What to plant and where to plant it; Modeling the biophysical effects of North American temperate forests on climate using the Community Earth System Model

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ABSTRACT

Forests affect climate by absorbing CO_2 but also by altering albedo, latent heat flux, and sensible heat flux. In this study we used the Community Earth System Model to assess the biophysical effect of North American temperate forests on climate and how this effect changes with location, tree type, and forest management. We calculated the change in annual temperature and energy balance associated with afforestation with either needle leaf evergreen trees (NET) or broadleaf deciduous trees (BDT) and between forests with high and low leaf-area indices (LAI). Afforestation from crops to forests resulted in lower albedo and higher sensible heat flux but no consistent difference in latent heat flux. Forests were consistently warmer than crops at high latitudes and colder at lower latitudes. In North America, the temperature response from afforestation shifted from warming to cooling between *34° N* and *40° N* for ground temperature and between *21° N* and *25° N* for near surface air temperature. NET tended to have lower albedo, higher sensible heat flux and warmer temperatures than BDT. The effect of tree PFT was larger than the effect of afforestation in the south and in the mid-Atlantic. Increasing LAI, a proxy for increased management intensity, caused a cooling effect in both tree types, but NET responded more strongly and albedo decreased while albedo increased for BDT. Our results show that forests' location, tree type, and management intensity can have nearly equal biophysical effects on temperature. A forest will have maximum biophysical cooling effect if it is in the south, composed of broadleaf PFT, and is managed to maximize leaf area index.

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INTRODUCTION

Forests influence both local and global climate by regulating the planetary energy balance. By absorbing CO_2 through photosynthesis trees can reduce the amount of long-wave radiation absorbed by the atmosphere, thus reducing the rate of climate change. In fact, forests' carbon uptake represents the vast majority of the terrestrial carbon sink (Pan et al. 2011). Beyond the sequestration of CO_2, forests also alter the amount and distribution of energy in the atmosphere by reflecting energy and by regulating the movement of energy from the land surface into the atmosphere. These biophysical pathways through which forests influence climate can have a larger influence than carbon sequestration at local scales, and can either offset or enhance the carbon sequestration effect at regional and global scales (Betts 2000; Bala et al. 2007).

Forests affect climate by changing, albedo, latent-heat flux, and sensible heat-flux. Forests generally reflect less solar energy (low albedo) than most other land-use types (Betts 2000). For example, snow, bare soil, grass, and crops are often brighter than dense forests (Jackson et al. 2008). The difference in albedo between forests and other land-use types is largest at high latitudes and in winter months due to forest canopy covering ground snow (Jackson et al. 2008). Once solar energy is absorbed by the land-surface, forests influence how that energy is transferred to the atmosphere. Because forests are taller than most other land-use types, they increase the turbulence of wind near the surface. The increased turbulence causes more mixing and vertical movement of air, which decreases the aerodynamic resistance to the transfer of energy in water vapor (latent heat) and in the temperature of air (sensible heat). The lower resistance can increase the amount of water and energy transported into the atmosphere, cooling the land surface (Bonan 1997). Increasing latent and sensible heat fluxes from the land surface can also increase cloud formation, which both reflects downward solar radiation (increasing albedo) and absorbs long wave radiation. Overall, the net biophysical effect of forest on climate is the sum of the changes in albedo, surface roughness, ET, and cloud formation associated with afforestation (replacing a non-forest land-use with a forest).

The net biophysical effect afforestation on regional and global climate varies by latitude and biome (Bonan 2008a). There is strong evidence that tropical and boreal forest have large and distinct biophysical effects on climate. In boreal regions, afforestation likely has a warming effect on local and regional temperatures despite the additional removal of carbon from the atmosphere (Betts 2000). This is due primarily to masking of bright snow with dark tree canopies, decreasing albedo and increasing the energy absorbed by the land surface. In contrast, forests in tropical regions have a cooling effect on the land surface temperature because high transpiration rates increase ET enough to outweigh the moderate decrease in albedo (Bala et al. 2007). Unlike tropical and boreal forests, where albedo and ET are the dominating factors, the biophysical influence of temperate forests on climate is less well understood.

One challenge for quantifying the influence of temperate forests on climate is the diversity of forest types. Forests in the temperate zone can range from needleleaf dominated to broadleaf dominated ecosystem, depending on environmental conditions. In addition, temperate forests are among the most intensely managed forests in the world (Hansen et al. 2013), which can alter forest structural characteristics important for land-atmosphere interactions. Furthermore, temperate forests span a wide range of temperature and precipitation, including forests in the temperate zone that experience snow for large portions of the year and others that experience little to no snow.

To test the biophysical effects temperate forests have on climate, many studies rely on Earth system models (ESMs). The majority of these climate simulations have found that afforestation in temperate regions has a warming effect on regional temperature due primarily to the increases in albedo associated with an increase in forest area (Brovkin et al. 2006; Bala et al. 2007; Bonan 1997; Oleson et al. 2004; Diffenbaugh 2009). However, there are empirical experiments using remote-sensing and forest eddy-covariance towers, as well as some regionally-focused modeling experiments that show temperate forests cool surface temperature on average (Wickham et al. 2012; Peng et al. 2014; Chen et al. 2012; Murphy et al. 2012; Li et al. 2015). Furthermore many studies have found a latitudinal gradient where forests have a warming effect in high latitudes and a cooling effect at low latitudes (Li et al. 2015; Zhang et al. 2014). This gradient has been attributed to a transition in the primary biophysical mechanism by which forests influence climate. In particular, the difference in latent heat flux (LHF) between forest and non-forest was an important driver in the tropics while the difference in albedo between forest and non-forest was an important driver at high latitudes (Li et al. 2015).

Across multiple methods and scale of analysis, the location where non-forest is replaced by forest (afforestation) appears to govern the magnitude and direction of the associated change in climate.

Beyond the decision of where to afforest, the type of tree used in afforestation can change the net climate effect of a forest. The type of trees used in afforestation fall into two broad categories, broadleaf (deciduous) and needleleaf (evergreen). Broadleaf trees tend to have higher annual mean albedo and higher summertime albedo than evergreen trees (Jackson et al. 2008). In addition, studies have shown that broadleaf trees in midsummer have nearly twice the capacity to evaporate water than do evergreen trees (Breuer et al. 2003). These differences suggest that broadleaf trees may provide a greater cooling effect than needleleaf trees, given the same carbon sequestration. It has been found that, in North America, broadleaf trees tend to cool near surface air locally while evergreen trees warm, when compared to grass and cropland land-cover types (Zhao and Jackson 2014). Overall, evidence suggests that decisions about what to tree PFT to plant may be as important or more important than decisions about the location of the afforestation project.

Finally, forest management has been shown to have biophysical effects on climate on a similar scale as land-use change (Luyssaert et al. 2014) and temperate forests are among the most managed forest systems in the world (Hansen et al. 2013). Forest management is generally performed for the purpose of increasing productivity across the stand, and these managed stands can be denser with higher leaf area index (LAI) than their unmanaged counterparts. Increasing LAI can have the duel effects of masking the ground more completely thereby increasing albedo, while simultaneously increasing canopy conductance and LHF(Bonan 2008b). The net biophysical effect on climate in response to forest management is largely unknown, but changes in forest-management may affect climate as strongly as afforestation (Luyssaert et al. 2014).

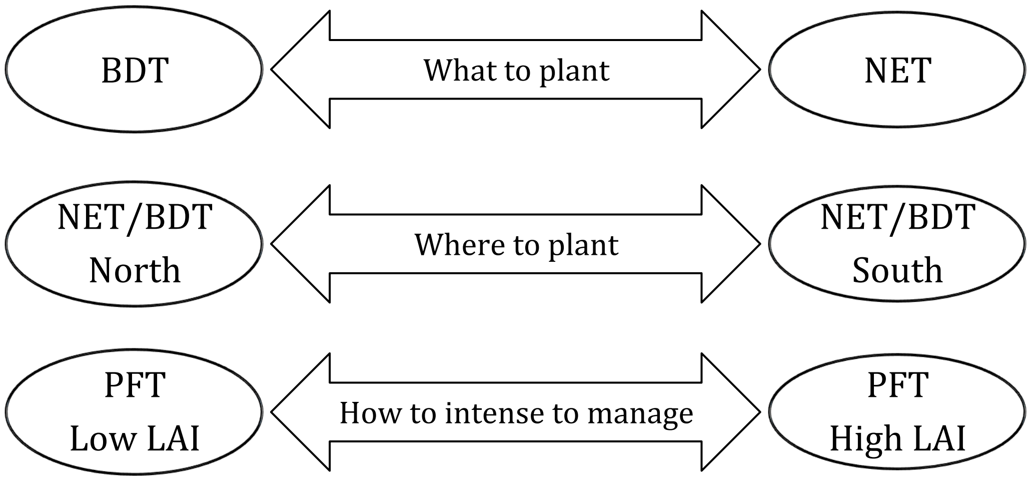

Figure 1: We compare needleleaf evergreen trees (NET) and broadleaf deciduous trees (BDT) to explore the effects of PFT. To assess the effects of location we take the difference of Crop and NET/BDT in each gridcell across the region. We compare high and low leaf area, a proxy for differing management intensities, within BDT and NET to explore the role of management

Together, research to date has determined that the biophysical influence of an afforestation project on climate depends on the location of the project, the tree PFT used in the project, and the intensity of forest management. However, the relative importance of these three factors has not been explicitly compared using a standardized methodology. Here we examine the influence of forests in the temperate region on climate and explicitly evaluate the relative importance of the location of the project, the tree PFT used in the project (evergreen needleleaf vs. broadleaf deciduous) and management intensity (represented by a change in LAI) (Fig 1). We use a state-of-the-art ESM to assess influence of afforestation on local and regional temperatures. To our knowledge, this is the first study to use an Earth system model to weigh the relative contribution of location, tree PFT and management to the biophysical effects of temperate forests on local and regional climate.

METHODS

Model Description

Simulations were performed by the Community Earth System Model 1.2.0 (CESM); a state-of-the-art fully coupled Earth system model (GCM) managed by the National Center for Atmospheric Research (Hurrell et al. 2013). The CESM includes several sub-models that separately model the atmosphere, land-surface, ocean, sea-ice, rivers, glaciers, and waves. We used the Community Land Model (CLM) version 4.5 (Oleson et al 2013), the Community Atmosphere Model version 5.0, the Sea-Ice model, and a prescribed data ocean. Within the CLM we used the satellite phenology routine, which prescribes the vegetation distribution and LAI rather than prognostically predicting LAI. The satellite phenology configuration simulates photosynthesis but does not include a coupled carbon cycle. In the CLM, vegetation is divided into 16 broad plant-functional types (PFTs). Each PFT has parameters that describe the structure (e.g. LAI and stem-area index), physiological parameters that govern photosynthesis and transpiration rates, and parameters that determine energy balance (e.g. albedo).

Simulation Description

To assess the relative contribution of location, tree PFT and management to the biophysical effects of forests on climate, we ran six global simulations that differ in PFT and LAI (Table 1). We examined the climate differences between NET and BDT across North America to assess the effects of afforestation location, the difference between NET and BDT to assess the effects of tree PFT, and differences between high and low LAI within a PFT to asses the effects of management. Using observed climate as initial conditions, we ran simulations run for thirty years model time to allow the system to reach a dynamic equilibrium with respect to simulation specific land surface. Simulations were run on a 1.9 ° x 2.5° horizontal resolution.

To limit our analysis to the temperate biome and to identity regions within the temperate biome with clear differences in temperature and precipitation. We used a hierarchical clustering algorithm to assign each gridcell with forest into one of twelve clusters based on average annual temperature and average annual precipitation. We then selected six of these clusters that, when combined, covered temperate North America.

Table 1: Simulation Descriptions

Simulations	Description
High LAI	
TEM_NET_LAI_4	Temperate region set to 100% needleleaf evergreen temperate trees, maximum LAI of 4
TEM_BDT_LAI_4	Temperate region set to 100% broadleaf deciduous temperate trees, maximum LAI of 4
TEM_CROP_LAI_3	Temperate region set to 100% unmanaged C3 crop, maximum LAI of 3
Low LAI	
TEM_NET_LAI_2	Temperate region set to 100% needleleaf evergreen temperate trees, maximum LAI of 2
TEM_BDT_LAI_2	Temperate region set to 100% broadleaf deciduous temperate trees, maximum LAI of 2

We manipulated the PFT and LAI distributions within these six clusters to create two sets of land-surface descriptions used as inputs to the land model (Table 1). Each set has PFT distributions of 100% NET, BDT, or Crop in every temperate region grid-cell. In order to ensure that differences between the two tree PFTs are not due to any differences in LAI we standardized a high and low LAI distribution (Table 1). We standardized the high LAI set by setting the maximum monthly LAI for Crop, BDT, and NET to 3,4,and 4 respectively. We preserved the seasonal cycle of LAI by scaling the remaining months to be proportionally identical to the baseline LAI. The above procedure was repeated for the low LAI simulations with CROP, BDT and NET LAI being set to 1.5,2, and 2 respectively (Table 1).

Analysis

We focused our analysis on the final 20 years of each simulation, discarding the first 10 years of simulation data as spin-up. We also limited our analysis to North America. We used changes in ground temperature (Tg), air temperature at 2-meters (T2m), daily maximum (Tmax) and nightly minimum temperatures (Tmin) as the metrics of climate response to changing land cover. We examined differences in albedo, latent heat flux (LHF) and sensible heat flux (SHF) to analyze the explanatory value of these biophysical processes. We also calculated the coefficient of determination (R^2) in each gridcell to examine the relationship between our response variables and changes in albedo, LHF, and SHF.

Differences between simulations were calculated for the 20-year annual mean response for each variable and calculated as the difference between two land-cover types. For example, the biophysical effect of converting from a Crop PFT to NET PFT is calculated as the temperature difference between NET and CROP in each gridcell. For each variable, we took the difference in NET and BDT (NET – BDT) to quantify the effects of tree-type on climate. Statistical significance was determined using a t-test, with the annual means of the last 20 years as the sample in each gridcell. In some cases the range of difference between PFTs crosses zero. In these cases we report the transitional latitude for the eastern United States, as determined by latitudinal means, as well as the mean response north and south of this latitude.

To measure the relative importance of tree-type compared to the transition from crop to forest, we took the ratio of the difference in the four temperature variables between PFT over the response of converting from crop to a mixed forest (Eq. 1), where $T_{NET} - T_{BDT}$ is the difference between NET and BDT for temperature variables and $T_{NET} - T_{CROP}$ is the effect of afforestation with NET and $T_{BDT} - T_{CROP}$ is the effect of afforestation with BDT. We used mean of the afforestation effects of NET and BDT to represent the effects of a mixed forest. Statistical significance of the ratio in each gridcell was determined using a Wilcoxon rank-sum test.

$$\frac{T_{NET} - T_{BDT}}{\left(\frac{(T_{NET} - T_{CROP}) + (T_{BDT} - T_{CROP})}{2}\right)} \qquad \textit{Equation 1}$$

To analyze the effect of forest management we used a change in LAI to represent a change in forest management. In particular, the biophysical effect of converting from a low LAI NET to high LAI NET is calculated as the difference between NET (LAI4) and NET (LAI2) in each gridcell.

RESULTS

The role of location on the biophysical effects of forests on climate

We found afforestation had a cooling effect on Tg in the southern US and a warming effect in the north (Fig 2). While the pattern was robust to difference in tree PFT, the latitude where the change in Tg transitions from warming to cooling differed between NET and BDT. The transitional latitudes in the eastern half of the United States were approximately 34° N and 40° **N** for NET and BDT respectively (Fig 3). The mean response north of the transitional latitude was 1.2 K for NET and 0.93 K for BDT. The mean response south of the transitional latitude was -1.4 K and -1.5 K for NET and BDT respectively.

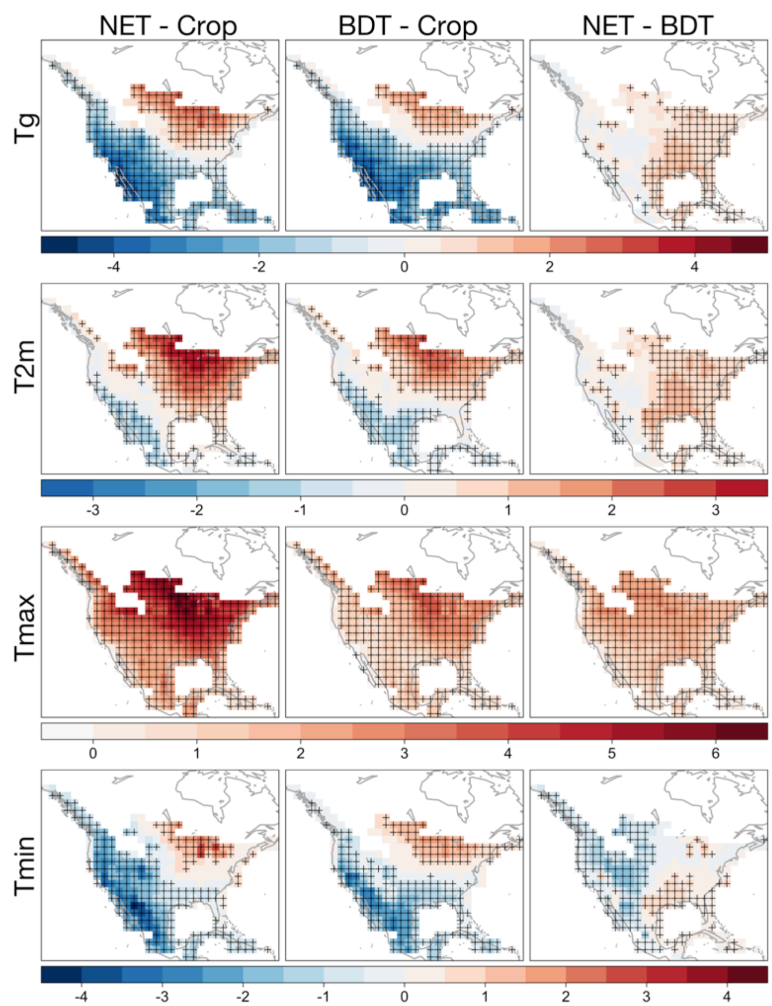

Figure 2: Comparison of afforestation with need leaf trees (NET-Crop), broadleaf trees (BDT-Crop), and between tree types (NET-BDT) with respect to change in temperature variables (Tg, T2m, Tmax, Tmin) with units of degrees Celsius/kelvin. Stipples indicates the mean response is significantly different from zero based on a students t-test (p< 0.05)

Similar to Tg, afforestation had a weak cooling effect on T2m in the south and a warming effect in the north (Fig 2). This pattern was robust to difference in tree PFT but NET had a much larger warming region than BDT (Fig 2). The transitional latitudes in the eastern half of the United States were approximately 21° N and 25° N for NET and BDT respectively (Fig 3). The mean response north of the transitional latitude was 1.7 K for NET and 0.99 K for BDT. The mean response south of the transitional latitude was -0.05 K and -0.27 K for NET and BDT respectively.

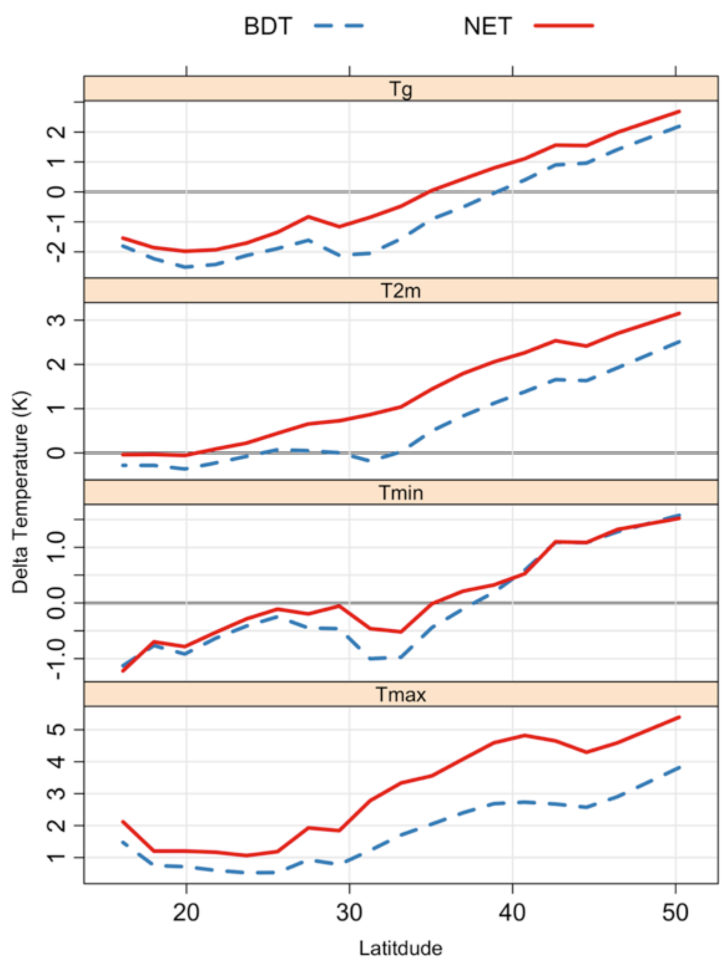

Figure 3: Mean temperature variables by latitude for the eastern half of the United States. Units are in Kelvin. Values were calculated as the row means in the eastern half of the study region. Latitude was taken from the center of each gridcell.)

Afforestation caused Tmax to increase across the region and Tmin to decrease in the south. Tmax had the strongest responses occurring at high latitudes (Fig 2), with mean responses of 3.3 K and 1.9 K for NET and BDT respectively. We found afforestation had a strong cooling effect on Tmin in the south and a weak-warming effect in the north (Fig 2). This pattern was nearly identical in both tree PFT. The transitional latitudes in the eastern half of the United States were approximately 36° N for NET and 38° N for BDT (Fig 3). The mean response north of the transitional latitude was 0.8 K and 0.88 K and the mean response south of the transitional latitude was -0.44 K and -0.64 K for NET and BDT respectively.

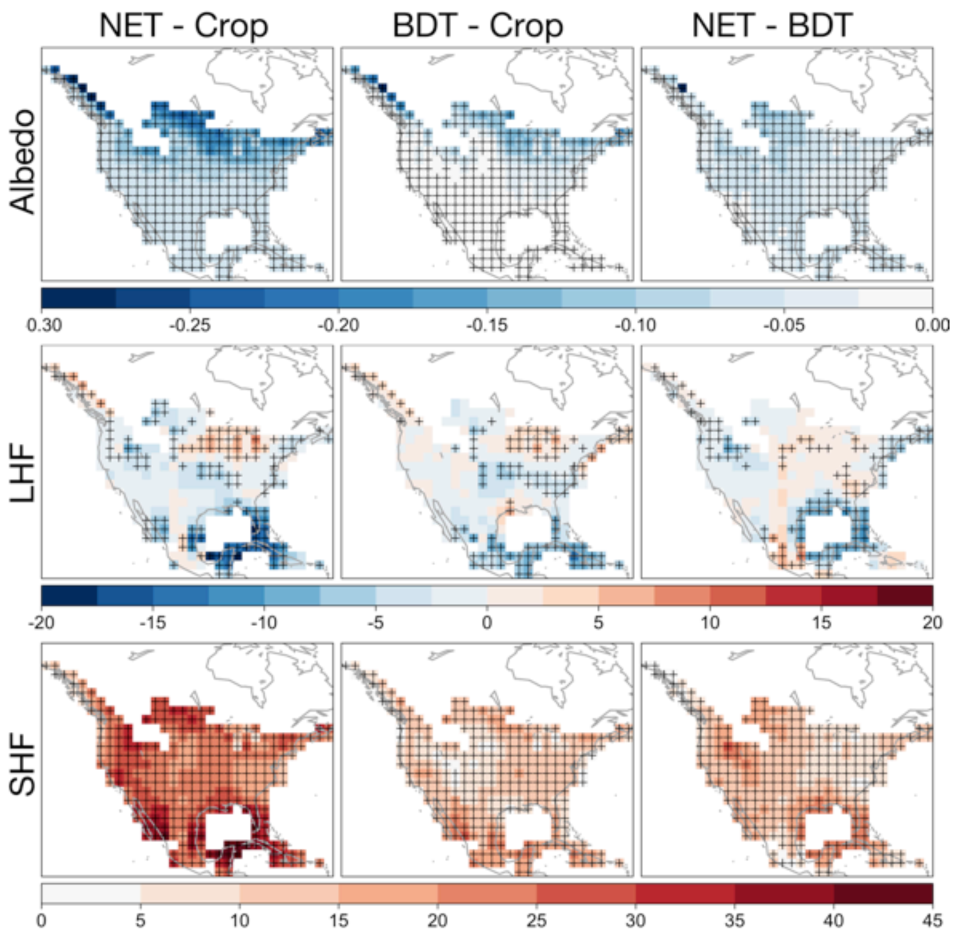

Figure 4: Comparison of afforestation with need leaf trees (NET-Crop), broadleaf trees (BDT-Crop), and between tree types (NET-BDT) with respect to biophysical forcing variables albedo, latent heat flux (LHF, W/m^2) and sensible heat flux (SHF, W/m^2). Stipples indicates the mean response is significantly different from zero based on a students t-test ($p< 0.05$)

Albedo decreased in response to afforestation for both NET (-0.096) and BDT (0.047). The largest decreases occurred at high latitudes and NET showed a stronger response than BDT (Fig 4). Afforestation also increased SHF across the region with NET again showing a larger response than BDT (Fig 4). The mean increases for NET and BDT were 24.6 W/m^2 and 12.7 W/m^2 respectively. LHF changed in response to afforestation as well, but there was no distinct transitional latitude (Fig 4). In general, areas with more available water showed a decrease in LHF in response to afforestation, and areas with less available water showed an increase in LHF (Fig 4).

The annual mean response to afforestation of all temperature variables across the region correlated most strongly with albedo (Table 2). However, there were regions that correlated more strongly with LHF and SHF (Fig 5). Albedo correlated most strongly with all temperature variables in the northern regions for both NET and BDT (Fig 5). In the Southwest, LHF and SHF correlated strongly with Tg, T2m and Tmax and weakly with Tmin, but NET tended to correlate more strongly than BDT (Fig 5). There was also an area in the Northeast where LHF showed moderate correlation with all temperature variables.

Table 2: Coefficient of determination (R^2) of annual mean responses across the region between temperature variables and biophysical mechanisms

	NET – Crop			**BDT - Crop**			**NET - BDT**		
	LHF	**Albedo**	**SHF**	**LHF**	**Albedo**	**SHF**	**LHF**	**Albedo**	**SHF**
Tg	0.105	**0.449**	0.104	0.119	**0.552**	0.042	**0.05**	0.017	0.002
T2m	0.086	**0.35**	0.066	0.108	**0.487**	0.027	0.002	0.003	**0.01**
Tmax	0.117	**0.343**	0.02	0.035	**0.427**	0.013	0.008	**0.226**	0.007
Tmin	0.032	**0.193**	0.082	0.113	**0.394**	0.076	0.006	**0.164**	0.036

The role of tree PFT in the biophysical effects of forests on climate

NET was generally warmer than BDT for both Tg and T2m (Fig 2). The difference between NET and BDT was strongest on the east coast where the mean changes in Tg and T2m were 0.73 K and 0.74 K. Also, NET increased Tmax across the region with very little spatial variation and a mean increase of 1.43 K. Finally, NET increased Tmin in the South and decreased Tmin in the West (Fig 2). In general, NET was warmer than BDT on the east coast of the United States with little latitudinal variation (Fig 2).

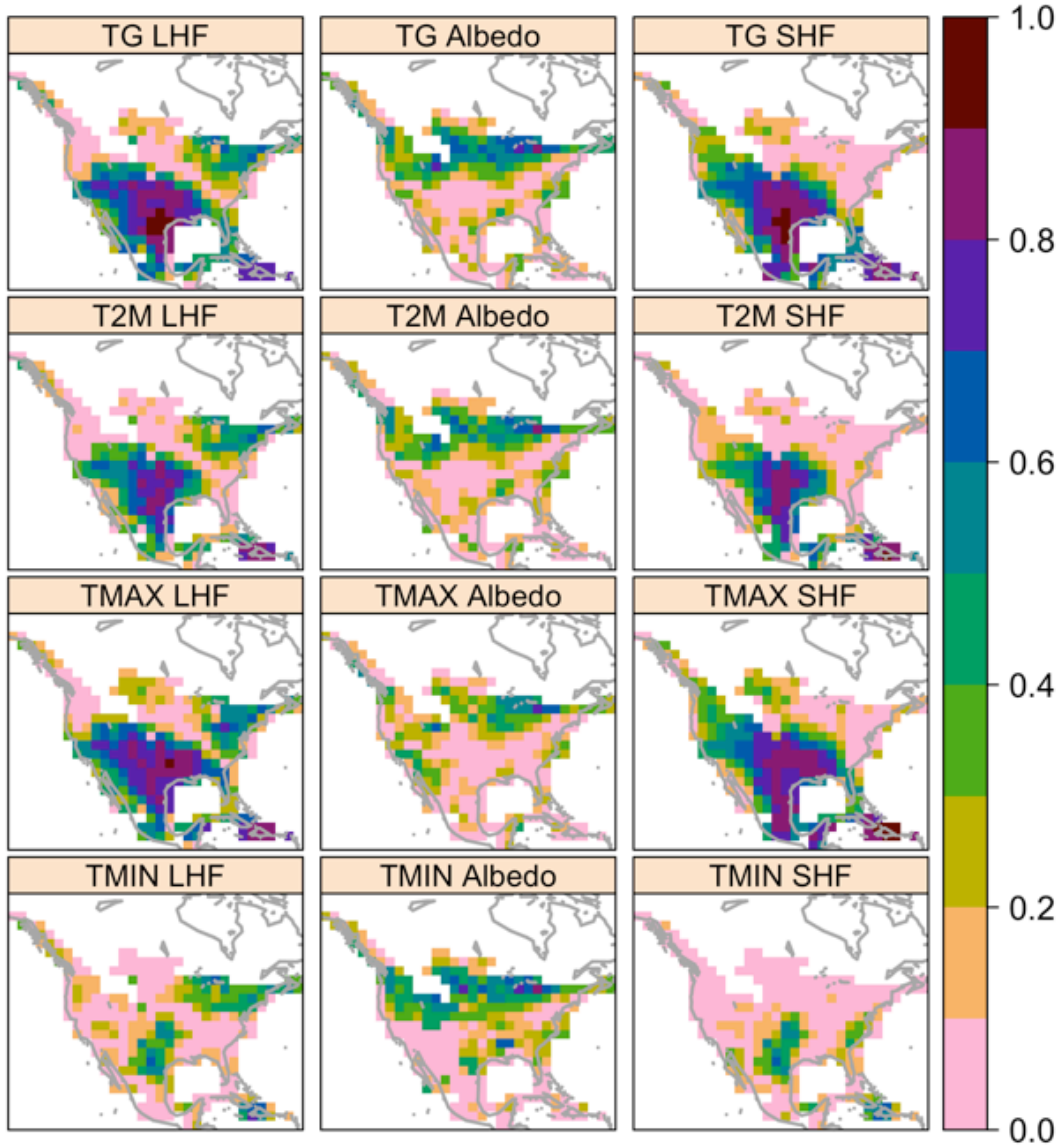

Figure 5: Coefficient of determination (R^2) between temperature variables and biophysical mechanisms latent heat flux (LHF), albedo, and sensible heat flux (SHF) when replacing crop with needle leaf evergreen trees (NET). Correlation was determined using the annual means of the last 20 years in each gridcell

The difference in biophysical mechanisms between NET and BDT followed a similar pattern to afforestation. NET had lower albedo than BDT across the region, and higher SHF (Fig 4). NET had lower LHF than BDT in areas with abundant water (e.g. surrounding the Gulf of Mexico) but very small changes in LHF everywhere else (Fig 4).

Regionally, none of the temperature variables correlated strongly with any of the biophysical mechanisms with the exception of the change in Tmax correlating with the change in albedo (Table 2). However, some of the temperature variables correlated very well with biophysical mechanisms in different regions (Appendix A: Figure 1). Albedo correlated strongly with all temperature variables in the north, but also with Tg, T2m, and Tmax in far southeastern United States and Cuba (Appendix A: Figure 1). In the south, LHF and SHF both correlated strongly with Tg, T2m and Tmax (Appendix A: Figure 1).

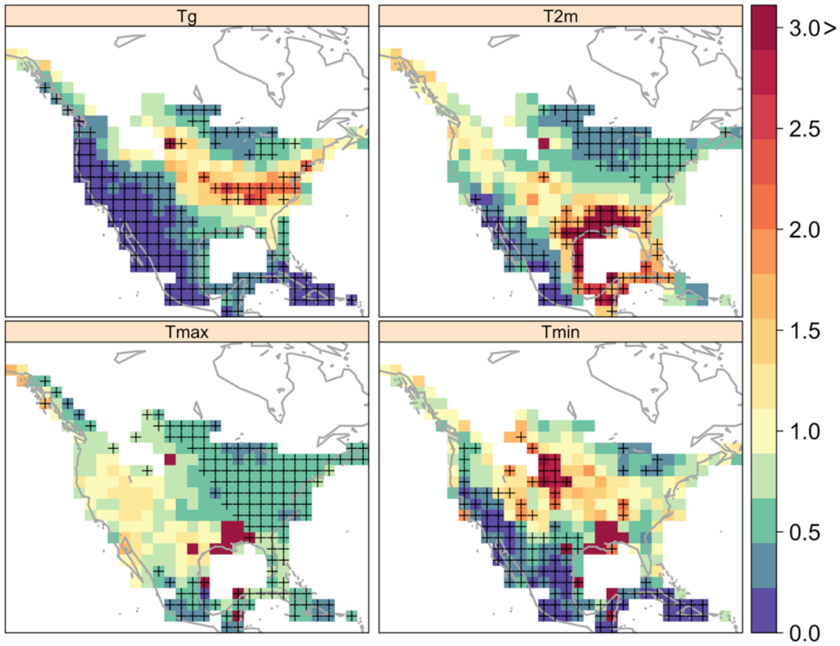

Figure 6: Relative effects of tree PFT determined using the relationship described in equation 1. Values plotted represent the median of the last 20 annual mean values. Values less than one indicate that afforestation with mixed forest has larger response, values greater than one indicate PFT effect is greater than afforestation, and areas that are approximately one show these two to be equal. Actual median values can be several orders of magnitude larger than what is shown here, anything larger than 3 was reduced to 3 for the purpose of this plot. Stipples indicate significant difference from 1 based on a Wilcoxon rank-sum test ($p<0.05$).

The difference between tree PFT had as large an effect on climate as afforestation in some places. Based on the ratio described in Eq.1, the choice of tree type was more important than afforestation (ratio > 1) where the effect of afforestation is closest to zero (Fig 6). In particular, the choice of tree PFT was most important in the mid-Atlantic for Tg and surrounding the Gulf of Mexico for T2m. The effect of afforestation significantly outweighs the choice of tree type in the north for T2m and in the southwest for Tg. However afforestation was significantly more important than the choice of PFT to Tmax on the whole eastern half of the region, and afforestation was significantly more important than the choice of PFT to Tmin in the southwest (Fig 6).

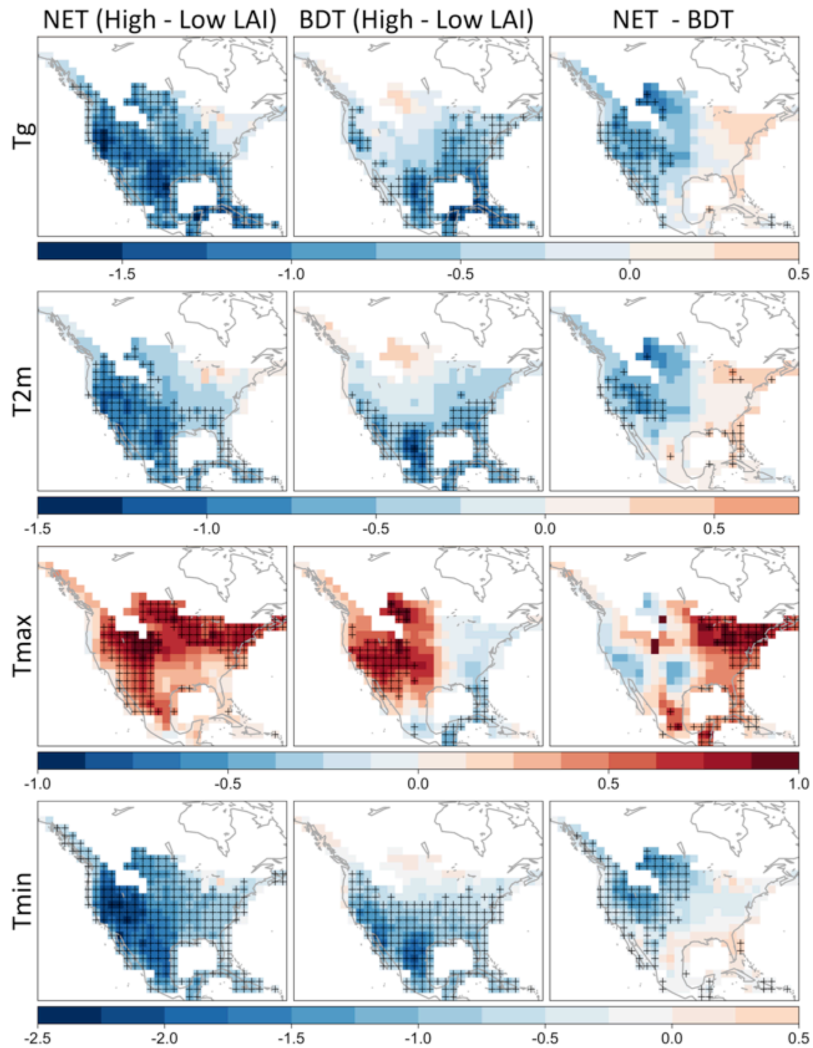

Figure 7: *Comparison of management intensification (LAI 2 to LAI 4) with need leaf trees (NET), broadleaf trees (BDT), and between tree types (NET-BDT) with respect to change in temperature variables (Tg, T2m, Tmax, Tmin) with units of degrees Celsius/kelvin. Stipples indicates the mean response is significantly different from zero based on a students t-test (p< 0.05) using the annual mean response of the final 20 years as the sample.*

How increasing management affects the biophysical effects of forests on climate

Increasing LAI had cooling effect on Tg and T2m, though this effect depended on the interaction of tree PFT and location (Fig 7). NET had a stronger cooling effect than BDT in the west and BDT had a stronger cooling effect than NET in the east, though only the former is significant (Fig 7). The region wide mean change in T2m was -0.47 K and -0.31 K for NET and BDT and the region wide mean change in Tg was -0.75 K and -0.48 K for NET and BDT. Tmax increased across the region for NET, and only in the west for BDT (Fig 7). Increasing LAI caused a decrease in Tmin for both tree PFTs but was significantly stronger in the western region for NET (Fig 7).

DISCUSSION

Afforestation and variable selection

Afforestation alters the energy balance and temperature of the land surface by changing albedo, latent heat flux (LHF), and sensible heat flux (SHF) (Jackson et al. 2008). These biophysical mechanisms have a greater effect on local climate than carbon sequestration, and can affect regional climate at a similar magnitude(Zhao and Jackson 2014). While the net biophysical effect of forests on climate changes with location, PFT, and management intensity of the forest (Li et al. 2015; Luyssaert et al. 2014; Zhao and Jackson 2014), the importance of these three factors has not been explicitly compared using a consistent method. Here, using a state-of-the-art ESM, we examined the influence of North American temperate forests on climate and explicitly evaluate the relative importance of the location of the project, the PFT used in the project and management intensity. We found that forest location, PFT, and management can have biophysical effects on climate on the same scale.

The mean effect of a forest on temperature was highly dependent on the scale of analysis and the temperature metric used. For example, using Tg as the metric indicated that forests had a net cooling effect between -1.5 K and 1.2 K. Using T2m as our metric indicated that temperate forests had a warming effect over most of the region (Fig 2). Accounting for both ground temperature and near surface air temperature was required for a complete picture of the effects a forest will have on temperature since both of these variables represent the temperature response at slightly different scales. Since Tg is the ground temperature under the canopy, we interpreted the change in Tg as the local response to small-scale afforestation. The change in Tg was likely due to strong decreases in albedo at high latitudes and a strong increase in SHF and LHF at low latitudes (Fig 5,6). The energy transported away from the ground by increased SHF warms the air at 2-meters above the vegetation, increasing T2m. We interpreted T2m as the temperature local response beyond the immediate area since T2m is subject to air circulation. Afforestation increased SHF across the region warming the maximum and mean air temperature over most of the region (Fig 4). Previous studies have found nighttime temperatures to increase and daytime temperatures to decrease in response to afforestation, exactly the opposite of our findings (Li et al. 2015). This difference may potentially be due to the use of different metrics in temperature response. Li et al. use land-surface temperature as their metric to determine daytime and nighttime responses, whereas we used air temperature.

Multiple studies have found afforestation to have a cooling effect in the south and a warming effect in the north (Zhang et al. 2014; Li et al. 2015; Peng et al. 2014). However the transitional latitude, where the temperature response shifts from warming to cooling, is not consistent. Using NET and BDT as bounds, we found the transitional latitude for the eastern coast of the United States to lie between *34° N* and *40° N* for Tg and between *21° N and 25° N* for T2m (Fig 3). The transitional latitude of Tg is consistent with other findings but our transitional latitude for T2m was farther south than other studies (Li et al. 2015; Lee et al. 2011; Zhang et al. 2014). This discrepancy deserves further investigation but is likely due to differences in the scale of the analysis (e.g. Local or regional) and the response metric used (e.g. Surface vs. air temperature).

Addressing the question of where to afforest, afforestation has a local and regional warming effect at high latitudes and a cooling effect at low latitudes within the temperate biome. This pattern is robust to differences in tree PFT however but different tree PFT have different magnitudes of response across the region as well as different transitional latitudes (Fig 2,3). It is in these middle latitudes (*21 to 40° N)* where choice of tree PFT is most important.

PFT effects

In general, BDT has a stronger cooling effect and a weaker warming effect on annual mean temperatures than NET across the region (Fig 2). This agrees with previous studies showing that, given equal carbon sequestration, a greater cooling benefit can be expected from BDT as opposed to NET (Zhao and Jackson 2014). However, we did not find that BDT cool near surface air by reducing SHF as reported by Zhao and Jackson, 2014 (Fig 2,4). We found that both NET and BDT warm near surface air relative to surface temperature, with BDT warming T2m slightly less than NET (Fig 2). This is because BDT had a smaller increase in SHF relative to NET when afforesting from croplands. In addition, we did not observe any significant increase in region wide LHF nor any distinct latitudinal gradient as reported by Zhao and Jackson, 2014 (Fig 4). In fact we found LHF to decrease over much of North America in response to afforestation.

Addressing the question of what type of tree to use during afforestation, BDT provides a greater cooling benefit than NET over the temperate region of North America, assuming equal capacity to sequester carbon. However, the relative importance of tree PFT varies across the region and is most important in the south and mid-Atlantic (Fig 6).

Forest Management

Increasing LAI, a proxy for intensifying management, has a cooling effect on Tg and T2m that varies by tree PFT and location (Fig 7). Our findings agree with previous studies that found a change in land management affects local climate on the same order of magnitude as a change in land cover (Luyssaert et al. 2014). In addition, changes in LAI affect Tg and T2m at nearly the same scale as changes in PFT (Fig 2, 9). While still on the same order of magnitude, the temperature response from a change in LAI tended to be smaller than a change in land-cover (afforestation). Possibly, this is due to how we represented forest management. We used a doubling of the yearly maximum LAI to represent a general increase in management intensity. In order to more accurately assess how forest management affects climate, forest management needs to be explicitly modeled in the ESM. This will also allow us to quantify the effects of different management strategies such as thinning, fertilization, changes in spacing and others.

It is unclear at this point if the radiative forcing from the small change in albedo is outweighed by the radiative forcing from the change in SHF as has been hypothesized (Luyssaert et al. 2014). While the change in albedo resulting from an increase in LAI is very small, the two PFTs examined show contrasting responses; increasing LAI decreases albedo for NET but increases albedo for BDT (Fig 8). The reason behind this phenomenon is unclear at this time and requires further investigation.

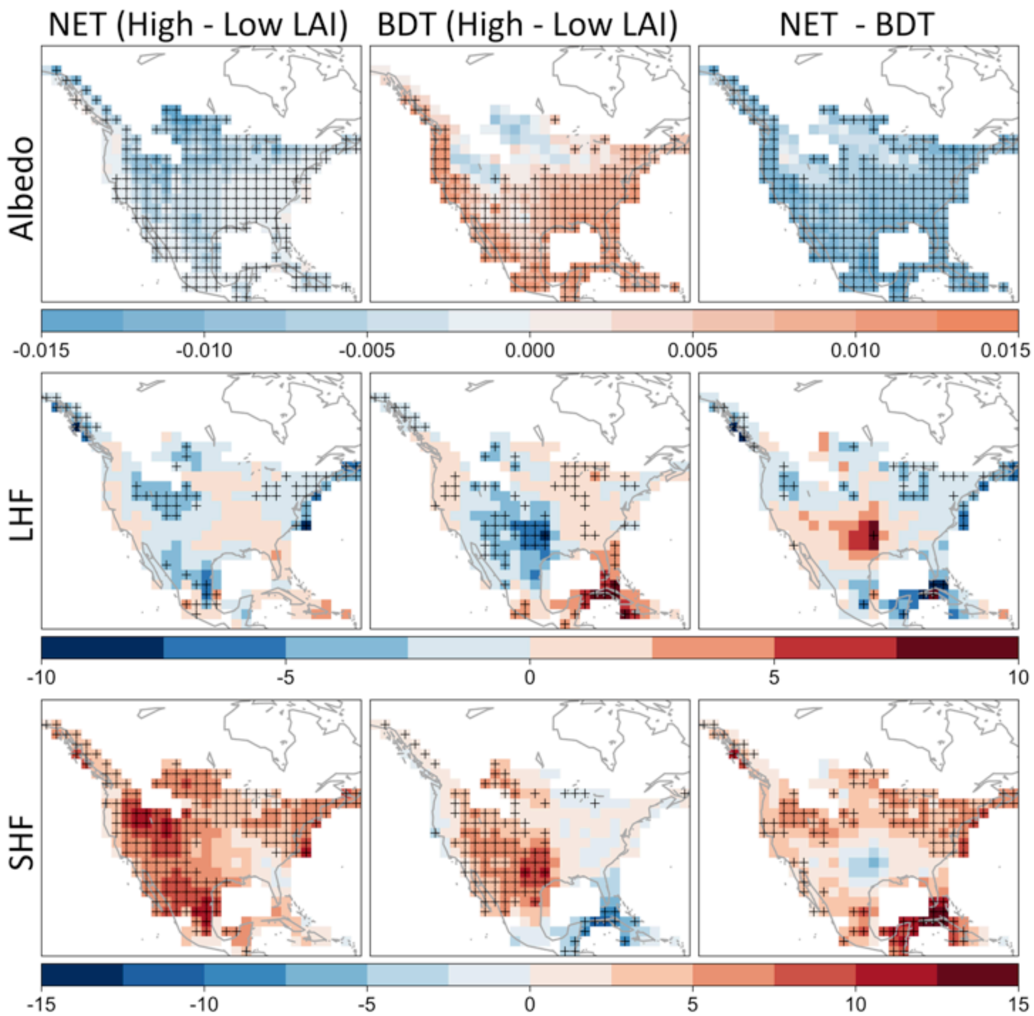

Figure 8: Comparison of management intensification (LAI 2 to LAI 4) with need leaf trees (NET), broadleaf trees (BDT), and between tree types (NET-BDT) with respect to change in biophysical mechanisms albedo, LHF (W/m^2) and SHF (W/m^2). Stipples indicates the mean response is significantly different from zero based on a students t-test ($p < 0.05$) using the annual mean response of the final 20 years as the sample.

Addressing the question of how management intensity can change forests effect on climate; increasing LAI through management has a cooling effect on local and regional temperature (Fig 7). NET tended to have a stronger cooling response to a doubling LAI than BDT (Fig 7). However, increasing LAI causes BDT to increase albedo, if only slightly (Fig 8).

Caveats

We have reduced the uncertainty in our results by examining multiple response metrics (Tg and T2m), by standardizing uniform LAI and PFT distributions across space, and by examining the energy balance without the complicating effects of CO_2 feedbacks. This has allowed us to determine the local and near local scale biophysical effects of forests on climate. Further research on this topic will demand the use of multiple models, with an active carbon cycle, and active ocean model. In addition, results could be more detailed if the model was at a finer resolution, with explicit forest management, and with vegetation growth and mortality dynamics.

Summary

We have found that the biophysical effects of forests on climate can vary greatly across temperate North America. Changes in LAI, potentially associated with the intensification of forest management, can have a significant effect on temperature, but this response was less than the response to afforestation from croplands. In general, BDT provides a greater cooling benefit than does NET, but the importance of this difference varies by latitude, which is a proxy for the background climate. Forests have a warming effect on Tg at high latitudes, and a cooling effect at mid to low latitudes. The results from this study show that, to maximize the biophysical cooling benefits of a forest, it would be best to plant a broad-leaf deciduous forest at low latitudes or in areas with minimal snow accumulation, in the eastern half of North America, and ensure that LAI of this forest is maximized.

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APPENDIX A: SUPPLEMENTARY FIGURE

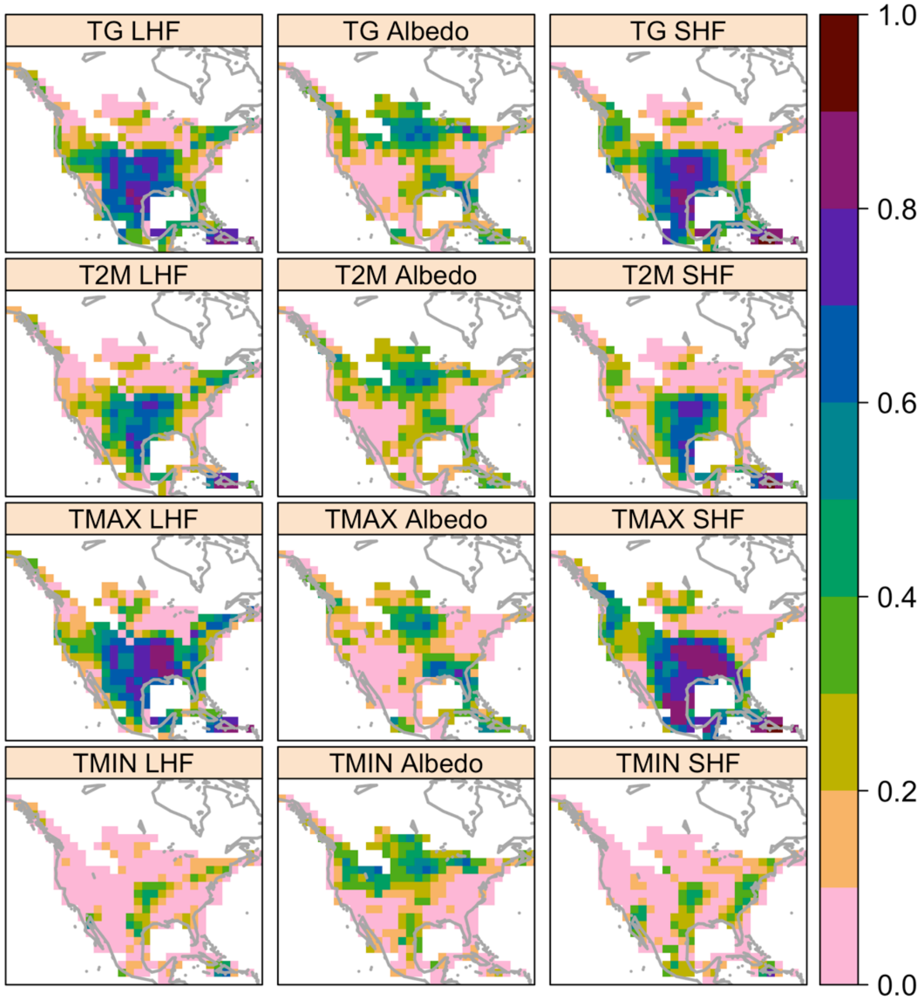

Figure 1: Coefficient of determination (R^2) between temperature variables and biophysical mechanisms latent heat flux (LHF), albedo, and sensible heat flux (SHF) when replacing broad leaf trees (BDT) with needleleaf trees (NET). Correlation was determined using the annual means of the last 20 years in each gridcell.