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Distance decay and directional diffusion of ecoclimate
teleconnections driven by regional-scale tree die-off

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Supplementary material for this article is available [online](#)

Abstract

Climate change is triggering regional-scale alterations in vegetation including land cover change such as forest die-off. At sufficient magnitudes, land cover change from forest die-off in one region can change not only local climate but also vegetation including agriculture elsewhere via changes in larger scale climate patterns, termed an ‘ecoclimate teleconnection’. Ecoclimate teleconnections can therefore have impacts on vegetative growth in distant regions, but the degrees to which the impact decays with distance or directionally diffuses relative to the initial perturbation are general properties that have not been evaluated. We used the Community Earth system model to study this, examining the implications of tree die-off in 14 major US forested regions. For each case we evaluated the ecological impact across North America as a function of distance and direction from the location of regional tree die-off. We found that the effects on gross primary productivity (GPP) generally decayed linearly with distance, with notable exceptions. Distance from the region of tree die-off alone explained up to ~30% of the variance in many regions. We also found that the GPP impact was not uniform across directions and that including an additional term to account for direction to regional land cover change from tree die-off was statistically significant for nearly all regions and explained up to ~40% of the variance in many regions, comparable in magnitude to the influence of El Nino on GPP in the Western US. Our results provide novel insights into the generality of distance decay and directional diffusion of ecoclimate teleconnections, and suggest that it may be hard to identify expected impacts of tree die-off without case-specific simulations. Such patterns of distance decay, directional diffusion, and their exceptions are relevant for cross-regional policy that links forests and other agriculture (e.g. US Department of Agriculture).

1. Introduction

Drier and hotter conditions associated with climate change are driving global tree mortality patterns (progressively documented in Allen *et al* (2010), Pachauri *et al* (2014), Allen *et al* (2015), Hartmann *et al* (2018) and Hammond *et al* (2022)). This includes large-scale tree die-off events due to drought and

warming (e.g. Breshears *et al* 2005, Anderegg *et al* 2013, Matusick *et al* 2013) and associated insect and pathogen attacks (Anderegg *et al* 2015, Robbins *et al* 2022), as well as wildfire and windthrow (Pugh *et al* 2019, Wu *et al* 2023). A ‘hotter-drought fingerprint’ has been identified that essentially defines how hot is too hot and how dry is too dry for trees to survive globally (Hammond *et al* 2022). Multiple

lines of evidence indicate that mortality is projected to increase as climate change proceeds (Adams *et al* 2009, Park Williams *et al* 2012, Hammond *et al* 2022). Consequently, the potential for forest loss through tree die-off from drought and warming, and associated insect and pathogen outbreaks, is substantial. Additionally, wildfire is also driven by warmer and drier conditions (Williams *et al* 2019, Mueller *et al* 2020) and can lead to additional tree mortality (Regelbrugge and Conard 1993). Collectively climate-driven tree die-off and wildfire pose significant risks to forest cover globally.

A shift from forests to grasses due to tree die-off would tend to have three distinct impacts. First, it would increase the surface albedo, thus decreasing absorbed solar radiation during snow-free seasons. Second, forests would have different rates of evapotranspiration, in many cases higher due to higher leaf area (as argued in Jackson *et al* 2005), but highly productive grasses could have larger ground to atmosphere water fluxes compared to water conservative trees. Third, forests generate more air turbulence compared to grasses by making a rougher surface which increases turbulent fluxes of energy and water. These three factors shift the balance of energy fluxes over the land surface leading to direct local climate impacts (Laguë *et al* 2019). The local climate impacts of a loss of forest cover in temperate to boreal climates depend strongly on region. At high latitudes, boreal forests tend to be substantially darker than other land cover types, and thus a loss of forest cover leads to cooling from reduced absorption of solar radiation (Bonan *et al* 1992, Foley *et al* 1994, Liu 2005, Bonan 2008, Villegas *et al* 2017). In the mid-latitudes the impact of albedo driven cooling competes against evapotranspiration driven warming associated with forest loss (Swann *et al* 2012), and the resulting surface climate outcome is likely determined by soil water availability (Laguë and Swann 2016). Taken together these biophysical changes have climate impacts, including altered surface temperature, near surface humidity, and local cloud cover. However the impacts are not contained to local regions (e.g. Avissar and Werth 2005, Findell *et al* 2006, Chen *et al* 2012, Swann *et al* 2012, Medvigy *et al* 2013, Badger and Dirmeyer 2016, Winckler *et al* 2019, Chen and Dirmeyer 2020), as surface changes in fluxes of water and energy can impact cloud formation and in turn climate and extent of radiative forcing elsewhere (Laguë and Swann 2016, Laguë *et al* 2019, 2021).

Forest loss impacts not only local climate, but also larger scale climate as signals can be propagated through the atmosphere, and alterations of energy gradients in the climate system can induce circulation responses (Zhao *et al* 2001, Findell *et al* 2006, Medvigy *et al* 2013, Devaraju *et al* 2015, 2018, Laguë *et al* 2019, 2021). These climate alterations have impacts on distant ecosystems, a phenomenon

called an ‘ecoclimate teleconnection’ (Swann *et al* 2012, Stark *et al* 2016). An ecoclimate teleconnection is similar in concept to that of an El Niño Southern Oscillation event, which begins in the tropical Pacific but leads to climate impacts elsewhere across the globe. Taken together, the spatial extent of the impact of forest loss is likely to be primarily ‘local’ but the exact spatial scale is not well characterized and depends on the sensitivity of the atmosphere to changes in the land surface in any given region.

Forest land cover change through tree die-off (and other forms of tree loss) can therefore have ecological impacts distant from the forest loss region. However, to our knowledge there have not been any evaluations about the generality of how such impacts for ecoclimate teleconnections vary across space. Distance and direction are two key spatial aspects that determine the spatial relationship between locations and form fundamental principles in spatial science. For example, the distance decay relationship is a long-recognized general principle in geography and ecology—interaction between two locations declines as the distance between them increases (Taylor 1983, Nekola and White 1999). Direction is a key factor in describing the (physical, chemical, biological) diffusion process across space (Okubo and Levin 2001), and by default one may expect the diffusion is uniform across directions in a homogeneous environment. Two general aspects of spatial patterns that have not been evaluated and are of particular interest are (1) distance decay: ‘to what degree does the effect of an ecoclimate teleconnection generally decay with distance?’, and (2) directional diffusion: ‘to what degree does the diffusion of an ecoclimate teleconnection diffuse uniformly with direction?’ The impacts involve a complex set of climate alterations including increases in peak summertime temperatures, reduction in water availability, and increase in atmospheric water supply/demand (Garcia *et al* 2016, Swann *et al* 2018). Our quantification of general patterns of distance decay and directional diffusion in ecoclimate teleconnections is motivated in part by their relevance for understanding implications of how a given region is impacted by forest die-off in another region for issues such as carbon storage or non-forest agricultural economics, as well as how one or more agencies may need to coordinate information sharing and management.

Here we evaluate how forest land cover change associated with extensive tree die-off impacts different forested regions of the US, and how spatial strength and structure of ecoclimate teleconnections varies across forested regions. Given the complexity in possible patterns of ecoclimate teleconnections discussed above, we proposed three sets of hypotheses (figure 1): (1) the relationship between spatial distance and strength of teleconnection will be either no correlation, linear decay/increase, or exponential

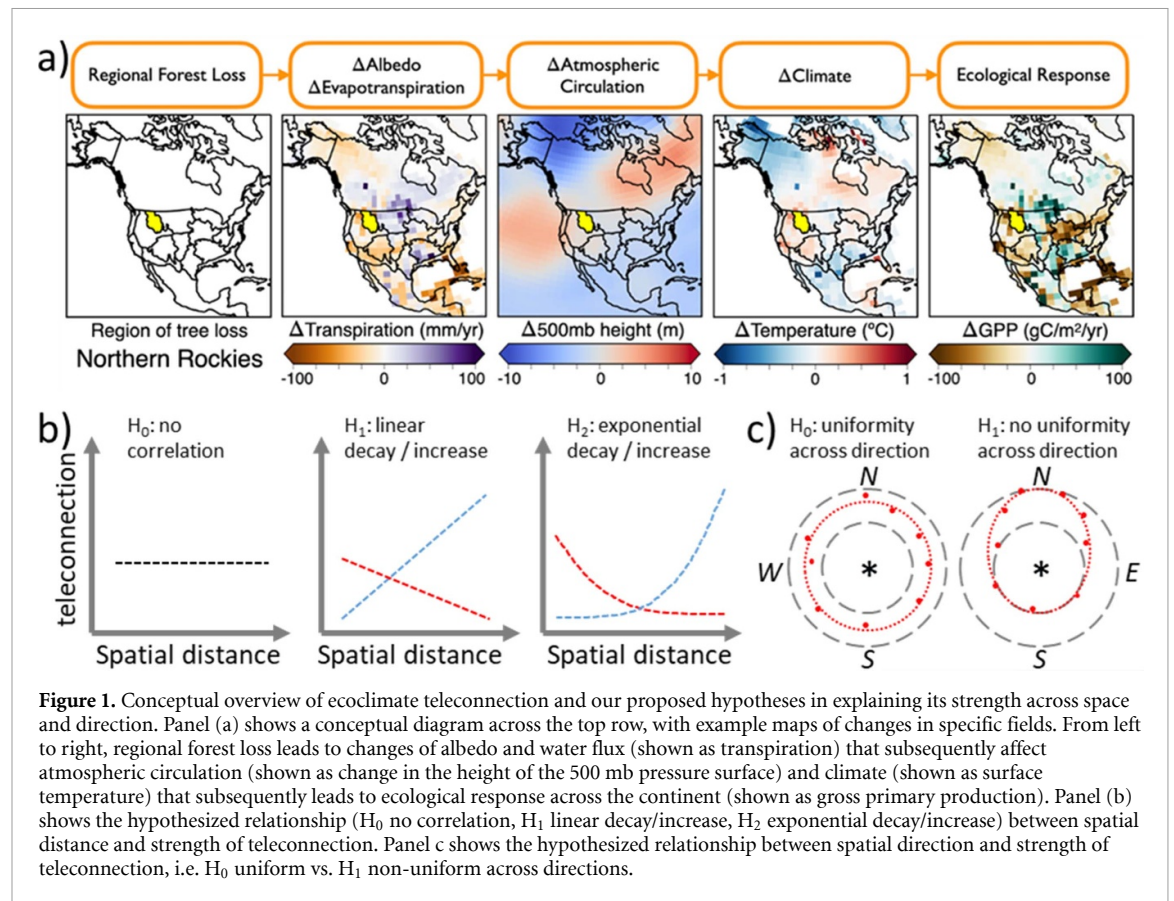


Figure 1. Conceptual overview of ecoclimate teleconnection and our proposed hypotheses in explaining its strength across space and direction. Panel (a) shows a conceptual diagram across the top row, with example maps of changes in specific fields. From left to right, regional forest loss leads to changes of albedo and water flux (shown as transpiration) that subsequently affect atmospheric circulation (shown as change in the height of the 500 mb pressure surface) and climate (shown as surface temperature) that subsequently leads to ecological response across the continent (shown as gross primary production). Panel (b) shows the hypothesized relationship (H_0 no correlation, H_1 linear decay/increase, H_2 exponential decay/increase) between spatial distance and strength of teleconnection. Panel (c) shows the hypothesized relationship between spatial direction and strength of teleconnection, i.e. H_0 uniform vs. H_1 non-uniform across directions.

decay/increase (referred to here as distance decay); (2) the influence of an ecoclimate teleconnection radiates out either uniformly or non-uniformly with direction (referred to here as directional diffusion); (3) considering spatial distance decay and directional diffusion together better explain the patterns of teleconnection than considering the two factors individually.

2. Methods

We used an Earth system model (CESM; Kay *et al* 2015) to implement tree die-off by converting tree cover to grass cover for each of 14 major forested regions of the US (Domains of the US National Ecological Observatory Network; NEON). NEON regions are based on climate and soil properties (Hargrove and Hoffman 2004) covering covariance across climate, soils, ecology, and land-management practices (Schimel *et al* 2007). We then evaluated the impact on climate and ecosystems scaled by the direction and distance to regional tree die-off. We focused on both general patterns that emerge but also notable exceptions, which could be an important characteristic of ecoclimate teleconnections.

2.1. CESM model setup

We conducted simulations using National Center for Atmospheric Research (NCAR) Community Earth System Model version 1.3 (CESM). The CESM model couples Community Atmosphere Model version 5

(CAM5) (Neale *et al* 2012) to the Community Land Model (CLM4.5) (Oleson *et al* 2013), the CICE4 sea ice model (Hunke *et al* 2010), and implements a slab ocean with prescribed heat transport derived from a fully-coupled ocean-atmosphere simulation (Neale *et al* 2012). Further details about the parameterization of the component models can be found in the papers above, as well as in the technical documentation (Oleson *et al* 2013). Year 2000 land use conditions based on satellite observations (Lawrence and Chase 2007) were used in the model setup, and the atmospheric CO_2 concentration was set to be constant at 400 ppm as our simulations are intended to represent approximately present-day ‘equilibrium’ conditions in a stable climate as discussed further below. The land model component calculates surface fluxes of energy, water, and momentum which are passed to the atmospheric model. Carbon fluxes are also calculated diagnostically, and leaf area dynamically responds to photosynthesis rates through allocation of fixed carbon to leaves. This allows both surface albedo and evapotranspiration rates to vary with climate as a function of atmospheric conditions, stomatal conductance per leaf area, and leaf area.

Model simulations were conducted at the spatial resolution of 1.9° latitude by 2.5° longitude for 100 years. Climate and terrestrial variables (e.g. global surface temperature, leaf area index) reach equilibrium after approximately 40 years of model spin up. The spin up period is discarded, and we then analyze

time series for the remaining 60 years. This 60 year period can be considered ‘equilibrium’ conditions, where variations over time represent samples over the expected internal variability of the climate system rather than a time series into the future. The CESM simulations were implemented on the NCAR Cheyenne supercomputing cluster (Computational and Information Systems Laboratory 2017).

2.2. Experiment

We conducted 15 simulations: a control with no tree die-off and 14 experimental simulations, each corresponding to the scenario of tree die-off in one of 14 most forested ecoregions in the United States (i.e. NE, MA, SE, GL, PP, AP, OZ, NR, SR, DS, GB, PN, PS, and TA Domains of the US National Ecological Observatory Network (NEON) as in Swann *et al* 2018). In each experiment, all forested area in an ecoregion (figure S1) was replaced with C3 grass. Present day tree abundance was based on satellite observations (Lawrence and Chase 2007). Thus the magnitude of tree die-off varies between experiments as a function of the present day forest cover (figure S1). These experiments are numerically different but conceptually similar to those reported in Swann *et al* (2018)—they differ slightly in area of tree cover removed and were computed on a different platform. While the experiments are similar, the analysis presented here is focused on a different objective—the general relationship between ecoclimate teleconnection strength with distance and direction to the source of tree die-off. To measure the strength of ecoclimate teleconnections (Swann *et al* 2018), we calculated the absolute difference of gross primary productivity (GPP) between experimental and control simulations averaged by month across 60 years in each North American grid pixel (1.9° latitude by 2.5° longitude). The analysis was also repeated by looking at positive and negative changes of GPP separately. The majority of our analysis uses the absolute difference of GPP (ΔGPP) in units of $\text{g C m}^{-2} \text{ yr}^{-1}$. We also report changes in GPP as a percentage of the control simulation, where samples with the lower ten percentiles of the base GPP were excluded to avoid extreme values in GPP percentage change.

2.3. Analysis

For each NEON ecoregion where land cover change was assumed to occur due to tree die-off we identified the centroid of the ecoregion. To analyze the impact of distance we calculated the spatial distance between each pixel in continental North America and the associated centroid where die-off occurred. To analyze the impact of direction we used the centroid of the ecoregion as the reference point with North as the reference direction to calculate the angle clockwise, with directions converted to degrees (i.e. north is 0°, east is 90°, south is 180° and west is 270°).

To test the distance decay hypothesis, we conducted least square regression using the strength of teleconnections (absolute difference of GPP; ΔGPP) as the dependent variable, and used distance (D) where we observed the GPP difference as independent variables (equation (1)) for each ecoregion. Since the hypotheses were about the monotonic relationship between the strength of teleconnections and distance, more complex terms (e.g. quadratic or cubic term) that we did not have a basis for hypothesizing were not included in the linear model,

$$\Delta\text{GPP} \sim \beta_0 + \beta_1 D. \quad (1)$$

Besides the linear relationship, we also used a non-linear form (exponential; equation (2)) with coefficients a and r and base of the natural logarithm e ,

$$\Delta\text{GPP} \sim a e^{rD}. \quad (2)$$

The non-linear model was used as a comparison to the linear model, to assess if a non-constant slope would better fit the distance decay relationship. The comparison between the linear and non-linear model was based on Akaike information criteria (AIC) and R^2 . Additionally, to test our hypothesis that strength of teleconnection radiated out uniformly with direction, we conducted another least square regression for each ecoregion using the strength of teleconnections in terms of ΔGPP as the dependent variable, and used direction, based on angle (A), as the independent variable (equation (3)),

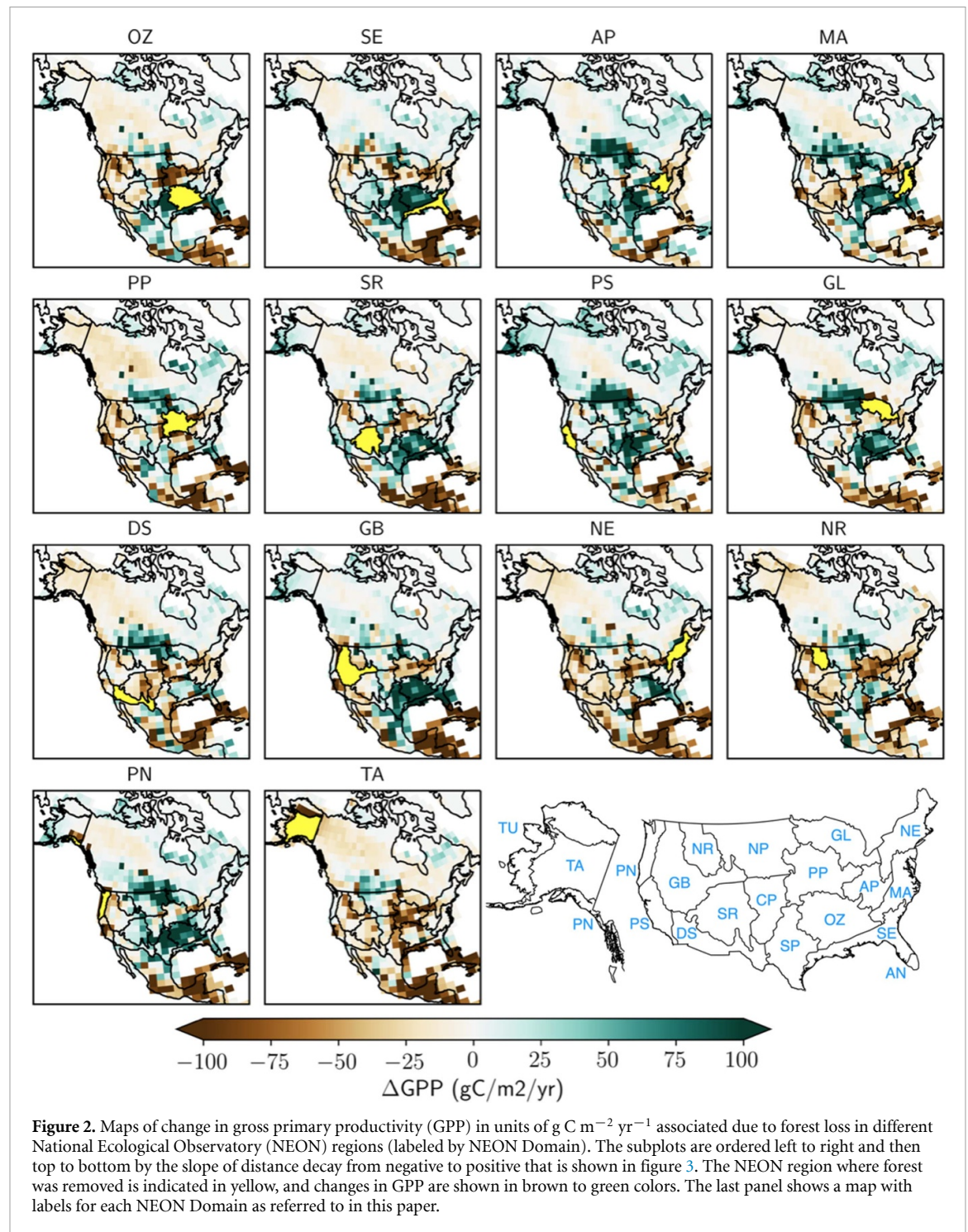
$$\Delta\text{GPP} \sim \beta_2 + \beta_3 A_t. \quad (3)$$

As angles are circular, we performed sine transformation of the angle using $A_t = \sin\left(\pi \frac{A}{180}\right)$. Lastly, we also performed multiple regressions using both distance and transformed angle as independent variables for strength of teleconnections (equation (4)). Here, because the values of the two independent variables were of different magnitudes, they were both transformed to have a mean of zero and standard deviation one (e.g. $\frac{D - D_{\text{mean}}}{D_{\text{sd}}}$) so that the estimated coefficients of both variables could be further compared and evaluated,

$$\Delta\text{GPP} \sim \beta_4 + \beta_5 D + \beta_6 A_t. \quad (4)$$

3. Results

Overall, regional tree die-off simulations triggered both local and large-scale climate responses (figures S2–S6) by altering local energy fluxes primarily through changes in evapotranspiration and surface albedo (e.g. figure 1). These ecologically-driven climate responses resulted in changes in GPP compared with the control run that varied depending on the



region of tree die-off (figure 2). Although there are many places with small changes in GPP, tree die-off generally leads to changes in surface climate conditions both locally and at farther distances due to atmospheric teleconnections (air temperature, figure S2; soil water stress, figure S3; low cloud cover, figure S4; rainfall, figure S5; 500 mb atmospheric pressure, figure S6). Annual mean GPP in any given location tended to decrease with hotter temperatures (figure S7) and drier summers (figures S8 and S9) (which subsequently have lower cloud cover, figure S10), as well as GPP tending to increase as summertime

soils get wetter (figure S8). The exception is in high northern latitudes, where higher summer temperatures tend to increase GPP (figure S7). These general responses were also seen and discussed in further detail for similar experiments in Swann *et al* (2018). These climate responses are not, however, inevitable outcomes of tree loss; instead they are an outcome of local climate responses including land-atmosphere feedbacks as well as larger scale climate responses including teleconnections. We evaluated these results in the context of relationships for distance decay, directional diffusion, and the two combined.

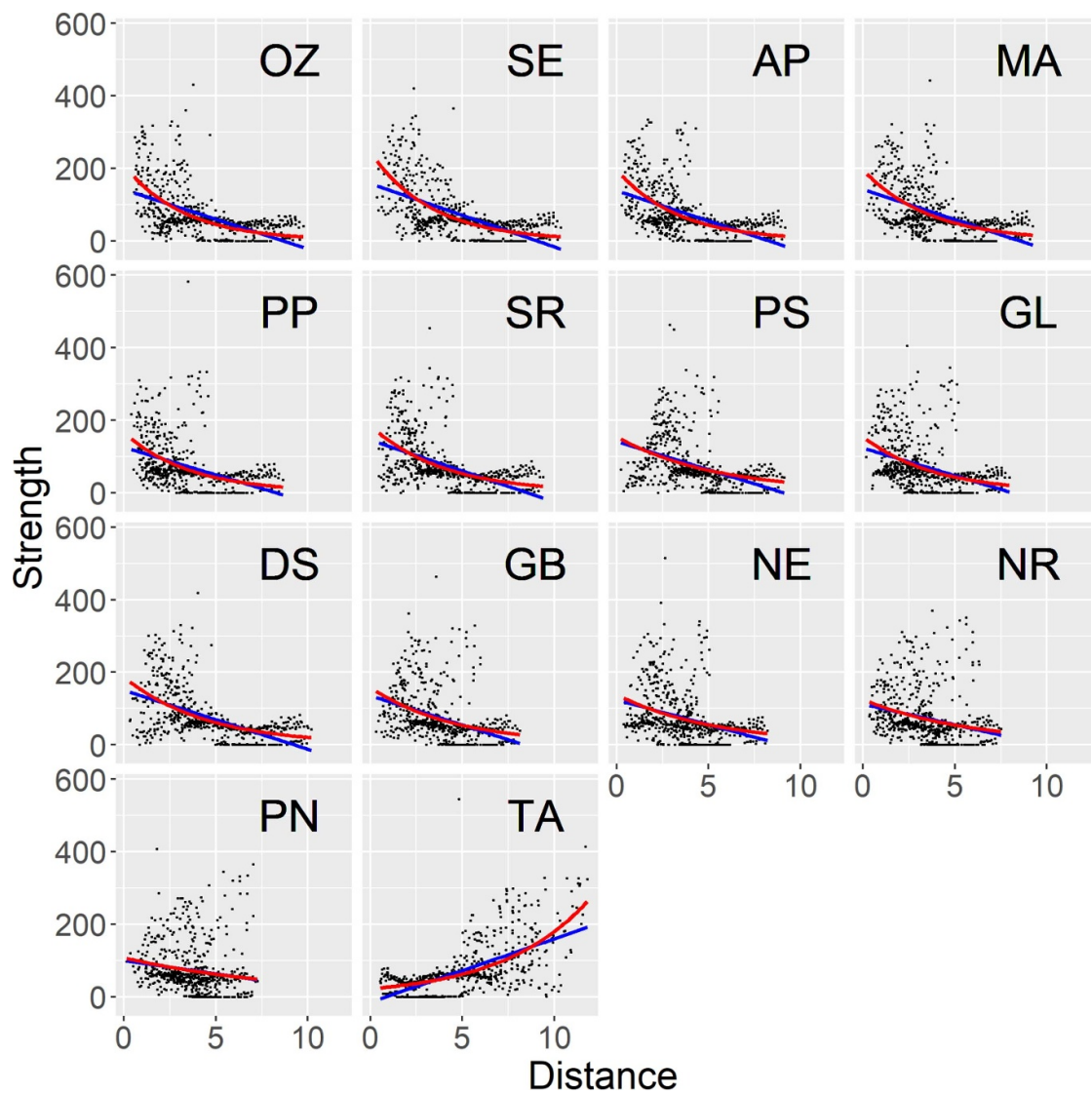


Figure 3. Scatter plots of spatial distance and strength of ecoclimate teleconnections. Each panel represents an experiment of forest loss in a NEON region (labeled by NEON id). The x-axis represents spatial distance (10^3 km) between a NEON region (centroid) and a pixel in North America and the y-axis represents strength of ecoclimate teleconnections (delta GPP; unit is $\text{g C m}^{-2}\text{yr}^{-1}$). The blue and red lines represent the fitted linear or exponential relationship between spatial distance and strength of ecoclimate teleconnections. The subplots are ordered left to right and then top to bottom by the slope of distance decay from negative to positive.

3.1. Distance decay relationships

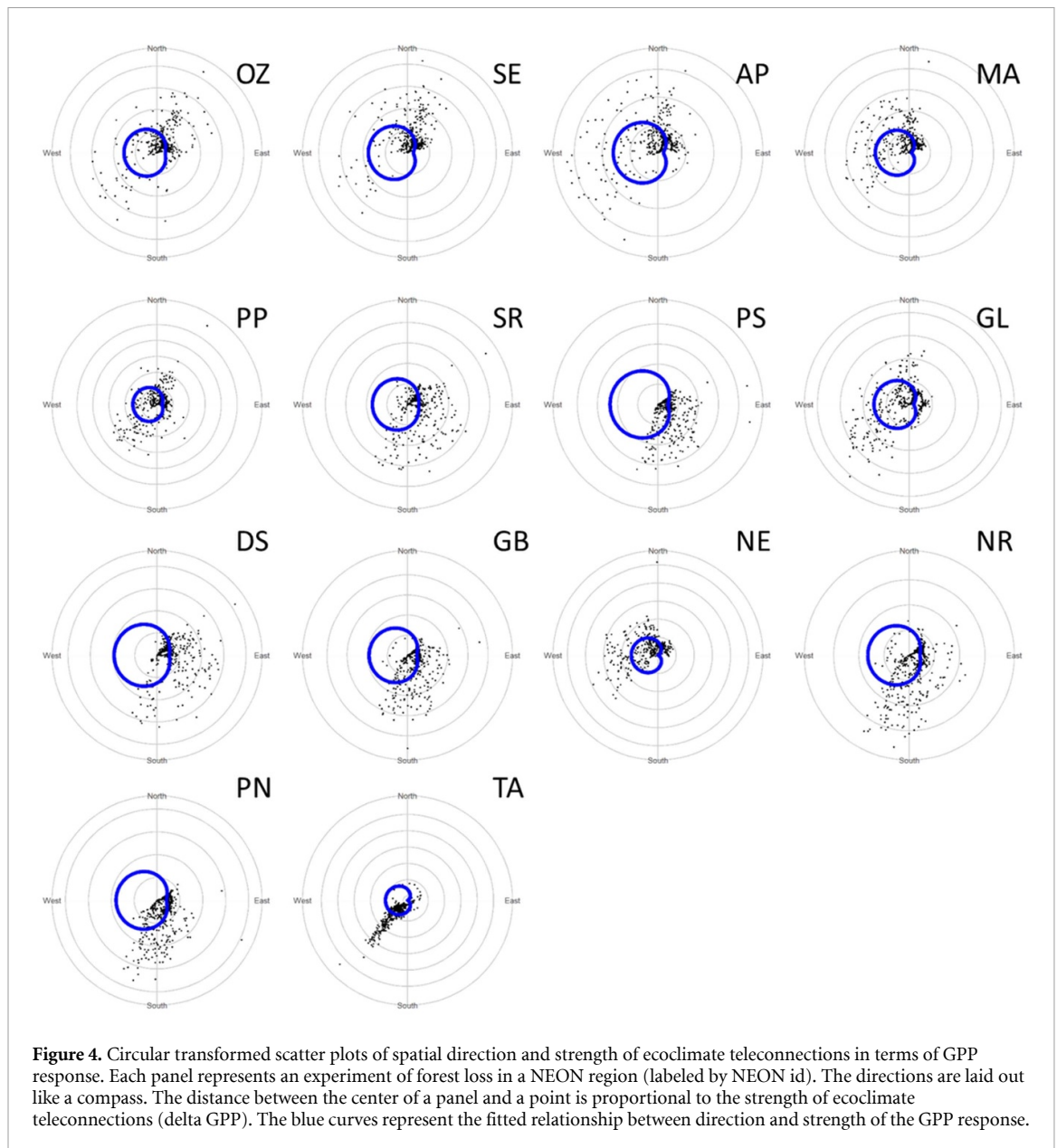
The strength of ecoclimate teleconnections, as quantified by the change in GPP resulting from remote tree die-off, decayed with spatial distance from the tree die-off region (reflected by the negative slope of the linear regression in figure 3); this was the case for all Domains except for tree die-off in Alaska (Taiga Domain; TA), for which strength of ecoclimate teleconnections (i.e. positive slope) increased with distance (table 1). However, few cases followed a tight linear decreasing trend—we found both larger and smaller GPP responses to tree die-off at the same distance from the die-off as evidenced by the scatter in response at a given distance. This range of responses suggests that other factors are important in determining the response of GPP to remote tree

die-off, which we investigated further below. Many of the simulation experiments show a strong decay of the impact of tree die-off within a few thousand km, with a sharply decreasing trend until ~ 4000 km, with the strength of the GPP response to remote tree die-off remaining somewhat constant at distances farther than ~ 4000 km. In some cases an exponential relationship better described the GPP response to tree die-off than a linear relationship (i.e. lower AIC values and/or higher R^2) (table S1). We found similar results of the relationship between GPP response to tree die-off and distance from the tree die-off when we considered a percentage change in GPP rather than the total change in GPP (table S2), or when considering the positive and negative changes separately (tables S3 and S4).

Table 1. Summary of regression analyses with strength of ecoclimate teleconnections (Δ GPP) as dependent variable and spatial distance and/or spatial direction as independent variables. NEON regions are shown in figure 2.

NEON region	GPP ~ Distance					GPP ~ Direction					GPP ~ Distance + Direction						
	Intercept	Distance	R ²	AIC	Residual (mean, SD)	Intercept	Direction	R ²	AIC	Residual (mean, SD)	Intercept	Distance	Direction	R ²	AIC	Residual (mean, SD)	Num. obs.
OZ	141.34***	-16.31***	0.30	6623.17	0.00, 59.02	95.27***	-57.23***	0.19	6709.65	0.00, 63.42	69.39***	-30.97***	-17.05***	0.35	6583.32	0.00, 57.00	602
SE	157.86***	-17.42***	0.34	6688.34	0.00, 58.98	101.53***	-74.96***	0.25	6768.32	0.00, 62.99	72.29***	-32.63***	-20.36***	0.40	6633.2	0.00, 56.27	608
AP	138.40***	-16.69***	0.27	6713.34	0.00, 59.66	90.09***	-70.19***	0.37	6619.80	0.00, 55.25	70.83***	-21.09***	-32.94***	0.44	6547.21	0.00, 51.97	609
MA	142.00***	-16.65***	0.25	6719.35	0.00, 60.51	85.60***	-75.51***	0.41	6575.66	0.00, 53.76	71.89***	-16.90***	-36.30***	0.45	6531.06	0.00, 51.74	608
PP	125.37***	-15.11***	0.19	6697.78	0.00, 63.97	91.84***	-59.12***	0.27	6630.01	0.00, 60.46	69.65***	-18.30***	-29.42***	0.33	6584.92	0.00, 58.13	600
SR	145.32***	-16.97***	0.28	6673.35	0.00, 60.97	112.87***	-58.13***	0.12	6794.00	0.00, 67.38	72.37***	-33.35***	-11.45***	0.30	6657.24	0.00, 60.06	603
PS	141.66***	-15.56***	0.19	6822.41	0.00, 64.07	144.22***	-93.13***	0.20	6815.02	0.00, 63.68	72.17***	-23.13***	-24.30***	0.30	6741.44	0.00, 59.86	611
GL	123.67***	-15.20***	0.14	6778.67	0.00, 67.16	86.62***	-66.98***	0.40	6559.22	0.00, 55.97	72.39***	-12.09***	-41.69***	0.43	6536.39	0.00, 54.82	602
DS	150.38***	-16.24***	0.32	6626.55	0.00, 57.59	124.59***	-68.27***	0.09	6803.87	0.00, 66.68	71.42***	-36.70***	-9.11***	0.34	6614.86	0.00, 56.95	605
GB	135.78***	-16.20***	0.15	6724.85	0.00, 67.29	119.02***	-71.65***	0.23	6664.80	0.00, 63.99	73.05***	-19.15***	-29.14***	0.29	6616.74	0.00, 61.37	597
NE	123.99***	-13.69***	0.11	6865.67	0.00, 69.52	73.86***	-73.61***	0.42	6608.21	0.00, 56.22	72.96***	-6.78***	-45.01***	0.43	6602.71	0.00, 55.87	606
NR	112.21***	-11.40***	0.07	6906.88	0.00, 69.94	103.79***	-60.90***	0.25	6777.62	0.00, 62.90	72.57***	-8.67***	-33.26***	0.26	6769.03	0.00, 62.35	609
PN	99.85***	-7.38***	0.03	6866.69	0.00, 70.24	110.09***	-68.93***	0.27	6693.71	0.00, 60.88	72.17***	-5.22***	-35.92***	0.27	6691.36	0.00, 60.66	605
TA	-14.99***	17.47***	0.37	6489.32	0.00, 60.04	40.99***	-67.45***	0.13	6681.33	0.00, 70.68	74.81***	42.69***	-8.10***	0.38	6482.79	0.00, 59.60	588

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



3.2. Directional diffusion relationships

In addition to variation in distance decay relationships, the strength of ecoclimate teleconnections were not uniform among directions in all cases (figure 4, table 1), meaning that there is a different GPP response based on the directional angle relative to the tree die-off. This indicates that directional diffusion is not uniform. The strength of direction effect varied across the experiments, with the R^2 ranging from 0.09 to 0.42, revealing weak to moderate relationships. Some of these directional relationships were influenced by obvious boundaries such as oceans (e.g. PN and PS), whereas the cause of others was less clear.

3.3. Combined distance decay and directional diffusion relationships

Regression models based on distance alone, direction alone, and on both distance and direction together all showed statistically significant relationships with

the explanatory variables but explained different proportions of the variance (table 1). Regression models for GPP response as a function of distance decay from tree die-off explained >20% of variance in the data for 7 of 14 Domains, and more than 10% of the variance in 5 additional Domains. Compared with distance decay, directional diffusion explained a larger fraction of variance overall, with more than 20% of variance for 11 of 14 Domains. When comparing the effects of distance decay vs. directional diffusion, the GPP response in some regions was explained better by one or the other; for example Southern Rockies Domain (SR) shows more variance explained by distance while Northeast Domain (NE) shows more variance explained by direction. Considering all Domains together, the largest fraction of variance in GPP was explained by the regression model that included both distance and direction as explanatory variables, with 5 Domains showing more than 40%

variance explained, 6 Domains with more than 30% explained, and all Domains explaining at least 26% (table 1). Although a model with more predictive variables is expected to explain a larger amount of variance overall we find that both distance and direction independently add explanatory power.

4. Discussion

4.1. Distance decay and directional diffusion hypotheses

Several modeling studies have identified ecoclimate teleconnections driven by changes in forest cover (Zhao *et al* 2001, Findell *et al* 2006, Swann *et al* 2012, 2018, Medvigy *et al* 2013, Devaraju *et al* 2015, 2018, Garcia *et al* 2016, Laguë and Swann 2016, Winckler *et al* 2017). However, to date whether any systematic forces influence the spatial patterns of these ecoclimate teleconnections have not been evaluated. Here we tested two hypotheses regarding the strength and direction of ecoclimate teleconnections. Regarding our first hypothesis that the response of GPP to forest loss elsewhere would decay with distance from the regional with land cover change from tree die-off ('distance decay hypothesis'), we used regression analyses and found support for the distance decay hypothesis, with less GPP change the further from the location where forest loss occurred in 13 of our 14 cases (table 1; the relationship for Alaska, TA, was a notable exception, see discussion of teleconnections below). Our second hypothesis was that the changes in GPP associated with a given ecoclimate teleconnection would be uniform among directions—that is, the influence of the tree die-off radiates out uniformly in all directions. Our results clearly indicate rejection of this hypothesis (table 1, figure 4) as we find that the direction of forest loss relative to an impacted region is a statistically significant factor for all domains.

Changes in land cover impact the atmosphere by modifying fluxes of energy and water. More specifically, changes in surface energy fluxes impact local temperatures, as well as have the potential to generate cloud feedbacks or circulation responses; however the direct local responses are expected to be larger. Consistent with our expectations, we found that the impact of a change in land cover was most important for nearby regions, such that the impact decayed with distance (figure 3; table 1).

The distance decay relationship is a long-recognized general principle in geography and ecology—interaction between two locations declines as the distance between them increases (Taylor 1983, Nekola and White 1999), but the degree to which this applies to complex atmospheric processes associated with ecoclimate teleconnections has not been

evaluated. We found evidence of this in the distance decay relationships that we quantified (figure 3; table 1). Where the distances are relatively short, the distance decay relationship is likely related to the direct advection of heat and moisture. Forests can modify an air mass by changing its temperature or moisture content and that anomaly can be advected with the air mass, with potential impacts in regions downwind.

However, impacts are not limited to directly advected quantities. The nonuniformity in directionality of response indicates simply that either teleconnectivity between regions or other upwind geographic variables can modify surface climate and thus the pattern of GPP impact. Geographic variables include coastal boundaries as well as topography and terrain. For instance, notice how the directions are shifted for tree die-off in the Great Basin Domain away from the Northern Rockies Domain (figures 2 and 4). Changes to the land surface could have non-local climate impacts, and the impact of forest loss could be felt at larger distances due to the propagation of atmospheric waves and potential associated modifications to atmospheric circulation with remote 'teleconnections' (Wallace *et al* 2023). Geographic factors and teleconnections would both tend to reduce the relationship between impact and distance, favoring either a dependence on direction when associated in particular with direct advection or orientation relative to terrain, or a signal that is not well explained by direction because the teleconnections may not have a preferred directional pattern. We find evidence of impacts of teleconnections in the directional relationships that we quantified (figure 4; table 1) as well as in anomalies of the height of the 500 mb atmospheric pressure level which suggests that atmospheric waves have been generated by changes in forest cover (figure S5).

To place the explanatory power of distance and direction in context, we highlight that, for example, the explanatory power of El Nino on western US GPP is only up to 36% (Dannenberg *et al* 2015). Therefore, in the context of complex atmospheric systems, distance and direction are relatively powerful explanatory variables. Note, however, that there is considerable spread around the distance decay relationship, whether using the linear or non-linear model fitting, indicating that there are substantial exceptions to this general trend for many specific locations. That is, the strength of this relationship varies by region. Some source regions do not fit this pattern because they have more distinct atmospheric responses, because either the circulation or the local responses driving circulation have higher sensitivity to local changes. For example, the case of Taiga Domain (TA) in Alaska shows as an exception to distance decay patterns, where the change in

GPP increases with distance (figure 2). This is likely due to the dominance of a teleconnection pattern, where propagation of atmospheric waves is leading to changes in climate and thus GPP at more distant locations (figure S5).

4.2. Limitations and implications for future studies

As with any model simulation experiment, there are some caveats and limitations of our study that should be noted. First, our simulations remove all tree cover within a given NEON Domain, a scenario unlikely to occur. However, as such, our simulations provide important bounding estimates on ecoclimate teleconnection patterns as well as creating enhanced levels of change where we can detect and evaluate distance and direction effects. Previous related work revealed that areas of tree loss at this scale were still large enough to trigger ecoclimate teleconnections (Swann *et al* 2018). Second, to date, simulated ecoclimate teleconnections have not been tested with observations in the field; future research is needed to test predicted ecoclimate teleconnections based on field observations and remote sensed variables. This would necessarily involve less tree loss than we have simulated. However, tree loss is becoming substantial in some areas. An especially notable example is the southern Sierra Nevadas, where 30% of the region's conifer forest extent transitioned to non-forest vegetation between 2011 and 2020 due to tree die-off, wildfire and associated bark beetle infestations (Steel *et al* 2022). Third, our simulations held CO₂ at a fixed amount and evaluated the mean for 100 years which tells us about the effect of tree loss under our current levels of CO₂, but does not account for the impact of plant responses to future climate and high CO₂, notably hotter temperatures along with photosynthetic and stomatal responses to elevated CO₂. Fourth, we have not decomposed the atmospheric mechanisms driving the ecoclimate teleconnection structure; this could be the focus of future research and would increase understanding about causality for ecoclimate teleconnections. Fifth, our GPP measure is one that ignores human responses, and humans might moderate or enhance the impacts by, say changing crops or forest incidence elsewhere—a topic requiring future study. Sixth, we use a single Earth system model to perform these simulations. To understand the robustness of the specific projections for any given tree loss pattern it would be necessary to test the climate impacts in multiple climate models. However, doing so is a computational and technical challenge that requires collaboration that crosses funding sources and often international borders. The results we present here represent a substantial computational effort and can be used to propose hypotheses about the behavior of the coupled Earth system

that can be tested subsequently for specific applications in future work. Seventh, we used simple relationships (linear or exponential) in testing the monotonic effect of distance and direction on delta GPP. The selection of those models were for the purpose of maximizing simplicity of the analyses, though future studies could consider exploring more complex relationships using non-monotonic terms (e.g. quadratic or cubic) or flexible non-parametric models that may be better suited to capture regional-level patterns of ecoclimate teleconnections.

4.3. Implications of ecoclimate teleconnections

This study and prior related research indicate that ecoclimate teleconnections are likely to become increasingly important to consider under climate change due to increased forest cover loss from drought and heat-related tree mortality, as well as wildfire. Our model simulations are bounding calculations because we completely removed tree cover within a given domain—a state unlikely to occur. However, actual forest land cover change due to tree cover loss is increasing substantially in some domains. Drought and heat are driving tree mortality around the globe (Hammond *et al* 2022) and wildfire thresholds are being exceeded, triggering additional tree die-off (e.g. Descals *et al* 2022). The recent tree die-off in the southern Sierra Nevadas of the US illustrates increasing potential to drive ecoclimate teleconnections (Steel *et al* 2022). Internationally, tree loss from fires, deforestation, and drought are pushing the Amazon rainforest toward a predicted tipping point of state transition to savanna (Lovejoy and Nobre 2018).

Motivation for our research included the need to inform cross-regional policy and management for issues such as carbon storage or non-forest agricultural economics. In the US, a single agency, the US Department of Agriculture (USDA), is responsible for promoting affordable future food supplies, reducing risk in agricultural production, improving the rural environment and managing forests. Organizationally and institutionally, the USDA's food, agricultural related environment and agricultural insurance programs are unconnected to its forest land management activities. Yet the ecoclimate teleconnections quantified here show potential linkages between forest management decisions, regional climates, and agricultural productivity. This suggests some areas where greater within-agency coordination might be fruitful. Since tree loss in one area can positively or negatively affect production elsewhere (figure 2), federal initiatives to account for carbon storage or to project future food supplies may need to account for ecoclimate teleconnections. Such effects may be particularly important when vegetation change in one region negatively impacts carbon storage or agricultural productivity

in another region. USDA may want to consider how ecoclimate teleconnections affect crop risk, food costs and related programs; and forest managers may want to consider ecoclimate teleconnections in their forest management and fire suppression plans (Baldwin *et al* 2023). Further, institutions that drive coordination and cooperation between forest and non-forest agriculture stakeholders across both sections of USDA may help tackle the governance challenges associated with ecoclimate teleconnections, either by prompting voluntary responses or by mandate (Lubell 2013, Baldwin *et al* 2023, McLaughlin 2023).

The distance decay and directional dependence that we quantify advances our understanding of ecoclimate teleconnections. Equally important are the exceptions to explained variance in that these simulations identified ecoclimate teleconnections can be substantial and need to be accounted for even though they do not follow the general distance decay patterns. A future goal is to develop a more systematic understanding of where the atmosphere is sensitive to changes in land cover and what spatial patterns result from those land surface perturbations (building on the recent work of Laguë *et al* 2019). Our results reveal that currently it may be hard to identify expected impacts of forest loss without explicit simulations. In conclusion, both general patterns of distance decay in ecoclimate teleconnections and their associated exceptions, as well as variation in directional patterns, potentially have important ecological and agency management implications.

Data availability statement

The data that support the findings of this study are available from: <https://doi.org/10.5061/dryad.stqjq2c8j>.

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