

# **Quantifying Albedo and Surface Temperature over Different Land Covers: Implications for Carbon Offsets**

by

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## **Abstract**

Many organizations, both internationally and within the United States, have invested in forest sequestration projects to offset their carbon emissions. However, changes in albedo and surface temperature due to reforestation and afforestation projects may have unintended regional and global climate consequences. The objective of this study was to quantify the change of surface albedo and temperature across different land covers over the eastern United States using Landsat 7 ETM+ satellite images. A second objective was to evaluate the results in the context of potential net climate effects of reforestation and afforestation and their implications on carbon offsets. Most land covers were found to differ in their shortwave albedo and surface temperature. Specifically, open land (cropland and grassland) had a higher shortwave albedo and surface temperature compared to forests. Albedo and temperature also differed seasonally and with latitude for the same land cover type, suggesting that other factors influence local energy balance and climate. The shortwave albedo results are consistent with previous studies, but this study is one of only a few that examined both albedo and surface temperature for many different land cover types. Additional research is needed to quantify all of the physical and environmental factors affecting local and regional climate over different land covers, how these factors relate to each other, and how they will change through time due with carbon offset projects. In this way the true value of carbon mitigation tools can be predicted.

Keywords: Albedo, Surface Temperature, Afforestation, Reforestation, Carbon Offsets, Land-cover Change, Net Climate Effect

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## INTRODUCTION

In their latest report, the IPCC stated with very high confidence that anthropogenic activities have led to a global net warming effect since 1750 (IPCC 2007). Recognizing a need to respond to global climate change, some members of the international community have adopted strategies including emission trading, emission reductions, and emission offsets (Europa 2005, Newell and Stavins 1999). Many organizations, both internationally and within the United States, have invested in sequestration projects to offset their own carbon emissions (Jindal 2006). However, changes in albedo and surface temperature due to reforestation and afforestation projects may have unintended regional and global climate consequences that need to be considered when determining the net climate impact of a project (Betts 2000, Pielke Sr *et. al.* 2002, Betts *et. al.* 2007).

## Benefits of Carbon Sequestration

Carbon accumulates not only in the atmosphere, but also in the oceans and in the soil and vegetation on land. While approximately 7.91 billion metric tons (7,910 Tg) of carbon were emitted globally in 2004, the Earth's forests sequestered more than 2,000 Tg of that carbon (Wofsy 2001, Marland *et. al.* 2007). In 2001 by comparison, the U.S. accumulated 230 Tg of carbon equivalent<sup>1</sup> within its forests, urban trees and agricultural soils, offsetting about 15% of total U.S. CO<sub>2</sub> emissions (EPA 2006). According to the Energy Information Agency (EIA), a total of 478 carbon sequestration projects were

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<sup>1</sup> The term "carbon equivalent" refers to a metric measure that is used to compare the emissions of all greenhouse gases based upon their global warming potential (GWP), usually expressed in the U.S. as "million metric tons of carbon equivalents" (MMTCE). Global warming potentials are used to convert greenhouse gases to carbon dioxide equivalents, which can then be converted to carbon equivalents by multiplying the carbon dioxide equivalents by 12/44 (California 2005).

reported in 2004 within the U.S., 363 (76%) of which consisted of afforestation or reforestation efforts (EIA 2004). These projects accounted for 0.8 Tg of carbon equivalent sequestered or emissions reduced, representing 11% of the total terrestrial carbon sequestration reported to the Energy Information Administration in 2004 (EIA 2004).

## **Benefits of Carbon Offsets**

Terrestrial carbon sequestration is increasingly seen as a viable option, environmentally and economically, for mitigating the United States' contribution to global warming. First, many pieces of current legislation propose a mandatory cap-and-trade program to control how much carbon is emitted by sources within the U.S. (Pew 2007a). This would allow facilities to satisfy a portion of their required emission reductions with terrestrial carbon sequestration projects. Second, planting trees to sequester carbon has been found by many studies to be a low net cost emission reduction tool in several countries, including the U.S. (Newell and Stavins 2000, Jackson and Schlesinger 2004). Third, in contrast to other alternative energy solutions, carbon sequestration as a large-scale mitigation tool is currently available. Finally, secondary benefits of carbon sequestration via reforestation and afforestation include the potential for increased habitat area, biodiversity, local air quality and erosion control (Brown *et al.* 2000, Matthews *et al.* 2002). However, there are numerous feedbacks between land and the atmosphere that make it hard to accurately predict local, regional and global climatic changes that occur due to changes in land cover (Rost and Mayer 2006).

## **The Energy Balance**

The net climate effect of forestation on local, regional and global climate depends on factors other than the amount of carbon sequestered. Physical characteristics of the surface, including albedo, emissivity, and soil moisture, vary between different land cover types and affect the net energy flux of each surface (Figure 1) (Betts 2000, Jackson et al. 2005, Goode and Palle 2007). As energy from the sun enters the Earth's atmosphere, some radiation is reflected or absorbed immediately while the remaining energy reaches the Earth's surface. A particular surface's albedo, which ranges from 0 to 1, determines how much shortwave radiation is reflected (light colored, high albedo) or absorbed (dark colored, low albedo) by that surface. A surface's emissivity determines how much longwave radiation is then emitted and available to clouds and greenhouse gases that will absorb or re-emit this radiation (Kessler and Jaeger 1999). A surface will also give off sensible heat when it holds more energy than its surroundings.

**Figure 1. The Energy Balance over Different Land Covers**

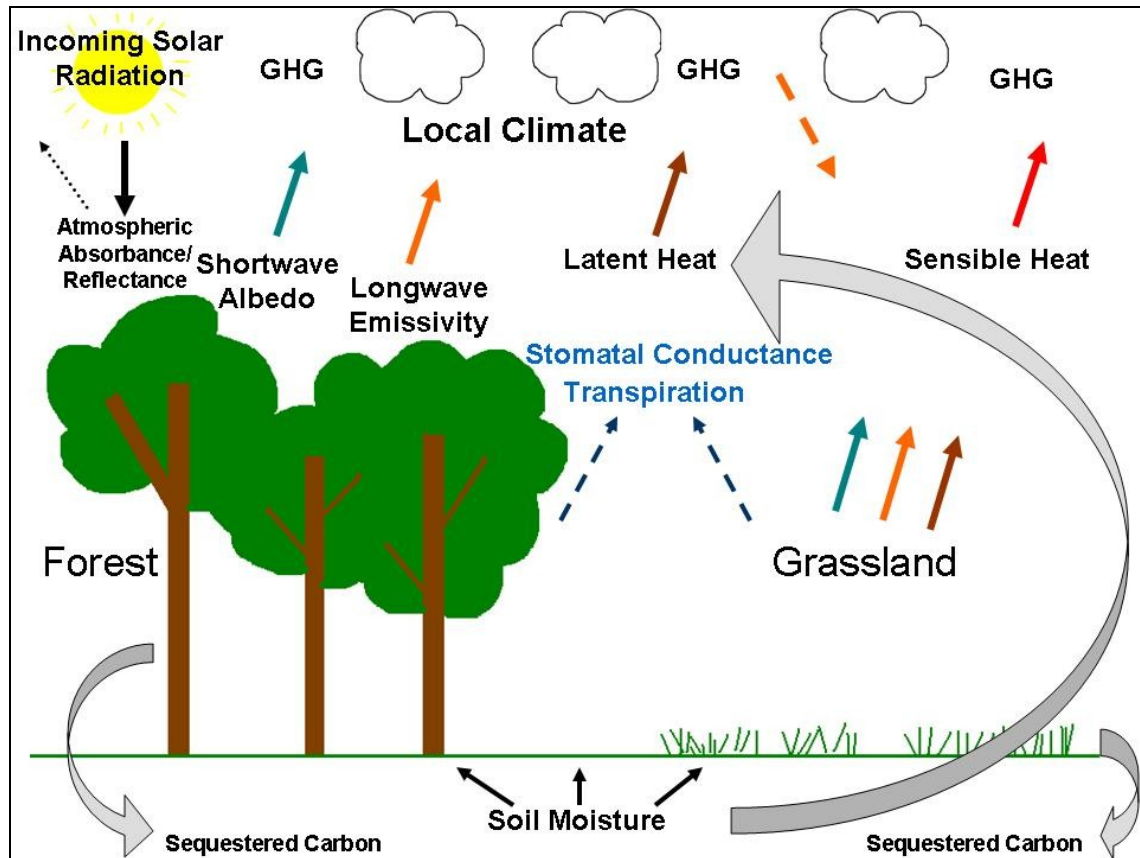


Figure 1 illustrates how as energy from the sun enters the Earth's atmosphere, some radiation is reflected or absorbed immediately while the remaining energy reaches the Earth's surface. A particular surface's albedo, emissivity and soil moisture determines how much energy is reflected, emitted, or available for latent heat, respectively. A surface will also give off sensible heat when it holds more energy than its surroundings. Additionally, vegetative surfaces can actively regulate their temperature with stomatal conductance and transpiration and absorb carbon dioxide during photosynthesis, thus affecting how the surface contributes to the local climate.

Vegetative surfaces hold additional characteristics that affect a surface's energy budget and local climate. Soil moisture affects the availability of latent heat, while vegetation can actively regulate their temperature with stomatal conductance and transpiration (Kessler and Jaeger 1999). Water vapor given off through transpiration holds latent heat that is later released as it condenses in the atmosphere; this process is controlled by a surface's soil moisture (Kessler and Jaeger 1999). Vegetated surfaces also



absorb carbon dioxide during photosynthesis, which accumulates within the soil and plant material allowing less carbon dioxide to remain in the atmosphere to absorb and re-emit longwave radiation. Therefore, with each vegetative surface having different properties, any change to that surface not only modifies the physical properties of the surface, but also has the potential to alter local climatic conditions such as air temperature, humidity and wind speed (Rost and Mayer 2006).

For example, studies of the Amazon rainforest have shown that deforestation of this area would cause a decrease in rainfall and surface evaporation, leading to an increase in surface temperature and a subsequent increase in rainfall across the Southeastern U.S., North Atlantic and Western European regions (Gedney and Valdes 2000). Models also suggest that the low-albedo surface that tree canopies create would cause a warming effect in boreal and cool-temperate forests and therefore the physical characteristics of these forested areas could play a bigger role than these forests' ability to sequester carbon (Betts 2000). Contrary to these findings, a recent study examining reforestation in a southeastern forest in the U.S. found that converting grass-covered old field to a planted pine forest or a hardwood forest resulted in a local surface cooling effect on annual time scales (Juang *et. al.* 2007).

## **Previous Energy Balance Studies**

Past research has focused on net radiation measurements over many surfaces, including grasslands, snow and ice in arctic climates, and bare soil in arid regions (Kessler and Jaeger 1999). More recent studies have focused on quantifying energy budget differences between evergreen and grassland land covers (Kessler and Jaeger 1999, Stiller *et. al.* 2005, Rost and Mayer 2006). However, studies that look at the albedo

and surface temperature over different types of forests and open areas are lacking. The following descriptions summarize previous studies which focused on quantifying either the net radiation or related physical properties over different land covers.

*Seasonal differences in surface albedo, Arizona U.S.A.*

Pielke *et. al.* (1993) studied seasonal differences in surface albedo above a topographically varied area of northern Arizona. The study area was completely covered with snow during the winter while only the highest elevations had snow during the summer, resulting in a mean winter albedo approximately twice that of summer. Large areas of new snow and differences of soil moisture during the winter caused the standard deviation of surface albedo to be much greater than the surface albedo during the summer. Additionally, Pielke *et. al.* (1993) found that regional albedo variations are an important contribution to surface fluxes of heat and moisture leading to thermal circulations during the summer.

*Net radiation over grasslands and pine forests, Germany*

Kessler and Jaeger (1999) found that the yearly net radiation above northern Germany pine forests was twice the radiation above southern Germany grasslands. They attributed this difference to the fact that the forest was located more south and inland than the grassland, thus resulting in a higher global radiation over the forest as well as the higher long-wave atmospheric radiation and lower albedo over the forest. In fact, the yearly average albedo was twice as big over the grassland ( $0.225 \pm 0.017$ ) than the albedo over the pine forest ( $0.101 \pm 0.009$ ), leading to a higher amount of shortwave radiation to be reflected over the grassland. Kessler and Jaeger (1999) also found that the pine forest

albedo showed smaller year-to-year variations than the grassland albedo and that thinning associated with forest management caused a short and very small decrease of the albedo over the pine forest.

In a study aimed at further understanding the average heat, momentum and water vapor flux over different land covers, Stiller *et. al.* (2005) found that differences in terrain affect diurnal and seasonal air temperature and net radiation in a German landscape. Pine forests had higher temperatures during the day while the grasslands exhibited higher temperatures at night. This trend is most likely caused by the forest canopy collecting cooler air during the night and is amplified during the winter. Stiller *et. al.* (2005) also found significant differences in the daytime net radiation between the pine forest and the grassland, with the pine forest having a larger net radiation budget during both summer and winter. This trend is explained simply by the fact that the albedo of a grassland is higher than the albedo of a forest. The albedo of the studied grassland usually varied between 0.16 and 0.20 during the warm season, depending on soil moisture. The albedo of the studied pine forest was usually about 0.1 without snow cover. Lower albedo values observed in May and June were most likely due to the maximum of the midday sun elevation.

Stiller *et. al.* (2005) also observed very large differences in net radiation during winter due to periods of snow cover: snow remained on the grassland and flat areas while wind blew snow off the forest's canopy. Without snow cover, the forest's dark canopy was exposed and more shortwave radiation was absorbed compared to the light, snow-covered grassland. The larger net radiation budget found over a forest allowed more energy to be available for both sensible and latent heat flux. During the day however, the

difference of sensible heat fluxes between pine forests and grasslands was much greater than the difference of latent heat fluxes. The soil moisture of each site helped determine the amount of water which was available for transpiration, thereby affecting how much energy was available during the sensible and latent heat fluxes.

Rost and Mayer (2006) examined the energy budget of an adjacent grassland and pine forest site in southwest Germany. Even though both sites were exposed to about the same amount of shortwave radiation, the albedo of both land cover types was different: the albedo of the grassland was about twice as high as the pine forest. Since these sites were adjacent and affected by similar weather conditions, Rost and Mayer (2006) concluded that the different albedo values must have been mainly caused by varying attributes of each land cover. Each site also had different longwave and net radiations associated with them; mean net radiation was about 23% higher for the Scots pine forest than for the grassland. The difference in available energy between the sites was slightly reduced with significant differences occurring only during the day due to the varying albedo values associated with each land cover. Sensible heat flux also varied daily between each site with a higher sensible heat flux for the pine forest and larger differences during the day. Nighttime cooling in the forest was caused by the movement of cold air to the forest floor and the creation of a thermal stratification with cold air accumulating within the stem layer until net radiation becomes positive sometime during the day. Latent heat fluxes were not as distinct between the pine forest and the grassland as they were for sensible heat fluxes and were only higher for the pine forest from March to September. Because the grassland reflected more radiation than the pine forest, the

mean minimum and maximum soil heat fluxes reached higher absolute values at the grassland site making the mean daily soil heat flux of the grassland more distinct.

### *Seasonal differences in surface albedo, Australia*

While Moore (1976) reported that previous studies obtained albedo ranges for pine forests of 0.08 to 0.29 and grassland albedo ranges of 0.21 to 0.29, Moore's own study of albedo across different land covers in Australia found that forests had an average albedo ranging from  $0.11 \pm 0.04$  to  $0.116 \pm 0.010$  during the winter and spring while grasslands had an average albedo ranging from  $0.24 \pm 0.01$  in spring and summer and  $0.27 \pm 0.03$  in winter. Moore (1976) found that grasslands reflected more shortwave radiation than forests but also lost more longwave radiation during the summer compared to forests. This suggested that the surface temperatures over the grassland was on average lower during the winter and higher in the summer than the surface temperature over the forest canopy, explained by the relative amounts of transpiration from each land cover.

## **Climate Change Mitigation and Carbon Offsets**

In a cap-and-trade system, such as the European Union's Emission Trading Scheme (EU ETS), greenhouse gases (GHG) can be reduced by three methods: (1) by using efficiency, technology, or a lower activity level, (2) purchasing allowances from other emitters who have already reduced their GHG emissions under their cap, or (3) purchasing carbon offsets which remove CO<sub>2</sub> from the atmosphere or prevent GHG emissions (Smith *et. al.* 2007). A recent EPA study found that as the price of carbon offsets rises, more farmers and land owners want to participate in the market and thus more greenhouse gas reductions are achieved. However, offsets are time-limited and

could peak in 2025 since soils and forests eventually reach their maximum amount of stored carbon and cannot store any more (Smith *et. al.* 2007). Lichter *et. al.* (2004) actually found that reforestation efforts within the eastern U.S. would never be able to hold the same amount of carbon that forests pre-European settlement were able to contain due to subsequent large-scale land clearings. The long-term effectiveness of terrestrial sequestration projects is therefore questionable and may only offer a short-term solution until alternative energies and energy efficiency are able to be implemented on a large scale.

### *Methods for Measuring Offsets*

Smith *et. al.* (2007) recently reviewed current and potential methods of measuring carbon accumulation and offset potential of forests and croplands. Since forests and farmlands naturally accumulate carbon, an increase in these land areas as well as adapting land-management practices could both contribute to decreasing global warming by slowing the rate of greenhouse gas accumulation in the atmosphere. The switch to a low-carbon economy would put a market value on these practices and promote carbon storage and reductions of greenhouse gases.

Current methods of monitoring and verifying carbon sequestration projects within the US have been developed by many organizations including the Chicago Climate Exchange (CCX), the Climate Registry, the California Climate Action Registry and the Eastern Climate Registry. However, reductions made through CCX are the only legally binding agreements whereas the other registries only offer a platform for members to voluntarily verify and report their greenhouse gas emissions and any actions taken to reduce those emissions (CCX 2004, CR 2008). In order to count offsets within the CCX,

afforestation offset projects must be verified by a CCX-approved agent and include the reporting of species mix and characteristics, verification of acreage enrolled in the program, confirmation that forest management practices on enrolled land conform to the program criteria, and identification of any acres not in compliance with the program criteria (CCX 2004). Carbon accumulated within vegetation, soil and long lived wood products can be quantified using CCX Carbon Accumulation and CCX developed Model-based accounting approaches. CCX also allows forest conservation to qualify for carbon offset projects: project locations must be approved by the CCX Offsets Committee and are issued based on annual deforestation rates within the same area.

### *Carbon Offset Measurement and Verification Limitations*

Even though land management practices used in carbon offset projects have the potential to store carbon and provide income for farmers and landowners, a process of correctly projecting the amount of carbon that would be offset within a specified time period needs to be developed so landowners can properly estimate their potential net economic gain (Smith *et. al.* 2007). In addition, methods to validate and document the amount of carbon offset reliably with each project need to be developed (Smith *et. al.* 2007). Monitoring carbon sequestration leads to other challenges: the tracking of climatic conditions during the project time period, the quantification of the exact amount of carbon stored in soil or forest wood within the project and surrounding areas, measuring the amount of methane captured from processed manure, and understanding the scientific and technical aspects of the carbon cycle and how carbon and other elements influence forest and agricultural systems as well as the climate system as a whole (Smith *et. al.* 2007). Any system developed for monitoring and verifying carbon offsets must consider

all of these dynamics as well as allow for any advances occurring in the scientific community (Smith *et. al.* 2007).

## **Current Policies and Options for Carbon Offsets**

There are many implemented and proposed climate change policies within Europe and the U.S. including the EU Emission Trading Scheme, the Regional Greenhouse Gas Initiative (RGGI), the California Global Warming Solutions Act (AB 32), and the Lieberman-Warner Climate Security Act (U.S. S2191), currently proposed in the U.S. Senate. All of these programs establish a cap-and-trade program with an ultimate goal of reducing greenhouse gas emissions.

### *The EU Emission Trading Scheme*

The European Union Greenhouse Gas Emission Trading Scheme (EU ETS) was established in 2005 after the Kyoto Protocol was implemented. Under the EU ETS, countries within the European Union must reduce their collective greenhouse gas emissions by at least 5% of the 1990 baseline emission rate between 2008 and 2012 (UNFCCC 2008a). In addition to decreasing emissions within their own country, participants may also implement projects that reduce emissions in non-Annex 1 Parties under the clean development mechanism (CDM) of the Protocol (UNFCCC 2008b). CDM projects help developing countries reduce their own greenhouse gas emissions and achieve sustainable development in return for certified emission reductions (CERs) for the Annex 1 Parties involved (UNFCCC 2008b). CDM projects could include the installation of alternative energy sources, the development of energy efficient electrical plants, or the act of reforestation or afforestation; however, according to the Kyoto



Protocol, countries are only allowed to count up to 1% of their base year emissions as reductions through reforestation and afforestation sink projects for each year during the second commitment period (UNFCCC 2008b). The EU ETS allows each country to choose whether to apply this limit to each facility individually or collectively and allows credits obtained beyond the limit to be traded in other member countries (EUROPA 2006)

### *The Regional Greenhouse Gas Initiative & the California Global Warming Solutions Act*

The Regional Greenhouse Gas Initiative (RGGI) and the California Global Warming Solutions Act (AB 32) are two examples of regional legislation that aim to reduce greenhouse gas emissions. RGGI currently consists of eight member states within the Northeast and Mid-Atlantic regions and aims to stabilize emissions from the power sector at current levels by 2015 and reduce emissions by 10% of current levels by 2019 (Maine 2005). During its first compliance period starting in 2009, each facility may offset up to 3.3% of its emissions from certified offset projects, with terrestrial carbon sequestration through reforestation and afforestation included (Murdock 2003). Like RGGI, California's Global Warming Solutions Act also aims to reduce emissions on a regional level, but has yet to establish protocols for measuring, verifying and counting carbon offset projects in a facility's total emission reductions (Nichols 2008).

### *The Lieberman-Warner Climate Security Act*

The Lieberman-Warner Climate Security Act (S.2191) requires a 70% reduction in greenhouse gas emissions from covered sources, which account for over 80% of total U.S. emissions (Pew 2007b). This reduction, along with complementary policies such as a low carbon fuel standard and energy efficiency provisions, could reduce overall GHG

emissions within the U.S by about 63% by 2050 (Pew 2007b). Under this act, facilities are allowed to satisfy up to 15% of their required emission reductions with specific domestic offsets, with an additional 15% allowed to be satisfied using international emission allowances.

## **Future Policy Options**

Most, if not all, carbon sequestration projects only measure the carbon flux of a project and do not take into account the net climate effect that results from land cover change. Marland *et. al.* (2003) describes a range of policy and mitigation options for dealing with the multiple and complex impacts that land surface change has on the global climate system. First, greenhouse gas concentrations could simply be limited to a particular sector and any changes in carbon stocks in the biosphere or changes in the land surface could be ignored. Another option would be to continue to not differentiate between carbon in or out of the atmosphere or between possible sources of carbon. More challenging alternatives includes focusing on the global mean climate where changes in surface albedo are regarded the same as changes in greenhouse gas concentrations and incorporating both global and regional climate implications resulting from changes in biosphere carbon stocks and the land surface.

Canadell *et. al.* (2004) also believes that the carbon cycle measurements must be more thoroughly evaluated than present-day measurements. Socio-economic constraints, such as the desire to use land for various uses, and resource trade-offs, such as impacts on biodiversity and effects on the hydrological cycle, must be incorporated into the quantification of the carbon cycle in order to understand the capacities and mitigation opportunities for land use changes related to carbon management. Therefore, the

development of tools that can not only approximate the full impact of land use changes on the global climate system, but also adjust carbon accounting appropriately, must be developed (Marland *et. al.* 2003, Canadell *et. al.* 2004).

Since more utilities, companies and organizations are becoming increasingly concerned with greenhouse gas emissions as the U.S. Congress gets closer to implementing a domestic cap and trade program, carbon sequestration projects and offset programs are likely to receive increased levels of interest. However, the net effects of these offset programs in general and forestation projects in particular must be well known before the exact climate-mitigating potential can be established. Research has shown varying climatic outcomes due to land use changes (Betts 2000, Juang *et. al.* 2007) and mitigation policies that track the absorption and emission of greenhouse gases would need to take into account simultaneous changes in carbon stocks, albedo, evaporation, surface roughness and transpiration in order to establish a comprehensive approach to understanding energy balances over time (Marland *et. al.* 2003).

## **OBJECTIVE**

The objective of this study is to quantify the change of surface albedo and temperature across different landcovers over the eastern United States using satellite data. These results will be evaluated in context of the potential net climate effects of reforestation, afforestation and avoided deforestation and their implications on carbon offsets.

## METHODS

Landsat ETM+ 7 satellite images were processed and corrected for satellite and atmospheric variability to obtain shortwave albedo and temperature values of different land covers. Previous studies have used satellite data to obtain albedo and temperature of the Earth's surface (Qin *et. al.* 2001, Goode and Palle 2007, Zhang *et. al.* 2007); however, many sources of error related to reflectance have been identified with these methods. For example, Zhang *et. al.* (2007) concluded that near-surface humidity and temperature are becoming important uncertainty sources since comprehensive cloud cover data sets have reduced much of previous uncertainty associated within surface radiation budgets. Correction equations from Qin *et. al.* (2001) were used to minimize error associated with these factors. Methods of obtaining and correcting the images are described below.

### **LANDSAT ETM+ 7: Obtaining Shortwave Albedo and Surface Temperature Values**

Landsat ETM+ images were downloaded from the Earth Science Data Interface at the Global Land Cover Facility (GLCF 2004) for areas that could be used for both spatial and seasonal analysis (Figure 2). Unfortunately, a wide range of dates for most areas were not obtainable. An image covering New York and Vermont from 21 July 1999 (NY-VT 7-21-99), Vermont and New Hampshire from 28 February 2002 (VT-NH 2/28/02) and a central North Carolina image from 24 May 2002 (NC 5/24/02) were analyzed (Appendix A: Figure 3, Figure 4, Figure 5).

**Figure 2.**

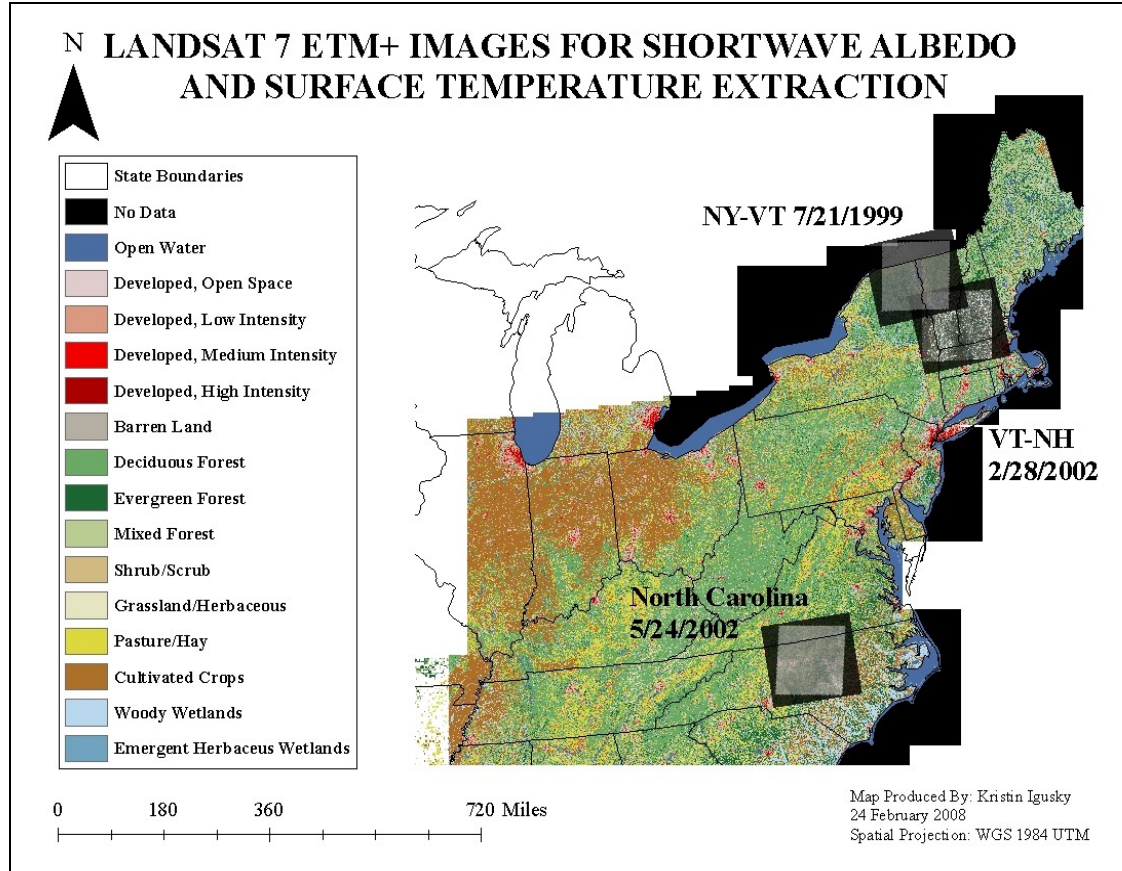


Figure 2 shows the land cover of the eastern U.S. and the locations of the three Landsat 7 ETM+ Images used to obtain shortwave albedo and surface temperatures across different ecosystems.

### *Obtaining Shortwave Albedo*

Image bands were converted from a .tiff format into an .img format in order to identify minimum DN numbers within ERDOS Imagine. Other image data was collected (solar elevation, gain, bias, sun-earth distance, julian day, solar spectral irradiances) and each band was corrected and converted into at-surface reflectance ( $\rho$ ) in ArcGIS (1).

$$(1) \quad \rho = (\pi * ((\text{Gain} * \text{DN} + \text{Bias}) - \text{Lhaze})) / (\text{ESUN}/d^2 * \cos(\theta))$$

Gain =  $(L_{\text{max}} - L_{\text{min}}) / 255$ , DN = based on band histogram, Bias =  $L_{\text{min}}$ , Lhaze =  $L_{\text{min}} - L_{1\%}$ , ESUN = Solar Spectral Irradiance in  $\text{W}/\text{m}^2 * \mu\text{m}$ ,  $d^2$  = Earth-Sun distance,  $\theta$  = 90-Solar Elevation, in radians.

The USGS NLCD (2001) was used to identify areas with homogeneous land cover. A shapefile layer was created for each image containing twenty-five polygons associated with major land covers (evergreen forest, mixed forest, deciduous forest, cropland, grassland, urban, water). Each polygon and its associated land cover was used as a zone to obtain values for bands 1, 3, 4, 5, and 7. Since each polygon covered multiple Landsat image cells, the value for each cell associated with each land cover was obtained. These values were plugged into an equation used to obtain shortwave albedo from Landsat ETM images (2) (Liang et. al. 2001).

$$(2) \quad 0.356*a1 + 0.130*a3 + 0.373*a4 + 0.085*a5 + 0.072*a7 - 0.0018$$

### *Obtaining Surface Temperature*

Following methods from Qin *et. al.* (2001), band 62 of each image was corrected for spectral radiance ( $L(\lambda)$ ) (3) and brightness temperature ( $T6$ ) (4) to obtain land surface temperature ( $T_s$ ) (5).

$$(3) \quad L(\lambda) = \text{Gain} * \text{DN} + \text{Bias}$$

$$(4) \quad T6 = K2 / \ln(1 + K1/L(\lambda))$$

K1 = 666.09 and K2 = 1282.71 for LANDSAT 7

$$(5) \quad T_s = [a6(1-C6-D6) + (b6(1-C6-D6) + C6 + D6)*T6 - D6*Ta] / C6$$

a6 = -67.355351, b6 = 0.458606, C6 = Ground Emissivity ( $\epsilon$ ) \* Atmospheric Transmittance ( $\tau$ ),  
D6 = (1- $\tau$ )[1+(1- $\epsilon$ )\* $\tau$ ], Mid-latitude Summer Ta = 6.0110 + 0.92621\*To, Mid-latitude Winter Ta = 19.2704 + 0.91118\*To, To = air temperature of the ground, in K (~2m height).

The same shapefile layers that were created to obtain shortwave albedo values were also used to obtain each Landsat image cell's  $T_s$ , although less individual points were obtained since band 62 has a coarser resolution (60m) than bands 1, 3, 4, 5 and 7 (30m).

## Testing Significant Differences Across Land Covers

A single factor ANOVA was executed to see if any significant differences were present between the land covers. A Tukey's HSD test was then performed in order to test for significant difference between the albedo and temperature values associated with the land covers within and between each image. Since there were twenty-one pairings of each land cover within an image, the Tukey's honestly significant difference (HSD) test was performed using a 0.00047619 significance level in order to minimize the experimentwise error rate. By testing significance at this high level, the overall probability that at least one of the pairwise tests would result in a Type I error is 0.01. When testing significant difference between each image, the same high significance level was used in order to remain consistent.

## RESULTS

Within the NY-VT 7/21/99 image, all of the land covers had significantly different ( $p < 0.01$ ) shortwave (SW) albedo and surface temperature values except when comparing the mixed forest and urban SW albedo values ( $p < 0.00047619$ ) (Figure 6). Deciduous forests actually had the highest mean SW albedo ( $0.164 \pm 0.0152$ , Table 1), with SW albedo decreasing over cropland, mixed forests and grasslands, respectively. Out of the vegetative surfaces, evergreen forests had the lowest mean SW albedo ( $0.108 \pm 0.0243$ ). Even with two of the highest mean SW albedos, the cropland and grassland land covers also had two of the highest average surface temperatures ( $31.21 \pm 3.810$  °C and  $34.80 \pm 3.507$  °C, Table 2), with urban areas having the highest temperature out of all the measured land covers ( $37.21 \pm 2.646$ ).

**Figure 6.**

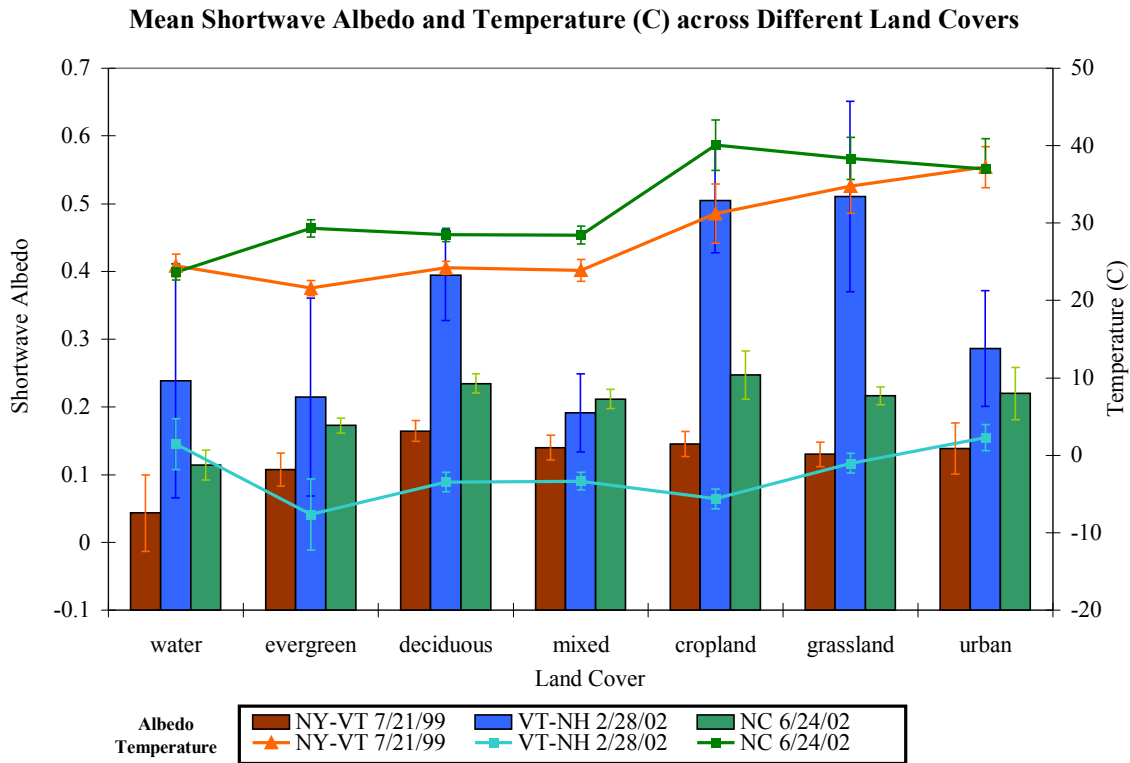


Figure 6 shows the shortwave albedo and surface temperatures for each land cover across the three images. Both the SW albedo and the surface temperature are generally lower over forested land covers than over grassland and cropland land covers. Snow cover obviously creates surfaces with higher albedo values.

**Table 1. Mean Shortwave Albedo**

Land Cover	NY-VT 7/21/99	VT-NH 2/28/02	NC 6/24/02
Water	0.0433 ± 0.0567	0.238 ± 0.173	0.114 ± 0.0222
Evergreen Forest	0.108 ± 0.0243	0.214 ± 0.146	0.172 ± 0.0112
Deciduous Forest	0.164 ± 0.0152	0.394 ± 0.0672	0.234 ± 0.0139
Mixed Forest	0.130 ± 0.0184	0.191 ± 0.0576	0.212 ± 0.0139
Cropland	0.145 ± 0.0184	0.505 ± 0.0772	0.247 ± 0.0355
Grassland	0.120 ± 0.0181	0.511 ± 0.140	0.216 ± 0.0129
Urban	0.139 ± 0.0376	0.286 ± 0.0855	0.220 ± 0.0387

Table 1 lists the mean surface albedo found for each land cover within each Landsat 7 ETM+ image.



**Table 2. Mean Surface Temperature (°C)**

Land Cover	NY-VT 7/21/99	VT-NH 2/28/02	NC 6/24/02
Water	24.49 ± 1.476	1.441 ± 3.307	23.65 ± 1.012
Evergreen Forest	21.58 ± 0.9922	-7.646 ± 4.592	29.32 ± 1.120
Deciduous Forest	24.20 ± 0.8389	-3.488 ± 1.250	28.48 ± 0.8547
Mixed Forest	23.89 ± 1.427	-3.347 ± 1.127	28.44 ± 1.146
Cropland	31.21 ± 3.810	-5.622 ± 1.281	40.05 ± 3.239
Grassland	34.80 ± 3.507	-1.053 ± 1.274	38.34 ± 2.743
Urban	37.21 ± 2.646	2.308 ± 1.677	36.97 ± 3.949

Table 2 lists the mean surface temperature found for each land cover within each Landsat 7 ETM+ image.

Snow cover was present in the VT-NH 2/28/02 image which resulted in high SW albedos across flat surfaces. Grassland and cropland had the highest SW albedo ( $0.505 \pm 0.0772$  and  $0.511 \pm 0.140$ ) and was the only pairing that did not result in a significant difference ( $p < 0.00047619$ ). Deciduous forest had the highest SW albedo among the forested land covers ( $0.394 \pm 0.0672$ ) and when compared with mixed forest, did not show a significant difference in surface temperature ( $p < 0.00047619$ ). Evergreen forest and cropland had the lowest surface temperatures ( $-7.646 \pm 4.592$  °C and  $-5.622 \pm 1.281$  °C) while grassland had the highest surface temperature out of all the vegetative surfaces and urban areas had the highest surface temperature overall ( $-1.053 \pm 1.274$  °C,  $2.308 \pm 1.677$  °C).

All of the land covers had significantly different SW albedo values within the NC 5/24/02 image ( $p < 0.01$ ). Cropland had the highest SW albedo value ( $0.247 \pm 0.0355$ ) while evergreen forest had the lowest SW albedo value out of the vegetative surfaces. The deciduous forest had the highest SW albedo among the forest types ( $0.234 \pm 0.0139$ )

and one of the lowest surface temperatures, along with the mixed forest ( $28.48 \pm 0.8547$  °C and  $28.44 \pm 1.146$  °C) which were the only land cover temperatures that were not significantly different from each other ( $p < 0.01$ ). Even though the cropland and grassland land covers had high SW albedos, they also had the highest surface temperatures.

Seasonal and latitudinal differences in shortwave albedo and surface temperatures exist within the eastern United States. Shortwave albedo and temperature values were significantly different when comparing the same land cover between the three images, except when comparing the temperature of urban areas between the NY-VT 7/21/99 and the NC 5/24/02 images. The NC 5/24/02 image had higher SW albedo and temperatures over vegetative surfaces than both the NY-VT 7/21/99 and the VT-NH 2/28/02 images while the NY-VT 7/21/99 image had higher temperatures than the VT-NH 2/28/02 image. Snow covered deciduous forest, cropland and grassland resulted in significantly higher SW albedo values over the VT-NH 2/28/02 compared to both of the other images. Evergreen forests had one of the lowest SW albedo and temperature values while cropland and grassland had some of the highest SW albedos and temperatures for all images. Similar results were found in previous studies (Figure 7, Appendix B: Table 3, Table 4).

**Figure 7.**

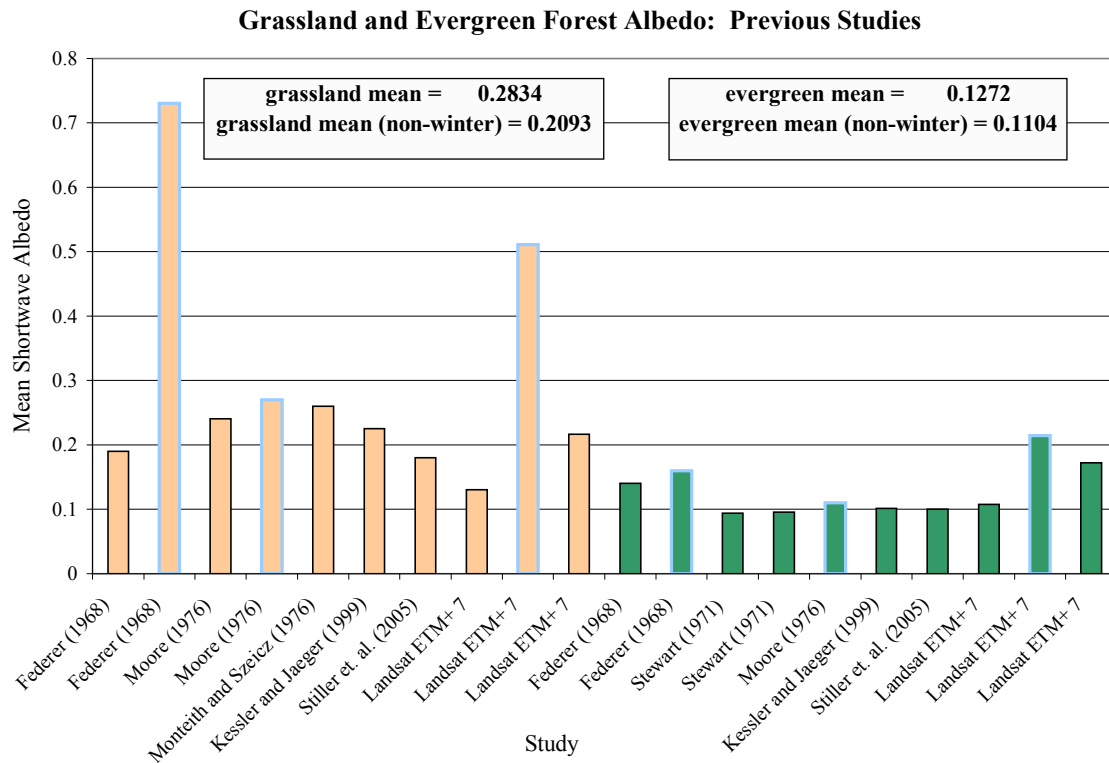


Figure 6 shows results from this study and previous studies as listed in Tables 3 and 4. Average albedo values for both evergreen and grassland land covers agree throughout the studies with evergreen forests having a lower albedo than grasslands. Albedo measurements taken during winter months (outlined in blue) show how snow cover and increase a surface's albedo.

## DISCUSSION

Landsat 7 ETM + images revealed that most land covers differ in their shortwave albedo and surface temperature. Albedo and temperature also differed for the same land cover based on season and latitude, suggesting that many other factors contribute to the local energy balance and climate. These results are consistent with previous studies which found lower albedo and energy balances over grassland areas while evergreen forests had higher albedo and energy balances. However, this study is one of a few which looked at not only the albedo, but also the temperature of many different land cover types.

## **The Energy Balance**

Forests in general appear to have lower surface temperatures than grassland and cropland areas, despite their low albedo. Even though deciduous and mixed forests had higher albedos than evergreen forests and were closer in value to the cropland and grassland area albedos, surface temperatures over the deciduous and mixed forests were lower by 6-12 °C during late spring and summer months. This trend is not as apparent during the winter in Vermont and New Hampshire due to snow cover, although the grassland area did have the highest average surface temperature.

Snow cover greatly affects the albedo of a surface; the high reflectivity of snow caused the albedo of cropland and grassland areas to increase greatly. For example, the mean albedo over cropland and grassland located in New York and Vermont in July was 0.12-0.145 while the mean albedo over cropland and grassland located in Vermont and New Hampshire in February was 0.505-0.511, more than a 3.5 fold increase. Deciduous forests had the highest albedo compared to all forest types during the winter and s

Forests were found to have a lower albedo and to be cooler than open vegetative land in the spring and summer, but variation was seen between different types of forests and open land. Sites from which albedo and surface temperatures were obtained from varied geographically and other characteristics affecting the local energy balance were not taken into account, including: soil moisture, canopy roughness, and color variation. Knowing that albedo and surface temperature differs among general types of vegetation and land covers is necessary in understanding a surface's energy budget and affect on the local and regional climate. Other recent studies have found that reforesting boreal and tropical regions would actually cause a local warming effect (Betts 2000, Gedney and

Valdes 2000). However, the results of this study show that forests are cooler than croplands and grasslands. Based on these results, reforestation and afforestation would probably cause a local cooling effect from North Carolina up into the New England region of the U.S. Additional physical measurements such as emissivity, roughness, and soil moisture over different land covers would allow for a more accurate representation of local climatic variations due to land cover change. Complete energy balance measurements would also give insight to subsequent changes of regional and global climatic conditions. With these types of general differences and trends present, a few questions become apparent:

- 1. What is the potential difference in albedo between actual tree and grass species and types of crops?**
- 2. What is the potential difference in albedo between the same species and crop type across different latitudes and through different seasons?**
- 3. Can these results and trends then be interpolated across the greater region, or the mid-latitude as a whole?**
- 4. How would large-scale change from grassland or cropland to forest within the mid-latitudes, particularly the U.S., affect the greater regional or global climate?**

## **Carbon Offsets and Policy Implications**

Reducing dramatic temperature increases, not necessarily reducing CO<sub>2</sub> concentrations, is the main objective behind climate change policy. Reducing CO<sub>2</sub> and other greenhouse gas concentrations just happens to be the most direct way of reaching this goal. Carbon sequestration is therefore looked upon as a viable mitigation option. Unfortunately, current methods for measuring and verifying carbon offsets only take into account carbon accumulated within the project and ignore other climatic and

environmental factors. The quantification of net carbon sequestered throughout time, the physical and ecological impacts of land use change, and the economic potential and implications of a carbon price all need to be addressed in order to get an idea of the net climate, environmental and social implications of carbon offset projects. Many researchers have looked at each of these aspects individually, but few have attempted to quantify all of these components together. Ideally, the verification of carbon offsets through reforestation and afforestation of a certain area should address the following in order to obtain the net climate effect of the project:

$$\text{Net Effect of Carbon Offset Project} = \text{Net Climate Effect} + \text{Net Economic Effect}$$

$$\textit{Net Climate Effect} =$$

**The amount of climate forcing avoided**  
(carbon sequestered throughout time)

**± The potential change in local climate due to changes in the energy cycle**  
(albedo, emissivity, soil moisture, surface temperature, etc...)

However, the above equation assumes that an economic price can be put on the factors determining the net climate effect, all of which vary depending on the tree species and season. With the Lieberman-Warner Climate Security Act only permitting 30% of all facilities emissions to come from offsets (15% from projects within the U.S. and potentially an additional 15% from international projects), projects with the highest net effect should be given priority. This can be obtained by using the above criteria. For example, one species of tree may have a lower carbon sequestration rate but a higher

albedo and lower surface temperature associated with it. This tree species could therefore contribute less net warming into the atmosphere compared to a tree species with a lower albedo and higher carbon sequestration rate and therefore would have a higher positive contribution to the overall climate effect of the project. Results from this study also suggest that latitudinal differences would need to be taken into account, especially since length of snow cover within an area could dramatically increase regional albedo.

Finally, the regional and global affects of large reforestation and afforestation projects need to be quantified: Large amounts of deforestation in the tropics could affect the climate of the Southeast U.S., Northern Atlantic and Western Europe (Gedney and Valdes 2000). Since forested areas in this study absorbed more energy and yet remained cooler than cropland or grassland areas, the fate of this absorbed energy needs to be better understood. Clearly, additional research is needed in each of the above determining factors of the net effect of carbon offset projects and how they can be related to each other so that the true value of this mitigation tool can be obtained and only projects with a net positive effect can be established.

## **Study Benefits and Limitations**

This study revealed many benefits and areas in need of improvement when it comes to using Landsat images to study the albedo and surface temperature differences across different land covers. While Landsat 7 ETM+ images have a small spectral band resolution (30m), their thermal band resolution twice as big (60m). The smaller resolution allows users to obtain values for smaller, more specific areas while the varying resolution size makes it hard to compare albedo and surface temperature values directly.

Additionally, the albedo and surface temperature values obtained in this study were from only one date in time, and even the two images covering the New York-Vermont-New Hampshire area during the summer and winter were from different years. While values from these dates and regions gave insight on how albedo and surface temperature changes between land covers and seasons, a more complete geographical and seasonal analysis would be ideal.

In fact, satellite data exists with more dates available for download at the same time; MODIS allows users to specify their desired monthly range from January 2002 to December 2006 for a wide array of data products, including albedo. However, the coarse resolution (1km) of MODIS data makes it difficult to obtain data for homogeneous land cover areas with smaller areas. Other data exist, such as soil moisture, which can be used along with Landsat images within ArcGIS in order to more accurately estimate potential energy flux differences between land covers.

## **Conclusion**

Although reducing atmospheric CO<sub>2</sub> concentrations will decrease the intensity of the greenhouse effect and the mean global temperature, other physical characteristics of forests and open land can also affect local and regional temperatures. The albedo of a vegetated surface determines how much shortwave energy is absorbed or reflected, however, it is not an exact indication of local climate. Other physical factors of vegetation such as canopy height, surface roughness, and soil moisture affect local surface temperature, humidity and energy fluxes. The albedo and surface temperature associated with various land covers differ latitudinally and seasonally, although



reforestation and afforestation occurring within the Eastern U.S. would probably cause local cooling. Landsat analysis allows for high resolution albedo and surface temperature results, although the process is time consuming. Additional research is needed to be able to quantify all of the contributing factors to the local net climate effect of land cover change as well as how land cover change may affect climate on the regional and global scale. Any cap-and-trade system ultimately implemented within the U.S. should therefore be able to easily incorporate new scientific research relating to the measurement and verification of the net effect of carbon offset projects.

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## APPENDIX A

**Landsat 7 ETM+ Images and Land Cover:** Examples of the shapefiles created and used to obtain shortwave albedo and surface temperature values

**Figure 3.**

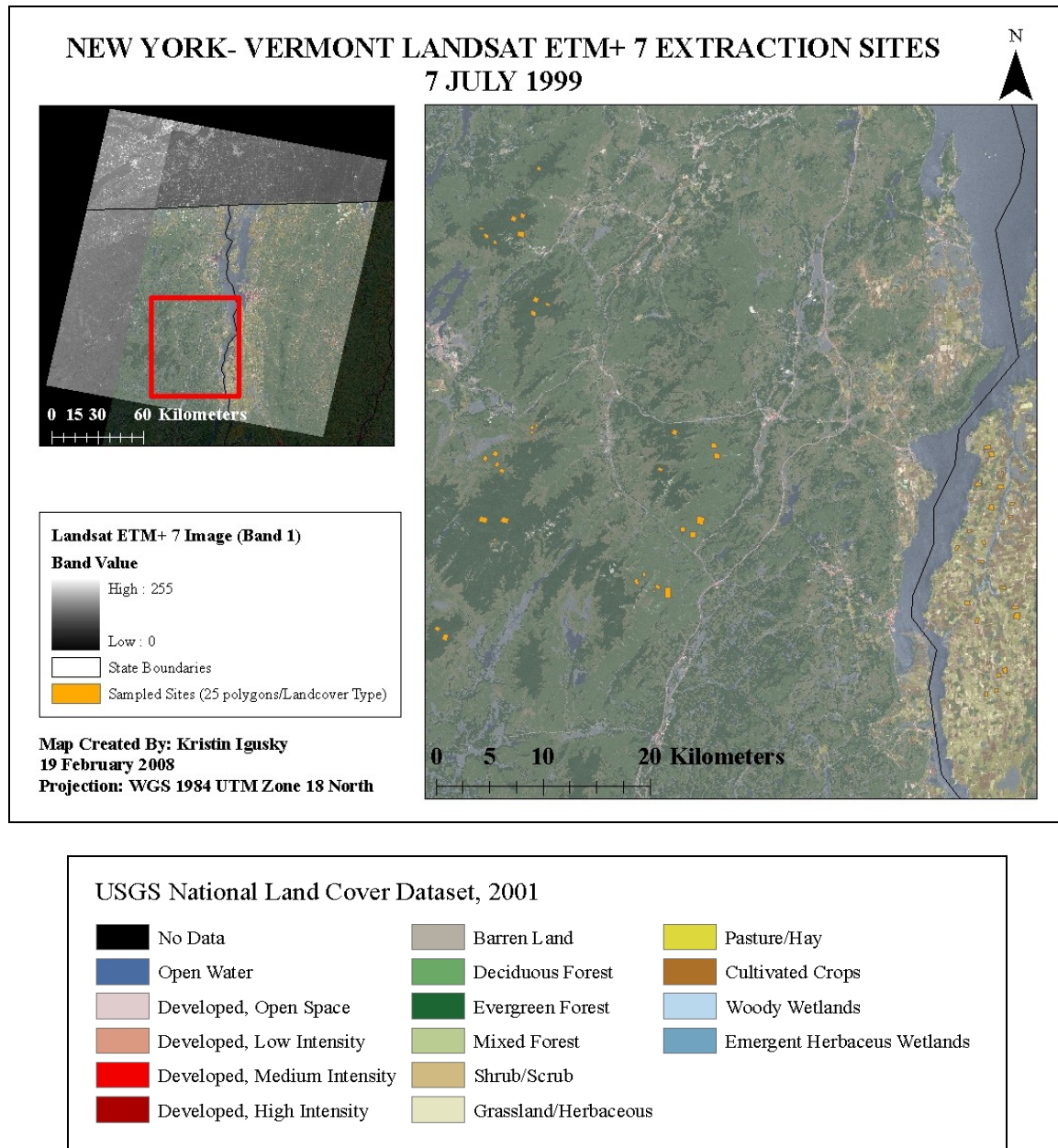


Figure 3 shows the land cover over northern New York and Vermont as well as the Landsat 7 ETM+ image used to obtain shortwave albedo and surface temperatures across the different land covers located within this area. SW albedo and surface temperatures were extracted from this image using 25 polygons/land cover as shown in orange.



**Figure 4.**

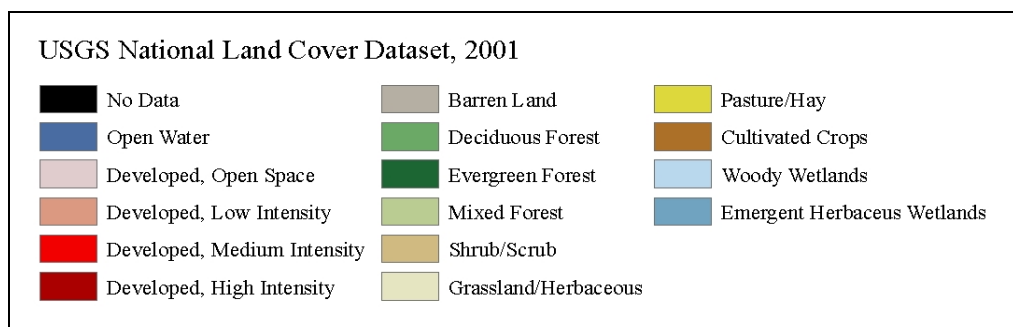
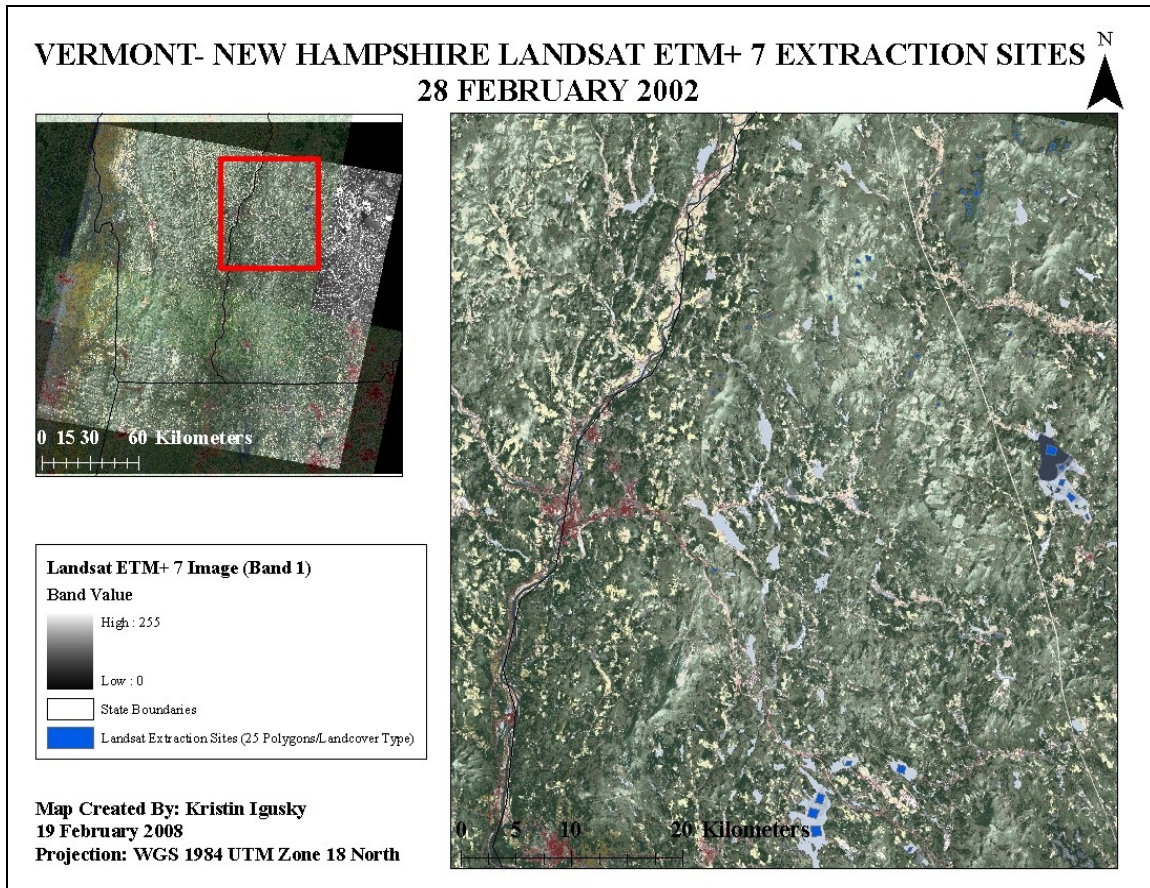


Figure 4 shows the land cover over northern Vermont and New Hampshire as well as the Landsat 7 ETM+ image used to obtain shortwave albedo and surface temperatures across the different land covers located within this area. SW albedo and surface temperatures were extracted from this image using 25 polygons/land cover as shown in blue.



**Figure 5.**

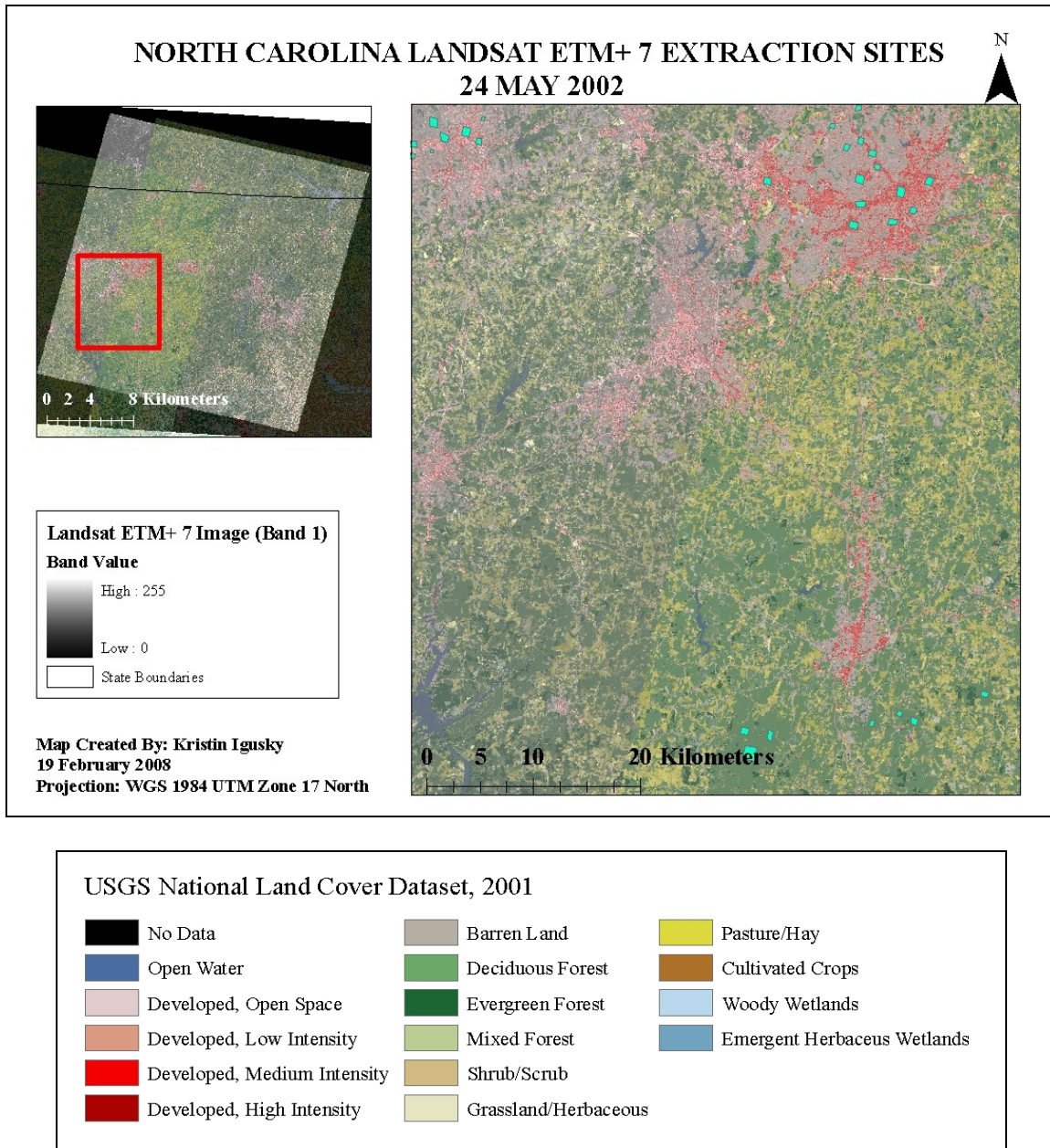


Figure 5 shows the land cover over central North Carolina as well as the Landsat 7 ETM+ image used to obtain shortwave albedo and surface temperatures across the different land covers located within this area. SW albedo and surface temperatures were extracted from this image using 25 polygons/land cover as shown in light green.

## APPENDIX B

### Summary of Previous Studies

**Table 3. Study Comparison: Grassland Albedo**

Study	Albedo/Energy Flux	Location	Additional Information
Federer (1968)	0.19	New Hampshire	Summer
Federer (1968)	0.73	New Hampshire	Winter
Moore (1976)	0.24±0.01	SE Australia	Spring and summer
Moore (1976)	0.27±0.03	SE Australia	Winter and spring
Monteith and Szeicz (1976)	0.26	rothamsted uk	Daily summer mean
Kessler and Jaeger (1999)	0.225±0.017	Northern Germany	Yearly average
Stiller <i>et. al.</i> (2005)	0.16-0.20	Falkenberg, Germany	Warm season
Rost and Mayer (2006)	51W/m2	Southwest Germany	4.5 year mean of net all-wave radiation
Landsat ETM+ 7	0.1300	New York-Vermont	7/21/1999
Landsat ETM+ 7	0.5104	Vermont-New Hampshire	2/28/2002
Landsat ETM+ 7	0.2163	North Carolina	6/24/2002

Table 3 shows albedo values of grassland sites obtained from previous studies.

**Table 4. Study Comparison: Evergreen Forest Albedo**

Study	Albedo/Energy Flux	Location	Additional Information
Federer (1968)	0.13-0.15	New Hampshire	Summer
Federer (1968)	0.16	New Hampshire	Winter
Stewart (1971)	0.088-0.099	Norfolk, UK	Mid June-mid August, dry canopy
Stewart (1971)	0.081-0.11	Norfolk, UK	Mid June-mid August, wet canopy
Moore (1976)	0.11±0.04	SE Australia	Winter and Spring
Kessler and Jaeger (1999)	0.101±0.009	Southern Germany	Yearly average
Stiller <i>et. al.</i> (2005)	0.1	Kehrigk Germany	Without snow cover
Rost and Mayer (2006)	66W/m2	Southwest Germany	4.5 year mean of net all-wave radiation
Landsat ETM+ 7	0.1075	New York-Vermont	7/21/1999
Landsat ETM+ 7	0.2144	Vermont-New Hampshire	2/28/2002
Landsat ETM+ 7	0.1725	North Carolina	6/24/2002

Table 4 shows albedo values of evergreen forest sites obtained from previous studies.