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Comparison of cropland and forest surface temperatures across the conterminous United States

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ABSTRACT

Global climate models (GCM) investigating the effects of land cover on climate have found that replacing extra-tropical forest with cropland promotes cooling. We compared cropland and forest surface temperatures across the continental United States in 16 cells that were approximately $1^\circ \times 2^\circ$ using 1 km^2 MODIS land surface temperature (LST) data and land cover from the 0.0009 km^2 National Land Cover Database (NLCD). We found that forest surface temperatures tended to be cooler than cropland surface temperatures. This relationship held for spring, summer, fall, and annually. In winter, cropland surface temperatures were cooler than forest surface temperatures except in the southeastern United States, where forest surface temperatures were also cooler in winter. The difference between cropland and forest surface temperatures was driven by daytime maxima, which tended to be twice as large as differences in nighttime minima. The dominance of daytime maxima was influenced by the degree of continentality. For cells on coastal margins or with a high proportion of inland lakes, differences between cropland and forest nighttime minima tended to be very small. In more continental locations croplands were noticeably cooler at night which often led to insignificant differences between cropland and forest average surface temperatures.

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1. Introduction

Spatial variation in vegetation characteristics helps to create an undulating temperature surface across the landscape (Pielke and Avissar, 1990). The contrasting properties of different types of vegetation have stimulated research on the climate response to land-cover change. These studies have been based on scenarios that compare the climate response from a predominantly forested landscape to one where forest is replaced by cropland (or grassland). One of the predominant results shared by these studies is replacement of extra-tropical forest with cropland tends to produce cooler surface air temperatures (Bala et al., 2007; Betts, 2001; Bonan, 1997, 1999; Bounoua et al., 2002; Brovkin et al., 2006, 1999; Davin and De Noblet-Ducoudré, 2010; Defries et al., 2002; Diffenbaugh, 2009; Feddema et al., 2005; Gibbard et al., 2005; Oleson et al., 2004; Matthews et al., 2004, 2003). Counterbalancing this predominant finding are a handful of studies that have found that conversion of extra-tropical forest to cropland produces warmer rather than cooler surface air temperatures (Baidya Roy et al., 2003; Diffenbaugh and Sloan, 2002; Jackson et al., 2005; Marshall et al., 2004; Ramankutty et al., 2006).

Principal among that factors attributed to the climate response to land-cover change are transpiration rate, surface roughness, and albedo (Brovkin et al., 2004; Davin and De Noblet-Ducoudré, 2010). The roles of each in driving surface energy fluxes are complex. Stomatal resistance of cropland species tends to be lower than temperate forest species (Bonan, 1997), but in global climate models (GCM), evapotranspiration from forest tends to produce more cooling than evapotranspiration from croplands (Davin and De Noblet-Ducoudré, 2010). Forests have higher surface roughness (taller canopies) than croplands, which promotes greater mixing and heat dissipation during the day, but may be a heat "trap" at nighttime (Lee et al., 2011). Forest albedo tends to be lower than cropland albedo because of the darkness of tree bark, but soil color and wetness, and snow cover in winter also influence albedo (Bonan, 1997).

Much of what is known about the influence of vegetation on climate comes from modeling (Bonan, 2008a), and comparatively little knowledge has been derived from empirical analysis (e.g., Lee et al., 2011; Juang et al., 2007). The objective of this research is to compare cropland and forest surface temperatures using the MODIS land surface temperature (LST) data (Wan, 2008) and land cover from the U.S. National Land Cover Database (NLCD, 2001)

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(Homer et al., 2007). By relying on remotely sensed observations, empirical data on surface temperature and land cover can be gathered across the continental United States, representing the range of climates found throughout the country. Comparing cropland and forest surface temperatures across a wide range of temperate climates should provide insight into how differences in the characteristics of the two vegetation types may influence climate. Because of our reliance on the MODIS data, our comparisons will be based on surface temperature rather than surface air temperature. Surface temperatures are a correlate of measured (flux tower) or modeled (GCM) near-surface air temperatures, and are used to measure sensible heat flux (Jin, 2004).

2. Methods

We used the MODIS-Aqua land surface temperature (LST) Version 5, 8-day composite (MYD11A2) for our surface temperature estimates. The MYD11A2 MODIS data have a spatial resolution of 1 km^2, and Version 5 of the MODIS LST data series includes the latest improvements and evaluations of data quality (Wan, 2008). We analyzed both the daytime and nighttime estimates from the MODIS-AQUA (afternoon) that are provided with the MODIS LST product. We used the afternoon rather than the morning (MODIS-TERRA) data so that daytime surface temperatures were reflective of daily maxima. The MODIS data were analyzed for the years 2007, 2008, and 2009 using annual and seasonal averages (winter = December, January, February; spring = March, April, May; summer = June, July, August; fall = September, October, November). Observations (pixels) were discarded (due to cloud cover) if there were less six values within the seasonal time periods. If a pixel was discarded for one or more seasons it was also discarded from the annual analysis.

Cropland and forest were taken from NLCD 2001 (Homer et al., 2007). NLCD 2001 is a national land-cover database derived from Landsat TM that preserves the native 30 m × 30 m (0.0009 km^2) spatial resolution of the satellite. The data are classified into 16 classes of land cover for the conterminous United States (http://www.mrlc.gov/nlcd01_leg.php). We defined forest as the upland deciduous, evergreen, mixed forest classes, and woody wetlands. There is only a general cropland class in the NLCD 2001 database, and it was used to define cropland for our study. The NLCD 2001 forest user's accuracies range from 87% to 96%, and cropland user's accuracies range from 74% to 87% (Wickham et al., 2010).

The MODIS data were converted to points (using the center of the 1 km^2 pixel) prior to assigning land cover to surface temperature observations. The land-cover data assigned to the point included the proportion of forest and cropland in the 1 km^2 neighborhood surrounding the point, as well as the proportions of each land-cover class in the NLCD 2001 product. Because of the differences in the spatial resolution between the MODIS and NLCD data, land-cover proportions for each MODIS point (pixel) were based on approximately 1000 pixels of NLCD data. The comparison was restricted to MODIS points whose proportion of cropland or forest within the 1 km^2 neighborhood represented by each point was at least 90%. We also used the 30 m × 30 m National Elevation Data (Gesch et al., 2002) to estimate an elevation for each MODIS point. Elevation was computed as the average of the values in the 1 km^2 neighborhood surrounding the MODIS point.

Cropland and forest surface temperatures were compared in 16 cells distributed throughout the conterminous United States that were 100 km × 200 km in size (Fig. 1). The 100 km N–S dimension (∼1°) was selected to control for the effect of latitude on surface temperatures. The cells were distributed throughout the conterminous United States to capture the effects of latitudinal and longitudinal changes (e.g., continentality) in climate. The cells selected had a sufficient number of forest and cropland observations (∼50 each) to permit statistical comparisons. Following selection of the 16 locations, a 5 km × 5 km lattice of cells was overlaid in each of the 100 km × 200 km cell and used to eliminate all but one observation of cropland and forest within each of these smaller cells (Fig. S1 [supplemental]). Eliminating all but one observation per class within each a 5 km × 5 km cell was done to control for the effect of spatial correlation on the interpretation of significance (Table S1 [supplemental]). By using the 5 km × 5 km, only 800 observations per class out of the potentially 20,000 observations per class in each 100 km × 200 km cell were used for statistical comparison. In practice, the 800 per-class maximum was never realized because of the relative rarity of encountering areas where forest and cropland are locally dominant (i.e., ≥90% in 1 km^2 neighborhood).

Analysis of variance was used to compare statistical significance of the differences in daytime maxima, daily average, and nighttime minima. Assessment of significance was based on a difference of means, with a significance level of $\alpha = 0.5$, using the Tukey–Kramer adjustment for unbalanced designs (Kramer, 1956). The total number of cropland–forest statistical comparisons was 240 (3 aspects of surface temperature × 5 seasons × 16 cells). Notched box plots were used to display differences between cropland and forest. Non-overlapping notches indicate that group means are significantly different (McGill et al., 1978).

The elevation data were used to "normalize" the ranges of elevations across cropland and forest sites within a cell, which was particularly important for the three western 100 km × 200 km cells. For example, in these cells, forest observations at higher elevations were removed until the inter-quartile range across the two sets of observations were close (Table S2 [supplemental]). We also tested for significant differences in surface temperatures among the four NLCD forest types. Examination of surface temperature differences among forest type was restricted to cell 15 (Fig. 1), principally because the cell had a relatively high number observations in each class. Surface temperatures were significantly different across forest types. Wetland forests were cooler than upland forests and mixed forest were cooler than deciduous and evergreen forest. However, the differences were generally small compared to cropland forest differences (Table S3 [Supplemental]).

3. Results

Overall, average surface temperatures for cropland were higher than average surface temperatures for forest in spring, summer, and fall, and annually (Table 1). This pattern was reversed in winter, where forest, on average, had higher surface temperatures than cropland. In the seasons where forest surface temperatures were lower, the averages differences ranged from −0.6 °C to −1.5 °C. The surface temperature patterns were nearly uniform across the sixteen 100 km × 200 km cells in that there were few exceptions to the predominant seasonal patterns.

Differences in cropland and forest surface temperatures were significant in 92% (222 of 240) of the comparisons (Table S4 [supplemental]). There were two main patterns of statistical insignificance. In some cases, warmer forest nighttime temperatures offset cooler forested daytime temperatures, rendering the differences in daily means insignificant (Table 1). The other main pattern was statistical insignificance of differences in nighttime surface temperatures. These two patterns accounted for 17 of the 18 comparisons found not to be significant.

Differences in daily averages were driven by daytime maxima (Fig. 2 and Figs. S3–S16) because differences between forest and cropland nighttime minima were small compared to differences in

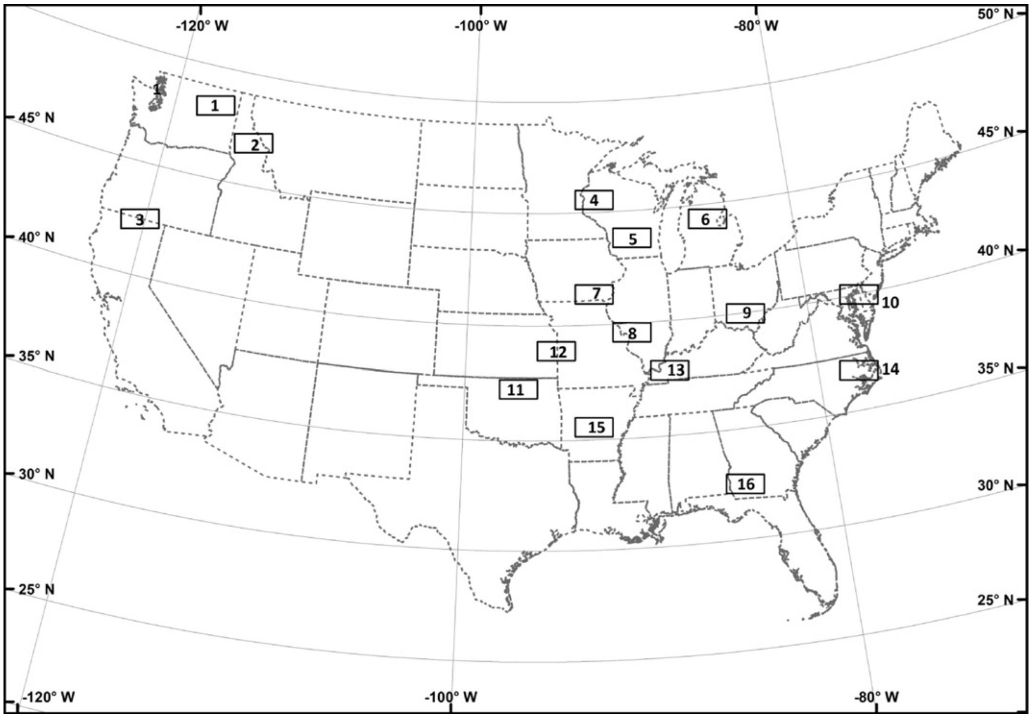

Fig. 1. Location of 100 km × 200 km cells.

daytime maxima (Table 2). Differences in daytime maxima were approximately twice as large as differences in nighttime minima except in winter. And, as noted above, nighttime differences between cropland and forest surface temperatures were not statistically significant for 10 of the 80 nighttime comparisons, whereas, statistical insignificance occurred for only 1 of the 80 daytime comparisons (Table S4). Lowering the significance threshold from 0.05 to 0.01 increased the number of statistically insignificant nighttime difference from 10 to 15 (Table S4).

There were also some noteworthy regional patterns. Many of the largest differences in surface temperatures between cropland and forest occurred in the three western cells. For example, daily average summer surface temperatures for cropland exceeded those for forest by 4.6 °C for cell 1, and similarly large differences occurred in cell 2. There was a tendency for forests to have cooler rather than warmer surface temperatures in winter in the southeastern United States. Average winter surface temperatures were lower for forests in cells 14 and 16, and equivalent in cell 15. There was also a geographic pattern that appears to be related to continentality. Cells 7, 8, and 9 are at approximately the same latitude as cell 10, but the contrast between cropland and forest average winter surface temperatures in the three Midwestern cells (7, 8, 9) is much stronger than for cell 10 on the eastern seaboard. A similar pattern holds for cells 11, 12, and 14. Cropland surface temperatures were cooler in winter in the Midwestern cells (11, 12), whereas the pattern was reversed for cell 14 on the eastern seaboard. However, winter cropland and forest surface temperatures in cell 13 are more similar to cell 14 despite its more continental location.

Table 1
Means of daily average surface temperatures for cropland and forest, including overall mean of forest minus cropland (X). Underlined cell entries were not significantly different.

Location	Annual		Winter		Spring		Summer		Fall	
	Forest	Crop	Forest	Crop	Forest	Crop	Forest	Crop	Forest	Crop
1	7.0	9.2	−6.9	−7.8	7.5	10.6	20.2	24.8	7.2	9.2
2	6.5	8.8	−6.7	−5.8	6.5	9.6	18.8	21.8	7.3	9.6
3	10.5	11.2	−1.3	−1.7	10.2	12.8	22.0	22.3	11.0	11.4
4	4.7	5.1	−14.5	−14.9	7.1	7.7	18.3	19.5	7.9	8.3
5	6.6	6.7	−11.8	−12.4	9.2	9.5	19.7	20.4	9.2	9.3
6	6.3	7.5	−10.4	−9.7	8.2	9.3	18.6	20.4	9.2	10.0
7	10.4	10.1	−4.0	−5.9	12.9	13.0	21.2	21.7	11.8	11.7
8	12.7	12.6	−0.2	−1.2	14.9	14.7	22.8	23.4	13.5	13.6
9	12.0	11.5	0.5	−2.6	13.8	14.0	21.0	21.7	12.6	12.8
10	12.6	13.2	1.9	1.6	13.4	13.8	22.2	23.6	12.8	13.6
11	16.4	16.8	6.2	4.9	17.8	17.2	25.6	29.1	16.2	16.0
12	14.0	13.7	3.2	1.4	15.3	15.1	23.5	24.6	14.2	13.9
13	14.2	14.5	3.0	2.8	16.0	16.2	23.4	24.3	14.4	14.9
14	15.9	16.5	7.3	7.5	16.3	17.3	24.4	25.0	15.7	16.4
15	16.2	17.0	6.8	6.8	17.5	18.4	25.0	26.4	15.7	16.6
16	18.7	19.8	10.7	11.2	19.8	21.6	26.1	27.0	18.3	19.4
X		−0.6		0.6		−0.9		−1.4		−0.6

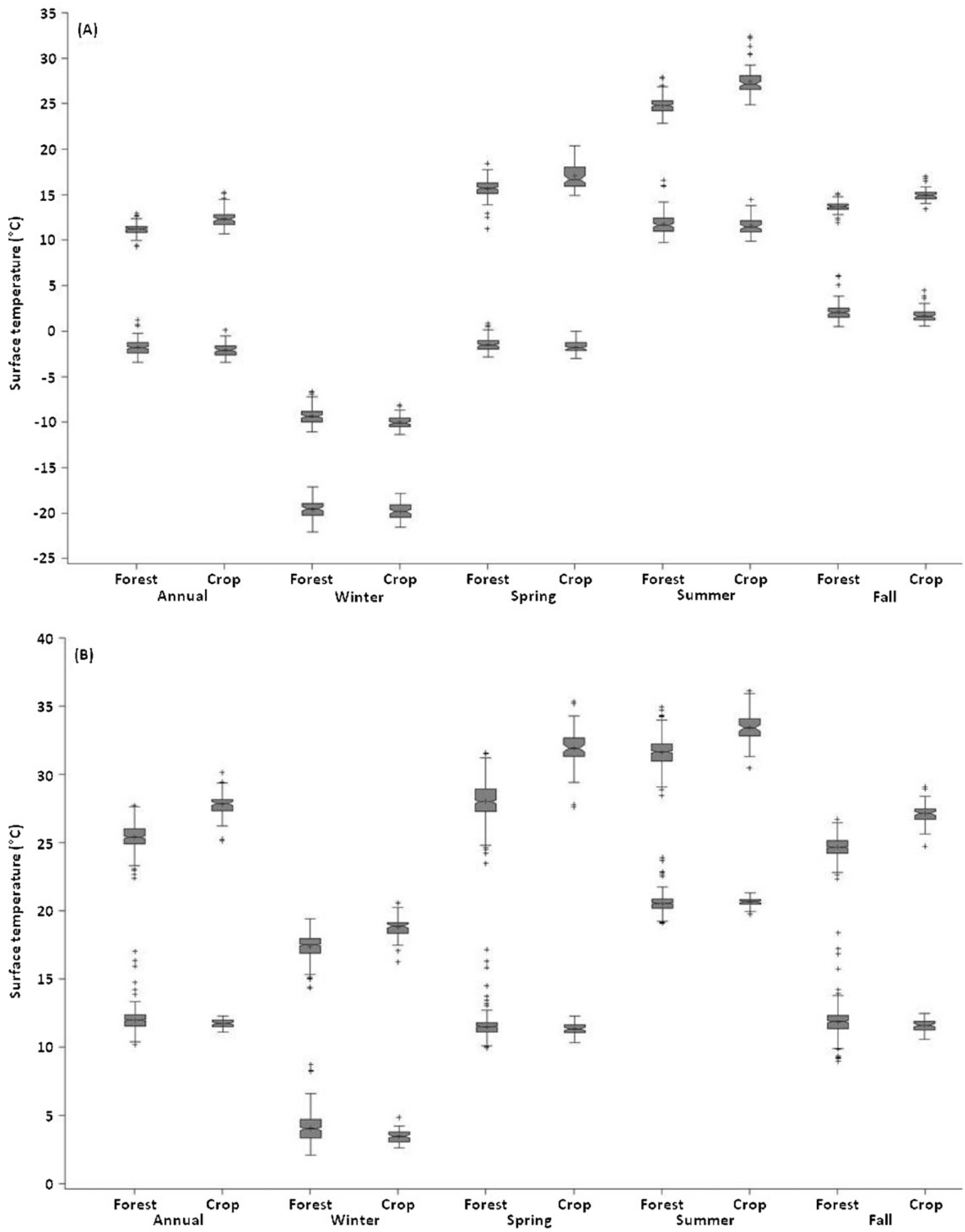

Fig. 2. Cropland and forest daytime maxima and nighttime minima for cells 4 (A) and 16 (B).

4. Discussion

Our empirical analysis suggests that croplands tend to be warmer than forests. Overall, average forest surface temperatures were cooler than croplands in spring, summer, fall, and annually. In winter, average forest surface temperatures were warmer than croplands, but there was evidence that the trend was reversed at southerly latitudes. The wintertime latitudinal trend in forest surface temperatures suggests that forests are cooler than croplands annually and in all seasons in the southeastern region of the conterminous United States. Our results are based on only a 3-year period; however, the consistency of the results suggests that they would not be fundamentally altered by a longer temporal record.

Our results are not consistent with most of the scenario-based climate studies that found replacing forest with cropland tends to produce cooler surface air temperatures (Bala et al., 2007; Betts, 2001; Bonan, 1997, 1999; Bounoua et al., 2002; Brovkin et al., 1999, 2006; Davin and De Noblet-Ducoudré, 2010; Defries et al., 2002; Diffenbaugh, 2009; Feddema et al., 2005; Gibbard et al., 2005; Oleson et al., 2004; Matthews et al., 2003, 2004). Rather, our results are more consistent with the handful of studies that found replacing forest with cropland tends to produce warmer surface air temperatures. Marshall et al. (2004) found that the large-scale replacement

Table 2
Difference (forest – cropland) in daytime maxima and nighttime minima, including the mean of the absolute value (Abs-*X*) of the differences. Differences underlined were not significantly different ($\alpha = 0.05$).

Location	Annual		Winter		Spring		Summer		Fall	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
1	−6.3	1.9	0.3	1.6	−7.7	1.5	−11.5	2.3	−6.2	2.2
2	−5.5	0.8	−1.4	−0.3	−6.9	0.6	−7.6	1.5	−6.3	1.7
3	−4.0	2.9	−1.6	3.4	−7.4	2.4	−2.8	2.1	−4.3	4.0
4	−1.2	0.3	0.6	0.2	−1.5	0.4	−2.6	0.2	−1.3	0.5
5	−0.6	0.5	1.0	0.2	−0.9	0.4	−1.6	0.6	−0.9	0.8
6	−1.4	−0.9	0.1	−1.6	−1.7	−0.5	−3.0	−0.5	−1.1	−0.5
7	−0.3	0.9	3.0	0.8	−1.4	1.1	−1.6	0.5	−1.0	1.1
8	−0.8	1.1	0.7	1.3	−0.5	0.9	−1.9	0.8	−1.4	1.3
9	−0.8	1.9	3.1	3.0	−1.7	1.3	−2.4	1.0	−2.5	2.0
10	−1.6	0.3	−0.2	0.7	−1.3	0.3	−2.7	−0.1	−2.1	0.5
11	−2.0	1.3	0.4	2.1	0.7	0.5	−7.1	0.3	−2.0	2.3
12	−0.6	1.1	1.7	1.8	−0.5	1.0	−2.6	0.5	−0.8	1.4
13	−1.7	1.1	−0.8	1.2	−1.2	0.9	−2.5	0.7	−2.4	1.5
14	−2.2	0.9	−1.5	1.1	−3.2	1.1	−1.6	0.3	−2.4	1.1
15	−1.2	−0.4	0.2	−0.3	−1.3	−0.4	−2.0	−0.7	−1.4	−0.4
16	−2.4	0.2	−1.4	0.6	−3.9	0.2	−1.8	−0.1	−2.4	0.2
Abs-*X*	2.0	1.0	1.1	1.3	2.6	0.8	3.5	0.8	2.4	1.4

of forest with agriculture that has occurred throughout Florida has led to warmer and drier conditions. Diffenbaugh and Sloan (2002), Baidya Roy et al. (2003), Jackson et al. (2005), and Ramankutty et al. (2006) also found that extra-tropical afforestation produced cooler temperatures. Our results are somewhat consistent with the field-based study of surface air temperatures by Lee et al. (2011). The authors compared field-based measurements of surface air temperature for neighboring pairs of forested and open (grassland) sites, and found that 8 of 20 sites between 25°N and 45°N had cooler surface air temperatures for forests than the neighboring fields.

Although albedo, transpiration rate, and surface roughness are all cited as factors contributing to differences in surface air temperatures between cropland and forest, albedo is commonly cited as the most influential of these factors (Betts, 2001; Defries et al., 2002; Davin and De Noblet-Ducoudré, 2010). The forest albedos used in global climate models (GCMs) are lower than cropland and grassland albedos (Bonan, 2008b), which results in greater absorption of solar radiation and higher temperatures. However, albedo is difficult to measure. Differences between cropland and forest albedos are often small, albedo is variable both diurnally and from day to day due to changing cloud cover conditions, and albedo is affected by foliar nitrogen content (Alton, 2009; Hollinger et al., 2010; Jackson et al., 2008; Ollinger et al., 2008; Wang and Davidson, 2007). We speculate that the simulated cooling produced by replacing forest with cropland in many GCMs may be more attributable to simulated boreal deforestation than replacement of forest with cropland at temperate latitudes. Simulated boreal deforestation produces a more influential change in albedo than temperate forest to cropland changes because the replacement (herbaceous vegetation) is covered by a snow pack that persists for much longer periods and extends over a much greater area. The conversion of boreal forest to a cover of persistent snow then cools ocean surface temperatures, which in turn leads to cooler temperatures at temperate latitudes (Davin and De Noblet-Ducoudré, 2010). However, our speculation does not agree with the results reported by Bonan (1999), who reported that replacement of forest with cropland produced cooling even though boreal forest remained unchanged between the two land cover scenarios and sea surface temperatures remained constant.

Snowpack persistence may explain the differences we found in wintertime cropland and forest surface temperatures for the Midwestern cells 7, 8, and 9 and the sole mid-latitude cell (10) on the eastern seaboard. Snow cover is more likely to be consistent and persistent in the continental climate of cells 7, 8, and 9, than in the oceanic climate of cell 10. A more consistent and persistent snow cover would more dramatically increase wintertime albedos compared to areas where snow cover is much less of a defining characteristic of winter (cell 10). Wintertime cropland average surface temperatures were 1.0–3.1 °C cooler than forest surface temperatures in cells 7, 8, and 9, whereas wintertime cropland surface temperatures were only 0.2 °C cooler than forest surface temperatures in cell 10.

Similar to Lee et al. (2011), we found that examination of both daytime and nighttime temperatures to be important for understanding differences between cropland and forest surface temperatures, but we did not find nighttime minima to be as influential. We found that daytime maxima drove differences between cropland and forest surface temperatures (Table 2). Lee et al. (2011) hypothesized that forests were warmer than open fields at night because of downwelling of heat due to the higher surface roughness of forests. Other factors have also been attributed to the diurnal flux of temperature. Zhou et al. (2009) have found that the largest increases in nighttime minima (and decreases in DTR) have tended to occur of drier regions where vegetation is sparse. Examining patterns in the eastern United States, Durre and Wallace (2001) found that DTR decreased during the warm season due to increased evapotranspiration. Collatz et al. (2000) suggested that vegetation stress could lead to an increase in DTR through a reduction in photosynthesis and subsequent increase in daytime maxima. We speculate that the amount of water in the landscape may also be a factor. Differences between cropland and forest nighttime minima were less than 1.0 °C for cells 2, 4, 5, 6, 10, 14, 15, and 16, and all but cell 2 had either a high proportion of inland water or were on coastal margins. Cells 4 through 6 included numerous glacial lakes or overlapped the Great Lakes. Cells 10 and 14 were on the Atlantic coast, and cell 16 is influenced by the Gulf of Mexico. The eastern half of cell 15 is in the Mississippi River alluvial valley and is characterized by wetlands and water bodies (Fig. S1A). Land-water breezes should homogenize cropland–forest surface temperature differences, and this effect may be more pronounced at night due to the dampening effect of vegetation transpiration during the daytime (Segal et al., 1997).

The strong cooling effect of forest relative to cropland in the three western cells was a surprise. The surface temperature differences were strongest for summer daytime maxima, which influenced daily and annual averages. It may be that forest transpiration is more of a counterbalance than cropland transpiration to the high solar radiation characteristic of these areas during the summer months. Adiabatic lapse rates would account for approximately a 0.25 °C (wet) to 0.50 °C (dry) reduction in forest versus cropland temperatures in the three western cells, since the forest median elevation was about 50 m higher than the cropland elevation. Forest daytime maxima in these three cells were 2.8–11.5 °C cooler than cropland daytime maxima.

Global analyses of the influence of forest on climate generally classify forests as tropical, temperate, and boreal (Bonan, 2008a). Our results suggest that there is a latitudinal gradient to the influence of forest on climate within the temperate region. Excluding the three cells in the western United States, the relative cooling effect of forest increased as latitude decreased such that forests were cooler than croplands in all seasons, including winter, for the three southern most cells. These results suggest that southern temperate forests may be more similar to tropical forests in their effect on climate. These results are consistent with the latitudinal gradient reported by Lee et al. (2011), and the year-round cooler temperatures for a forest as compared to a grassland site in North Carolina (Juang et al., 2007).

The predominant finding that replacing extra-tropical forests with croplands promotes cooling has led some to acknowledge the policy implications of temperate and boreal deforestation (Bala et al., 2007). Our results suggests that the cooling influence of temperate forest as compared to cropland can be added to the numerous other ecological benefits of afforestation, including biodiversity protection (Saunders et al., 1991), flood mitigation (Ponce and Hawkins, 1996), and water quality improvement (Wickham et al., 2008a). Forest loss and fragmentation in the continental United States is severe (Riitters et al., 2002; Wickham et al., 2008b). Based on our results, reforestation in the continental United States can add promotion of cooler surface temperatures to the numerous other ecological benefits that forests provide.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2012.07.002.

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