940–943.

White, E. M., A. T. Morzillo, and R. J. Alig (2009), Past and projected rural land conversion in the US at state, regional, and national levels. *Landscape and Urban Planning,* 89, 37–48.

Whitney, G. G. (1994), *From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America from 1500 to the Present*, 451 pp., Cambridge Univ. Press, New York.

Wichansky P. S., L. T. Steyaert, R. L. Walko, C. P. Weaver (2008), Evaluating the effects of historical land cover change on summertime weather and climate in New Jersey: Land cover and surface energy budget changes, *J. Geophys. Res.,* 113, D10107, doi:10.1029/2007JD008514.

Williams, M. (1989), *Americans and Their Forests: A Historical Geography*, 599 pp., Cambridge Univ. Press, New York.

Zhou, L., R. E. Dickinson, Y. Tian, X. Zeng, Y. Dai, Z.-L. Yang, C. B. Schaaf, F. Gao, Y. Jin, A. Strahler, R. B. Myneni, H. Yu, W. Wu, and M. Shaikh (2003), Comparison of seasonal and spatial variations of albedos from Moderate-Resolution Imaging Spectroradiometer (MODIS) and Common Land Model, *J. Geophys. Res.*, 108(D15), 4488, doi:10.1029/2002JD003326.

CHAPTER 3

RADIATIVE FORCING OVER THE CONTERMINOUS UNITED STATES DUE TO CONTEMPORARY LAND COVER LAND USE ALBEDO CHANGE

Barnes, C.A. and Roy, D.P. (2008), *Geophysical Research Letters,* 35, L09706, doi:10.1029/2008GL033567, (Journal impact factor: 3.204).

This paper is also:

- illustrated on the cover of *Geophysical Research Letters,* Vol. 35, number 9.
- an American Geophysical Union Journal Highlight that is summarized in *EOS*, 89, 24, 10th June 2008, p 221.

This chapter describes the research undertaken to address research hypotheses:

***#1** that over the last 30 years LCLU change across the CONUS has led to a mean net positive albedo increase and a consequent albedo-related cooling, and,*

***#4** large regional disparities in LCLU change will modify the outcome of hypotheses **#1** at the regional scale.*

3.1 Abstract

Recently available satellite land cover land use (LCLU) and albedo data are used to study the impact of LCLU change from 1973 to 2000 on surface albedo and radiative forcing for 36 ecoregions covering 43% of the conterminous United States (CONUS). Moderate Resolution Imaging Spectroradiometer (MODIS) snow-free broadband albedo values are derived from Landsat LCLU classification maps located using a stratified random sampling methodology to estimate ecoregion estimates of LCLU induced albedo change and surface radiative forcing. The results illustrate that radiative forcing due to LCLU change may be disguised when spatially and temporally explicit data sets are not used. The radiative forcing due to contemporary LCLU albedo change varies geographically in sign and magnitude, with the most positive forcings (up to 0.284 Wm^{-2}) due to conversion of agriculture to other LCLU types, and the most negative forcings (as low as -0.247 Wm^{-2}) due to forest loss. For the 36 ecoregions considered a small net positive forcing (i.e., warming) of 0.012 Wm^{-2} is estimated.

3.2 Introduction

Land cover land use (LCLU) affects Earth surface properties including albedo that impose a radiative forcing on the climate. It is thought that LCLU change during the twentieth century has induced a net cooling effect on mid latitude climate [*Oleson et al*., 2004; *Gibbard et al*., 2005] and globally has resulted in a radiative forcing of approximately -0.25 Wm^{-2} [*IPCC*, 2007]. Albedo changes due to LCLU depend on both the type and spatial extent of LCLU change, and the spatial averaging of opposite signs of LCLU forcing may under represent LCLU contributions over larger areas [*Pielke et al*., 2002; *Kleidon,* 2006]. Previous studies have considered hypothetical LCLU change scenarios using representative albedo values. For example, *Betts* [2000] simulated a net climate warming influence with boreal afforestation in the presence of snow, and *Bala et al.* [2007] simulated a net cooling influence with large scale global deforestation. Satellite driven studies have been undertaken using spatially and/or temporally explicit albedo retrievals but have not considered contemporary LCLU change [*Jin and Roy,* 2005; *Myhre et al.*, 2005; *Randerson et al.,* 2006]. In this paper we quantify the surface radiative forcing of contemporary LCLU albedo change (1973 to 2000) for 43% of the conterminous United States (CONUS) using recently available satellite derived LCLU change and albedo data.

3.2 Data

Classification techniques are being used to generate 60 m LCLU maps from Landsat scenes located within 84 contiguous ecoregions across the CONUS [*Loveland et al.,* 2002; P. Jellison, and W. Acevedo, United States Geological Survey Land Cover Trends Project, unpublished data, 2010]. The Landsat data are classified by visual interpretation, inspection of aerial photography and ground survey, into 10 LCLU classes (Table 3-1).

LCLU Class	1973 LCLU (Km^2)	2000LCLU (Km^2)	LCLU change 1973-2000 (%)
Water	86298	88618	0.07
Developed (e.g., residential and industrial land uses)	**164579**	**211232**	**1.35**
Mechanically Disturbed	20512	43737	0.67
Mining	9854	10742	0.03
Barren	32463	32740	0.01
Forest	1142148	1094247	-1.39
Grass/Shrubland	1156826	1182751	0.75
Agriculture	**695532**	**644747**	**-1.47**
Wetland	139567	133384	-0.18
Naturally Disturbed	2075	7638	0.16

Table 3-1. The 10 land cover land use (LCLU) classes, the LCLU class areal proportions for 1973 and 2000, and the net change from 1973 to 2000, for the 36 conterminous United States ecoregions considered in this study (Figure 3-1). Classes in bold denote the greatest net LCLU changes.

The classes are defined to capture LCLU discernable in Landsat data and include mechanically and naturally disturbed classes that describe land that is in an altered unvegetated state. Mechanical disturbances include those such as forest clear cutting, earthmoving, or reservoir draw down; natural disturbances include those due to wind, fire, or insect infestation [*Stehman et al*., 2003]. Each ecoregion includes 9 to 48 Landsat 10kmx10km or 20kmx20km classified spatial subsets located using a stratified random sampling methodology that are used to estimate areal LCLU class proportions [*Stehman et al.,* 2005]. At the time of writing only 36 of the 84 ecoregions have been processed by the United States Geological Survey and these are used in this study. The ecoregion areal LCLU class proportions and classified Landsat subsets defined for 1973 and for 2000 are considered. The 36 ecoregions are illustrated in Figure 3-1 and cover 43% of the

CONUS; the classified Landsat subsets cover 3.7% of this area. The ecoregions vary in area from 14,458 km^2 (Willamette Valley, ecoregion 3) to 346,883 km^2 (Northwestern Great Plains, ecoregion 43).

Albedo data are provided by the most recent Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5 BRDF/Albedo 16-day 500m product [*Schaff et al.,* 2002] that is available every 8 days [*Roy et al.,* 2006]. Three years of 500m broadband (0.3-5.0μm) snow-free broadband white sky albedo data (February 18th 2000 to February 18th 2003) are used to capture inter-annual albedo variability.

The European Center for Medium-Range Weather Forecasts (ECMWF) 40 year Reanalysis data set (ERA-40) provides global monthly mean incoming surface solar radiation (SSRD) at 2.5° by 2.5° grid cells from September 1957 to August 2002 [*Allan et al*., 2004]. Data from January 1973 to December 2000 are used to derive mean monthly SSRD for each ecoregion.

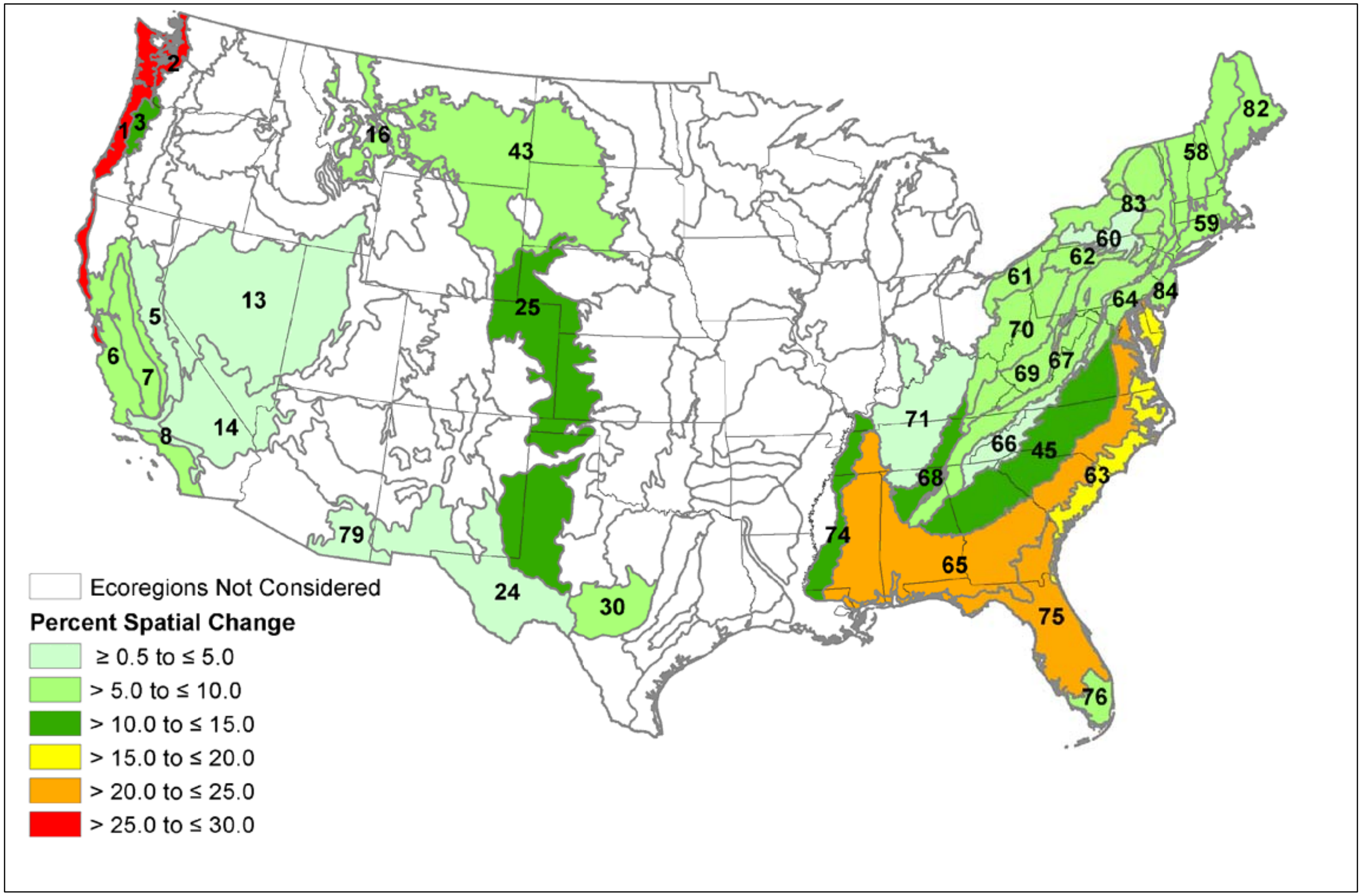

Figure 3-1. The 36 ecoregions, available to date, used in this study (numbered and colored) and their proportions of land cover and land use change, from 1973 to 2000 [P. Jellison, and W. Acevedo (unpublished data, 2010)].

3.3 Methods

Monthly albedos for each ecoregion were estimated independently for 1973 and 2000 as:

$$\alpha_{ecoregion, month, year} = \sum_{class\ i=1}^{10} \left(p_{i, ecoregion, year} \ \overline{\alpha}_{i, ecoregion, month} \right) \quad [1]$$

where, for each LCLU class *i*, p_i is the LCLU class area proportion, and $\overline{\alpha}_i$ is the mean monthly snow-free broadband white sky MODIS albedo derived from the three years of MODIS data. The albedo values were derived at locations defined by the Landsat 2000 classified subsets. To ensure that MODIS 500 m pixels containing only a single LCLU class were considered, the boundaries of the LCLU classes in each subset were morphologically eroded by 240m [*Serra*, 1982]. Albedo values were then extracted at the remaining LCLU class centroids for 3 years of snow-free non-missing MODIS data every 8 days after the Landsat 2000 acquisition date to February 18th 2003. A total of 197,205 MODIS albedo values were extracted and used in this study. In some ecoregions, for certain LCLU classes and months, there were insufficient MODIS data to compute $\overline{\alpha}_i$; this typically occurred in ecoregions with small areal LCLU class proportions (<0.005) in cloudy and snow contaminated months. In these cases, and when $p_i > 0$, $\overline{\alpha}_i$ was set as the median of the mean monthly class albedos computed for the ecoregions with available MODIS data.

The monthly surface radiative forcing ($\Delta F_{surface\ month}$) in each ecoregion due to LCLU induced albedo change, defined as the instantaneous change in energy flux at the surface [*Hansen et al.,* 1997], was estimated as:

$$\Delta F_{ecoregion,\, month} = -\bar{I}^{\downarrow}{}_{ecoregion,\, month}\left(\alpha_{ecoregion,\, month,\, 2000} - \alpha_{ecoregion,\, month,\, 1973}\right) \qquad [2]$$

where $\bar{I}^{\downarrow}$ is the mean monthly incoming surface solar radiation (Wm^{-2}) derived from the ERA40 dataset, and α_{2000} and α_{1973} are the monthly ecoregion albedos for 2000 and 1973 respectively (Equation 1). The mean annual forcing for each ecoregion was derived as the mean of the 12 monthly forcings as:

$$\Delta F_{ecoregion,\, annual} = \frac{\sum_{month=1}^{12} \Delta F_{ecoregion,\, month}}{12} \qquad [3]$$

3.4 Results

For the 36 CONUS ecoregions considered, the dominant contemporary (1973-2000) LCLU changes were a net areal increase in developed land (1.35%) and a net decrease in agricultural land (-1.47%) (Table 3-1). The most extensive LCLU changes occurred in the Pacific Northwest (> 25%) and in the Southeast (> 20%), and the least (< 5%) in the Central Basin region (Figure 3-1). This pattern of LCLU change is driven primarily by socio-economic factors causing exurban sprawl [*Theobold,* 2005] and the conversion and abandonment of agricultural land mainly for development [*Brown et al.,* 2005].

Table 3-2 summarizes the CONUS MODIS 3 year mean snow-free broadband white sky albedos for each LCLU class. The mean CONUS albedo class values are broadly comparable to other worker's results [*Myhre et al*., 2005], with the barren and agriculture classes having the highest mean albedo (0.240 and 0.171 respectively) and the water class the lowest mean albedo (0.058). The CONUS standard deviation albedo values and the minimum, median, and maximum within-ecoregion standard deviations for each LCLU class are also tabulated, and are indicative of geographic albedo variation. The CONUS standard deviations for the different classes are always greater than the median within-ecoregion albedo standard deviations, but are not significantly smaller than the maximum within-ecoregion albedo standard deviations. This in part reflects noise in the MODIS data, but is not unexpected as the ecoregion LCLU stratification was not designed with respect to albedo directly, and because albedo varies as function of numerous factors not captured by the LCLU classes. For example, the forest class is present in all the ecoregions considered, except for the Western High Plains (ecoregion 25), and encompasses a wide variety of tree species, stand densities, ages, and soil backgrounds. By using ecoregion specific mean monthly albedo values in Equation 1 we reduce this geographic variability.

LCLU Class	Mean of CONUS albedos	Standard deviation of CONUS albedos	*n*	Minimum within ecoregion albedo standard deviation	Median within ecoregion albedo standard deviation	Maximum within ecoregion albedo standard deviation
Barren	0.240	0.095	1727	0.059	0.068	0.077
Agriculture	0.171	0.026	47484	0.015	0.019	0.033
Grassland/ Shrubland	0.168	0.039	34597	0.014	0.023	0.047
Mining	0.153	0.038	4818	0.013	0.023	0.039
Developed	0.150	0.030	24297	0.014	0.018	0.034
Mechanically Disturbed	0.138	0.027	8501	0.016	0.019	0.025
Forest	0.128	0.026	50821	0.014	0.022	0.031
Wetland	0.127	0.028	12731	0.016	0.024	0.044
Naturally Disturbed	0.120	0.026	732	0.017	0.017	0.018
Water	0.058	0.043	11497	0.016	0.028	0.038

Table 3-2. Mean and standard deviation of snow-free broadband white sky albedos for each land cover land use (LCLU) class computed over the 36 conterminous United States (CONUS) ecoregions considered in this study (Figure 3-1) from three years of MODIS data; n is the number of albedo values considered; the LCLU classes are ranked in descending mean albedo order. The minimum, median, and maximum albedo standard deviations are also shown to indicate the variability of within ecoregion albedo.

The net changes in ecoregion albedo due to LCLU change are illustrated in Figure 3-2. The albedos of the LCLU classes and the extent of LCLU change determine these results; consequently ecoregions with the highest areal proportions of LCLU change (Figure 3-1) do not consistently coincide with the ecoregions of highest albedo change (Figure 3-2) and the correlation between these data is low (0.189). Timber harvesting in the Puget Lowland (ecoregion 2) produced the largest albedo increase (0.0016), whereas the conversion of agricultural land to forest in the Mississippi Valley Loess Plains (ecoregion 74) produced the largest decrease in albedo (-0.0015). To put these albedo changes into context, the mean annual SSRD for the 36 ecoregions considered is 190

Wm^{-2}; thus, a change in albedo of 0.0015 represents a surface forcing of 0.285 Wm^{-2}, which is not insignificant. Rather than apply regional annual averages however, Equation 2, is used to compute surface forcings in an ecoregion specific manner using monthly data.

Figure 3-3 illustrates the mean annual surface radiative forcing computed using ecoregion specific and monthly data [Equation 2]. The surface radiative forcing ranged from -0.247 Wm^{-2} in the Puget Lowland (ecoregion 2) to 0.284 Wm^{-2} in the Mississippi Valley Loess Plains (ecoregion 74). The geographic distribution of forcing is highly correlated (-0.984) with the LCLU albedo change and only weakly (-0.119) correlated with the mean annual SSRD. Table 3-3 summarizes the five ecoregions with the highest observed positive and negative surface radiative forcings. The LCLU changes that resulted in the net largest magnitude of albedo change are also summarized (Table 3-3, column 5) and may not necessarily be the most extensive LCLU changes; for example, LCLU change between classes with very different albedos may have a greater net albedo impact than more extensive changes between classes with similar albedos. All five ecoregions with the highest positive radiative forcings experienced a LCLU conversion from agriculture (to forest, developed, or grass/shrub), whereas forest loss was a common conversion in the five ecoregions with the most negative forcings.

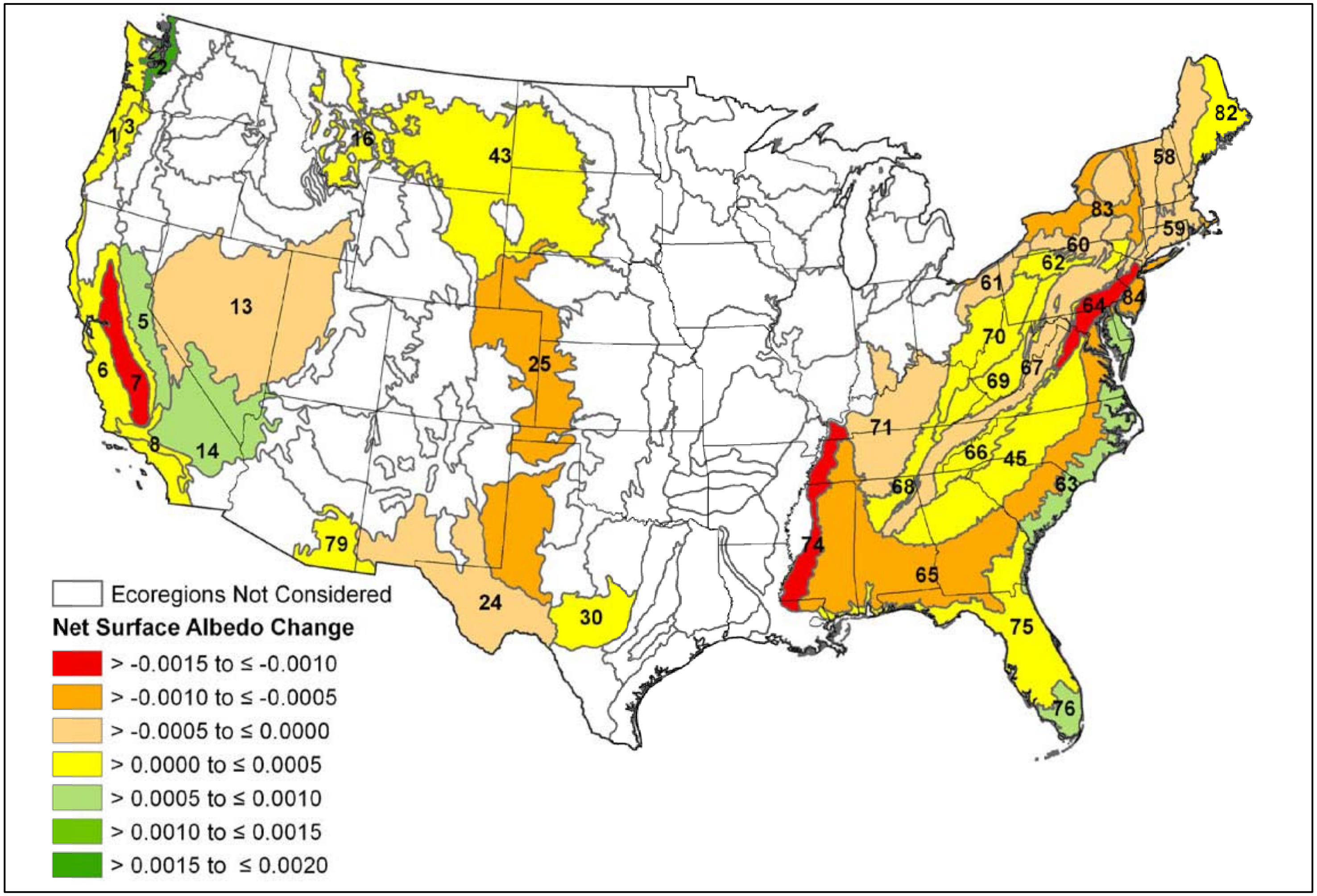

Figure 3-2. The estimated net albedo change due to contemporary land cover land use change from 1973 to 2000 ($\alpha_{2000} - \alpha_{1973}$) for the 36 ecoregions used in this study.

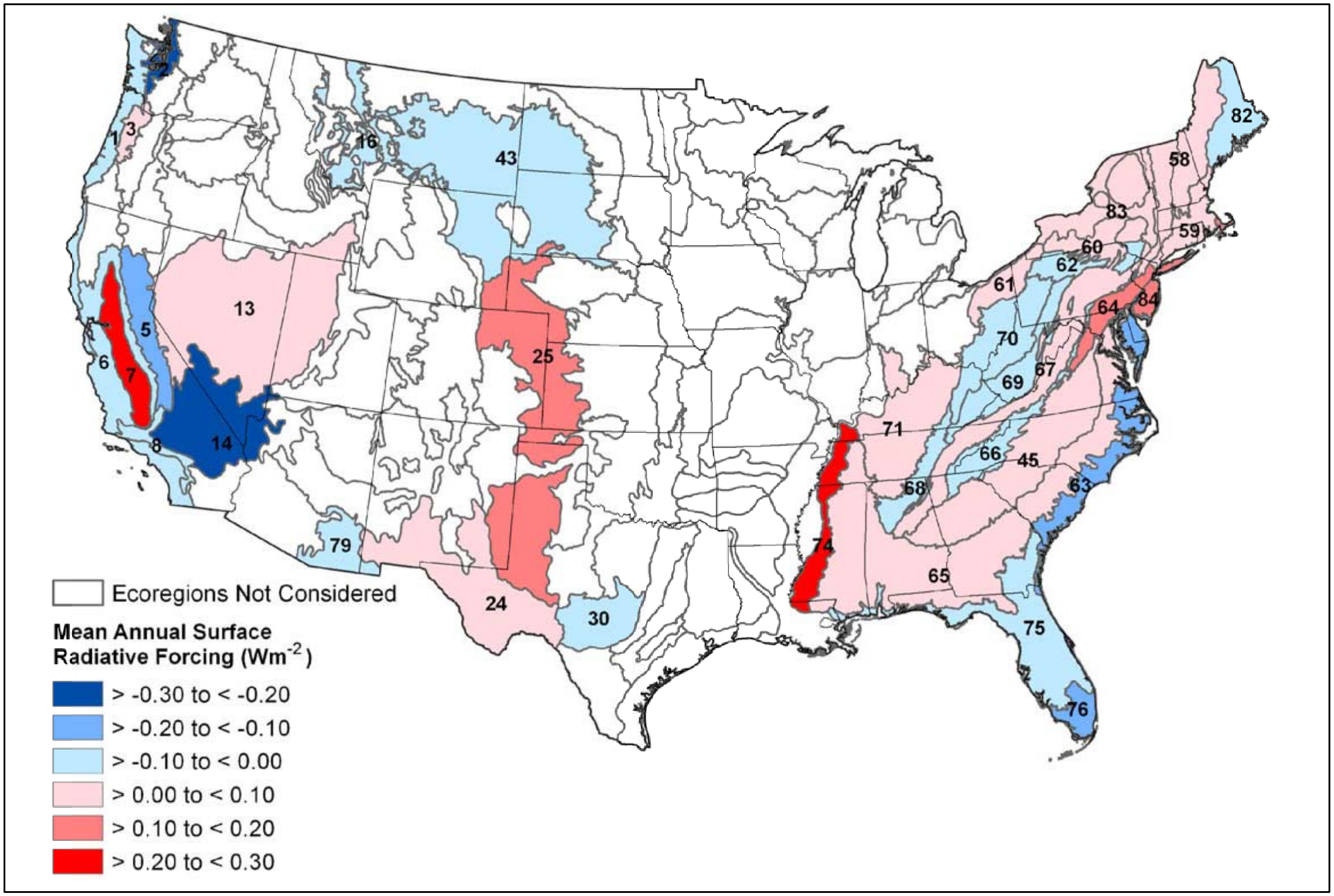

Figure 3-3. The mean annual surface radiative forcing due to contemporary land cover land use albedo change from 1973 to 2000 (Equation 2) for the 36 ecoregions used in this study.

Ecoregion	Mean Annual Surface Radiative Forcing (Wm^{-2})	Mean Annual Monthly SSRD (Wm^{-2})	Net Mean Annual Surface Albedo Change (α_{2000} -α_{1973})	LCLU change conversion From / To
Positive Radiative Forcing				
Mississippi Valley Loess Plain (74)	0.284	194	-0.001	Agriculture to Forest
Central California Valley (7)	0.236	226	-0.001	Agriculture to Grass/Shrub
Northern Piedmont (64)	0.164	177	-0.001	Agriculture to Developed
Atlantic Coastal Pine Barrens (84)	0.156	180	-0.001	Agriculture to Developed
Western High Plains (25)	0.140	212	-0.001	Agriculture to Grass/Shrub
Negative Radiative Forcing				
Puget Lowland (2)	-0.247	151	0.002	Forest to M. Disturbed
Mojave Basin and Range (14)	-0.210	244	0.001	Grass/Shrub to Developed
Sierra Nevada (5)	-0.153	221	0.001	Forest to M. Disturbed
Southern Florida Coastal Plain (76)	-0.132	202	0.001	Wetland to Agriculture
Middle Atlantic Coastal Plain (63)	-0.127	191	0.001	Forest to M. Disturbed

Table 3-3. The 5 ecoregions that observed the highest mean annual positive and negative radiative forcing, their corresponding mean monthly incoming surface solar radiation (SSRD), net mean annual surface albedo change (α_{2000} - α_{1973}), and the land cover land use (LCLU) change that resulted in the net largest magnitude of albedo change from 1973 to 2000. Ecoregion numbering is included in Figure 3-1.

Figure 3-4 shows a histogram of the mean annual surface radiative forcing values illustrated in Figure 3-3. The histogram shape illustrates an almost balanced distribution of positive and negative forcing for the 36 ecoregions (mean 0.001 Wm^{-2}, median -0.006 Wm^{-2}). A CONUS scale forcing estimate, derived by summing the product of the ecoregion areas (m^2) and forcing estimates (Wm^{-2}), divided by the total area (m^2) of the

36 ecoregions, provides a small positive (i.e. warming) net surface radiative forcing of 0.012 Wm^{-2}.

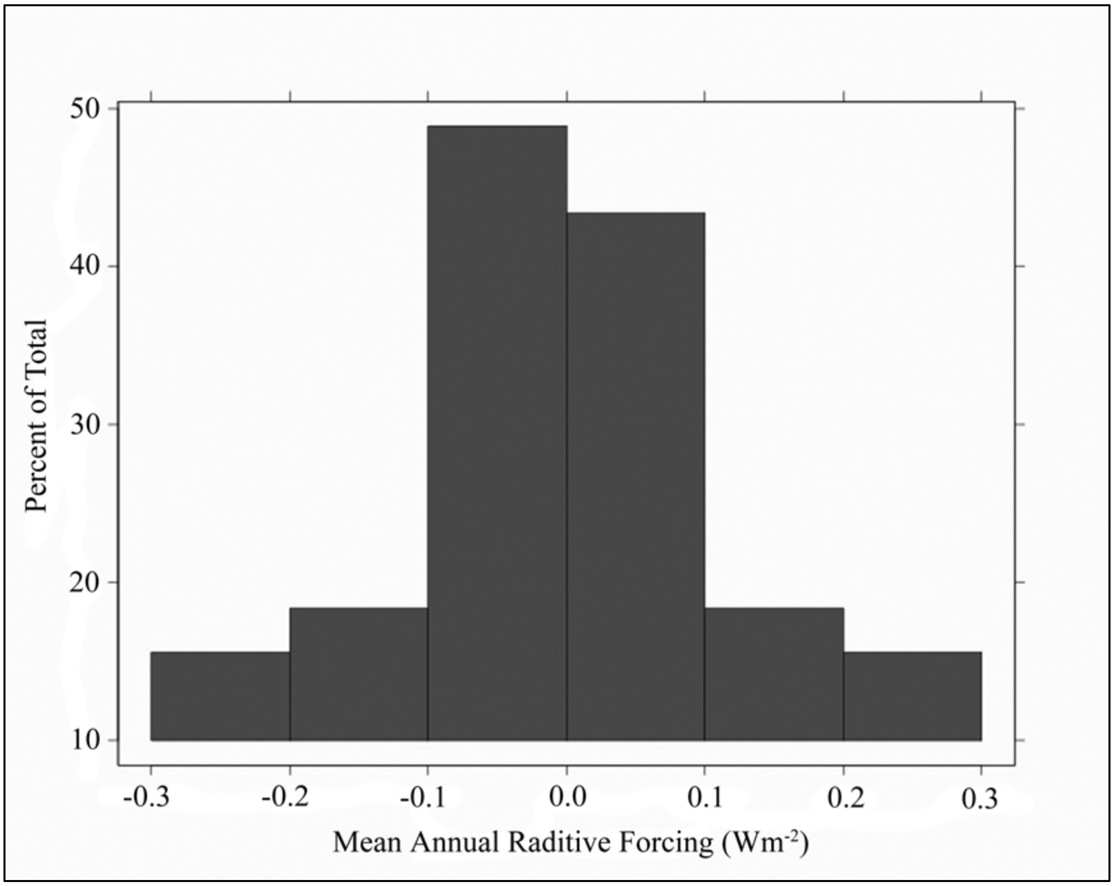

Figure 3-4. Histogram of the mean annual surface radiative forcing due to contemporary land cover land use albedo change from 1973 to 2000 for the 36 ecoregions used in this study (Figure 3-3 data).

3.5 Conclusions

This letter has demonstrated the value of regional spatially and temporally explicit data to quantify, and begin to understand, the drivers of LCLU related radiative forcing which remains poorly understood [*Pielke et al*., 2002; *NRC,* 2005; *IPCC*, 2007]. Previous United States historical [*Bounoua et al.,* 2002; *Matthews et al.,* 2003] and contemporary

[*Hale et al.,* 2006] LCLU climate studies have indicated directional uncertainty in radiative forcing estimates. Our results also indicate this, with a large geographic variation in forcing due to LCLU albedo change, varying from -0.247 Wm^{-2} to 0.284 Wm^{-2}, for 36 ecoregions covering 43% of the CONUS. At the ecoregion level this magnitude of forcing is not insignificant, being similar in magnitude to global forcing estimates due to LCLU change during the twentieth century [*IPCC,* 2007].

Loss of agricultural and forested lands was observed to be the LCLU changes that caused the greatest absolute albedo induced forcing. Across the CONUS however there is no single profile of LCLU change, rather, there are varying pulses affected by clusters of change agents [*Loveland et al.,* 2002]. This argues strongly for the ecoregion based analysis we have described, as continental averages may mask regional differences; indeed, because of the variability in magnitude and sign of forcing, we estimate only a small, 0.012 Wm^{-2}, net CONUS forcing due to contemporary LCLU albedo change. This work did not consider snow, which may have a significant land cover dependent albedo effect [*Jin et al*., 2002] and so may impact the forcing associated with actual albedo change [*Betts,* 2000]; however, only about one eighth of the CONUS ecoregions considered in this study have significant annual snow cover. Further research will be undertaken to address these impacts for a larger number of ecoregions as more LCLU change data become available.

3.6 References

Allan, R. P., M. A. Ringer, J. A. Pamment, and A. Slingo (2004), Simulation of the Earth's radiation budget by the European Centre for Medium- Range Weather Forecasts 40-year reanalysis (ERA40), *Geophys. Res. Lett.*, *109*, D18107, doi:10.1029/2004JD004816.

Bala, G., K. Caldeira, M. Wickett, T. J. Phillips, D. B. Lobell, C. Delire, and A. Mirin (2007), Combined climate and carbon-cycle effects of large-scale deforestation, *Proc. Nat. Acad. Sci. U.S.A., 104,* 6550-6555.

Betts, R. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature, 408*, 187-190.

Bounoua L., R, DeFries, G.J. Collatz, P. Sellers, and H. Khan (2002), Effects of land cover conversion on surface climate, *Clim. Chg.*, *52*, 29-64.

Brown, D.G., K.M. Johnson, T. R. Loveland, and D.M. Theobald (2005), Rural land use trends in the conterminous United States, 1950 – 2000, *Ecol. Appl., 15*, 1851-1863.

Gibbard, S., K. Caldeira, G. Bala, T. J. Philips, and M. Wickett (2005), Climate effects of global land cover change, *Geophys. Res. Lett.*, *32*, L23705, doi:10.1029/2005GL024550.

Hale, R. C., K. P. Gallo, T. W. Owen, and T. R. Loveland (2006), Land use/land cover change effects on temperature trends at U.S. Climate Normals stations, *Geophys. Res. Lett.*, *33*, L11703, doi:10.1029/2006GL026358.

Hansen, J., M. Sato, and R. Ruedy (1997), Radiative forcing and climate response, *J. Geophys. Res.*, *102* (D6), 6831-6864, 10.1029/96JD03436.

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*, edited by S. Solomon et al., 996pp., Cambridge Univ. Press, New York.

Jin, Y., C. B. Schaaf, F. Gao, X. Li, A. H. Strahler, X. Zeng, and R. E. Dickinson (2002), How does snow impact the albedo of vegetated land surfaces as analyzed with MODIS data?, *Geophys. Res. Lett.*, *29*(10), 1374, doi:10.1029/2001GL014132.

Jin, Y., and D.P. Roy (2005), Fire-induced albedo change and its radiative forcing at the surface in northern Australia, *Geophys. Res. Lett*., *32*, L13401, doi:10.1029/2005GL022822.

Kleidon, A. (2006), The climate sensitivity to human appropriation of vegetation productivity and its thermodynamic characterization, *Global Planet. Ch., 54*, 109–127.

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

Matthews, H.D., A.J., Weaver, M. Eby, and K.J., Meissner (2003), Radiative forcing of climate by historical land cover change. *Geophys. Res. Lett., 30*(2), 1055 doi: 10.1029/2002GL016098.

Myhre, G., M. Kvalevag, and C. Schaaf (2005), Radiative forcing due to anthropogenic vegetation change based on MODIS surface albedo data. *Geophys. Res. Lett.*, *32*, L21410, doi:10.1029/2005GL024004.

National Research Council (2005), *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, 207pp National Academic Press, Washington, D.C.

Oleson, K. W., G.B. Bonan, S. Levis, and M. Vertenstein (2004), Effects of land use change on North American climate: Impacts of surface datasets and model biogeophysics, *Clim. Dyn*., *23*, 117 – 132.

Pielke, R. A., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. D. S. Niyogi, S. and W. Running (2002), The influence of landuse change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases, *Philos. Trans. R. Soc. London Ser. A., 360*, 1705– 1719.

Randerson, J. T*.,* **H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, C. S. Zender** (2006), The impact of boreal forest fire on climate warming, *Science*, 314: 1130–1132.

Roy, D.P., P, Lewis, C, Schaaf, S, Devadiga, and L, Boschetti (2006), The Global impact of cloud on the production of MODIS bi-directional reflectance model based composites for terrestrial monitoring, *IEEE Geoscience and Remote Sensing Letters, 3,* 452-456.

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

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

Stehman, S.V., T.L. Sohl, and T.R. Loveland (2003), Statistical sampling to characterize recent United States land-cover change, Remote Sensing of Environment, *86* , 517-529.

Stehman, S.V., T.L. Sohl, and T.R. Loveland (2005). An evaluation of sampling strategies to improve precision of estimates of gross change in land use and land cover, *Int. J. Remote. Sens.*, *26*, 4941-4957.

Theobald, D.M. (2005), Landscape patterns of exurban growth in the USA from 1980 to 2020, *Ecol and Soc.* 10(1):32.

CHAPTER 4

RADIATIVE FORCING OVER THE CONTERMINOUS UNITED STATES DUE TO CONTEMPORARY LAND COVER LAND USE CHANGE AND SENSITIVITY TO SNOW AND INTER-ANNUAL ALBEDO VARIABILITY

Barnes, C.A. and Roy, D.P. (in press), *Geophysical Research Biogeosciences*,

doi:10.1029/2010JG001428, (Journal impact factor: 3.082).

Accepted 7 September 2010.

This chapter describes the research undertaken to address research hypotheses:

***#2** that radiative forcing due to LCLU albedo change is greater than that due to inter-annual albedo variability, and,*

***#4** large regional disparities in LCLU change will modify the outcome of hypotheses **#2** at the regional scale.*

4.1 Abstract

Satellite derived land cover land use (LCLU), snow and albedo data, and incoming surface solar radiation reanalysis data, were used to study the impact of LCLU change from 1973 to 2000 on surface albedo and radiative forcing for 58 ecoregions covering 69% of the conterminous United States (CONUS). A net positive surface radiative forcing (i.e., warming) of 0.029 Wm^{-2} due to LCLU albedo change from 1973 to 2000 was estimated. The forcings for individual ecoregions were similar in magnitude to current global forcing estimates, with the most negative forcing (as low as -0.367 Wm^{-2}) due to the transition to forest and the most positive forcing (up to 0.337 Wm^{-2}) due to the conversion to grass/shrub. Snow exacerbated both negative and positive forcing for LCLU transitions between snow-hiding and snow-revealing LCLU classes. The surface radiative forcing estimates were highly sensitive to snow-free inter-annual albedo variability, which had a percent average monthly variation from 1.6% to 4.3% across the ecoregions. The results described in this paper enhance our understanding of contemporary LCLU change on surface radiative forcing and suggest that future forcing estimates should model snow and inter-annual albedo variation.

4.2 Introduction

Surface albedo affects the Earth's radiative budget by controlling how much incoming solar radiation is absorbed and reflected by the Earth's surface and is a fundamental parameter for characterizing the Earth's radiative regime [*Dickinson,* 1995]. It is thought that land cover land use (LCLU) change during the twentieth century, primarily increasing croplands and pastures and decreasing forested land [*Ramankutty and Foley,* 1999], has resulted in a global net cooling of approximately -0.25 Wm^{-2} [*Intergovernmental Panel on Climate Change* (IPCC), 2007]. Changes in surface albedo depend on both the type and spatial extent of LCLU change and the spatial averaging of opposite signs of LCLU induced radiative forcing may under represent LCLU contributions over large areas [*Pielke et al*., 2002; *Kleidon,* 2006; *Barnes and Roy,* 2008]. Surface albedos vary seasonally because of factors including land management practices and phenology [*Gao et al., 2005*] and failure to adequately prescribe seasonal vegetation variations may significantly bias LCLU change forcing estimates [*Nair et al.,* 2007]. Similarly, snow is temporally variable and because the albedo of snow is high relative to that of vegetation and soil, changes from snow-hiding to snow-revealing LCLU types may have a significant surface radiative forcing effect [*Betts,* 2000].

In this paper we update earlier work [*Barnes and Roy*, 2008] to quantify the surface radiative forcing due to contemporary LCLU albedo change (1973 to 2000) for the conterminous United States (CONUS) using spatially and temporally explicit satellite derived LCLU change and albedo data. We provide a revised estimate of the CONUS surface radiative forcing by considering a greater area, 69% of the CONUS, and by improving the representation of the LCLU class albedos. Median monthly snow and snow-free albedo climatology values are derived from nine years of MODerate Resolution Imaging Spectroradiometer (MODIS) albedo product data for ten LCLU classes in 58 ecoregions. These, and monthly surface solar radiation, monthly snow fraction, and 1973 to 2000 LCLU change data, are used to compute monthly and annual ecoregion forcing estimates.

The sensitivity of the forcing estimates to inter-annual albedo variations that are not associated with LCLU change are examined. Although inter-annual albedo variability is usually lower than seasonal variability [*Wang et al*., 2004; *Gao et al., 2005*; *Matsui et al.,* 2007] it is unknown if albedo changes from one year to another significantly impact LCLU albedo change forcing estimates. In addition, by incorporating spatially and temporally explicit snow albedo data we examine what impact modeling snow conditions has on contemporary LCLU albedo change surface radiative forcing, particularly in the northern and high altitude snow prone regions of the CONUS.

4.2 Study Area and Data

LCLU information for the CONUS are currently being generated from decadal Landsat data (1973 to 2000) at the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center [*Loveland et al.,* 2002; P. Jellison and W. Acevedo, USGS Land Cover Trends Project, unpublished data, 2010]. Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) data with reflective wavelength pixel sizes of 80 m, 30 m and 30 m respectively are re-sampled to 60 m and then classified by visual interpretation, inspection of aerial photography and ground survey, into 10 classes (Table 4-4, first column). The classes are defined to capture LCLU discernable in the Landsat data and include mechanically disturbed (forest clear cutting, earthmoving, or reservoir draw down) and naturally disturbed classes (due to wind, fire, or insect infestation) that describe land that is in an altered unvegetated state. The Landsat data are located using a stratified random sampling methodology with respect to the 84 contiguous Level III ecoregions defined by *Omernik* [1987]. At the time of writing only 58 of the 84 ecoregions have been processed by the United States Geological Survey and these are used in this study.

Figure 4-1 shows the CONUS study area and the 58 ecoregions that have Landsat derived LCLU data generated to date. The ecoregion numbering system (1 to 84) used to refer to specific ecoregions is illustrated in Figure 4-1. In each ecoregion, classification of 10 km x 10 km or 20 km x 20 km Landsat spatial subsets acquired in 1973, 1980, 1986, 1992, and 2000 was performed. A total of 1,796 subsets fall in the 58 ecoregions considered and are located using a stratified random sampling methodology with 9 to 48 Landsat classified spatial subsets per ecoregion. The sampling was designed to enable a statistically robust 'scaling up' of the classification data to estimate areal LCLU class proportions and LCLU class temporal change within each ecoregion [*Stehman et al.,* 2005]. The 58 ecoregions cover 69% of the CONUS and vary in area from 14,458 km^2 (Willamette Valley, ecoregion 3) to 346,883 km^2 (Northwestern Great Plains, ecoregion 43). Statistical estimates of the LCLU class proportions in each of these ecoregions [*Stehman et al.,* 2005] and the classified Landsat subsets that fall within them for years 1973 and 2000 are used in this study.

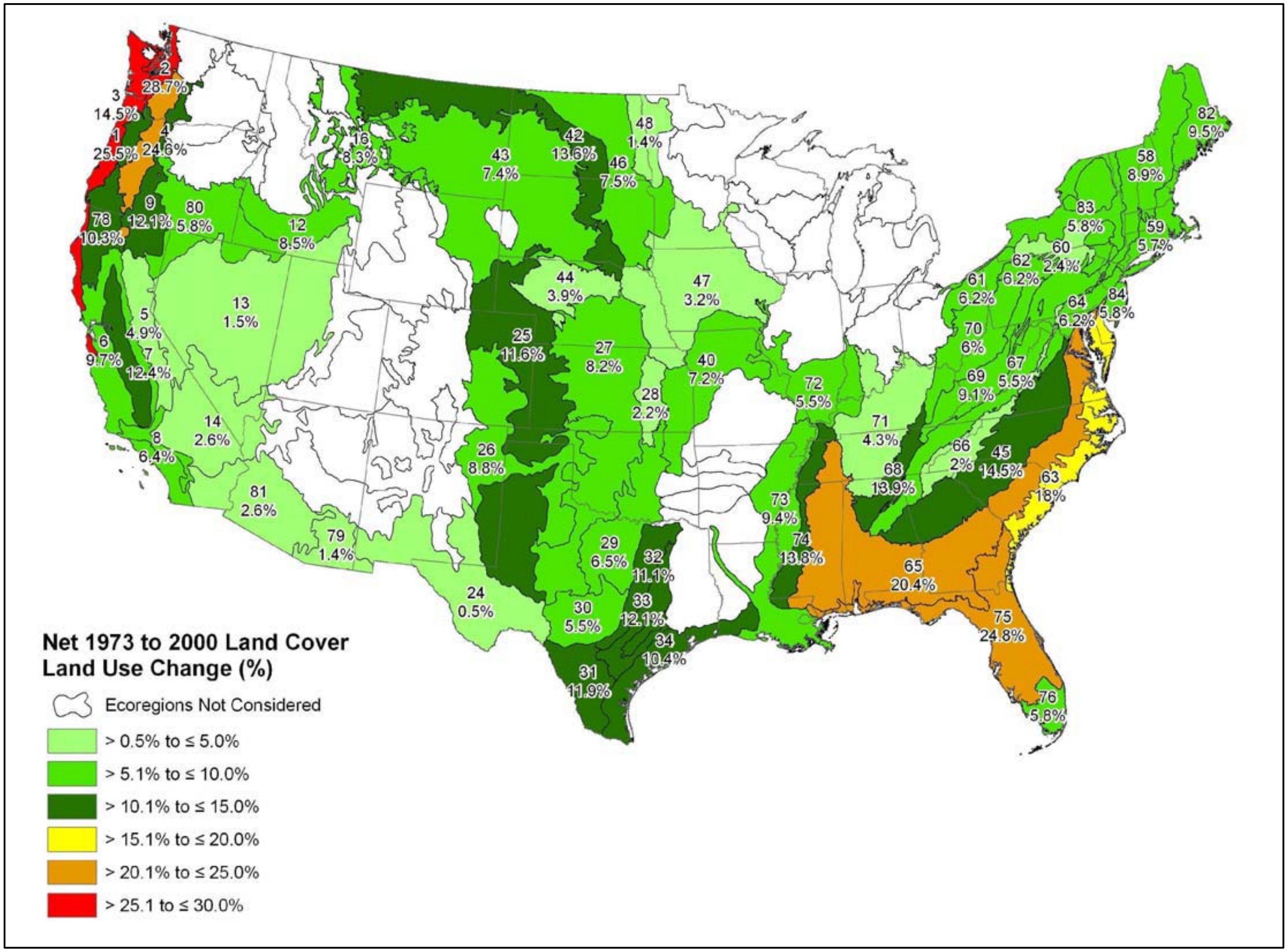

Figure 4-1. Completed ecoregions to date (colored and numbered) and their percentage of land cover land use changes from 1973 to 2000.

Albedo data are provided by the most recent MODIS Collection 5 BRDF/Albedo 16-day 500m product [*Schaaf et al.,* 2002]. The MODIS BRDF/Albedo product is generated every 8 days by inversion of the Ross-Thick/Li-Sparse-Reciprocal Bi-directional Reflectance Distribution Function (BRDF) model against the MODIS observations (surface reflectance and solar and viewing geometry values) sensed in a 16-day period [*Schaaf et al.,* 2002; 2008]. The MODIS albedo product provides both the black-sky albedo (directional-hemispherical reflectance) computed by integration of the BRDF over all view angles, and the white-sky albedo (bihemispherical reflectance under isotropic illumination) derived by a further integration over all solar zenith angles [*Schaaf et al.,* 2002]. In this work the MODIS broadband (0.3-5.0µm) white-sky albedo and associated per-pixel product quality assessment (QA) information that describe the processing method and whether a snow or snow-free albedo was retrieved are used. Only good quality (full BRDF inversion), non-fill, snow, and snow-free albedo values are used. Nine years of MODIS 500 m broadband white-sky albedo, February 18th 2000 – March 31st 2009, defined every 8 days are used in order to capture inter-annual albedo variability.

Snow cover data are provided by the MODIS Collection 5 monthly average snow cover 0.05° climate modeling grid (CMG) product (MOD10CM) [*Hall et al.,* 2006; *Hall et al.,* 2007]. The monthly products for January 2004 to December 2008 (the complete full years currently available) are used to compute ecoregion monthly snow climatology, i.e., the mean fractional snow cover (0-1) for each calendar month, and the mean of the 12 monthly values are used to compute the ecoregion mean annual snow fraction.

Monthly incoming surface solar radiation downwards (SSRD) are provided in 2.5° by 2.5° cells from January 1973 to December 2000 by the European Center for Medium Range Weather Forecasts 40 year Reanalysis (ERA-40) data set [*Allan et al.,* 2004]. ERA-40 is a 45-year second-generation reanalysis that has been supplied with more observations and makes more comprehensive use of satellite data, re-processed from raw observations where possible [*Uppala et al.,* 2005]. These data are used to define mean monthly SSRD climatology in watts per meter square (Wm^{-2}) for each ecoregion.

LCLU Class	CONUS Snow-free Albedo	CONUS Snow Albedo
Barren	0.1938	0.4864 (2)
Agriculture	0.1686	0.5673 (1)
Mining	0.1573	0.4421 (5)
Developed	0.1569	0.4153 (7)
Grass/shrub	0.1562	0.4562 (4)
Wetland	0.1418	0.4645 (3)
Mechanically Disturbed	0.1387	0.3148 (9)
Non Mechanically Disturbed	0.1301	0.4323 (6)
Forest	0.1296	0.2433 (10)
Water	0.0745	0.3463 (8)

Table 4-1. The 10 land cover land use classes defined in the decadal conterminous United States (CONUS) Landsat classifications. Corresponding CONUS estimates of the annual snow and snow-free broadband white-sky MODIS albedo values are tabulated for each class. The land cover land use classes are ranked in descending snow-free albedo order. The rank of the snow albedos are denoted in brackets in the 3rd column. The land cover land use class albedos are shown here for interpretive purposes only, they were not used in the described analyses. The albedos were computed for each class i from all the valid MODIS albedo samples for each month m (1…12), ecoregion e (Figure 4-1), and year y (2000-2009) as:

$$CONUS\ \alpha_i = \underset{12\ months}{median} \left\{ \underset{58\ ecoregions}{median} \left\{ \underset{9\ years}{median} \left\{ \alpha_{i,m,e,y} \right\} \right\} \right\}$$

4.3 Methods

4.3.1 Ecoregion LCLU Class Monthly Albedo

MODIS 500 m broadband white-sky albedo values were extracted at fixed geographic locations defined by analysis of the 60 m Landsat 2000 LCLU classified subsets. In each of the 58 ecoregions there were 9 to 48 Landsat 2000 LCLU classified subsets; in the larger ecoregions, there were more Landsat subsets, and so typically more albedo values available for extraction. To ensure that the MODIS 500 m pixels contained only a single LCLU class, the boundaries of each LCLU class in each subset were morphologically eroded by 240 m [*Serra,* 1982]. MODIS albedo values were then extracted at the remaining LCLU class centroids from the 9 year time series of MODIS albedo data starting after each Landsat subset 2000 acquisition date to March 31st 2009. A total of 60,423 snow and 1,307,902 snow-free MODIS albedo values were extracted.

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

$$\overline{\alpha}_{i,\ ecoregion,\ month,\ snow} = \underset{9\ years}{median}\left\{ snow\ albedo_{i,\ ecoregion,\ month} \right\}$$

$$\overline{\alpha}_{i,\ ecoregion,\ month,\ snowfree} = \underset{9\ years}{median}\left\{ snowfree\ albedo_{i,\ ecoregion,\ month} \right\} \quad [1]$$

where $\overline{\alpha}_{i,\ ecoregion,\ month,\ snow}$ and $\overline{\alpha}_{i,\ ecoregion,\ month,\ snowfree}$ are the monthly median snow and snow-free monthly albedos for LCLU class *i* respectively in the ecoregion, and *snow albedo* and *snowfree albedo* are the snow and snow-free broadband white-sky MODIS 500 m albedo values. The median rather than the mean value was taken as it is less sensitive to infrequent but anomalously low or high MODIS albedo values associated with residual shadow or cloud contamination [*Román et al.,* 2009].

In some ecoregions, and for certain months and LCLU classes, there were insufficient MODIS snow and snow-free albedos to estimate [1]. This typically occurred in ecoregions with small areal LCLU class proportions (<0.005), in persistently cloudy months, and for the snow albedo in snow-free ecoregions and summer months. In these cases, the median monthly (snow or snow-free) class albedos computed for each ecoregion with at least 3 valid (non-fill, full BRDF inversion) class albedo values were computed and the median of the CONUS median albedo values used as:

$$\bar{\alpha}_{i,\ ecoregion,\ month,\ snow} = \underset{58\ ecoregions}{median}\left\{\underset{9\ years}{median}\left\{snow\ albedo_{i,\ ecoregion,\ month}\right\}\right\}$$

$$\bar{\alpha}_{i,\ ecoregion,\ month,\ snowfree} = \underset{58\ ecoregions}{median}\left\{\underset{9\ years}{median}\left\{snowfree\ albedo_{i,\ ecoregion,\ month}\right\}\right\} \quad [2]$$

where $\bar{\alpha}_{i,\ ecoregion,\ month,\ snow}$ and $\bar{\alpha}_{i,\ ecoregion,\ month,\ snowfree}$ are the monthly median snow and snow-free monthly albedos for LCLU class *i* respectively.

The median albedos were used to estimate the ecoregion monthly LCLU class albedos, using the ecoregion snow fraction, following the approach of *Roesch at al.* [2002], as:

$$\alpha_{i,\ ecoregion,\ month} = \left(1 - f_{snow,\ month,\ ecoregion}\right).\bar{\alpha}_{i,\ ecoregion,\ month,\ snowfree} + f_{snow,\ month,\ ecoregion}.\bar{\alpha}_{i,\ ecoregion,\ month,\ snow} \quad [3]$$

where $\alpha_{i,\,ecoregion,\,month}$ is the monthly albedo for LCLU class *i,* $\overline{\alpha}_{i,\,ecoregion,\,month,\,snow}$ and $\overline{\alpha}_{i,\,ecoregion,\,month,\,snowfree}$ are the median snow and snow-free monthly albedos for LCLU class *i* respectively defined as Equation [1] or [2], and $f_{snow,\,month,\,ecoregion}$ is the monthly snow fraction [0-1] derived from the MODIS snow product.

4.3.2 Ecoregion Monthly Albedo

An estimate of the monthly albedo for each ecoregion and year was computed independently for the LCLU class areal proportions in 1973 and 2000 as:

$$\alpha_{ecoregion,\,month,\,year} = \sum_{i=1}^{10} \left(p_{i,\,ecoregion,\,year} \, . \, \alpha_{i,\,ecoregion,\,month} \right) \qquad [4]$$

where, *year* is 1973 or 2000, and for each LCLU class *i*, p_i is the LCLU class areal proportion in the ecoregion for the year defined by the USGS Land Cover Trends Project data [*Stehman et al.,* 2005], and $\alpha_{i,ecoregion,\,month}$ is defined as Equation [3].

To help interpret our results the annual LCLU induced albedo change from 1973 to 2000 was computed as:

$$\Delta\alpha_{ecoregion,\,annual} = \frac{\sum_{month=1}^{12} \left(\alpha_{ecoregion,\,month,\,2000} - \alpha_{ecoregion,\,month,\,1973} \right)}{12} \qquad [5]$$

where $\alpha_{ecoregion,\, month,\, year}$ is defined as Equation [4].

4.3.3 Ecoregion Monthly Albedo Inter-Annual Variability

The inter-annual monthly albedo variability was estimated for each LCLU class as:

$$MAD_{i,\ ecoregion,\ month} = \underset{9\,years}{median}\left\{\left|\overline{\alpha}_{i,\ ecoregion,\ month,\ snowfree} - \underset{9\,years}{median}\left\{\overline{\alpha}_{i,\ ecoregion,\ month,\ snowfree}\right\}\right|\right\}$$

[6]

where $MAD_{i,\ ecoregion,\ month}$ is the albedo median absolute deviation (MAD) for each LCLU class *i*, month, and ecoregion, and $\overline{\alpha}_{i,\, ecoregion,\, month,\, snowfree}$ is defined as Equation [1] or [2]. These MAD values reflect for each month the inter-annual albedo variation derived over the 9 years of MODIS data from 2000 to 2009. The MAD rather than the standard deviation was used as it is less sensitive to infrequent but anomalously low or high MODIS albedo values. Only snow-free MODIS albedo data were considered as many ecoregions had insufficient snow albedo LCLU class values in each month to compute MAD statistics. Inter-annual albedo variability statistics were computed for snow-free conditions for a total of 45 ecoregions.

The inter-annual monthly albedo variability for each ecoregion was estimated as:

$$MAD_{ecoregion,month,year} = \sum_{i=1}^{10}\left(p_{i,ecoregion,year} \,.\, MAD_{i,ecoregion,month}\right) \qquad [7]$$

where for each LCLU class i, p_i is the LCLU class areal proportion in the ecoregion defined for year 1973 or 2000, $\alpha_{i,\,ecoregion,\,month}$ is defined as Equation [3] and $MAD_{i,\,ecoregion,\,month}$ is defined as Equation [6].

To help interpret our results the percentage average monthly variation in the ecoregion albedo due to inter-annual albedo variability was computed as:

$$v_{ecoregion,\,year} = \frac{\sum_{month=1}^{12}\left(MAD_{ecoregion,\,month,\,year} \Big/ \alpha_{ecoregion,\,month,\,year} \right)}{12} * 100$$

[8]

where $year$ is 1973 or 2000 and $MAD_{ecoregion,\,month,\,year}$ is defined as Equation 7 and $\alpha_{ecoregion,\,month,\,year}$ is defined as Equation 4.

4.3.4 Surface Radiative Forcing due to LCLU Albedo Change from 1973 to 2000

In each ecoregion, the monthly surface radiative forcing (Wm^{-2}) due to LCLU albedo change from 1973 to 2000 was estimated following [*Jin and Roy*, 2005; *Barnes and Roy,* 2008] as:

$$\Delta F_{ecoregion,\,month} = \bar{I}^{\downarrow}_{ecoregion,\,month} \,.\, \left(\alpha_{ecoregion,\,month,\,2000} - \alpha_{ecoregion,\,month,\,1973}\right)$$

[9]

where $-\bar{I}^{\downarrow}_{ecoregion,\, month}$ is the mean monthly incoming SSRD climatology (Wm^{-2}) for the ecoregion, and $\alpha_{ecoregion,\, month,\, 2000}$ and $\alpha_{ecoregion,\, month,\, 1973}$ are the monthly ecoregion albedos for 2000 and 1973 respectively defined as Equation [4]. The annual surface radiative forcing (Wm^{-2}) in each ecoregion due to LCLU albedo change from 1973 to 2000 was computed as:

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

[10]

where $\Delta F_{ecoregion,\, month}$ is defined by Equation [9].

The CONUS scale net surface radiative forcing (Wm^{-2}) was estimated as:

$$\Delta F_{CONUS,\, annual} = \frac{\sum_{ecoregion=1}^{58} a_{ecoregion}\, \Delta F_{ecoregion,\, annual}}{\sum_{ecoregion=1}^{58} a_{ecoregion}}$$

[11]

where $a_{ecoregion}$ is the ecoregion area (km^2) and $\Delta F_{ecoregion,\, annual}$ is defined by Equation [10].

4.3.5 Sensitivity of Surface Radiative Forcing due to Inter-Annual Albedo Variability

The sensitivity of the monthly surface radiative forcing was estimated by applying standard propagation of variance formulae to Equation [9], assuming that there was no error in the incoming SSRD climatology (as this is not defined) and that the monthly ecoregion albedos for 2000 and 1973 were independent, as:

$$\varepsilon_{\Delta F_{ecoregion,\, month}} = -\bar{I}^{\downarrow}{}_{ecoregion,\, month} \sqrt{\varepsilon^2_{\alpha_{ecoregion,\, month,\, 2000}} + \varepsilon^2_{\alpha_{ecoregion,\, month,\, 1973}}}$$

[12]

where $\varepsilon_{\Delta F_{ecoregion,\, month}}$ is the monthly ecoregion surface radiative forcing error, $-\bar{I}^{\downarrow}{}_{ecoregion,\, month}$ is the mean monthly incoming SSRD climatology (Wm^{-2}) for the ecoregion, and $\varepsilon_{\alpha\, ecoregion,\, month,\, 2000}$ and $\varepsilon_{\alpha\, ecoregion,\, month,\, 1973}$ are defined as:

$$\varepsilon_{\alpha\, ecoregion,\, month,\, year} = \left(\sum_{i=1}^{10} \left(p_{i,ecoregion,year} \,.\, MAD_{i,ecoregion,month} \right) \right)$$

[13]

where, for each LCLU class i, p_i is the class areal proportion in the ecoregion for the year defined by the USGS Land Cover Trends Project data [*Stehman et al.,* 2005] and $MAD_{i,\, ecoregion,\, month}$ is the albedo median absolute deviation defined by [Equation 6].

The sensitivity of the annual surface radiative forcing imposed by inter-annual albedo variability was estimated by applying standard propagation of variance formulae to Equation [10], assuming that the monthly forcing estimates were independent as:

$$\varepsilon_{\Delta F_{ecoregion,\ annual}} = \frac{1}{12} \cdot \sqrt{\sum_{month=1}^{12} \varepsilon^{2}_{\Delta F_{ecoregion,\ month}}}$$

[14]

where $\varepsilon_{\Delta F_{ecoregion,\ month}}$ is defined by Equation [12].

Similarly, the CONUS scale net surface radiative forcing error was estimated by applying standard propagation of variance formulae to Equation [11], assuming that the ecoregion area estimates were without error and that the monthly forcing estimates were independent as:

$$\varepsilon_{\Delta F_{CONUS,\ annual}} = \sqrt{\sum_{ecoregion=1}^{45} \left(\left(\frac{a_{ecoregion}}{\sum_{1}^{45} a_{ecoregion}} \right)^{2} \varepsilon^{2}_{\Delta F_{ecoregion,\ annual}} \right)}$$

[15]

where $a_{ecoregion}$ is the ecoregion area (km^2) and $\varepsilon_{\Delta F_{ecoregion,\ annual}}$ is defined by Equation [14].

4.4 Results

4.4.1 LCLU Change from 1973 to 2000

Between 1973 and 2000 all of the 58 ecoregions considered had LCLU change (Figure 4-1). The greatest estimated percentage areal changes occurred in the north-west: 28.7% in the Puget Lowland (ecoregion 2), 25.5% Coast Range (ecoregion 1), and 14.5% Willamette Valley (ecoregion 3), and in the southeast: 24.8% in the Southern Coastal Plain (ecoregion 75) and 20.4% in the Southeastern Plains (ecoregion 65). The smallest estimated percentage areal changes occurred in the Chihuahuan Desert (ecoregion 24) 0.5% and in the Lake Agassiz Plain (ecoregion 48) 1.4%. At the CONUS scale, the dominant LCLU changes were a net areal decrease in agricultural land from 1.652 million km^2 in 1973, to 1.577 million km^2 in 2000, and a net areal increase in developed land from 194.3 thousand km^2 in 1973 to 259.0 thousand km^2 in 2000.

Figure 4-2 illustrates the leading LCLU class transitions by areal change from 1973 to 2000 for the ecoregions considered. The greatest amounts of change were generally in ecoregions with active timber harvesting, while the lowest amounts of change were in ecoregions where urbanization was the leading change. A transition of agriculture to grass/shrub was concentrated in the Great Plains ecoregions and can be attributed primarily to the 1985 Farm Bill that established the Conservation Reserve Program [*Johnson and Maxwell,* 2001]. This voluntary program offered financial incentives for farmers to retire marginal agricultural land to native grasses or trees, usually for ten years in duration. A transition from forest to mechanically disturbed classes occurred primarily in ecoregions of the Pacific Northwest and in the East, which is indicative of the active timber harvesting industries in these ecoregions. All ecoregions experienced significant increases in developed land between 1973 and 2000 [*Loveland and Acevedo,* 2010], but were not the leading LCLU class area transition. The pattern of LCLU change is driven primarily by agricultural abandonment, ex-urban development and by government policy [*Loveland and Acevedo,* 2010]. The purpose of this paper is to quantify the surface albedo radiative forcing impact of these LCLU changes and so the driving forces of LCLU changes are not discussed further.

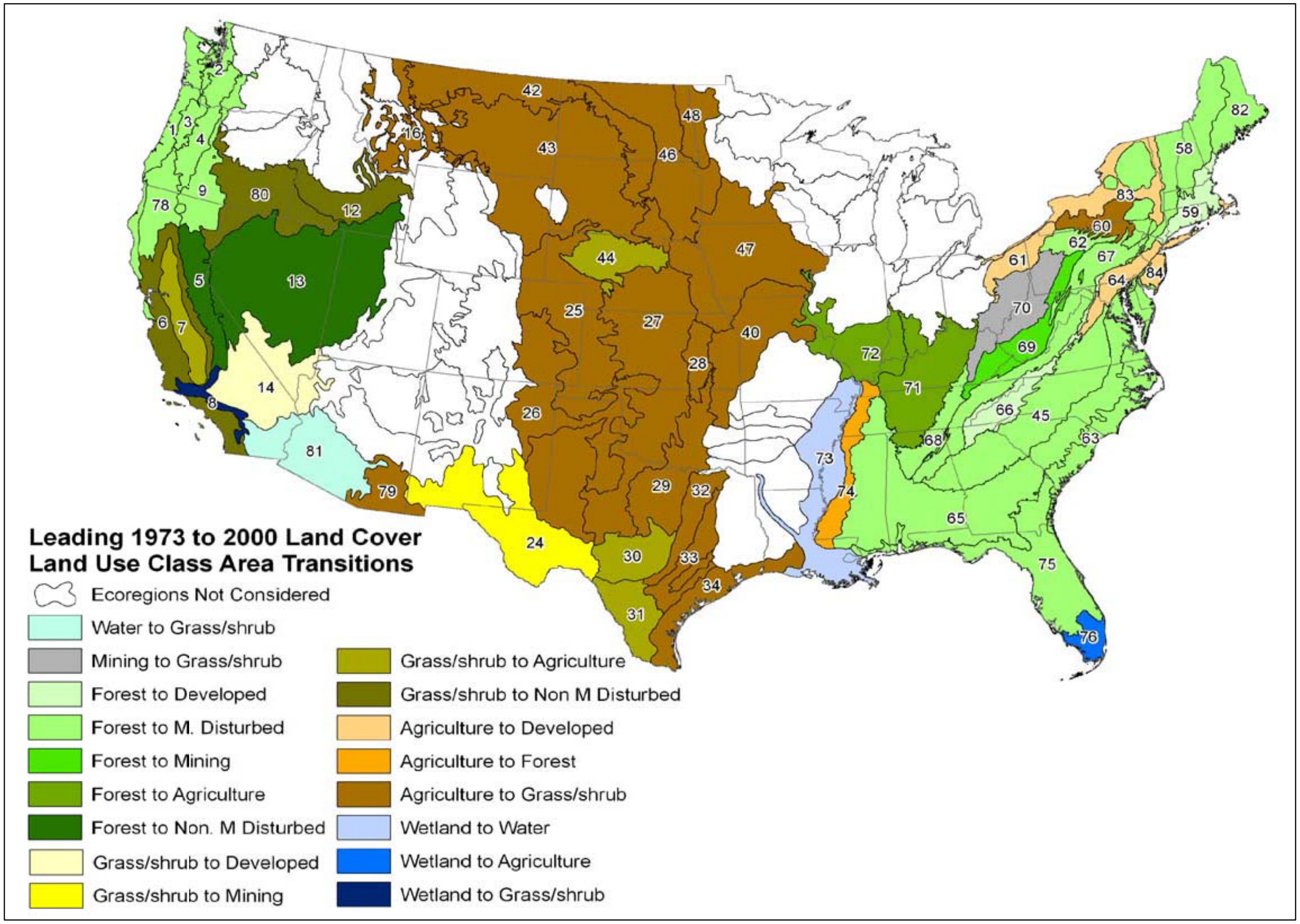

Figure 4-2. Leading 1973 to 2000 class transitions by areal change for the 58 ecoregions considered in this study (numbered).

4.4.2 CONUS MODIS albedo estimates

Table 4-1 summarizes the MODIS broadband white-sky snow and snow-free albedos for the 10 LCLU classes derived from all of the valid CONUS MODIS albedo data. These values are included to help interpret the LCLU class albedos only, they are not used in the forcing analysis.

The snow-free albedo class values summarized in Table 4-1 are comparable to those described by *Jin et al.* [2002] and *Zouh et al.* [2003], and the snow albedos are comparable to those of *Gao et al.* [2005] and *Myhre and Myhre* [2003]. Snow increases least the albedo of the vegetated surfaces with high canopy density and vertical structure (e.g., evergreen forests) and increases most the albedo of surfaces with sparse and/or short vegetation (e.g., barren). The barren and agricultural classes have the highest snow and snow-free albedos, and the water and forest classes have the lowest albedos. The forest class, which includes deciduous and coniferous types, has the smallest difference between snow and snow-free albedo of 0.243 and 0.130 respectively, which is due mainly to snow being hidden underneath the forest. *Betts and Ball* [1997] found similar snow to snow-free albedo differences for boreal forest albedo which they noted seldom exceeds 0.3.

4.4.3 LCLU Albedo Change from 1973 to 2000

The ecoregion annual LCLU induced albedo change from 1973 to 2000 computed as Equation [5] is illustrated in Figure 4-3. *Barnes and Roy* [2008] demonstrated that albedo change associated with LCLU change is dependent on the albedo of the LCLU classes and on the areal extent of the LCLU change. Hence, the ecoregions with the highest areal proportions of LCLU change (Figure 4-1) do not consistently coincide with the ecoregions of highest albedo change (Figure 4-3), and the correlation between these data is low (0.192).

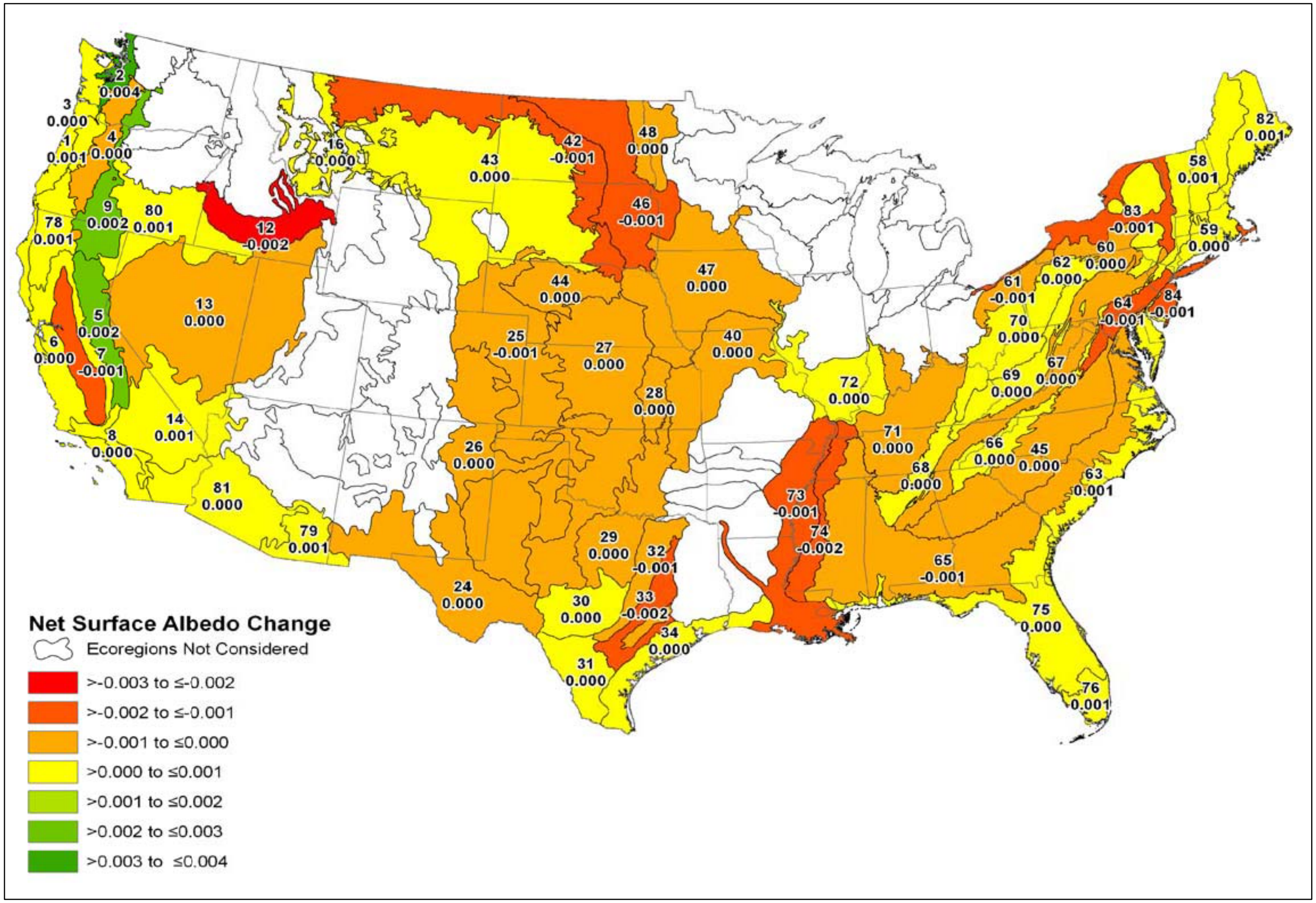

Figure 4-3. The annual surface albedo change due to contemporary land cover land use change from 1973 to 2000 modeling snow conditions, for the 58 ecoregions considered in this study.

Figure 4-4 illustrates the leading LCLU class transitions that resulted in the greatest absolute change in albedo from 1973 to 2000. The leading LCLU class transitions shown in Figure 4-4 do not always coincide with the leading transitions due only to LCLU areal change shown in Figure 4-2. LCLU change between classes with different albedos may have a greater net albedo impact than more areally extensive changes between classes with similar albedos. For example, in the Eastern Great Lakes and Hudson Lowlands (ecoregion 83, mean annual snow fraction 0.18) the primary areal LCLU transition is from agriculture to developed (Figure 4-2), whereas the primary (areal and albedo) transition is from agriculture to forest (Figure 4-4). More than half of the ecoregions in this study had a different leading LCLU transition when areal and albedo were considered compared to considering LCLU areal change only.

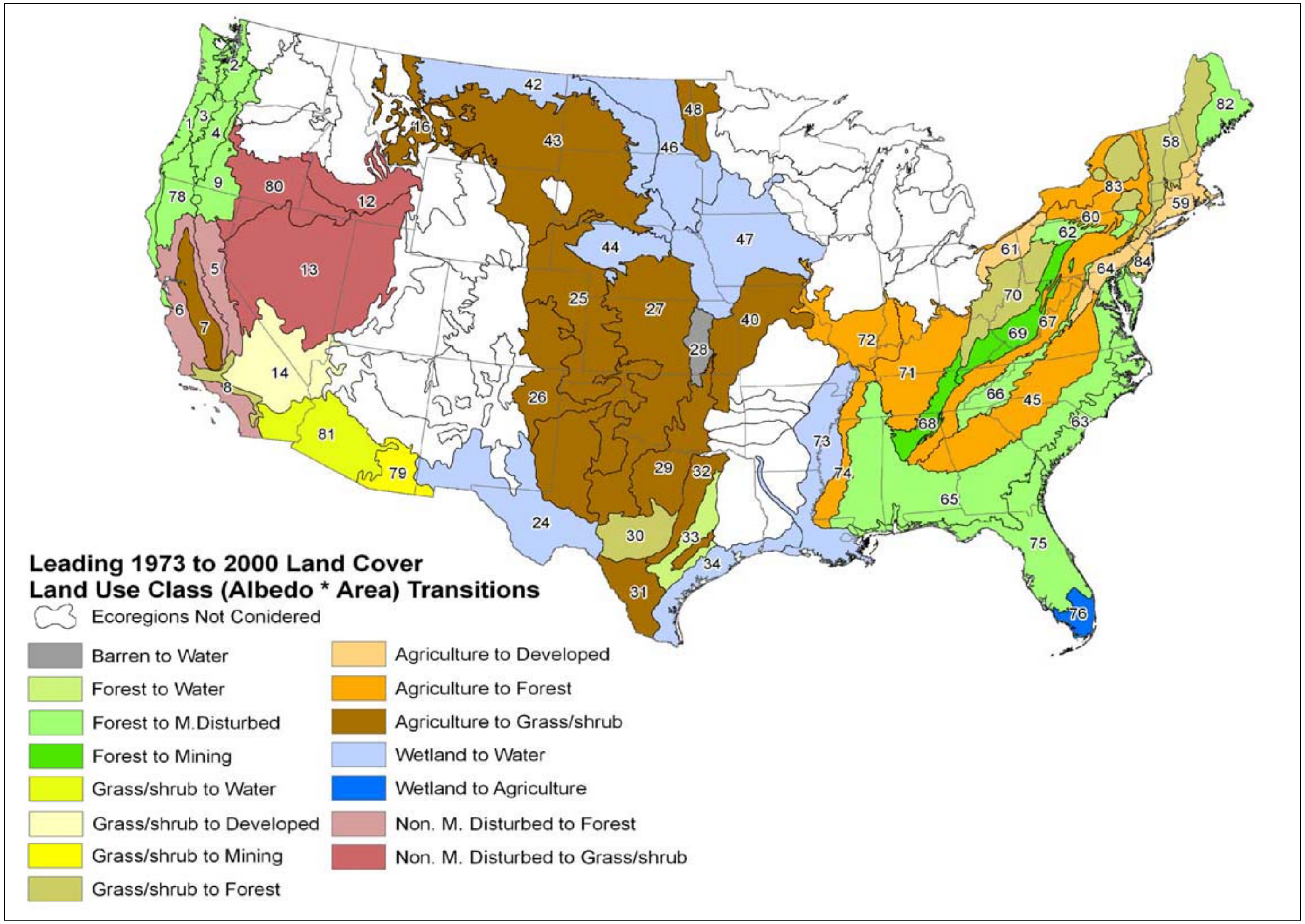

Figure 4-4. Leading land cover land use class transitions due to albedo and areal land cover land use change from 1973 to 2000 modeling snow conditions, for the 58 ecoregions considered in this study.

Figure 4-5 illustrates for the 2000 LCLU class proportions the 12-month average monthly variation in ecoregion albedo due to inter-annual variability [Equation 8]. Only results for 45 of the 58 ecoregions that had sufficient snow-free MODIS albedo data to compute the MAD statistics that capture inter-annual albedo variability are shown. The results for 1973 are not plotted and are very similar to the 2000 results (0.999 correlation over the 45 ecoregions). The minimum, median and maximum inter-annual albedo variability percentages were 1.6%, 2.4% and 4.3% respectively. The maximum occurred in the Northwestern Glaciated Plains (ecoregion 42), which was primarily agriculture (57%) and grass/shrub (37%). The other two maxima occurred in ecoregions 26 (Southwestern Tablelands, inter-annual albedo variability 4.0%) and 24 (Chihuahuan Deserts, inter-annual albedo variability 3.9%), which in 2000 both had a primary LCLU class proportion of grass/shrub (82% and 96% respectively).

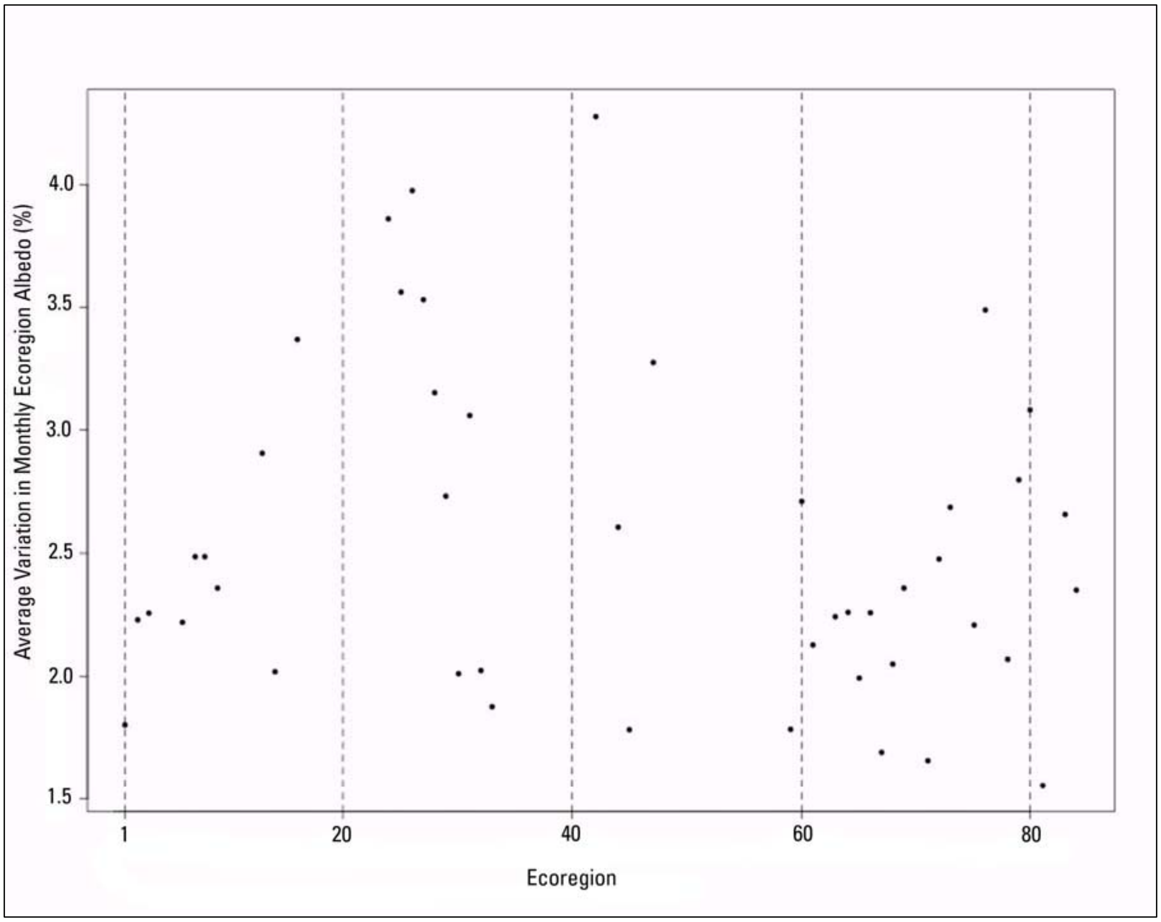

Figure 4-5. Ecoregion percent average monthly variation in ecoregion albedo due to inter-annual albedo variability, defined as Equation [8], for the year 2000 land cover land use class proportions. Only snow-free results for 45 ecoregions where inter-annual variability statistics can be computed are illustrated.

4.4.4 Surface Radiative Forcing due to LCLU Albedo Change from 1973 to 2000

Figure 4-6 illustrates the annual surface radiative forcing due to contemporary LCLU albedo change from 1973 to 2000, for the 58 ecoregions considered in this study, estimated using Equation [10] by taking into consideration the monthly variation of albedo, snow cover and incoming SSRD. The geographic distribution of the annual surface radiative forcing is strongly correlated (-0.956) with the annual 1973 to 2000

LCLU albedo change (Figure 4-3), and only weakly (-0.068) with the annual incoming SSRD.

The geographic distribution of surface radiative forcing cooling or warming illustrated in Figure 4-6 is complex. The most negative surface radiative forcing, i.e., cooling, was -0.367 Wm^{-2} and occurred in the Sierra Nevada (ecoregion 5) due primarily to the transition of non-mechanically disturbed to forest (Figure 4-4). The most positive forcing, i.e. warming, was 0.337 Wm^{-2} in the Snake River Basin (ecoregion 12) due primarily to the conversion of non-mechanically disturbed to grass/shrub. This magnitude of ecoregion forcing is not insignificant, for example, it is greater than the magnitude of global forcing estimates due to LCLU change during the twentieth century [*IPCC,* 2007].

At the CONUS scale we estimate a positive (i.e., warming) net surface radiative forcing of 0.029 Wm^{-2} due to LCLU albedo change from 1973 to 2000 [Equation 11]. This CONUS net surface radiative forcing is greater than our earlier reported result of 0.012 Wm^{-2} [*Barnes and Roy,* 2008], which we attribute to our considering in this study 26% more of the CONUS and because we modeled snow effects, which we demonstrate below is important for certain LCLU transitions and ecoregions.

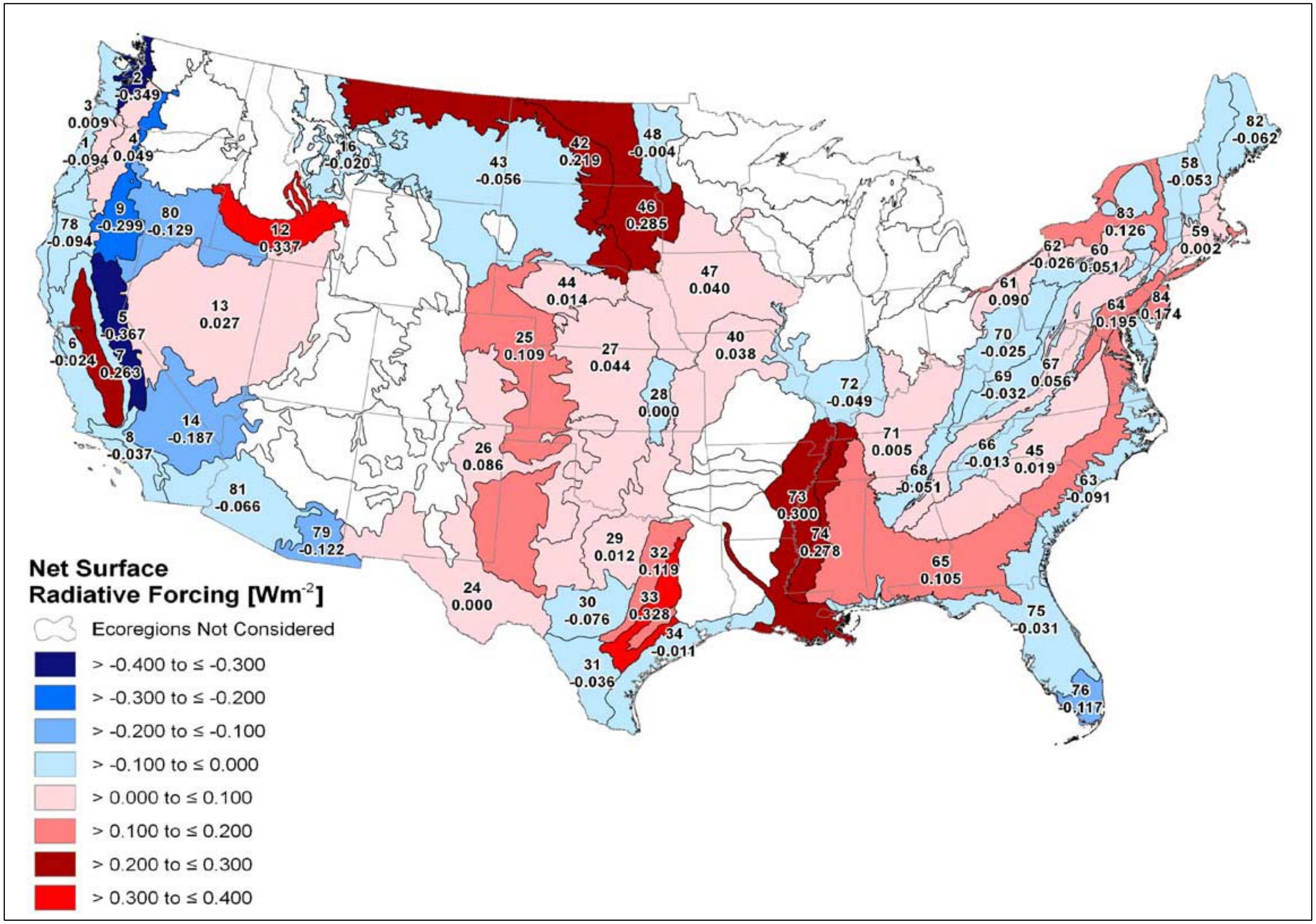

Figure 4-6. The annual surface radiative forcing due to contemporary land cover land use albedo change from 1973 to 2000 modeling snow conditions, for the 58 ecoregions considered in this study.

4.4.5 Snow Sensitivity Analysis of Surface Radiative Forcing due to LCLU Albedo Change from 1973 to 2000

The impact of snow has been shown to be important when LCLU change is between snow hiding and snow revealing classes, such as between forest and grass/shrub or agricultural classes [*Betts,* 2000; *Gao et al.,* 2005; *Gibbard et al.,* 2005; *Wang and Davidson,* 2007]. The mean annual snow fraction for years 2004 to 2008 derived from the MODIS global monthly average snow product is illustrated in Figure 4-7. Of the 58 ecoregions considered, 22 had more than 0.10 mean annual snow fraction. The greatest mean annual snow fraction occurred predominantly in the northern ecoregions, up to 0.30 in the Laurentian Plains and Hills (ecoregion 82) but also in some high altitude ecoregions such as the Cascades (0.27) (ecoregion 4). The southern most ecoregions had mean annual snow fraction <0.10.

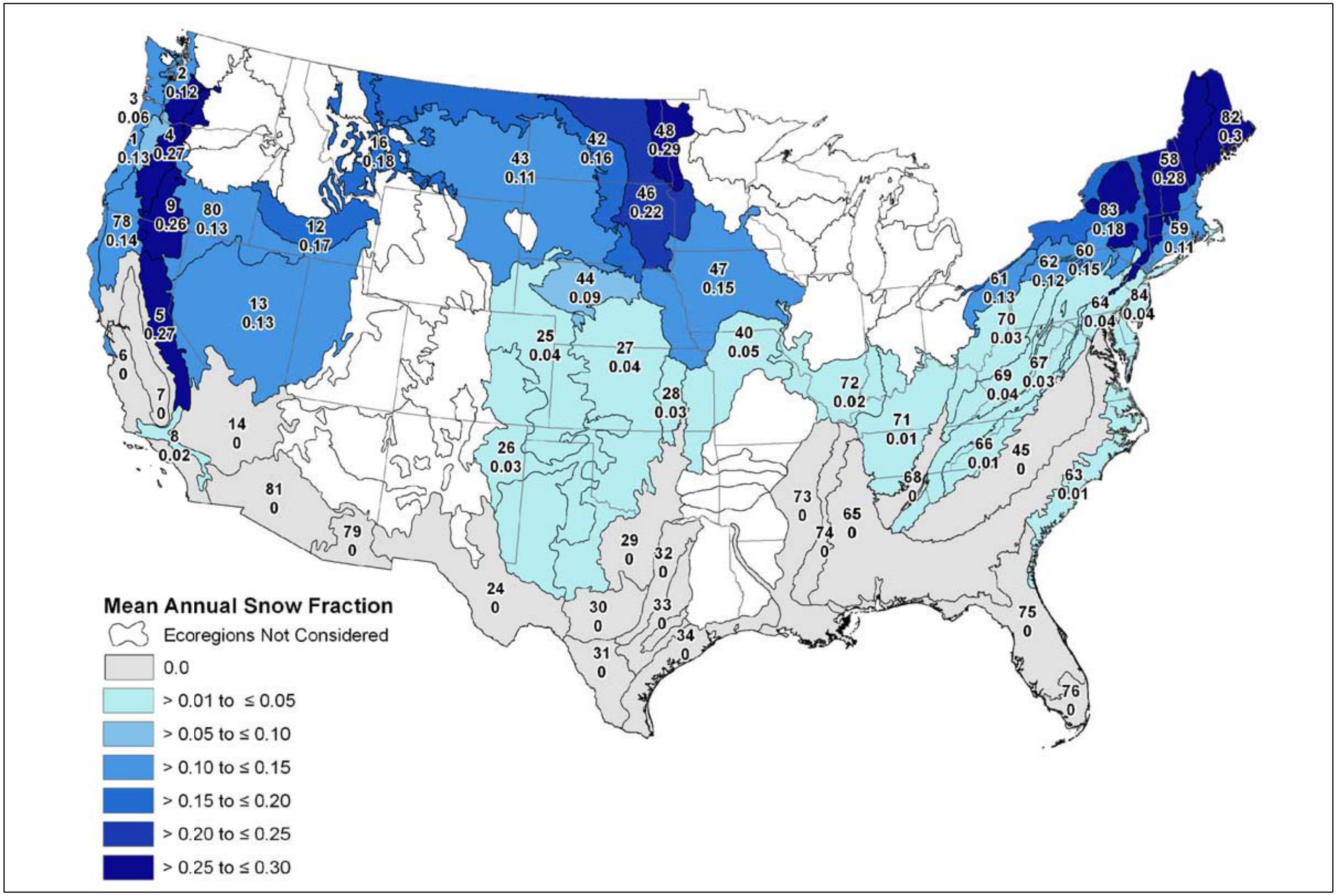

Figure 4-7. The mean annual snow fraction from years 2004 to 2008 derived from the MODIS 0.05° cell global monthly average snow cover product (*Hall et al.,* 2006), for the 58 ecoregions considered in this study (numbered), and their snow fraction.

A scatter plot of the annual surface radiative forcing due to LCLU albedo change, modeling snow and snow-free conditions, for the 58 ecoregions is illustrated in Figure 4-8. The surface radiative forcing modeling snow-free conditions was computed by setting the monthly snow fraction ($f_{snow,\, month,\, ecoregion}$) in Equation [3] to zero. The illustrated sensitivity is determined by the extent of the LCLU change, the snow and snow-free albedos of the LCLU change classes, and the monthly snow fraction. Consequently, ecoregions with low snow fraction had little or no radiative forcing sensitivity (southern ecoregions), and ecoregions with high snow fraction had a greater radiative forcing sensitivity (predominantly northern ecoregions). The annual snow fraction values for ecoregions with snow fractions >0.10 are labeled in Figure 4-8 for visual reference.

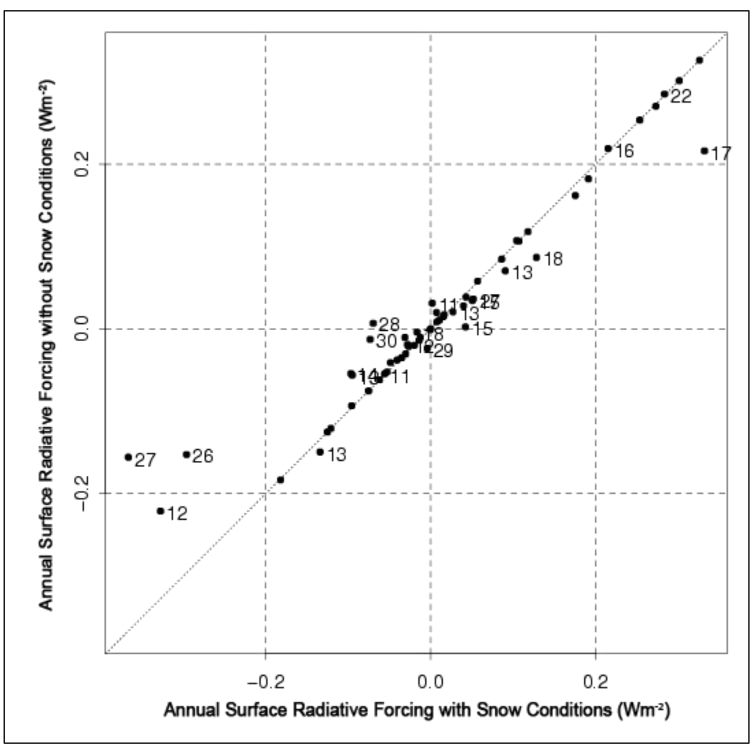

Figure 4-8. Scatter plot of the annual surface radiative forcing modeling snow (x axis) and snow-free (y axis) effects, for the 58 ecoregions considered in this study (black dots); some ecoregions have similar values and so overlap. The mean seasonal snow fraction values for ecoregions with snow fractions >0.10 are labeled (values are shown multiplied by 100 for visual clarity).

Ecoregions 42 (Northwestern Glaciated Plains) and 46 (Northern Glaciated Plains) had high annual snow fractions of 0.16 and 0.22 respectively but had a negligible radiative forcing sensitivity to snow albedo effects (Figure 4-8, points lying close to the 1:1 line, top right). This is because in both these ecoregions the primary LCLU transition was from agriculture to grass/shrub (Figure 4-2) i.e., transitions between snow revealing LCLU classes with similar albedos.

In snow prone ecoregions where LCLU transitions were between snow-hiding and snow-revealing LCLU classes the surface radiative forcing becomes more negative or more positive when snow is modeled (Figure 4-8). The most extreme example of this effect is ecoregion 5 (Sierra Nevada, 0.27 annual snow fraction) that had a surface radiative forcing of -0.367 Wm^{-2} (modeling snow conditions) and -0.160 Wm^{-2} (modeling snow-free conditions). Figure 4-9 shows the monthly surface radiative forcing, albedo change, SSRD and snow fraction values for ecoregion 5. The seasonal variation of these values is very evident. During the winter months (December, January, February, March) the monthly snow fraction is between 0.57 to 0.73. When snow is modeled (black circles) the winter monthly albedo change and surface radiative forcing estimates are significantly higher and lower respectively than the snow-free (white circles) estimates. This is because for this ecoregion the primary LCLU transition is from forest to non-mechanically disturbed, i.e., snow-hiding to snow-revealing classes.

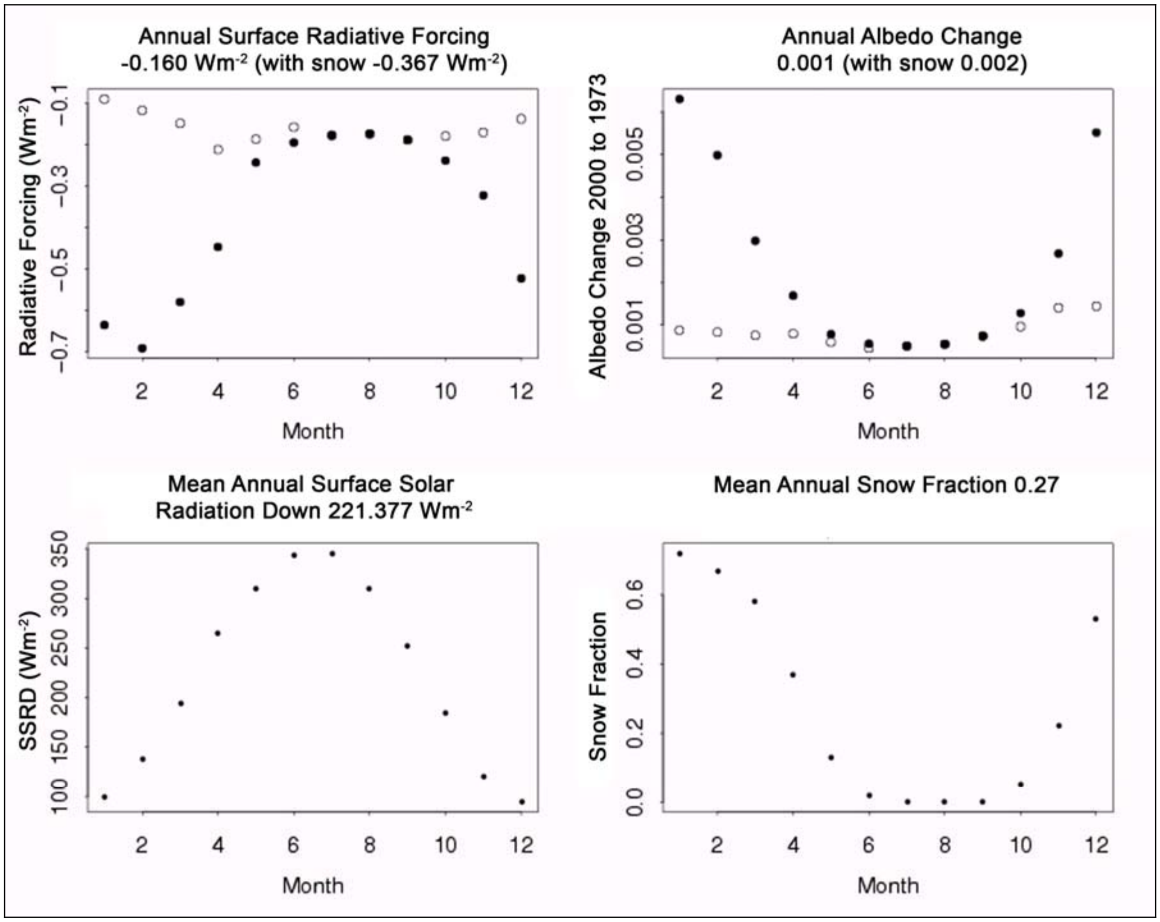

Figure 4-9. Ecoregion 5 (Sierra Nevada) monthly variability in surface radiative forcing, 1973 to 2000 LCLU albedo change, surface solar radiation and snow fraction. The monthly surface radiative forcing and albedo change estimates modeling snow (black circles) and snow-free (white circles) conditions are shown.

At the CONUS level, failure to model snow albedo conditions results in an over-estimation in the net CONUS surface radiative forcing. We estimated a net CONUS surface radiative forcing of 0.029 Wm^{-2} due to LCLU albedo change from 1973 to 2000 when snow is modeled (*see section 4.4.4*) and 0.031 Wm^{-2} when snow is not modeled.

4.4.6 Radiative Forcing Sensitivity Analysis to Inter-Annual Variability

Figure 4-10 illustrates the annual surface radiative forcing due to contemporary LCLU albedo change for each ecoregion (black circles) and the associated forcing error (vertical error bar lines) defined by Equations [10] and [14] respectively. These values are based on median and MAD albedo estimates respectively; the errors are expected to describe 50% of the surface radiative forcing variability around the annual estimates. Only snow-free forcing results for 45 of the 58 ecoregions considered in this study are illustrated.

The annual surface radiative forcing error estimates are a function of the magnitude of the incoming SSRD and the inter-annual monthly class albedo variability [Equation 14]. They are correlated with the incoming SSRD (0.591) and with the estimates of the 12 month average monthly variation in ecoregion albedo due to inter-annual variability 0.753 ($v_{ecoregion,\ 1973}$) and 0.753 ($v_{ecoregion,\ 2000}$). The minimum error (0.138 Wm^{-2}) occurred in the Northeastern Coastal Zone (ecoregion 59) because of a combination of relatively low incoming SSRD found at higher latitudes (ecoregion 59 has a 168.238 Wm^{-2} mean annual SSRD) and low inter-annual monthly class albedo variability (1.8% for $v_{ecoregion,\ 1973}$ and $v_{ecoregion,\ 2000}$). The maximum annual surface radiative forcing error (0.842 Wm^{-2}) occurred in the Chihuahuan Deserts (ecoregion 24) and was driven by the high incoming SSRD (this ecoregion has the fifth highest mean annual SSRD of 237.920 Wm^{-2}) and high inter-annual monthly class albedo variability (3.9% for $v_{ecoregion,\ 1973}$ and $v_{ecoregion,\ 2000}$) that is perhaps associated with variable vegetation response to rainfall in the near desert conditions. For all but two of the 45 ecoregions the vertical error bar lines intersect the zero surface radiative forcing horizontal line. Only ecoregion 2 (Puget Lowland) and ecoregion 33 (East Central Texas Plains) have unambiguous cooling and forcing estimates respectively. Evidently the ecoregion annual surface radiative forcing estimates are highly sensitive to inter-annual albedo variability.

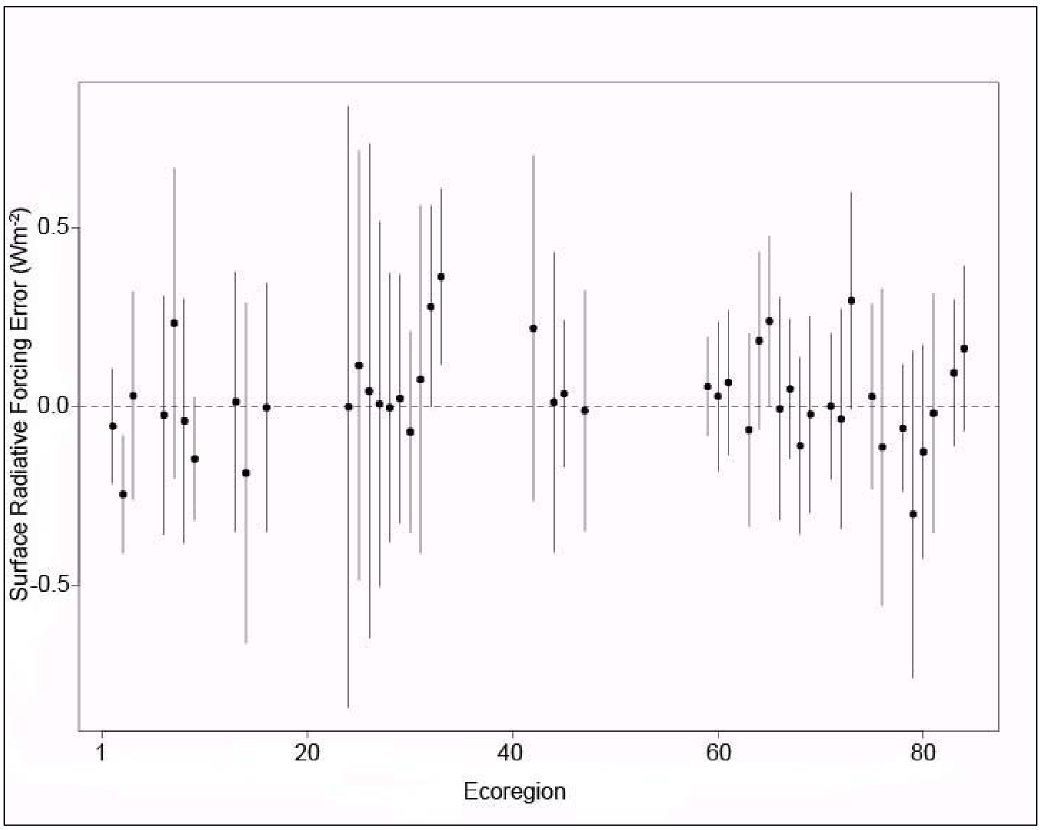

Figure 4-10. Ecoregion snow-free annual surface radiative forcing due to contemporary land cover land use albedo change from 1973 to 2000 (black circles) [Equation 10] ± the annual surface radiative forcing error imposed by inter-annual albedo variability (vertical lines) [Equation 14]. Only snow-free forcing results for 45 of the 58 ecoregions considered in this study are illustrated.

At the CONUS scale for the 45 ecoregions we estimate a snow-free net surface radiative forcing of 0.043 Wm^{-2} due to LCLU albedo change from 1973 to 2000 [Equation 11] with an error of 0.084 Wm^{-2} [Equation 15]. This net surface radiative forcing error is very high and illustrates the ecoregion annual surface radiative forcing estimates are very sensitive to inter-annual albedo variability.

4.5 Conclusions

The monthly variation of albedo, snow cover and incoming surface solar radiation were used to: (*i*) quantify the surface radiative forcing due to contemporary (1973 to 2000) LCLU albedo change for 69% of the CONUS, (*ii*) analyze the impact of modeling snow conditions on surface radiative forcing and, (*iii*) to determine the sensitivity of surface radiative forcing to inter-annual albedo variation.

Across the CONUS, agricultural land use has been in decline [*Drummond and Loveland,* 2010] and the rates of forest harvesting [*Pinder et al.,* 1999] and exurban sprawl have been accelerating [*Brown et al.,* 2005; *Steyaert and Knox,* 2008]. For the 58 CONUS ecoregions considered, the dominant contemporary LCLU changes from 1973 to 2000 documented by the USGS Land Cover Trends Project data were a net areal decrease in agricultural land (-1.3%) and forest (-0.9%) and a net increase in developed (1.2%) and grass/shrub (0.7%). The most extensive LCLU changes occurred in the Pacific Northwest (>25%) and in the Southeast (>20%) and the least (<1%) in the desert southwest.

Nine years of MODIS albedo data were used to extract, for each ecoregion and month, the median broadband white-sky snow and snow-free albedos for each of ten

LCLU classes defined by the USGS Land Cover Trends data set. The snow and snow-free albedo class values were broadly comparable to other worker's results [*Jin et al.,* 2002; *Gao et al.,* 2005]. The median monthly LCLU class albedos were used to compute ecoregion specific albedo estimates independently for years 1973 and 2000.

It is established that snow has a significant land cover dependent albedo and radiative forcing effect [*Betts,* 2000]. In this study, approximately two thirds of the 58 CONUS ecoregions had significant mean annual snow cover. However, the net CONUS surface radiative forcing only changed by 0.003 Wm^{-2} when snow and snow-free conditions were modeled over the 58 ecoregions. The extent of the LCLU change, the snow and snow-free albedos of the LCLU change classes, and the monthly snow fraction determined the surface radiative forcing. In snow prone ecoregions where the dominant LCLU transitions were between snow-hiding and snow-revealing LCLU classes both the negative and positive ecoregion forcings were amplified. This snow/ snow-free difference was most significant in the Sierra Nevada ecoregion where the surface radiative forcing modeling snow conditions was 0.207 Wm^{-2} more negative than when snow was not modeled, due to high winter monthly snow fractions (between 0.57 to 0.73) and a primary 1973 to 2000 LCLU transition from forest (snow-hiding) to non-mechanically disturbed (snow-revealing) classes.

The monthly inter-annual albedo variability over 9 years of MODIS data was used to examine the sensitivity of the contemporary LCLU albedo change radiative forcing estimates. Only the inter-annual variability for 45 of the 58 ecoregions with sufficient snow-free MODIS albedo observations to compute the MAD statistic were quantified.

The ecoregion percent average monthly variation in snow-free albedo ranged from 1.6% to 4.3% across the 45 ecoregions. This inter-annual albedo variability and the magnitude of the incoming surface solar radiation determined the ecoregion surface radiative forcing errors, which were large, from 0.138 Wm^{-2} to 0.842 Wm^{-2}. For the 45 ecoregions considered, a CONUS snow-free net surface radiative forcing of 0.044 Wm^{-2} with a relatively large error of 0.084 Wm^{-2} was estimated.

At the CONUS scale, for the 58 ecoregions considered, we estimated a net positive (i.e., warming) surface radiative forcing of 0.029 Wm^{-2} due to contemporary LCLU albedo change. Similarly, a recent study on the impact of CONUS LCLU change on surface temperature indicated that LCLU changes often resulted in more warming than cooling [*Fall et al.,* 2009]. The surface radiative forcing varied in sign and magnitude among the 58 ecoregions, with the transition to forest causing the most negative forcing (-0.367 Wm^{-2}), and the conversion to grass/shrub causing the most positive forcing (0.337 Wm^{-2}). This magnitude of ecoregion scale forcing is similar to global LCLU change forcing estimates for the twentieth century [*IPCC*, 2007]. The surface radiative forcing of 0.029 Wm^{-2} is greater than our earlier 0.012 Wm^{-2} reported estimate [*Barnes and Roy,* 2008] as 26% more area of the CONUS was considered and because we modeled snow conditions.

The research reported in this paper underscores the value of spatially and temporally explicit data to quantify, and begin to understand, LCLU albedo change related surface radiative forcing. However, our analysis illustrates, as observed by previous studies [*Pielke et al., 2002*; *National Research Council,* 2005; *IPCC,* 2007], that the radiative forcing of LCLU albedo change remains uncertain. The need to improve and accurately represent LCLU and other surface characteristics including albedo is clear. The MODIS satellite derived albedo product used in this study is a significant improvement on previous model and scenario based albedo estimates [*Betts,* 2000; *Roesch et al.,* 2002] but there is potential for improved spatially and temporally explicit albedo by calibration with land surface model outputs [*Matsui et al.,* 2007]. Improved continental incoming solar radiation data may also provide more reliable forcing estimates. For example, the North American Regional Reanalysis data set was recently reprocessed [*Mesinger et al.,* 2006] and is defined with 32 km grid cells that will capture spatial variability in incoming solar radiation more precisely than the ERA-40 data used in this study. Further research will be undertaken building on these new data sets and using a greater number of CONUS ecoregion LCLU data sets as they become available from the USGS Land Cover Trends Project.

4.6 References

Allan, R. P., M. A. Ringer, J. A. Pamment, A. Slingo (2004), Simulation of the Earth's radiation budget by the European Centre for Medium- Range Weather Forecasts 40-year reanalysis (ERA40), *Geophys. Res. Lett.*,109, D18107,doi:10.1029/2004JD004816.

Barnes, C. A., and D. P. Roy (2008), Radiative forcing over the conterminous United States due to contemporary land cover land use albedo change, *Geophys. Res. Lett.*, 35, L09706, doi:10.1029/2008GL033567.

Betts, R. A. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature*, 408, 187–190.

Betts, A.K., and J.H. Ball (1997), Albedo over the boreal forest, *J. Geophys. Res*. 102, 28,901-28,909.

Brown, D. G., K. M. Johnson, T. R. Loveland, and D. M. Theobald (2005), Rural land use trends in the conterminous United States, 1950– 2000, Ecol. Appl., 15, 1851– 1863.

Dickinson, R. E (1995), Land processes in climate models, *Remote Sens. Environ*., 51, 27–38.

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

Fall, S., D. Niyogi, A. Gluhovsky, R. A. Pielke Sr., E. Kalnay, and G. Rochon (2009), Impacts of land use land cover on temperature trends over the continental United States: Assessment using the North American Regional Reanalysis. *Int. J. Climatol.,* DOI: 10.1002/joc.1996.

Gao, F., C. B. Schaaf, A. H. Strahler, A. Roesch, W. Lucht, and R. Dickinson (2005), MODIS bidirectional reflectance distribution function and albedo Climate Modeling Grid products and the variability of albedo for major global vegetation types, *J. Geophys. Res*., 110, D01104, doi:10.1029/2004JD005190.

Gibbard, S., K. Caldeira, G. Bala, T. J. Philips, and M. Wickett (2005), Climate effects of global land cover change, *Geophys. Res. Lett*., 32, L23705, doi:10.1029/2005GL024550.

Hall, D. K., G.A. Riggs, and V.V. Salomonson (2006), updated monthly. MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG V005, [Dates used; January 2004 to December 2008]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Hall, D.K. and G.A. Riggs (2007) Accuracy assessment of the MODIS snow-cover products, *Hydrol Process*, 21(12):1534-1547, DOI: 10.1002/hyp.6715.

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*, edited by S. Solomon *et al.,* 996pp., Cambridge Univ. Press, New York.

Jin, Y., C. B. Schaaf, F. Gao, X. Li, A. H. Strahler, X. Zeng, and R. E. Dickinson (2002), How does snow impact the albedo of vegetated land surfaces as analyzed with MODIS data?, *Geophys. Res. Lett.*, 29(10), 1374, doi:10.1029/2001GL014132.

Jin, Y. and D.P. Roy (2005), Fire-induced albedo change and its radiative forcing at the surface in northern Australia, *Geophys. Res. Let.,* 32, L13401, doi:10.1029/2005GL022822

Johnson, J. and B. Maxwell (2001), The role of the Conservation Reserve Program in controlling rural residential development*. J. Rural Stud.,* 17, 323-332.

Kleidon, A (2006), The climate sensitivity to human appropriation of vegetation productivity and its thermodynamic characterization, *Global Planet. Change,* 54: 109–127.

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

Loveland, T. R., and W. Acevedo (2010), Land cover change in the Eastern United States. In *Status and Trends of Eastern United States Land Cover*, ed. W. Acevedo and P. J. Jellison. U.S. Geological Survey Professional Paper, in press.

Matsui, T., A. Beltran-Przekurat, R.A. Pielke Sr., D. Niyogi, and M. Coughenour (2007), Continental-scale multi-objective calibration and assessment of Colorado State University Unified Land Model. Part I: Surface albedo. *J. Geophys. Res,* 112, G02028, doi:10.1029/2006JG000229.

Mesinger F., G., Di Mego, E., Kalnay, K., Mitchell, P.C., Shafran, W., Ebisuzaki, D., Jovic, J., Woollen, E., Rogers, E.H., Berbery, M.B., Ek, Y., Fan, R., Grumbine, W., Higgins, H., Li, Y., Lin, G., Manikin, D., Parrish, W., Shi (2006), North American regional reanalysis: A long-term, consistent, high-resolution climate dataset for the North American domain, as a major improvement upon the earlier global reanalysis datasets in both resolution and accuracy. *B. Am. Meteorol. Soc.* 87: 343–360.

Myhre, G. and A. Myhre (2003), Uncertainties in radiative forcing due to surface albedo changes caused by land-use changes. *Am. Meteoro. Soc.*, 16. 1511-1524.

Nair, U.S., D.K. Ray, J. Wang, S.A Christopher, T. Lyons, R.M. Welch, and R.A. Pielke Sr. (2007), Observational estimates of radiative forcing due to land use change in southwest Australia. *J. Geophys. Res.,* 112, D09117, doi:10.1029/2006JD007505.

National Research Council (2005), *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, 207pp., Natl., Acad., Washington, D.C. Omernik, J.M (1987), Ecoregions of the conterminous United States, *Ann. Assoc. Am. Geogr*., 77:118-125.

Pielke, R.A., G., Marland, R.A., Betts, T.N., Chase, J.L., Eastman, J.O., Niles, D.S., Niyogi, and S.W. Running (2002), The influence of land-use change and landscape dynamics on the climate system - relevance to climate change policy beyond the radioactive effect of greenhouse gases, *Phil. Trans. R. Soc. Lond. A.,* 360: 1705–1719.

Pinder, J.E. III., T.E. Rea, and D.E. Funsch (1999), Deforestation, reforestation and forest fragmentation on the upper coastal plain of South Carolina and Georgia. *American Midland Naturalist,* 142: 213–228.

Pitman, A. J., N. de Noblet-Ducoudré, F.T. Cruz, E. L. Davin, G. B. Bonan, V. Brovkin, M. Claussen, C. Delire, L. Ganzeveld, V. Gayler, B. J. J. M. van den Hurk, P. J. Lawrence, M. K. van der Molen, C. Műller, C. H. Reick, S. I. Seneviratne, B. J. Strengers, and A. Voldoire (2009), Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study, *Geophys. Res. Lett.,* 36, L14814, doi:10.1029/2009GL039076.

Ramankutty, N., and J.A. Foley (1999), Estimating historical changes in global landcover: croplands from 1700 to 1992, *Global Biogeochem. Cycles*, 14: 997–1027.

Roesch, A., M. Wild, R. Pinker, and A. Ohmura (2002), Comparison of spectral surface albedos and their impact on the general circulation model simulated surface climate, *J. Geophys. Res.,* 107(D14), 4221, doi:10.1029/2001JD000809.

Román, M. O., C. B. Schaaf, P. Lewis, F. Gao, G. P. Anderson, J. L. Privette, A. H. Strahler, C. E. Woodcock, and M. Barnsley (2009), The MODIS (Collection V005) BRDF/albedo product: Assessment of spatial representativeness over forested landscapes, *Remote Sens. Environ.*, 113, 2476-2498.

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

Schaaf, C. L., J. Martonchik, B. Pinty, Y. Govaerts, F. Gao, A. Lattanzio, J. Liu, A. H. Strahler, and M. Taberner (2008), Retrieval of Surface Albedo from Satellite Sensors, in *Advances in Land Remote Sensing: System, Modeling, Inversion and Application*, S. Liang, Ed., Springer, ISBN 978-1-4020-6449-4, page 219-243.

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

Stehman, S.V., T.L. Sohl, and T.R. Loveland (2005), An evaluation of sampling strategies to improve precision of estimates of gross change in land use and land cover, *Int. J. Remote. Sens.*, *26*, 4941-4957.

Steyaert, L.T., and R.G. Knox (2008), Reconstructed historical land cover and biophysical parameters for studies of land-atmosphere interactions within the eastern United States*, J. Geophys. Res.,* 113, D02101, doi:10.1029/2006JD008277.

Uppala, S. M., P. W. KÅllberg, A. J. Simmons, U. Andrae, V. Da Costa Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L. Van De Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hólm, B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. Mcnally, J. F. Mahfouf, J. J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Sterl, K. E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, J. Woollen (2005), ERA-40 re-analysis, *Quart. J. R. Meteorol. Soc.,* 131, 2961-3012.doi:10.1256/qj.04.176.

Wang, Z., X. Zeng, M. Barlage, R. E. Dickinson, F. Gao, and C. Schaaf (2004), Using MODIS BRDF and Albedo Data to Evaluate Global Model Land Surface Albedo, *J. Hydrometeorl*., 5, 3-14.

Wang, S., and A. Davidson (2007), Impact of climate variations on surface albedo of a temperate grassland, *Agr Forest Meterol*, 142, 133-142.

CHAPTER 5

PROJECTED SURFACE RADIATIVE FORCING DUE TO 2000 TO 2050 LAND COVER LAND USE ALBEDO CHANGE OVER THE EASTERN UNITED STATES

Barnes, C.A., Roy, D.P., and Loveland, T.R. *Environmental Research Letters,* Submitted November 4th 2010, (Journal impact factor: 3.342).

This chapter describes the research undertaken to address research hypotheses:

***#3** that current rates of LCLU change imply future net albedo increases and associated albedo-related cooling effects, and,*

***#4** large regional disparities in LCLU change will modify the outcome of hypotheses **#3** at the regional scale.*

5.1 Abstract

Satellite derived contemporary land cover land use (LCLU) and albedo data and projected spatially explicit future LCLU data derived by the FOREcasting SCEnarios (FORE-SCE) model 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. A projected net positive forcing (i.e., warming) of 0.112 Wm^{-2} is estimated associated with decreasing agricultural and forested land (by 2.5 and 2.1 percent respectively) and increasing developed land (4.4 percent). This overall forcing is almost four times greater than the forcing estimated for 1973 to 2000 LCLU albedo change estimated in a previous study using the same methods. There is considerable geographic variability in results, with individual ecoregion forcings ranging from -0.175 Wm^{-2} to 0.432 Wm^{-2} driven predominately by differences in the area and type of projected LCLU change across the Eastern U.S. (Figure 5.1).

5.2 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 as -0.25 Wm^{-2} [*IPCC*, 2007]. However, the level of scientific understanding associated with this forcing estimate is 'low to medium', and reflects the complexity and uncertainty of land surface atmospheric interaction parameterization in surface and climate models [*Matsui et al.,* 2007; *Nair et al.,* 2007; *Pitman et al.,* 2009].

Although extensive modeling studies on past LCLU change and its impacts on climate have been undertaken [*Pielke et al.,* 2002; *Kalnay and Cai,* 2003; *Feddema et al.,* 2005; *Nuñez et al.,* 2008], there is a need to consider future LCLU to examine potential impacts on water quality, biodiversity, carbon balances, and climate [*Loveland et al.,* 2003]. Modeling future LCLU is complex and scenarios are used to provide plausible descriptions of what could happen on the landscape as a result of different factors including socioeconomic, technological, environmental and climatic changes [*Moss et al.,* 2010].

Recent research has used a spatially explicit modeling framework to produce scenario-based, thematic LCLU maps in annual time steps to 2050 in the Eastern United States (U.S.) [*Sohl et al.,* 2007; *Sohl and Sayler,* 2008] driven by changes associated with urban development, agricultural decline, and timber harvesting [*Nowak et al.,* 2005; *White et al.,* 2009]. In this letter the surface radiative forcing of the projected 2000 to 2050 LCLU albedo change is quantified for the Eastern U.S.

5.3 Data and Methods

The United States Geological Survey (USGS) Land Cover Trends project is analyzing LCLU change across the conterminous United States (CONUS) using a historical archive of 1973 to 2000 Landsat data [*Loveland et al.,* 2002; *Drummond and Loveland,* 2010]. The Landsat data are classified by visual interpretation, inspection of aerial photography and ground survey into ten classes: water, developed, mechanically disturbed, mining, barren, forest, grass/ shrub, agriculture, wetland, and naturally disturbed. The data are located using a stratified random sampling methodology defined with respect to 84 contiguous ecoregions [*Omernik,* 1987] where each ecoregion includes 9 to 48 Landsat 10 km^2 or 20 km^2 classified spatial subsets that are used to quantify the ecoregion LCLU change [*Stehman et al.,* 2005]. 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 FOREcasting SCEnarios (FORE-SCE) model which uses a spatially explicit modeling framework to produce scenario-based, 250 m LCLU maps [*Sohl and Sayler*, 2008]. The Eastern U.S. scenario models the likely decreasing distribution of forest and agricultural land and increasing urban development [*Nowak et al.,* 2005; *Sohl and Sayler*, 2008; *White et al.,* 2009]. Prescriptions for future LCLU classes are provided by ecoregion-based contemporary (1973 to 2000) LCLU change variables derived from the USGS Land Cover Trends 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 by 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 given by *Sohl and Sayler* [2008].

At the time of writing, 19 of the 84 CONUS ecoregions have both contemporary 2000 and FORE-SCE 2050 projected LCLU information generated, and these are used in this study. The 19 ecoregions vary in area from 15,917 km^2 (Atlantic Coastal Pine

Barrens, ecoregion 84) to 335,482 km^2 (Southeastern Plains, ecoregion 65), and encompass approximately 1.5 million km^2 of the Eastern U.S. (Figure 5-1).

Nine years (February 18th 2000 to March 31st 2009) of MODerate Resolution Imaging Spectroradiometer (MODIS) Collection 5 BRDF/Albedo 16-day 500 meter product [*Schaaf et al.,* 2002] were used to compute for each of the 19 ecoregions the median monthly broadband white-sky snow and snow-free albedos for each of the ten LCLU classes following the approach described by *Barnes and Roy* [2010]. The MODIS Collection 5 Global Monthly Average Snow Cover product [*Hall et al.,* 2007] from January 2004 to December 2008 was used to determine the ecoregion mean monthly fractional snow cover (0-1).

Monthly incoming surface solar radiation downwards (SSRD) were obtained and processed from the European Center for Medium Range Weather Forecasts 40 year Reanalysis (ERA-40) data set [*Allan et al.,* 2004]. Data from January 1973 to December 2000 were used to derive mean monthly SSRD climatology (Wm^{-2}) for each ecoregion.

The ecoregion monthly LCLU class albedos were computed, following *Roesch et al.* [2002], as:

$$\alpha_{i,\ ecoregion,\ month} = \left(1 - f_{\ snow,\ month,\ ecoregion}\right).\overline{\alpha}_{\ i,\ ecoregion,\ month,\ snowfree} + f_{snow,\ month,\ ecoregion}.\overline{\alpha}_{\ i,\ ecoregion,\ month,\ snow} \qquad [1]$$

where $\alpha_{i,\,ecoregion,\,month}$ is the monthly albedo for LCLU class *i*, $\overline{\alpha}_{i,\,ecoregion,\,month,\,snow}$ and $\overline{\alpha}_{i,\,ecoregion,\,month,\,snowfree}$ are the median snow and snow-free monthly albedos for LCLU class *i* respectively, and $f_{snow,\,month,\,ecoregion}$ is the ecoregion monthly MODIS snow fraction (0-1).

Monthly albedo estimates for each ecoregion were computed independently for the LCLU class areal proportions in 2000 and 2050 following *Barnes and Roy* [2008, 2010], as:

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

[2]

where, *year* is 2000 or 2050, and for each LCLU class *i*, $p_{i,\,ecoregion,\,year}$ 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 $\alpha_{i,ecoregion,\,month}$ is defined as Equation [1]. To help interpret our results the annual LCLU induced albedo change from 2000 to 2050 was derived [*Barnes and Roy,* 2008], as:

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

[3]

where $\alpha_{ecoregion,\, month,\, year}$ is defined as Equation [2].

The monthly surface radiative forcing (Wm^{-2}) for each ecoregion due to LCLU albedo change from 2000 to 2050 was estimated following *Jin and Roy* [2005] as:

$$\Delta F_{ecoregion,\, month} = \bar{I}^{\downarrow}_{ecoregion,\, month} \cdot \left(\alpha_{ecoregion,\, month,\, 2050} - \alpha_{ecoregion,\, month,\, 2000}\right) \quad [4]$$

where $-\bar{I}^{\downarrow}_{ecoregion,\, month}$ is the ecoregion mean monthly incoming surface solar radiation downwards climatology (Wm^{-2}), and $\alpha_{ecoregion,\, month,\, 2050}$ and $\alpha_{ecoregion,\, month,\, 2000}$ are the monthly ecoregion albedos for 2050 and 2000 respectively defined as Equation [2]. The annual surface radiative forcing in each ecoregion, due to projected LCLU albedo change, was estimated as the mean of the 12 monthly forcings computed in Equation [4].

5.4 Results

For the 19 Eastern U.S. ecoregions considered, 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 5-1 summarizes these changes, and other parameters used in this study, for the 19 ecoregions.

Ecoregion Number	Annual Surface Radiative Forcing Modeling Snow (Wm^{-2})	Annual Surface Radiative Forcing Assuming No Snow (Wm^{-2})	Mean Annual Monthly SSRD (Wm^{-2})	Mean Annual Snow Fraction	2000 to 2050 LCLU Change (%)	Annual Surface Albedo Change (α_{2050}-α_{2000})	Leading 2000 to 2050 LCLU Class Transition by Area Only	Leading 2000 to 2050 LCLU Transition by Albedo and Areal Change
Ecoregion 64	**0.423**	**0.409**	**177**	**0.037**	**14.0**	**-0.0025**	**Agriculture to Developed**	**Agriculture to Developed**
Ecoregion 65	**0.300**	**0.298**	**195**	**0.002**	**15.0**	**-0.0015**	**Agriculture to Forest**	**Agriculture to Forest**
Ecoregion 74	**0.258**	**0.256**	**194**	**0.002**	**14.0**	**-0.0013**	**Agriculture to Developed**	**Agriculture to Forest**
Ecoregion 76	0.256	0.256	202	0.000	3.0	-0.0012	Agriculture to Developed	Wetland to Agriculture
Ecoregion 83	0.222	0.164	157	0.181	8.0	-0.0017	Agriculture to Developed	Agriculture to Developed
Ecoregion 84	0.196	0.188	180	0.040	9.0	-0.0011	Forest to Developed	Agriculture to Developed
Ecoregion 67	0.092	0.086	176	0.033	9.0	-0.0005	Agriculture to Forest	Agriculture to Forest
Ecoregion 45	0.090	0.093	188	0.003	16.0	-0.0003	Forest to Developed	Agriculture to Forest
Ecoregion 70	0.084	0.077	169	0.030	5.0	-0.0005	Agriculture to Forest	Agriculture to Forest
Ecoregion 60	0.077	0.051	160	0.150	3.0	-0.0006	Agriculture to Forest	Agriculture to Forest
Ecoregion 63	0.077	0.078	191	0.008	11.0	-0.0004	Forest to Developed	Agriculture to Forest
Ecoregion 68	0.057	0.058	184	0.001	10.0	-0.0002	Forest to Mining	Forest to Mining
Ecoregion 58	0.030	0.033	155	0.284	5.0	-0.0001	Forest to M. Disturbed	Forest to Developed
Ecoregion 69	0.003	0.016	172	0.037	7.0	0.0001	Forest to Mining	Agriculture to Forest
Ecoregion 66	-0.003	-0.001	181	0.002	3.0	0.0001	Forest to Developed	Forest to Developed
Ecoregion 59	-0.026	0.043	168	0.108	9.0	0.0005	Forest to Developed	Forest to Developed
Ecoregion 62	**-0.030**	**-0.019**	**162**	**0.118**	**4.0**	**0.0002**	**Forest to M. Disturbed**	**Agriculture to Forest**
Ecoregion 82	**-0.055**	**-0.010**	**154**	**0.303**	**6.0**	**0.0006**	**Forest to M. Disturbed**	**Agriculture to Forest**
Ecoregion 75	**-0.175**	**-0.175**	**197**	**0.000**	**21.0**	**0.0009**	**Forest to Developed**	**Forest to Developed**

Table 5-1. Estimated annual surface radiative forcing, for the 19 Eastern United States ecoregions and ecoregion summary statistics of the parameters used in this study. 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.

Figure 5-1 illustrates the leading LCLU class transitions that cause the greatest absolute change in albedo from 2000 to 2050. These leading LCLU class transitions do not always coincide with the leading transitions due only to LCLU areal change. For example, in the Mississippi Valley Loess Plains (ecoregion 74) the primary areal LCLU transition is from agriculture to developed land (Table 5-1, penultimate column), whereas the primary (areal and albedo) transition is from agriculture to forest land (Figure 5-1 and Table 5-1, last column). This is because LCLU changes between classes with different albedos (e.g., agriculture to forest) may have a greater net albedo impact than more areally extensive changes between classes with similar albedos (e.g., agriculture to developed) [*Barnes and Roy*, 2008]. Furthermore, 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*, 2000]. For these reasons 10 of the 19 ecoregions had a different leading LCLU transition when areal and albedo were considered compared to considering LCLU areal change only.

The annual LCLU induced albedo change from 2000 to 2050 (Equation 3) is summarized in Table 5-1 (column 7) and ranged from -0.0025 in the Northern Piedmont (ecoregion 64), up to 0.0009 in the Southern Coastal Plain (ecoregion 75). To illustrate the significance of these albedo changes, the mean annual incoming surface solar radiation for the 19 ecoregions is 177 Wm^{-2} and a change in albedo of 0.0025 with this mean incoming solar radiation amount would induce a forcing of 0.442 Wm^{-2}, which is nearly twice the global forcing estimates due to LCLU albedo change since 1750 [*IPCC*, 2007].

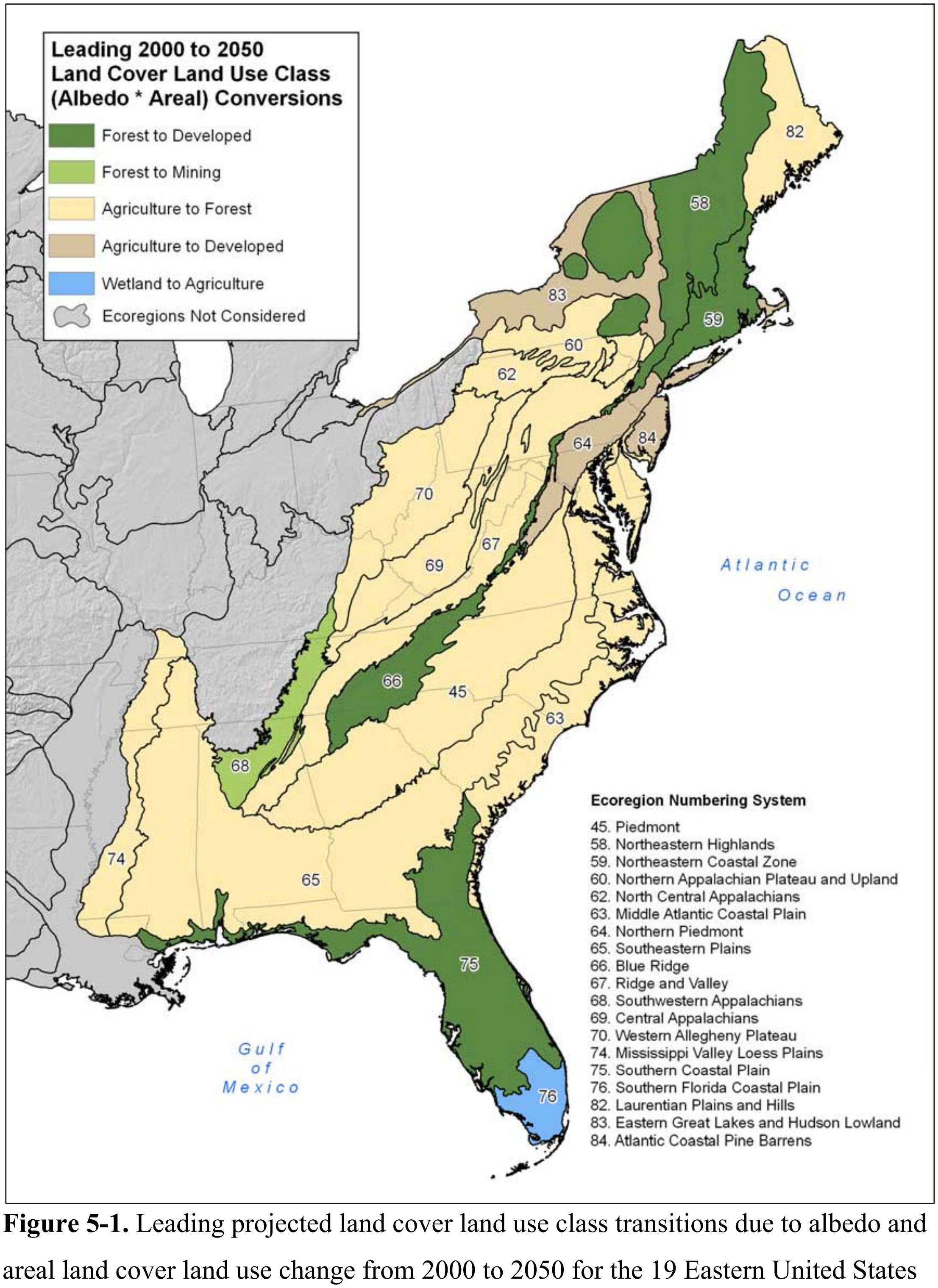

Figure 5-1. Leading projected land cover land use class transitions due to albedo and areal land cover land use change from 2000 to 2050 for the 19 Eastern United States ecoregions used in this study (numbered and colored).

Figure 5-2 illustrates the estimated annual surface radiative forcing due to the FORE-SCE projected 2000 to 2050 LCLU albedo changes. About two thirds of the ecoregions have a positive surface radiative forcing i.e., warming but with no clear regional spatial pattern. The 19 ecoregion forcing estimates are highly correlated with the net 2000 to 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 three ecoregions with the most positive radiative forcings have relatively high percentages of net 2000 to 2050 LCLU change (14.0% to 15.0%) and relatively high incoming solar radiation (177 Wm^{-2} to 195 Wm^{-2}) and low mean annual snow fractions (0.002 to 0.037). The most positive surface radiative forcing is 0.423 Wm^{-2} in the Northern Piedmont (ecoregion 64) due primarily to the extensive transition of agriculture to developed land. The most negative forcing is -0.175 Wm^{-2} in the Southern Coastal Plain (ecoregion 75) due primarily to the extensive transition of forest to developed land.

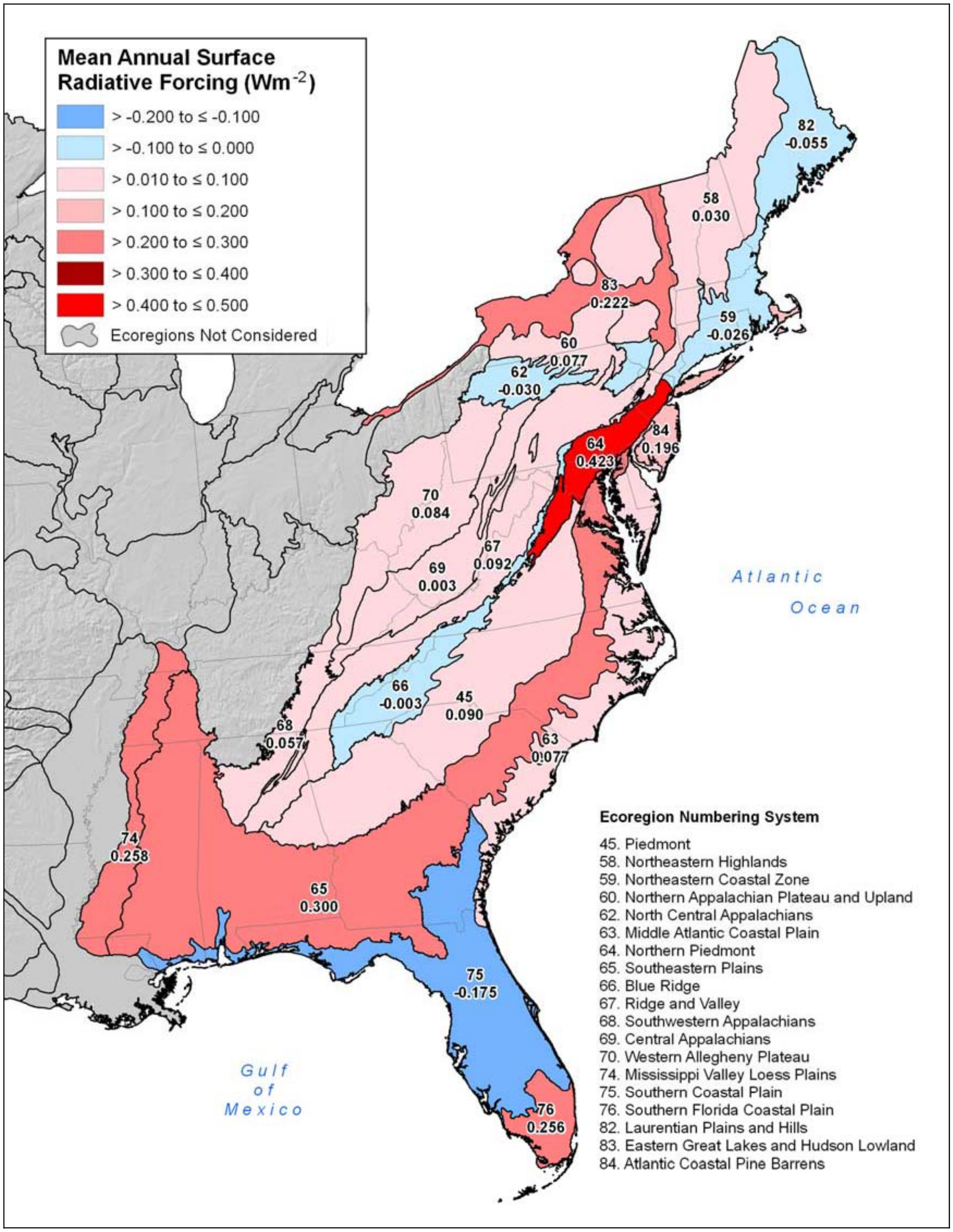

Figure 5-2. Estimated annual surface radiative forcing due to projected 2000 to 2050 land cover land use albedo change for the 19 Eastern United States ecoregions used in this study (numbered and colored).

For all 19 Eastern U.S. ecoregions we estimate a positive (i.e., warming) net surface radiative forcing of 0.112 Wm^{-2} due to LCLU albedo change from 2000 to 2050. This was estimated by summing the product of the ecoregion areas (m^2) and annual forcing estimates (Wm^{-2}), divided by the total area (m^2) of the 19 ecoregions. The impact of snow at the regional level was negligible, only changing this regional forcing estimate in the third decimal place. However, in six ecoregions the mean annual snow fraction was greater than 0.1 and the absolute difference between the surface radiative forcing estimates modeling snow (Table 5-1, column 2) and assuming snow-free conditions (Table 5-1, column 3) (computed by setting the monthly snow fraction in Equation [1] to zero) could be significant, with the greatest difference (0.069 Wm^{-2}) in the Northeastern Coastal Zone (ecoregion 59) where the primary LCLU transition is between snow-hiding (forest) and snow-revealing (developed) LCLU classes.

5.5 Conclusion

This letter has demonstrated the utility of regional spatially and temporally explicit data to quantify the effects of future LCLU albedo change on surface radiative forcing. The FORE-SCE projected 2000 to 2050 LCLU changes indicate a decrease in both agricultural and forested land and an increase in developed land that we model will induce a regional warming of 0.112 Wm^{-2}. This regional forcing estimate is almost four times greater than the 0.030 Wm^{-2} forcing estimated for 1973 to 2000 LCLU albedo change that was driven primarily by the conversion of forest to mechanically disturbed and agriculture to forest lands [*Barnes and Roy,* 2010], and contrasts even more with historical climate studies that indicated a cooling in the Eastern U.S. due to conversion of forest to agriculture in the late nineteenth and early twentieth centuries [*Bonan,* 1999; *Bounoua et al.,* 2002].

The radiative forcing estimates vary geographically in sign and magnitude, driven mainly by differences in the area and type of projected LCLU change across the Eastern U.S., with the most positive (0.423 Wm^{-2}) and negative (-0.175 Wm^{-2}) forcings due primarily to the transition of agriculture to developed land and the transition of forest to developed land respectively.

This research only considered the forcing effect of a single plausible LCLU change projection scenario. Continued development of scenario-driven LCLU change studies to generate an envelope of spatially and temporally explicit future LCLU maps is needed to undertake more comprehensive forcing studies and to provide more definitive confirmation of the LCLU albedo surface warming trend suggested by this research.

5.6 References

Allan, R. P., M. A. Ringer, J. A. Pamment, A. Slingo (2004), Simulation of the Earth's radiation budget by the European Centre for Medium- Range Weather Forecasts 40-year reanalysis (ERA40), *Geophys. Res. Lett*.,109, D18107, doi:10.1029/2004JD004816.

Barnes, C. A., and D. P. Roy (2008), Radiative forcing over the conterminous United States due to contemporary land cover land use albedo change, *Geophys. Res. Lett*., 35, L09706, doi:10.1029/2008GL033567.

Barnes, C. A., and D. P. Roy (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, *J. Geophys. Res.*, doi:10.1029/2010JG001428, in press.

Betts, R. A. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature*, 408, 187–190.

Bonan, G.B. (1999), Frost followed the plow: impacts of deforestation on the climate of the United States. *Ecological Appl.* 9:1305-1315.

Bounoua, L., R. DeFries, G.J. Collatz, P. Sellers, and H. Khan (2002), Effects of land cover conversion on surface climate. *Climatic Change* 52:29-64.

Drummond, M.A. and T.R. Loveland (2010), Land-use pressure and a transition to forest-cover loss in the Eastern United States. *BioScience,* 60: 286-298.

Feddema, J. J., K. W. Oleson, G. B. Bonan, L. O. Mearns, L. E. Buja, G. A. Meehl, and W. M. Washington (2005), The importance of land-cover change in simulating future climates. *Science,* 310, 1674–1678.

Hall, D. K., G.A. Riggs, and V.V. Salomonson (2006), updated monthly. MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG V005, [Dates used; January 2004 to December 2008]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Hall, D.K. and G.A. Riggs (2007), Accuracy assessment of the MODIS snow-cover products, *Hydrol Process*, 21(12):1534-1547, doi:10.1002/hyp.6715.

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*, edited by S. Solomon *et al.,* 996pp., Cambridge Univ. Press, New York.

Jin, Y., C. B. Schaaf, F. Gao, X. Li, A. H. Strahler, X. Zeng, and R. E. Dickinson (2002), How does snow impact the albedo of vegetated land surfaces as analyzed with MODIS data?, *Geophys. Res. Lett.*, 29(10), 1374, doi:10.1029/2001GL014132.

Jin, Y. and D.P. Roy (2005), Fire-induced albedo change and its radiative forcing at the surface in northern Australia, *Geophys. Res. Let.,* 32, L13401, doi:10.1029/2005GL022822.

Kalnay, E., and M. Cai (2003), Impact of urbanization and land use on climate change. *Nature,* 423, 528–531.

Loveland, T.R., T.L. Sohl, S.V. Stehman, A.L. Gallant, K.L. Sayler, and D.E. Napton (2002), A Strategy for Estimating the Rates of Recent United States Land Cover Changes, *Photo. Engin. Rem. Sens.*, 68. 1091-1099.

Loveland T.R., G. Gutman, M. Buford, K. Chattwejee, C. Justice, C. Rogers, B. Stokes, J. Thomas (2003), Chapter 6: land use/land cover change. In: Strategic plan for the climate change science program. U.S. Climate Change Science Program, Washington, pp118-134.

Matsui, T., A. Beltran-Przekurat, R.A. Pielke Sr., D. Niyogi, and M. Coughenour (2007), Continental-scale multi-objective calibration and assessment of Colorado State University Unified Land Model. Part I: Surface albedo. *J. Geophys. Res,* 112, G02028, doi:10.1029/2006JG000229.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S.Emori, M. Kainuma, T. Kram, G.A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant and T.J. Wilbanks (2010), The next generation of scenarios for climate change research and assessment, *Nature*, 463, 747-756, doi:10.1038/nature08823.

Nair, U.S., D.K. Ray, J. Wang, S.A Christopher, T. Lyons, R.M. Welch, and R.A. Pielke Sr. (2007), Observational estimates of radiative forcing due to land use change in southwest Australia, *J. Geophys. Res.,* 112, D09117, doi:10.1029/2006JD007505.

National Research Council (NRC) (2005), *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, 207pp National Academic Press, Washington, D.C.

Nowak, D.J., J.T. Walton (2005), Projected urban growth (2000–2050) and its estimated impact on the U.S. forest resource. *J. Forestry*, 103 (8), 383–389.

Nuñez, M. N, H. H. Ciapessoni, A. Rolla, E. Kalnay, and M. Cai (2008), Impact of land use and precipitation changes on surface temperature trends in Argentina. *J. Geophys. Res.,* 113**,** D06111, doi:10.1029/2007JD008638.

Omernik, J.M. (1987), Ecoregions of the conterminous United States, *Annuals of the Association of American Geographers*. 77:118-125.

Pielke, R. A., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. D. S. Niyogi, S. W. Running (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, *Philos. Trans. R. Soc. London Ser. A., 360*, 1705– 1719.

Pitman, A. J., N. de Noblet-Ducoudré, F.T. Cruz, E. L. Davin, G. B. Bonan, V. Brovkin, M. Claussen, C. Delire, L. Ganzeveld, V. Gayler, B. J. J. M. van den Hurk, P. J. Lawrence, M. K. van der Molen, C. Műller, C. H. Reick, S. I. Seneviratne, B. J. Strengers, and A. Voldoire (2009), Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study, *Geophys. Res. Lett.,* 36, L14814, doi:10.1029/2009GL039076.

Roesch, A., M. Wild, R. Pinker, and A. Ohmura (2002), Comparison of spectral surface albedos and their impact on the general circulation model simulated surface climate, *J. Geophys. Res.,* 107(D14), 4221, doi:10.1029/2001JD000809.

Sagan, C., O.B. Toon, J.B. Pollack (1979), Anthropogenic albedo changes and the Earth's climate, *Science*, 206, 1363-1368.

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

Sohl, T.L., K.L. Sayler, M.A. Drummond, and T.R. Loveland (2007), The FORE-SCE model: a practical approach for projecting land cover change using scenario-based modeling, *Journal of Land Use Science*, 2: 2, 103 — 126, doi:0.1080/17474230701218202.

Sohl, T., and K. Sayler (2008), Using the FORE-SCE model to project land-cover change in the southeastern United States, *Ecological Modeling*, 219:49-65.

Stehman, S.V., T.L. Sohl, and T.R. Loveland (2005), An evaluation of sampling strategies to improve precision of estimates of gross change in land use and land cover, *Int. J. Remote. Sens.*, 26, 4941-4957.

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

White, E.M., A.T. Morzillo, and R.J. Alig (2009), Past and projected rural land conversion in the US at state, regional, and national levels, *Landscape and Urban Planning,* 89, 37–48.

CHAPTER 6

RESEARCH SUMMARY AND RECOMMENDATIONS

6.1 Summary of Research Hypotheses

Recent spatially explicit satellite derived contemporary LCLU, albedo and projected future LCLU data were used to study the impact of conterminous United States (CONUS) LCLU change from 1973 to 2000, and from 2000 to 2050, on albedo and surface radiative forcing. Four research hypotheses concerned with past and potential future climate implications of human land surface activity were addressed. A summary of the research hypotheses and the research findings are described below:

Hypothesis 1: Over the last 30 years LCLU change across the CONUS has led to a mean net positive albedo increase and a consequent albedo-related cooling

This hypothesis was *negated*. For the 36 ecoregions (43% of the CONUS) considered in Chapter 3 [*Barnes and Roy*, 2008], a net CONUS positive forcing (i.e., warming) of **0.012 Wm^{-2}** due to LCLU albedo change from 1973 to 2000 was estimated. More comprehensively, for the 58 ecoregions (69% of the CONUS) considered in Chapter 4 [*Barnes and Roy*, in press], a net CONUS positive forcing (i.e., warming) of **0.029 Wm^{-2}**, driven primarily by the conversion of forest to mechanically disturbed and the conversion of agriculture to forest LCLU types, was estimated. The surface radiative forcing of **0.029 Wm^{-2}** [*Barnes and Roy*, in press] was greater than the **0.012 Wm^{-2}** forcing [*Barnes and Roy,* 2008] as 26% more area of the CONUS was considered and because snow conditions were modeled. Snow was illustrated in Chapter 4 to have a significant land cover dependent albedo and radiative forcing effect, which has been suggested by other researchers [*Betts*, 2000]. In snow prone ecoregions, where the dominant LCLU transitions were between snow-hiding (e.g., forest) and snow-revealing (e.g., agriculture) LCLU classes, the negative and positive ecoregion radiative forcing estimates were amplified.

Hypothesis 2: Radiative forcing due to LCLU albedo change is greater than that due to inter-annual albedo variability

This hypothesis was *negated*. The CONUS ecoregion surface radiative forcing estimates described in Chapter 4 [*Barnes and Roy*, in press] were found to be highly sensitive to monthly inter-annual albedo variability derived from 9 years of MODIS data. The snow-free inter-annual albedo variability for 45 of the 58 ecoregions was considered as many ecoregions had insufficient monthly snow albedo LCLU class values in all or certain years to compute the inter-annual variability modeling snow effects. The snow-free inter-annual albedo variability for a given month ranged from **1.6%** to **4.3%**. This variability and the magnitude of the incoming surface solar radiation determined the surface radiative forcing errors defined analytically by propagation of variance analysis for each ecoregion. For the 45 ecoregions considered, a CONUS snow-free net surface radiative forcing of **0.044 Wm^{-2}** with a relatively large error of **0.084 Wm^{-2}** was estimated. Evidently, radiative forcing due to LCLU albedo change is not greater than that due to inter-annual albedo variability.

Hypothesis 3: Current rates of LCLU change imply future net albedo increases and associated albedo-related cooling effects

This hypothesis was *negated* for the Eastern United States where regionally some of the greatest future CONUS LCLU changes are predicted [*Nowak and Walton,* 2005; *Sohl and Sayler,* 2008]. The Eastern U.S. was considered because it was the only region available with projected LCLU forecast data defined using the 2000 Land Cover Trends class nomenclature. The projected 2000 to 2050 LCLU changes indicated a future decrease in both agricultural and forested land and an increase in developed land that induced a regional net negative albedo decrease (-0.001) and a regional warming of **0.112 Wm^{-2}** [Chapter 5, *Barnes et al.,* submitted]. The projected 2050 warming contrasts with historical Eastern U.S. climate studies that indicate a cooling due to extensive conversion of forest to agriculture in the late nineteenth and early twentieth centuries [*Bonan,* 1999; *Bounoua et al.,* 2002]. At the ecoregion level the future forcing estimates varied geographically in sign and magnitude, driven mainly by differences in the area and type of projected LCLU change across the Eastern U.S., with the most positive **(0.423 Wm^{-2})** and negative **(-0.175 Wm^{-2})** forcings due primarily to the transition of agriculture to developed land and the transition of forest to developed land respectively.

Hypothesis 4: There are large regional disparities in LCLU change, consequently large regional disparities in albedo change and RF will modify the outcomes of hypotheses #1, #2 and #3 at the regional scale

This hypothesis was *confirmed*. The results described in Chapter 3 [*Barnes and Roy*, 2008], Chapter 4 [*Barnes and Roy*, in press] and Chapter 5 [*Barnes et al.,* submitted] revealed positive and negative LCLU albedo change and radiative forcing estimates, which were driven primarily by differences in the area and type of LCLU change in the different CONUS ecoregions. The magnitude of the ecoregion forcing estimates was not insignificant, being similar in magnitude to global forcing estimates due to LCLU change since pre-industrial times [*IPCC*, 2007]. Evidently, large area CONUS averages may mask regional LCLU albedo and radiative forcing differences.

6.2 Recommendations for Future Research

The research reported in this dissertation underscores the value of spatially and temporally explicit data to quantify, and to begin to understand, LCLU albedo change related surface radiative forcing. Recommendations for future work building on this dissertation research that could increase the level of scientific understanding of LCLU albedo change radiative forcing are described below.

- **More Spatially Comprehensive Land Cover Land Use Data**

The USGS Land Cover Trends project uses a stratified random sampling methodology defined with respect to 84 contiguous CONUS ecoregions [*Omernik*, 1987] that enables a statically robust 'scaling up' of the sample classification data to assess LCLU change within each ecoregion [*Stehman et al.,* 2005]. At the time of writing only 58 of the 84 ecoregions had been processed by the USGS, and these were used in this research. Inclusion of all the Land Cover Trends data when they become available would enable the first LCLU albedo change surface radiative forcing analysis for the entire CONUS to be accomplished. Furthermore, if an initiative for transforming the United States Multi-Resolution Land Characteristics Consortium's National Land Cover Database [*Homer et al.,* 2004] into an operational spatially explicit land cover monitoring system is achieved, it would establish the first extensive wall-to-wall LCLU change map product defined in a reliable and systematic manner, that could be used to investigate LCLU albedo change forcing impacts more comprehensively.

- **Temporally Richer Land Cover Land Use Change Time Series Data**

Ecoregion areal LCLU class proportions and classified Landsat subsets defined for 1973 and 2000 by the Land Cover Trends project were used in this research as this was the greatest temporal period available. However, impermanent changes such as forest to fallow followed by reforestation may induce shorter-term radiative forcings that would not be captured in the reported research. The Land Cover Trends project has generated classified Landsat subsets not only for 1973 and 2000 but also for 1980, 1986, and 1992. These periods would provide four temporal epochs i.e., 1973 to 1980, 1980 to 1986, 1986 to 1992 and 1992 to 2001, which could be used to investigate the impact of impermanent contemporary LCLU changes on radiative forcing.

- **Improved Incoming Surface Solar Radiation Data**

More reliable forcing estimates may be provided by using improved regional incoming solar radiation data. For example, the recent North American Regional Reanalysis (NARR) dataset [*Messinger et al.,* 2006] could be used. The NARR data have improved spatial resolution (32 km grid cells) compared to the 2.5° grid cell ERA-40 data that were used in this research, and so provide the opportunity for more precise characterization of the spatial variability of incoming solar radiation. For example, in the smallest CONUS ecoregion considered (Willamette Valley, ecoregion 3), only three ERA-40 grid cells covered the ecoregion, whereas about 25 NARR grid cells would cover it to provide a more representative ecoregion incoming solar radiation estimate. In addition to improved spatial resolution, improvements in the incoming surface solar radiation values could be made by taking into consideration more comprehensive atmospheric characterization information that better quantify the scattering and absorption of the incoming solar radiation [*Pinker et al.,* 2003].

- **Improved MODIS Albedo Data**

This research used nine years of MODIS snow and snow-free broadband white-sky albedo to capture inter-annual variability as these were the only years available.

Therefore, to improve the reliable representation of the snow and snow-free LCLU class albedo climatology values, more years of MODIS albedo data should be used. Similarly, only 4 years of the MODIS global monthly snow product were used and additional years of data could provide more accurate mean annual snow fraction climatology information.

- **More Comprehensive Projected Future Land Cover Land Use Scenarios**

The forcing effect of a single plausible LCLU change projection scenario from 2000 to 2050 was considered in this research because it was the only scenario available with the same LCLU class nomenclature as the Land Cover Trends project data. Continued development of scenario-driven LCLU change studies to generate an envelope of spatially and temporally explicit future LCLU maps is needed; especially given that LCLU conversion in the United States is expected to continue [*Alig and Plantinga*, 2004; *Nowak and Walton*, 2005; *White et al.,* 2009]. Projecting future LCLU is difficult and complex as plausible scenarios of what potentially could happen on the landscape as a result of many factors including socioeconomic, technological and environmental conditions, emissions of greenhouse gases and aerosols, and climate, need to be considered [*Turner II et al.,* 2007; *Moss et al.,* 2010]. The Intergovernmental Panel on Climate Change (IPCC) has used a series of Standardized Reference Emissions Scenarios (SRES) as a central component of its work in assessing likely future climate. However, the IPCC decided in 2006 not to commission another set of SRES, leaving new scenario development to the research community [*Moss et al.,* 2010]. Given this new opportunity, the research community selected from the published literature a set of Representative

Concentration Pathways (RCPs) to map a broad range of climate outcomes. The RCPs could provide a starting point for new and wide-ranging research to yield valuable insights into the interaction of human-induced climate processes and are recommended to be included in future LCLU radiative forcing studies [*Moss et al.,* 2010].

- **Integrate Forcing Results into Climate Models**

This research only considered the surface radiative forcing effect of LCLU albedo change, which is defined as the '*instantaneous change in radiative flux at the surface*' [*Hansen et al.,* 1997] and is distinct from top of atmosphere (TOA) radiative forcing, which is defined as '*the change in the net irradiance at the troposphere after allowing for stratospheric temperatures to re-adjust to equilibrium*' [*IPCC*, 2007]. The relationship between surface and TOA forcing is affected by the vertical distribution of radiative forcing within the atmosphere [*NRC*, 2005]. *Randerson et al.* [2006] emphasized the importance of considering the complex linkages and feedbacks between surface and TOA radiative forcing before reliable conclusions on the overall net effects of LCLU change on climate could be drawn. Thus, the results presented in this research provide inputs that should be included in regional climate models to assess to what extent surface radiative forcing associated with LCLU albedo change influences TOA radiative forcing.

- **Global Context**

This research needs to be placed in a global context, as regional variations in radiative forcing may have global climatic implications [*NRC*, 2005]. Regional forcings can lead to global climate responses, while global forcings can be associated with regional climate responses. For example, recent studies have illustrated that LCLU change can cause atmospheric *teleconnections* that influence regional climate thousands of miles away from the LCLU change. Teleconnections are defined by the American Metrological Society as '*a linkage between weather changes occurring in widely separated regions of the Earth*'. For example, *Werth and Avissar* [2002] found significant U.S. precipitation teleconnections due deforestation in Amazonia, Central Africa and South East Asia. A global assessment is needed if LCLU change becomes part of future global climate modeling and climate change mitigation strategies. This implies the need to repeat this dissertation research at a global scale, which is not currently feasible because global LCLU change data are not available.

- **The Intergovernmental Panel on Climate Change Focus**

Finally, the current *IPCC* [2007] focus on radiative forcing of well-mixed greenhouse gases is considered to be too limiting, a broadening in its perspective is suggested as being overdue. The current IPCC approach does not properly address the role of land-surface forcing and feedbacks within the climate system [*Pielke and Niyogi*, 2010]. If there is no change in the current IPCC focus only energy policies will be promoted that will not provide effective climate policy, which necessarily also needs to include how humans are altering the climate system through land surface modifications.

6.3 References

Alig, R.J., and A.J. Plantinga (2004), Future forestland area: impacts from population growth and other factors that affect land values, *J. Forestry,* 102 (8), 19–24.

Barnes, C. A., and D. P. Roy (2008), Radiative forcing over the conterminous United States due to contemporary land cover land use albedo change, *Geophys. Res. Lett.*, 35, L09706, doi:10.1029/2008GL033567.

Barnes, C. A., and D. P. Roy (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, *J. Geophys. Res.*, doi:10.1029/2010JG001428, in press.

Barnes, C. A., D. P. Roy, T.R. Loveland, Projected surface radiative forcing due to 2000 to 2050 land cover land use albedo change over the Eastern United States, *Geophys. Res. Lett.,* submitted October 6th 2010.

Betts, R.A. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature*, 408, 187–190.

Bonan, G.B. (1999), Frost followed the plow: impacts of deforestation on the climate of the United States. *Ecological Appl.* 9:1305-1315.

Bounoua, L., R. DeFries, G.J. Collatz, P. Sellers, and H. Khan (2002), Effects of land cover conversion on surface climate. *Climatic Change* 52:29-64.

Hansen, J., M. Sato, and R. Ruedy (1997), Radiative forcing and climate response, *J. Geophys. Res.*, *102*(D6), 6831–6864.

Homer, C., C. Huang, L. Yang, B. Wylie and M. Coan (2004), Development of a 2001 National Land Cover Database for the United States. *Photogramm. Eng. Rem. S.*, 70(7): 829-840.

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*, edited by S. Solomon *et al.,* 996pp., Cambridge Univ. Press, New York.

Loveland, T. R., B.C. Reed, J.F. Brown, D.O. Ohlen, J. Zhu, L. Yang, and J.W. Merchant (2000), Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR Data. *Int. J. Rem. Sens.* 21(6/7):1303-1330.

Loveland, T.R., T.L. Sohl, S.V. Stehman, A.L. Gallant, K.L. Sayler, and D.E. Napton 2002. A strategy for estimating the rates of recent United States land-cover changes. *Photogramm. Eng. Rem. S.* 68(10):1091-1099.

Mesinger F., G., DiMego, E., Kalnay, K., Mitchell, P.C., Shafran, W., Ebisuzaki, D., Jovic, J., Woollen, E., Rogers, E.H., Berbery, M.B., Ek, Y., Fan, R., Grumbine, W., Higgins, H., Li, Y., Lin, G., Manikin, D., Parrish, W., Shi (2006), North American regional reanalysis: A long-term, consistent, high-resolution climate dataset for the North American domain, as a major improvement upon the earlier global reanalysis datasets in both resolution and accuracy. *B. Am. Meteorol. Soc.* 87: 343–360.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S.Emori, M. Kainuma, T. Kram, G.A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant and T.J. Wilbanks (2010), The next generation of scenarios for climate change research and assessment, *Nature*, 463, 747-756, doi:10.1038/nature08823.

National Research Council (2005), *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, 207pp., Natl., Acad., Washington, D.C.

Nowak, D.J., and J.T. Walton (2005), Projected urban growth (2000–2050) and its estimated impact on the U.S. forest resource, *J. Forestry*, 103 (8), 383–389.

Omernik, J.M. (1987), Ecoregions of the conterminous United States, *Annuals of the Association of American Geographers*. 77:118-125.

Pielke, R.A., and D. Niyogi (2010), The role of landscape processes within the climate system. In: Otto, J.C. and R. Dikaum, Eds., in *Landform - Structure, Evolution, Process Control: Proceedings of the International Symposium on Landforms organised by the Research Training Group 437*. Lecture Notes in Earth Sciences, Springer, 115, doi 10.1007/978-3-540-75761-0_5.

Pinker, R.T., J.D. Tarpley, I. Laszlo, K.E. Mitchell, P.R. Houser, E.F. Wood, J.C. Schaake, A. Robock, D. Lohmann, B.A. Cosgrove, J. Sheffield, Q. Duan, L. Luo, and R.W. Higgins (2003), Surface radiation budgets in support of the GEWEX Continental-Scale International Project (GCIP) and the GEWEX Americas Prediction Project (GAPP), including the North American Land Data Assimilation System (NLDAS) project, J. Geophys. Res., 108(D22), 8844, doi:10.1029/2002JD003301.

Randerson, J. T., **H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, C. S. Zender** (2006), The impact of boreal forest fire on climate warming, *Science*, 314: 1130–1132.

Stehman, S.V., T.L. Sohl, and T.R. Loveland (2005), An evaluation of sampling strategies to improve precision of estimates of gross change in land use and land cover, *Int. J. Remote. Sens.*, 26, 4941-4957.

Turner II, B.L., E.F. Lambin, and A. Reenberg (2007), The emergence of land change science for global environmental change and sustainability, *Proced. Nat. Acad. Sci.*, 104(52), 20666-20671.

Werth, D., and R. Avissar (2002), The local and global effects of Amazon deforestation, *J. Geophys. Res.,* 107 (D20), 8087, doi:10.1029/2001JD000717.

White, E.M., A.T. Morzillo, and R.J. Alig (2009), Past and projected rural land conversion in the US at state, regional, and national levels, *Landscape and Urban Planning,* 89, 37–48.