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RESEARCH PAPER

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 modelling studies indicate that removal of temperate forest 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 8-day composite (MYD11A2). Forest–surface temperature relationships were developed for winter, spring, summer, autumn and annually using 5 years of MODIS land surface temperature data (2007–11) across six spatial scales (1, 4, 9, 16, 25 and 36 km^2). Regression models controlled for the effects of 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, autumn 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 modelling 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.

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INTRODUCTION

Most scenario-based climate modelling 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

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Table 1 Studies of the effect of deforestation on temperature.

Author(s) and year	GCM	Surface model	Resolution	Geographic extent	Main finding
Temperate deforestation produces cooler temperatures					
Bonan (1997)	CCM2	LSM	2.8° × 2.8°	Continental US	Present-day LC ↓ spring temperature by 1 °C over eastern US compared with PNV
Hansen *et al*. (1998)				Global	Deforestation ↓ temperature up to 1.9 °C over much of the eastern US
Bonan (1999)	CCM3	LSM	2.8° × 2.8°	Continental US	Present-day LC ↓ annual temperature 0.6–1.0 °C over eastern US compared with PNV
Brovkin *et al*. (1999)	CLIMBER-2	BATS	10° × 51°	Global	Global deforestation ↓ temperature 0.5 °C over the NH
Betts (2001)	HadAM3	MOSES	3.75° × 2.5°	Global	Present-day LC ↓ seasonal temperatures 0.5–2.0°K in eastern US compared with PNV
Bounoua *et al*. (2002)	CSU-GCM	SiB2	4° × 5°	Global	Replacing forest and grassland with cropland ↓summer and winter temperatures
Defries *et al*. (2002)	CSU-GCM	SiB2	4° × 5°	Global	Replacing forest with cropland ↓ annual temperatures for NAM sites
Diffenbaugh and Sloan (2002)	CCM3	LSM	2.8° × 2.8°	Global	Present-day LC produced summer cooling compared with Mid-Holocene PNV
Matthews *et al*. (2003, 2004)	Uvic	Bucket/MOSES	1.8° × 3.6°	Global	Present-day LC ↓ temperature up to 0.3 °C over eastern NAM compared with PNV
Brovkin *et al*. (2004)	CLIMBER-2		10° × 51°	Global	Present-day LC ↓ temperature at mid- and higher latitudes over land
Oleson *et al*. (2004)	CCM	LSM	2.8°	NAM	Present-day LC ↓ summer temperature, compared with PNV
Feddema *et al*. (2005)	DOE-PCM				Agricultural expansion in mid-latitudes produced cooling
Gibbard *et al*. (2005)	CAM3	CLM3	2.0° × 2.5°	Global	Mid-latitude afforestation ↑ temperature
Brovkin *et al*. (2006)	6 models		4° × 4° to 10° × 51°	Global	All models showed ↓ in annual temperature as a result of deforestation
Bala *et al*. (2007)	INCCA			Global	Deforestation ↓ temperature by 0.7 K over NH mid-latitudes
Diffenbaugh (2009)	RegCM3	BATS	25 km	Continental US	Present-day LC ↓ temperatures by 0.19 K over continental US compared with PNV
Temperate deforestation produces warmer temperatures					
Baidya Roy *et al*. (2003b)	RAMS	LEAF-2	100 km	Continental US	Present-day LC ↑ July temperature 0.3–0.6 K over eastern US compared with PNV
Marshall *et al*. (2004)	RAMS	LEAF-2	10 and 40 km	Florida	Present-day LC ↑ warm season daily maxima compared with pre-1900 PNV
Jackson *et al*. (2005)	RAMS	LEAF-2	60 km	Continental US	Afforestation ↓ temperatures in the Midwest, Texas and the south-east
Ramankutty *et al*. (2006)	CCM3	IBIS	3.75° × 3.75°	Global	Replacing forest with grasslands ↑ temperature

Blank entries indicate information was not reported. Resolution is expressed in latitude and longitude unless otherwise noted. Abbreviations: GCM, atmospheric general circulation model; PNV, potential natural vegetation; NH, Northern Hemisphere; LC, land cover; NAM, North American; ↑, increase; ↓, decrease.

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 with 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 modelling 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 modelling 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 modelling 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 (Chen *et al.*, 1993; Matlack, 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, 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 night-time MODIS observations in our analysis because omission of night-time 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; autumn = September, October, November; winter = December, January, February) and annual means for the 5-year period. All averages were based on the mean of the daily maximum and minimum surface temperatures. For each season, pixels with fewer 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 (30 m × 30 m). For analysis of relationships between forest and surface temperature, we aggregated the four forest classes (upland deciduous, upland evergreen, upland mixed, 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 centre) 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

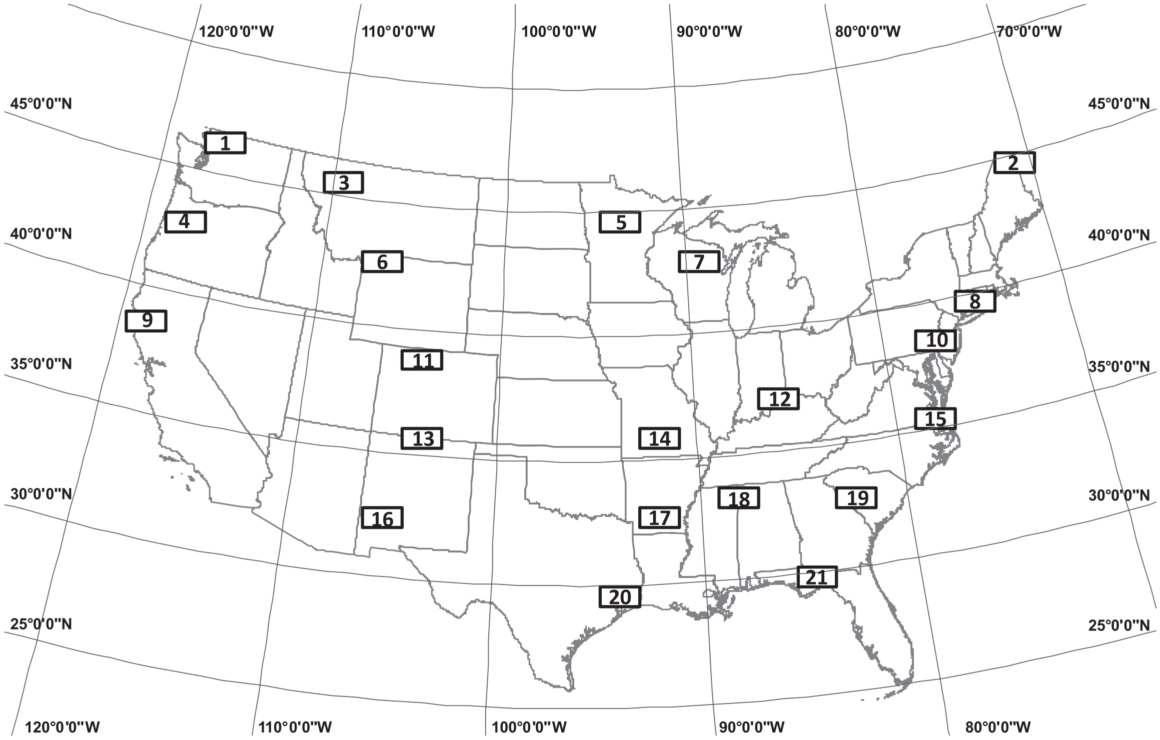

Figure 1 Study area, showing location of cells used for analysis. Cell numbers are referenced in Tables 2 & 3, and all figures.

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 modelled 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 21 100 km × 200 km cells distributed across the continental United States (Fig. 1). The 100 km (*c.* 0.9° latitude) north–south cell dimension was chosen to control for the effect of latitude. Within each 100 km × 200 km cell, one MODIS LST observation (point) was chosen from a 5 km × 5 km grid (Fig. S1 in Supporting Information) to control for the effect of spatial correlation on the interpretation of significance. Where needed, regressions included observations 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 8-day composites are constructed to provide surface temperatures under clear-sky conditions. Cloud-contaminated pixels are not included (Wan, 2008) in construction of the 8-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 & 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 than in 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

Table 2 Slope and goodness of fit for average annual surface temperature versus proportion of forest at 6 and 1 km length scales.

Cell	No. of obs	Slope, 6 km	Slope, 1 km	R^2, 6 km	R^2, 1 km	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	

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.

Table 3 Slope and goodness of fit between average seasonal surface temperatures and proportion of forest for the 6 km length scale.

Cell	Winter		Spring		Summer		Autumn	
	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

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.

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 (Figs 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 area 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–S15). Model R^2 values increased substantially between the 1 and 2 km scales and sometimes between the 2 and 3 km scales with comparatively smaller changes in model R^2 values through the 3 to 6 km 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 autumn 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

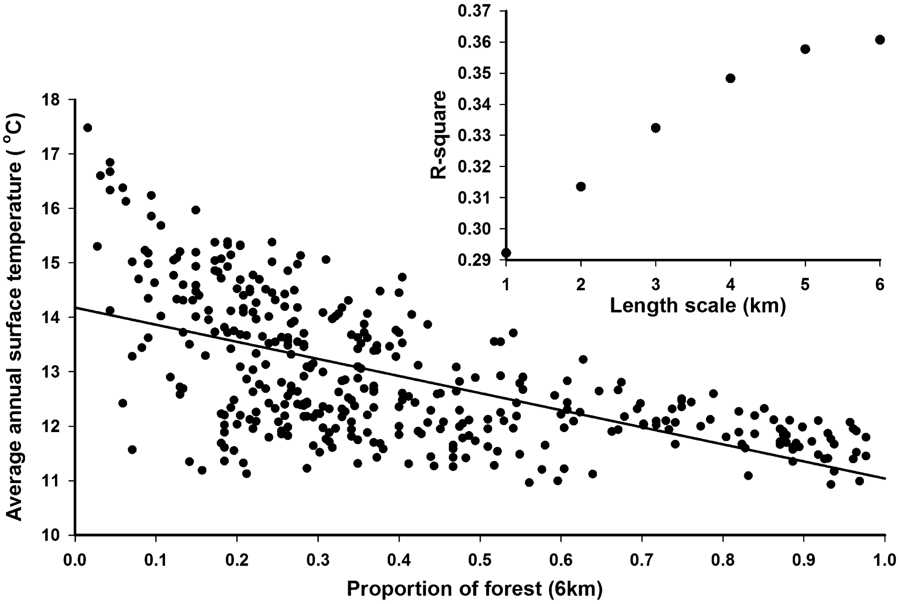

Figure 2 Average annual surface temperature versus proportion of forest for cell 10 at the 6 km length scale and R^2 values for average annual surface temperature versus proportion of forest for all six scales.

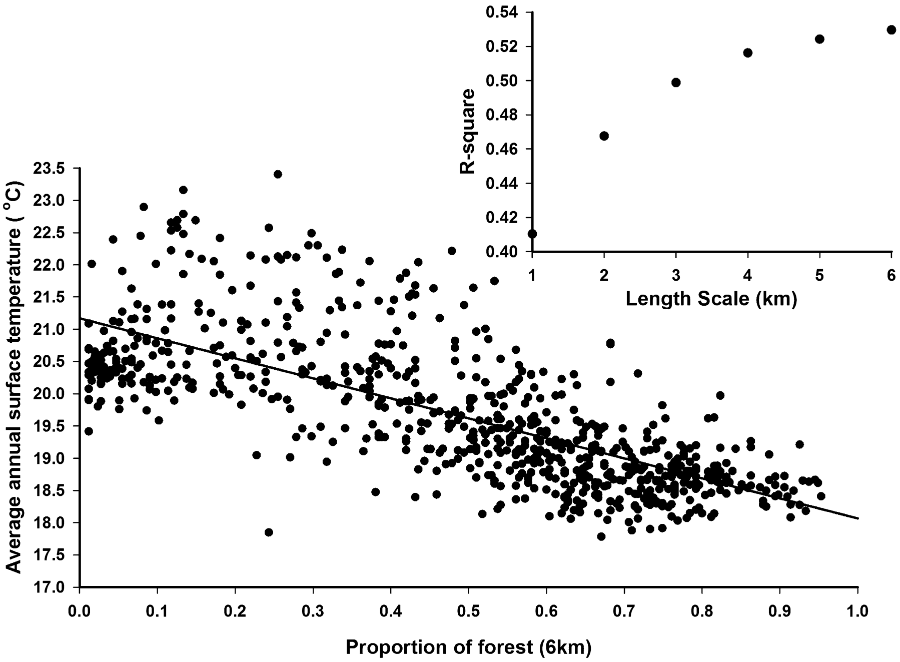

Figure 3 Average annual surface temperature versus proportion of forest for cell 20 at the 6 km length scale and R^2 values for average annual surface temperature versus proportion of forest for all six scales.

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 other 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

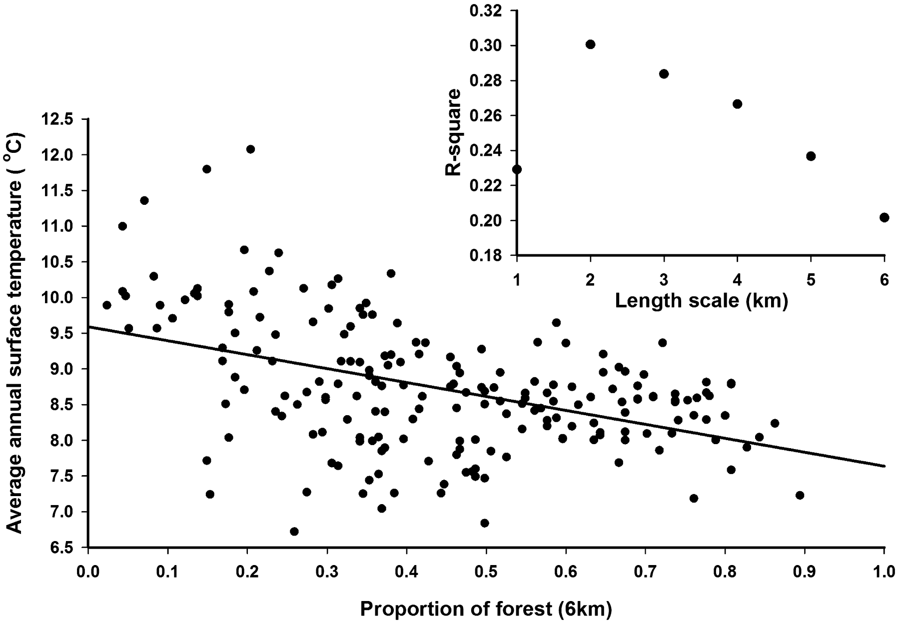

Figure 4 Average annual surface temperature versus proportion of forest for cell 1 at the 6 km length scale and R^2 values for average annual surface temperature versus proportion of forest for all six scales.

to warming (Table 1), and the field-based studies that report that forests tend to be cooler and wetter than surrounding fields (Chen *et al.*, 1993; Matlack, 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 United States and Canada, Lee *et al.* (2011) reported that forested sites were cooler for 8 of 20 of the pairs between 25 and 45° N.

Our results were based on a 5-year temporal domain. Climate models generally use longer time horizons for calibration than the 5 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 LSM 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. the 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 modelled 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; Heilman *et al.*, 2010; Hollinger *et al.*, 2010). Albedo is influenced by atmospheric conditions (cloudy versus clear), sun angle (season and time of day), soil colour and foliage nitrogen concentration (Bonan, 1997; Heilman *et al.*, 2010; Hollinger *et al.*, 2010). Hollinger *et al.* (2010) reported albedo estimates from six different climate modelling 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 comprising 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 & 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 probably 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 temperature. For many cells, the strength of the modelled 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 impacts on biodiversity from habitat fragmentation (Saunders *et al*., 1991; Bissonette & Storch, 2002), and to generally inform forest management and preservation (Stein *et al*., 2009). Forests in the continental United States are heavily fragmented (Heilman *et al*. 2002; Riitters *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 is likely to 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 temperature.

Model outcomes that show that temperate forests are a relative source of heat have 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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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Figure S1 MODIS land surface temperature (LST) points overlaid on NLCD 2001 land cover for cell 1.

Figures S2–S15 As depicted in Figs 2–4, show average annual surface temperature versus proportion of forest and R^2 versus length scale for all cells with model R^2 values greater than or equal to 0.10. Regression plots are not reported for cells 2, 6, 7 and 11 because model R^2 values for all four cells at all six length scales were less than 0.10.

BIOSKETCH

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Contribution statement: J.D.W. designed the project, conducted the analyses and wrote the paper. T.W. processed the MODIS data and wrote the paper. K.R. processed the land-cover data and wrote the paper.

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