Empirical analysis of the influence of forest extent on annual and seasonal surface temperatures for the continental United States

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Abstract

Aim Because of the low albedo of forests and other biophysical factors, most scenario-based climate modeling studies indicate that temperate forest removal will promote cooling, indicating that temperate forests are a source of heat relative to other classes of land cover. Our objective was to test the hypothesis that US temperate forests reduce surface temperatures.

Location The continental United States.

Methods Ordinary least squares regression was used to develop relationships between forest extent and surface temperature. Forest extent was derived from the 900 m^2 2001 National Land Cover Database (NLCD 2001) and surface temperature data were from the MODIS 1 km^2 eight-day composite (MYD11A2). Forest - surface temperature relationships were developed for winter, spring, summer, fall, and annually using five years of MODIS Land Surface Temperature (LST) data (2007-2011) across six spatial scales (1 km^2, 4 km^2, 9 km^2, 16 km^2, 25 km^2, 36 km^2). Regression models controlled for the effects elevation, aspect, and latitude(by constraining the regressions within a 1° range).

Results We did not find any significant positive slopes in regressions of average annual surface temperatures versus the proportion of forest, indicating that forests are not a source of heat relative to other types of land cover. We found that surface temperatures declined as the proportion of forest increased for spring, summer, fall, and annually. The forest-surface temperature relationship was also scale dependent in that spatially extensive forests produced cooler surface temperatures than forests that were dominant only locally.

Main Conclusions Our results are not consistent with most scenario-based climate modeling studies. Because of their warming potential, the value of temperate afforestation as a potential climate change mitigation strategy is unclear. Our results indicate that temperate afforestation is a climate change mitigation strategy that should be implemented to promote spatially extensive forests.

Keywords
Albedo, Climate change, Ecosystem services, Land cover, MODIS, NLCD, Scale, Sustainability

Introduction

Most scenario-based climate modeling studies show that removal of temperate forest decreases surface temperatures (Table 1). These findings are based on comparisons of climate model outputs for different land cover scenarios, with the main difference being that forest in one scenario (e.g., historical) is replaced by agriculture in the other scenario (e.g., current). Model outputs that report cooler surface temperatures when forest is removed attribute these results primarily to lower surface albedos for forests (Bonan, 1997, 1999; Betts, 2001; Bounoua et al. 2002, Defries et al. 2002; Matthews et al. 2003, 2004; Bala et al. 2007; Jackson et al. 2008; Diffenbaugh, 2009), as well as greater frictional resistance to transpiration in forests than croplands(Bonan, 1997) and the increased roughness length of forests (Bonan 2002; Lee et al. 2011).

Albedo and transpiration are two competing biophysical factors that influence the degree to which forests increase or decrease surface temperatures. Forest albedo tends to be low (Hollinger et al. 2010), making forests comparatively dark objects that absorb incoming solar radiation leading to higher surface temperatures compared to other types of land cover (e.g., cropland). Transpiration is a counteracting radiative force that cools and moistens the atmosphere. The relative influences of albedo and transpiration change along a gradient from the equator to the poles (Bonan, 2008). In tropical forests, evaporative cooling from transpiration is greater than sensible warming attributable to a low forest albedo. However, for extra-tropical latitudes, the relative influences of albedo and transpiration are reversed, and sensible warming from a low albedo is greater than the cooling effect of transpiration. The gradient of net cooling in tropical forests to net warming in temperate and boreal forests is ultimately driven by sun angle and seasonality. Transpiration is essentially a year-round process in the tropics, but it is only seasonally active at higher latitudes. Conversion of the sun's energy to sensible heat is not counteracted by the cooling effects of transpiration when forests are seasonally dormant.

An implication of the scenario-based climate modeling studies is that temperate forests are a source of heat relative to other land-cover classes, such as cropland. In the absence of transpiration, the lower albedo of forest leads to higher surface temperatures. These results suggest that there should be a positive relationship between surface temperatures and extant temperate forest. Here we develop relationships between forest (and other land-cover classes) and surface temperature for the continental United States. In contrast to the results from most of the scenario-based climate modeling studies, we hypothesize that surface temperatures will be cooler for locations surrounded by forest than locations surrounded by other land-cover classes. We anticipate an inverse relationship between the proportion of forest and surface temperatures for all seasons (including annual). Confirmation of our hypothesis would be consistent with the comparatively few scenario-based climate modeling studies that found that temperate forests decreased surface temperatures (Table 1), and field-based studies that show that temperate forests are cooler, wetter, and less windy than surrounding fields (Matlack, 1993; Chen et al. 1993; Davies-Colley et al. 2000; Juang et al. 2007).

We also hypothesize that the forest- surface temperature relationship will change as a function of the spatial scale (i.e., geographic extent) over which the proportion of forest is measured. The landscape is heterogeneous and composed of smaller "hotspots" (e.g., cities) within a mix of other types of land cover (Baidya Roy et al. 2003a). Such "hotspots" lead to higher surface temperatures relative to locations where "hotspots" are absent. The abundance of "hotspots" decreases as the amount of forest increases. Surface temperatures will be cooler for those locations surrounded by regionally extensive forest as compared to locations where forest is dominant only locally.

Methods

Surface temperatures were taken from the MODIS-Aqua Version 5, 8-day composite (MYD11A2). MODIS Version 5 includes the latest developments and refinements to the MODIS Land Surface Temperature (LST) data (Wan 2008). MODIS LST data measure the surface or "skin" temperature. The MODIS LST values represent the canopy temperature for vegetated surfaces and substrate temperature for bare ground. Surface temperature is an important climatic variable that is used to derive sensible and latent heat fluxes (Jin et al. 2004). The MYD11A2 data have a spatial resolution of 1 km^2. We chose the afternoon overpasses (MODIS-AQUA) rather than the morning overpasses (MODIS-TERRA) so that the forest - surface temperature relationship was based on the warmer part of the day. We also included the nighttime MODIS observations in our analysis because omission of nighttime temperatures could lead to biased estimates of the effect of forest on surface temperature (Lee et al. 2011). The surface temperatures were collected for the years 2007, 2008, 2009, 2010, and 2011 to calculate seasonal (spring = March, April, May; summer = June, July, August; fall = September, October, November; winter = December, January, February) and annual means for the five-year period. All averages were based on the mean of the daily maxima and minima surface temperatures. For each season, pixels with less than six values (due to cloud cover) were discarded, and annual averages were not computed for discarded pixels.

We used the NLCD 2001 land-cover data (Homer et al. 2007) to estimate land-cover proportions surrounding each MODIS LST pixel. The NLCD 2001 land-cover data have a spatial resolution of 0.09 ha (30m-X-30 m). For analysis of relationships between forest and surface temperature, we aggregated the four forest classes (upland deciduous, upland evergreen, upland mixed, and woody wetland) into a single forest class; however, nearly the full thematic resolution of the data was retained to support the forest - surface temperature analyses. The full NLCD 2001 class definitions are available at http://www.mrlc.gov/nlcd01_leg.php. The NLCD 2001 land-cover data were processed by using a moving window analysis to calculate the proportion of each land-cover class at six spatial scales (Riitters *et al.* 2000). The moving window side-length scales (hereafter length scales) were 1, 2, 3, 4, 5, and 6 km, yielding window size areas of 1, 4, 9, 16, 25, and 36 km^2. Once the moving window analysis was completed, we converted the MODIS data to points (at the pixel center) and overlaid them on the NLCD land-cover data. The overlay assigned land-cover proportions for each land-cover class at each spatial scale to each MODIS point (pixel). We also calculated elevation, aspect, latitude, and longitude for each MODIS point. Elevation and aspect were computed using the 0.09 ha National Elevation Data (NED) set (Gesch et al. 2002). Elevation was computed as the average of the 0.09 ha pixels within each 1 km^2 MODIS pixel, and aspect was computed as the modal (most common) value of the 0.09 ha pixels within each 1 km^2 MODIS pixel. Latitude and longitude were computed using routines available in commercial GIS packages.

Relationships between forest and surface temperature were modeled using ordinary least squares regression using a simple bivariate (Y=X) format. We chose this format to provide straightforward, interpretable results. Significant positive (negative) slopes would indicate that forests are warmer (cooler) than surrounding land-cover classes. The regression analyses were conducted for 21 100km-X-200km cells distributed across the continental United States (Fig. 1). The 100km (~0.9° latitude) N-S cell dimension was chosen to control for the effect of latitude. Within each 100km-X-200km cell, one MODIS LST observation (point) was chosen from a 5km-X-5km grid (Fig. S1) to control of the effect of spatial correlation on the interpretation of significance. Where needed, regressions included observation within an elevation range that did not have a significant correlation with surface temperature. The effect of aspect was also tested using analysis of covariance and found not to be significant.

The MODIS LST eight-day composites are constructed to provide surface temperatures under clear-sky conditions. Cloud contaminated pixels are not included (Wan 2008) in construction of the eight-day averages (Wan et al. 2002). Thus, our regression models represent forest - surface temperature relationships under conditions when albedo, an important biophysical factor controlling the influence of forest on surface temperature (Betts 2001; Defries et al. 2002; Brovkin et al. 2004; Davin and Noblet-Ducoudré 2010), is most influential (Hollinger et al. 2010).

Results

None of the cells had a significant positive relationship between forest proportion and surface temperature (Table 2). Overall, there was either no relationship or an inverse relationship between average annual surface temperatures and proportion of forest. Using an R^2 value of 0.30 as a nominal (conservative) threshold for significance, 12 of the 21 cells had a significant inverse relationship between surface temperature and proportion of forest, indicating that average annual surface temperatures decline as the amount of forest increases. For the remaining cells, model slopes were still negative for six, positive for two, and not significantly different from zero for one. However, since the model R^2 values for these nine cells were less than 0.30, our interpretation is that there was not a "significant" spatial pattern between surface temperature and proportion of forest for these locations. For the 12 cells with significant inverse relationships, the slopes provide a coarse estimate of the cooling effect of forest. The median slope for the 12 cells was -2.8°C, indicating that average annual surface temperatures are substantially cooler in homogeneous forest as compared to the absence of forest.

Agriculture in the eastern United States and shrublands in the western United States tend to dominate the landscape when the amount of forest is low, suggesting that substituting either agriculture or shrubland into the regression equations as a replacement for forest would produce the opposite effect. This was found to be the case (results not shown). Regressions of surface temperature versus the proportion of agriculture or shrubland resulted in significant positive slopes for those cells that had significant inverse relationships between average annual surface temperatures and proportion of forest.

In part because of the simple models (Y=X) used, there was substantial variation around the regression line, and a common (but not universal) error pattern was substantially higher residuals at lower forest proportions than at higher forest proportions (Fig. 2 & 3). This heteroscedastic residual pattern indicates that the goodness-of-fit improves as the proportion of forest increases. In addition, this pattern was expected because surface temperatures would tend to be much warmer in urban settings and much cooler for observations close to large water bodies. These contextual settings probably reduced the R^2 value for cell 1 (Fig. 4). The four observations with average annual surface temperatures above 11.0°C had high proportions of urban and many of the observations with very low surface temperatures and forest proportions less than 0.5 were located along coastal islands (see Fig. S1).

Many (e.g., Figs. 2 & 3) but not all (e.g., Fig. 4) of the models had an asymptotic-like relationship between model R^2 values and the spatial extent over which forest proportion was measured (Figs. S2-S10). Model R^2 values increased substantially between the 1km and 2km scale and sometimes between the 2km and 3km scale with comparatively smaller changes in model R^2 values through the 3km to 6km scales.

There was a geographic pattern related to the model R^2 values. Excluding cell 3, cells with significant inverse relationships between average annual surface temperatures and proportion of forest formed a U-shaped pattern that included all southern cells (south of 35°N) and coastal cells as far north Oregon (cell 4) and Connecticut (cell 8), suggesting that maritime settings influenced the surface temperature-forest relationship. Again excluding cell 3, the continental cells (5-7, 11-14) had weak to insignificant relationships between average annual surface temperature and the proportion of forest.

The spring and the fall patterns were nearly identical to the average annual pattern (Table 3). Nearly the same set of cells had model R^2 values greater than the nominal threshold of 0.30 and negative slopes. In the summer, as expected, there was nearly a uniform response of negative slopes and high model R^2 values. All slopes except one were negative and model R^2 values were greater than our nominal threshold of 0.30 for 16 of 21 cells. In winter, model R^2 values were lower overall, with fewer model R^2 values meeting the 0.3 nominal threshold and a higher incidence of positive slopes.

Discussion

Our results were not consistent with the predominant finding of scenario-based climate change studies that temperate forests are a source of heat relative to types of land cover. We found that average annual surface temperatures declined as the proportion of forest increased for 12 of 21 cells studied and weakly inverse or insignificant relationships for the other nine cells. No significant positive relationships between average annual surface temperature and the amount of forest were found.

Our results are consistent with the comparatively few climate change studies that found the removal of temperate forest leads to warming (Table 1), and the field-based studies that report that forests tend to be cooler and wetter than surrounding fields (Matlack, 1993; Chen et al. 1993; Davies-Colley et al. 2000; Juang et al. 2007). There is also modest agreement between our results and those of Lee et al. (2011). Using paired forest - open field observations across the continental U.S. and Canada, Lee et al (2010) reported that forested sites were cooler for 8 of 20 of the pairs between 25° N and 45° N.

Our results are based on a five-year temporal domain. Climate models generally use longer time horizons for calibration than the five years used in this study (Bonan, 1997). Given the strong consistency in the inverse relationship between the proportion of forest and surface temperature, we expect that a longer temporal record would strengthen and not fundamentally change the relationships that we found, which was that temperate forests tend to reduce surface temperatures.

Two factors may contribute to the inconsistency between our results and those from the majority of the scenario-based climate change studies. Our results are more similar to the output from land surface models than the scenario-based climate studies that couple land surface and general circulation models (GCM) to assess the impact of land-cover change on global climate. Land surface models (LSM) provide the land-atmosphere energy fluxes that are used to drive GCMs (Bonan, 1997), and our empirical analyses address just one aspect of the land-atmosphere energy flux (temperature). Bonan (1999) noted that output from a land surface model alone (i.e., not linked to a GCM) showed that replacement of forest with bare ground increased surface temperature, which is consistent with our results. Also, Bala et al. (2007) pointed out that biophysical effects (e.g., albedo, transpiration) tend to be local, whereas biogeochemical effects (e.g., carbon cycle) tend to be global. The inconsistency between our results and studies that reported cooling as a result of forest removal (Table 1) may be attributable to atmospheric processes that are modeled in GCMs but are not captured in our empirical analysis.

Another possible explanation of the inconsistency may lie in the estimation of albedo. Estimation of albedo has not improved at that same pace as other model parameters (Alton, 2009; Hollinger et al. 2010; Heilman et al. 2010). Albedo is influenced by atmospheric conditions (cloudy versus clear), sun angle (season and time of day), soil color, and foliage nitrogen concentration (Bonan 1997; Hollinger et al. 2010; Heilman et al. 2010). Hollinger et al. (2010) reported albedo estimates from six different climate modeling studies. September and October albedos ranged from 0.16 to 0.25 for croplands and 0.12 to 0.19 for broadleaf deciduous trees, yielding a mean difference of only 0.05 between the two vegetation types across the six studies. The albedo gradient across a landscape comprised of cropland and temperate deciduous forest appears to be small and may be non-existent in some cases since there is considerable overlap among reported cropland and forest albedos.

We speculate that boreal deforestation may be driving the cooling realized in the scenario-based climate change studies. Boreal deforestation changes the wintertime albedo from one that could be characterized as "dirty" snow (snow and dark trees) to a more "pristine" snow cover (snow without dark trees). Bonan (2002) reports an albedo range for fresh snow of 0.80 to 0.95 and an albedo range for old snow of 0.45 to 0.70. Using fresh snow to represent the albedo of a deforested boreal region and old snow to represent the albedo of a forested boreal region produces a greater difference in albedo than the differences reported between deciduous forest and cropland (e.g., Hollinger et al. 2010). Davin and Noblet-Ducoudré (2010) found that cooling in the temperate region arose from the reduction in sea surface temperature that was driven by boreal deforestation.

The influence of snow on surface temperature may in part explain the geographic "U-shaped" pattern of significant inverse relationships between forest and surface temperatures in our study. The "U-shaped" pattern is in general agreement with the long-term snowfall pattern for the conterminous United States (Kunkel et al. 2009). According to Kunkel et al. (2009), snowfall is absent in the southern United States, has been declining over the long-term along the coastal margins, and increasing over the long term in the mid-continental region. Most of the cells in the mid-continental region had weak to insignificant relationships between forest and average annual surface temperatures that were the result of positive relationships for the winter season and negative relationships for the summer season (Table 3). The positive relationship between forest and winter surface temperature in the mid-continental region is likely attributable to the reduction in albedo that arises from mixing trees and snow cover as compared to a herbaceous vegetation with snow cover that does not include trees.

A novelty in our results was the scale-dependent relationship between the proportion of forest and surface temperatures. For many cells, the strength of the modeled relationships increased and predicted surface temperatures decreased as the scale at which the proportion of forest was measured increased. Spatially extensive forests produced greater cooling than forests that were not spatially extensive, and the certainty of that statement increased as the spatial scale of forest dominance increased. Our scale-dependent relationship between the proportion of forest and surface temperature is consistent with Kapos (1989), who found that the interior sections of 100 ha forests were cooler and wetter than the interior sections of 1 ha forests. Our results also link forest fragmentation and climate over broad regions. Historically, the primary motivation for most forest fragmentation studies has been to evaluate biodiversity impacts from habitat fragmentation (Saunders et al. 1991; Bissonette & Storch, 2002), and to generally inform forest management and preservation (Stein 2009). Forests in the continental United States are heavily fragmented (Riitters et al. 2002; Heilman et al. 2002), and continued forest loss appears to be reducing the spatial scale at which forest dominates the landscape (Wickham et al. 2008). Future forest loss will likely reduce the amount of spatially extensive forests (Wickham et al. 2008), and this change in the pattern of forest extent may result in increases in surface temperatures.

Model outcomes that show that temperate forests are a relative source of heat has motivated discussion about the value of temperate afforestation as a strategy for mitigation of global warming (Bala et al. 2007; Bonan 2008; Jackson et al. 2008). Our results indicate that temperate forests tend to produce cooler surface temperatures. The policy implication of our results is that temperate afforestation is an ecologically intuitive strategy for mitigation of global warming, and that it should be implemented in such a way as to promote spatially extensive forests.

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Supplementary Material

Additional supporting information may be found in the online version of this article:

Appendix S1 Supplemental figures.

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Biosketch

James D. Wickham is a Senior Research Biologist with the National Exposure Research Laboratory (NERL), U.S. Environmental Protection Agency. His research interests include remote sensing, GIS, the role of land-cover change in understanding environmental condition.

Table 1: Studies of the effect of deforestation on temperature. Blank entries indicate information was not reported. Only the first author is reported. Resolution is expressed in latitude and longitude unless otherwise noted. Abbreviations include GCM (atmospheric general circulation model), PNV (potential natural vegetation), NH (northern hemisphere), LC (land cover), NAM (North America)l, ↑ (increase), and ↓(decrease).

Author	Year	GCM	Surface Model	Resolution	Geographic extent	Main finding
Temperate deforestation produces cooler temperatures						
Bonan	1997	CCM2	LSM	2.8°x2.8°	Continental US	Present-day LC ↓ spring temperature by 1°C over eastern US compared to PNV.
Hansen	1998				Global	Deforestation ↓temperature up to 1.9°C over much of the eastern US.
Bonan	1999	CCM3	LSM	2.8°x2.8°	Continental US	Present-day LC ↓annual temperature 0.6-1.0°C over eastern US compared to PNV.
Brovkin	1999	CLIMBER-2	BATS	10°x51°	Global	Global deforestation ↓ temperature 0.5°C over the NH.
Betts	2001	HadAM3	MOSES	3.75°x2.5°	Global	Present-day LC ↓ seasonal temperatures 0.5-2.0°K in eastern US compared to PNV.
Bounoua	2002	CSU-GCM	SiB2	4°x5°	Global	Replacing forest & grassland with cropland ↓summer and winter temperatures.
Defries	2002	CSU-GCM	SiB2	4°x5°	Global	Replacing forest with cropland ↓ annual temperatures for NAM sites.
Diffenbaugh	2002	CCM3	LSM	2.8°x2.8°	Global	Present-day LC produced summer cooling compared to Mid Holocene PNV.
Matthews	2003 &2004	Uvic	Bucket/ MOSES	1.8°x3.6°	Global	Present-day LC ↓ temperature up to 0.3°C over eastern NAM compared to PNV.
Brovkin	2004	CLIMBER-2		10°x51°	Global	Present-day LC ↓ temperature at mid- and higher latitudes over land.
Oleson	2004	CCM	LSM	2.8°	NAM	Present-day LC ↓summer temperature, compared to PNV.
Feddema	2005	DOE-PCM				Agricultural expansion in mid-latitudes produced cooling.
Gibbard	2005	CAM3	CLM3	2.0°x2.5°	Global	Mid-latitude afforestion↑ temperature.
Brovkin	2006	6 models		4°x4° to 10°x51°	Global	All models showed ↓in annual temperature as a result of deforestation.
Bala	2007	INCCA			Global	Deforestation ↓temperature by 0.7°K over NH mid-latitudes.
Diffenbaugh	2009	RegCM3	BATS	25km	Continental US	Present-day LC ↓temperatures by0.19° K over continental US compared to PNV.
Temperate deforestation produces warmer temperatures						
Baidya Roy	2003b	RAMS	LEAF-2	100km	Continental US	Present-day LC ↑ July temperature 0.3-0.6°K over eastern US compared to PNV.
Marshall	2004	RAMS	LEAF-2	10 & 40 km	Florida	Present-day LC ↑warm season daily maxima compared to pre-1900 PNV.
Jackson	2005	RAMS	LEAF-2	60 km	Continental US	Afforestation ↓ temperatures in the Midwest, Texas, and the southeast.
Ramankutty	2006	CCM3	IBIS	3.75°x3.75°	Global	Replacing forest with grasslands ↑ temperature

Table 2: Slope and goodness-of-fit for average annual surface temperature versus proportion of forest at 6km and 1km length scales. Insignificant models ($p > 0.05$) are denoted with a value of 0 for the slope and n.s. (not significant) in the R^2 column. The column elevation range reports the range of elevations over which the bivariate regressions were conducted. Blank entries for elevation range indicate that elevation and average annual surface temperature were not correlated and thus no constraints were imposed.

Cell	# obs	Slope, 6km	Slope, 1km	R^2, 6km	R^2, 1km	Elevation range (m)
1	194	-1.95	-1.44	0.20	0.23	$0 \leq x \leq 200$
2	166	0.60	0.33	0.06	0.04	$114 \leq x \leq 215$
3	292	-4.12	-2.95	0.54	0.39	$775 \leq x \leq 1250$
4	240	-4.03	-3.35	0.73	0.65	$50 \leq x \leq 250$
5	652	-1.05	-0.30	0.10	0.02	
6	165	1.60	1.27	0.03	0.05	$2200 \leq x \leq 2450$
7	246	-0.46	0.00	0.04	n.s.	$420 \leq x \leq 549$
8	263	-2.82	-1.91	0.50	0.38	$0 \leq x \leq 100$
9	133	-7.69	-6.33	0.83	0.74	$300 \leq x \leq 600$
10	372	-3.14	-2.29	0.36	0.29	$0 \leq x \leq 100$
11	118	0.00	0.00	n.s.	n.s.	$2000 \leq x \leq 2250$
12	578	-1.07	-0.70	0.13	0.12	
13	325	-1.77	-1.60	0.09	0.11	$2013 \leq x \leq 2400$
14	775	-0.69	-0.35	0.16	0.07	
15	588	-2.82	-1.77	0.44	0.33	
16	113	-2.85	-2.33	0.41	0.33	$2100 \leq x \leq 2300$
17	797	-1.50	-0.95	0.45	0.34	
18	470	-1.83	-1.10	0.45	0.31	$150 \leq x \leq 317$
19	796	-4.03	-1.93	0.55	0.33	
20	739	-3.10	-2.10	0.53	0.41	
21	784	-2.52	-1.52	0.49	0.36	

Table 3: Slope and goodness-of-fit between average seasonal surface temperatures and proportion of forest for the 6km length scale. Insignificant models ($p > 0.05$) are denoted with a value of 0 for the slope and n.s. (not significant) in the R^2 column. Regressions were conducted over the same elevations ranges as reported in Table 2.

	Winter		**Spring**		**Summer**		**Fall**	
Cell	**Slope**	**R^2**	**Slope**	**R^2**	**Slope**	**R^2**	**Slope**	**R^2**
1	-2.90	0.36	-2.03	0.11	-1.29	0.02	-1.56	0.21
2	4.82	0.58	0.00	n.s	-1.65	0.33	-0.54	0.06
3	-1.30	0.02	-6.85	0.49	-5.76	0.37	-2.55	0.28
4	-2.27	0.64	-3.46	0.53	-7.05	0.69	-3.33	0.68
5	-1.22	0.04	0.94	0.03	-2.16	0.22	-1.76	0.12
6	3.01	0.05	3.92	0.09	0.00	n.s	0.00	n.s
7	1.37	0.17	-1.15	0.14	-1.78	0.26	0.00	n.s
8	-1.82	0.17	-1.79	0.15	-4.93	0.49	-2.73	0.53
9	-1.87	0.32	-8.22	0.84	-14.27	0.88	-6.40	0.77
10	0.00	n.s	-3.47	0.38	-5.96	0.52	-2.84	0.42
11	5.61	0.22	-1.51	0.03	-6.99	0.56	-1.39	0.08
12	0.65	0.03	-1.05	0.11	-2.80	0.31	-1.09	0.13
13	2.59	0.08	-4.03	0.30	-4.05	0.21	-1.61	0.14
14	0.00	n.s	0.96	0.21	-2.93	0.62	-0.89	0.25
15	-1.21	0.20	-2.46	0.28	-4.21	0.47	-3.41	0.54
16	0.00	n.s	-3.59	0.50	-4.84	0.61	-2.34	0.32
17	-0.65	0.10	-2.09	0.50	-1.73	0.35	-1.53	0.41
18	-0.27	0.01	-1.71	0.35	-3.17	0.58	-2.19	0.38
19	-2.16	0.28	-4.88	0.46	-5.02	0.51	-4.06	0.52
20	-2.08	0.43	-3.84	0.54	-3.06	0.41	-3.44	0.56
21	-0.64	0.05	-3.54	0.47	-3.40	0.54	-2.51	0.48

Figure Legends

Figure1: Study area, showing location of cells used for analysis. Cell numbers are referenced in Tables 2 and 3, and all figures.

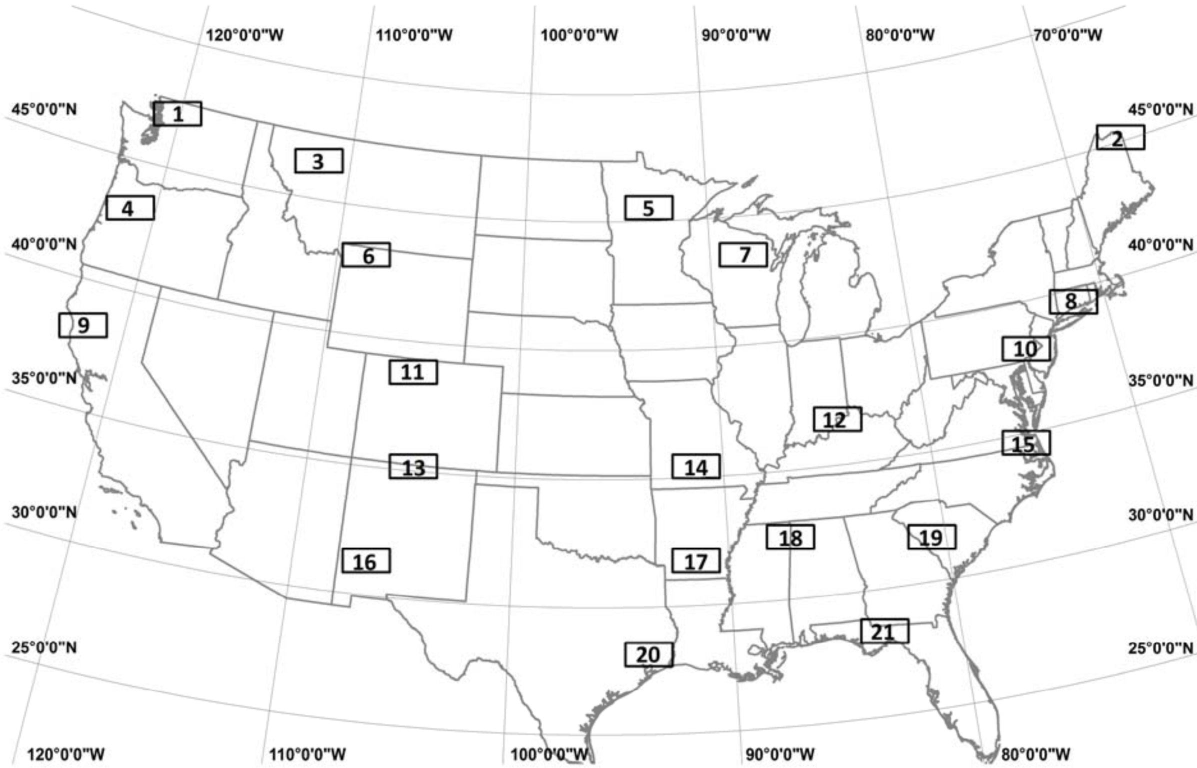
Figure 2: Average annual surface temperature versus proportion of forest for cell 10 at the 6km length scale and R^2 values for average annual surface temperature versus proportion of forest for all six scales.

Figure 3: Average annual surface temperature versus proportion of forest for cell 20 at the 6km length scale and R^2 values for average annual surface temperature versus proportion of forest for all six scales.

Figure 4: Average annual surface temperature versus proportion of forest for cell 1 at the 6km length scale and R^2 values for average annual surface temperature versus proportion of forest for all six scales.

Figure1

295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110°0'0"W
100°0'0"W
90°0'0"W
80°0'0"W
70°0'0"W
45°0'0"N
40°0'0"N
35°0'0"N
30°0'0"N
25°0'0"N
1
2
3
4
5
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18
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20
21

Figure 2

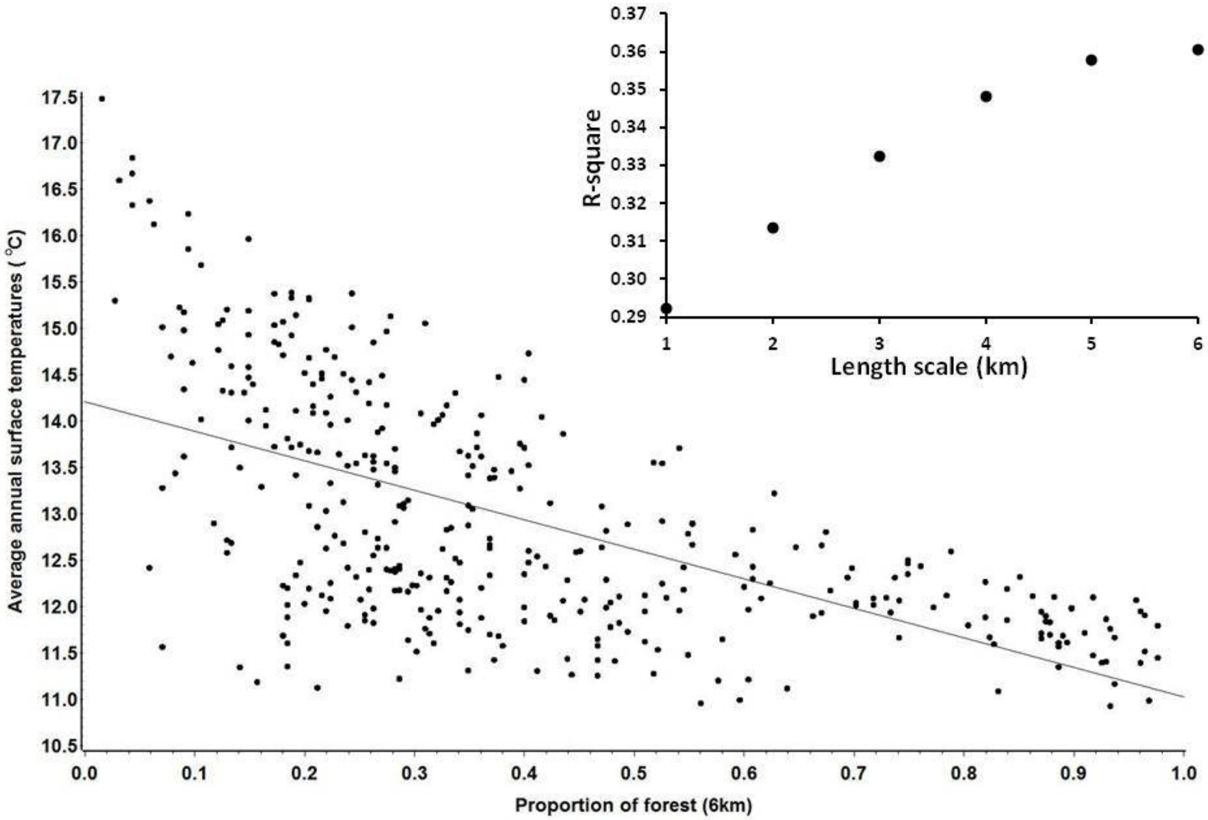

0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
R-square
1
2
3
4
5
6
Length scale (km)
17.5
17.0
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
Average annual surface temperatures (°C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Proportion of forest (6km)

Figure 3

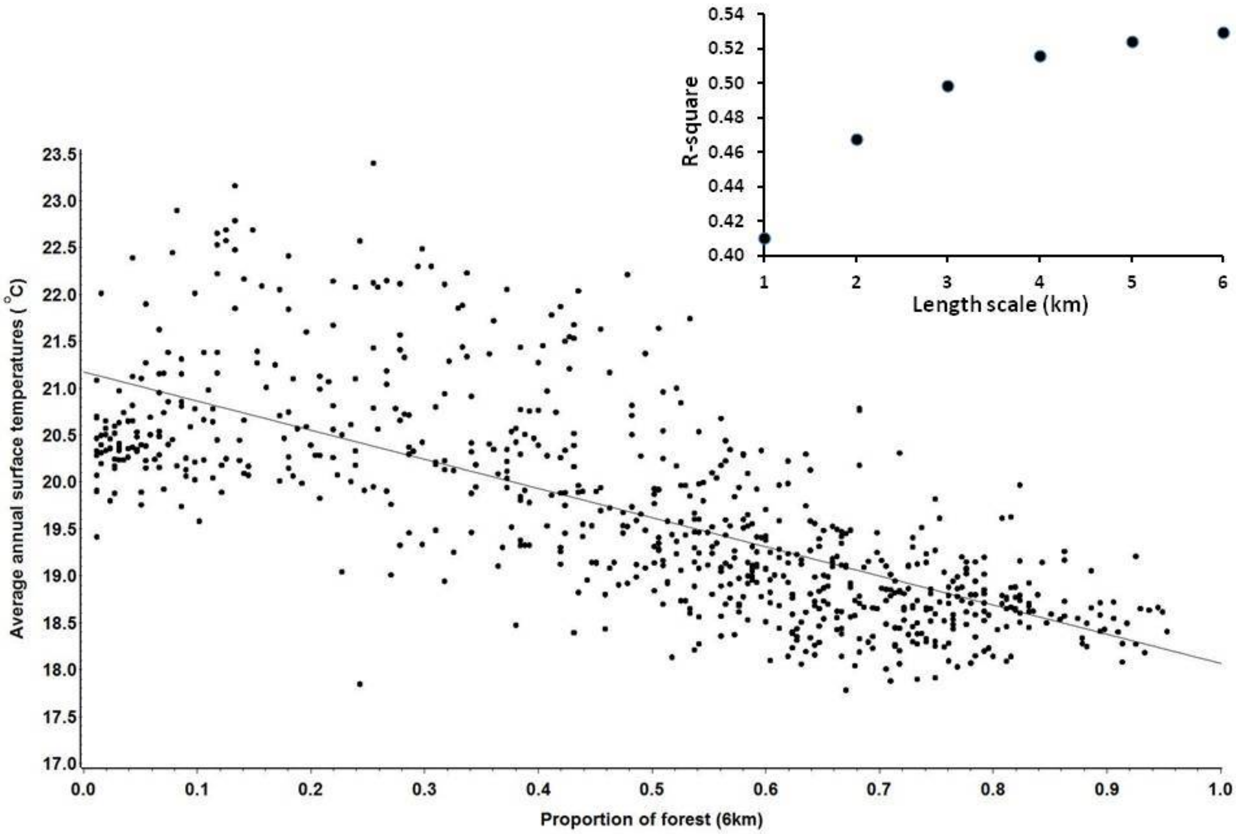
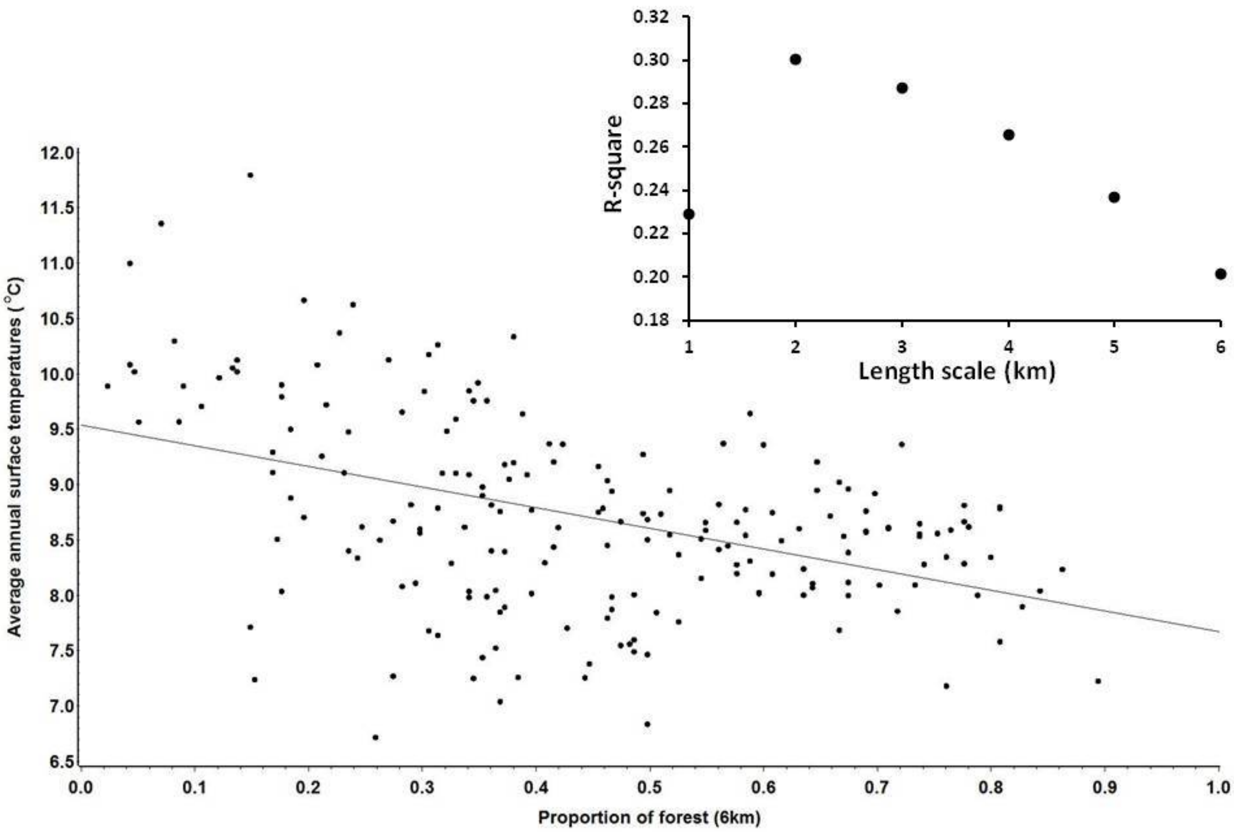

0.54
0.52
0.50
0.48
0.46
0.44
0.42
0.40
R-square
1
2
3
4
5
6
Length scale (km)
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
19.5
19.0
18.5
18.0
17.5
17.0
Average annual surface temperatures (°C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Proportion of forest (6km)

Figure 4


0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
R-square
1
2
3
4
5
6
Length scale (km)
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
Average annual surface temperatures (°C)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Proportion of forest (6km)