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RESEARCH ARTICLE

Toward accounting for ecoclimate teleconnections: intra- and inter-continental consequences of altered energy balance after vegetation change

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Abstract

Context Vegetation is projected to continue to undergo major structural changes in coming decades due to land conversion and climate change, including widespread forest die-offs. These vegetation changes are important not only for their local or regional climatic effects, but also because they can affect climate and subsequently vegetation in other regions or continents through "ecoclimate teleconnections".

Objectives We propose that ecoclimate teleconnections are a fundamental link among regions within and across continents, and are central to advancing large-scale macrosystems ecology.

Methods and results We illustrate potential ecoclimate teleconnections in a bounding simulation that assumes complete tree cover loss in western North America due to tree die-off, and which predicts subsequent drying and reduced net primary productivity in other areas of North America, the Amazon and elsewhere. Central to accurately modeling such

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ecoclimate teleconnections is characterizing how vegetation change alters albedo and other components of the land-surface energy balance and then scales up to impact the climate system. We introduce a framework for rapid field-based characterization of vegetation structure and energy balance to help address this challenge.

Conclusions Ecoclimate teleconnections are likely a fundamental aspect of macrosystems ecology needed to account for alterations to large-scale atmospheric-ecological couplings in response to vegetation change, including deforestation, afforestation and die-off.

Keywords Amazon · CESM · Ecoclimate teleconnections · Energy balance · Forest die-off · Hemispherical photography · LiDAR · Macrosystems ecology · North America · Vegetation change

Introduction

> *If ecologists are to be successful in distinguishing competing and interacting causes of large-scale ecological changes and associated feedbacks to the atmosphere and hydrosphere, they will need to match the spatial and temporal scales of analysis employed routinely by climatologists* (AIBS 2004).

Macrosystems ecology focuses on "diverse ecological phenomena at the scale of regions to continents and their interactions with phenomena at other scales" (Heffernan et al. 2014). Critical questions of this type include (AIBS 2004): "*What are the time–space domains of ecological variance, and how are they influenced by the spatial and temporal scales at which climate varies and changes?*", "*How does climate variation impact the dynamics of biologically available water in terrestrial systems, and how do those dynamics in turn affect ecological patterns and processes at regional-to-continental scales?*", and more generally "*How will changes in climate influence regional ecosystem structure and function, and how will these ecosystem changes feedback to climate, hydrology, and biogeochemical cycles?*". While much macrosystems biology has predicted patterns at large scales, central to many types of macrosystems issues is connectivity: how processes from one region influence another region (Peters et al. 2008; Heffernan et al. 2014). A frontier in addressing these questions is the specific role of "ecoclimate teleconnections", in which ecological changes in one area influence climate and associated ecological responses in another. This requires considering the links between vegetation, soil, and climate at a hierarchy of spatial scales spanning local, regional and synoptic scales normally considered in climatology but often not all considered in ecology.

At regional and larger scales, vegetation is projected to continue to undergo major structural changes in coming decades due to land conversion and climate change. Such patterns of change are often related to pronounced increases or decreases in the proportion of woody cover within a region. These can include afforestation, deforestation, forest degradation, woody plant encroachment, desertification, and forest die-off (Breshears 2006). These changes represent potentially critical forces for altering land surface-atmosphere feedbacks (Bonan 2008a). Global scale modeling studies are beginning to suggest how ecoclimate teleconnections may link the fates of vegetation—

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and atmospheric circulation—across regions and even continents (e.g., Swann et al. 2012). For instance, recent model estimates to determine the upper bounds of responses to conversion of northern hemisphere grasslands to forests—a potential afforestation effort—show that conversion could increase energy transfer between northern and southern hemispheres, leading to increased drought in the Amazon (Swann et al. 2012). Similarly, Amazon deforestation could have global impacts including across North America (e.g., Medvigy et al. 2013). Such teleconnection effects may impact local vegetation structure and function, altering local vegetation-atmosphere feedbacks, such as those between forest cover and rainfall in the Amazon (Spracklen et al. 2012), or potentially creating inter-regional feedbacks when the teleconnection is bidirectional. Of particular concern with global warming is an emerging pattern of widespread tree mortality due to drought, warmer temperature, and associated pests, pathogens and fires (Allen et al. 2010, 2015). Climate change may drive rapid vegetation change across large regions of the Earth's land surfaces over the coming decades, based on recent rates of observed mortality and basic climate-vegetation relationships (Breshears et al. 2005; Adams et al. 2009; Phillips et al. 2009, 2010; van Mantgem et al. 2009; Allen et al. 2010, 2015; Choat et al. 2012; Williams et al. 2013; Brienen et al. 2015). These large-scale die-off events are likely candidates for altering ecoclimate teleconnections but have not yet been evaluated for this potential.

Here we describe how such ecoclimate teleconnections can fundamentally connect regions within and across continents and argue that understanding this connectivity is central to advancing macrosystems ecology. We focus on forest die-off as a key type of vegetation change. First, we introduce the concept of ecoclimate teleconnections. Second, we illustrate potential ecoclimate teleconnections in a bounding simulation assuming complete tree-cover loss in western North America due to die-off, which predicts subsequent drying and reduced net primary productivity in other areas of North America, the Amazon and elsewhere. Third, we argue that characterizing how contemporary vegetation change such as die-off alters surface properties including albedo and other components of energy balance is particularly important for modeling ecoclimate teleconnections. Finally, we introduce a framework for rapid field-based characterization of vegetation structure and energy balance that can aid in addressing this challenge. To effectively characterize ecoclimate teleconnections, an integration of continental-scale observing networks, such as the National Ecological Observatory Network (NEON; Keller et al. 2008), The Amazon Forest Inventory Network (RAINFOR; Peacock et al. 2007) and Large Scale Biosphere–Atmosphere experiment in Amazonia (LBA; Avissar et al. 2002) with earth system models is needed. However, NEON and other network observations must be strategically supplemented with direct observation in locations undergoing vegetation change. More generally, we highlight that ecoclimate teleconnections are a fundamental aspect of macrosystems ecology that may be needed to account for alterations to large-scale atmospheric-ecological couplings in response to major types of vegetation change.

Components of ecoclimate teleconnections

The role of vegetation: the "Ecoclimate" component

The influence of the atmosphere on vegetation

Global vegetation patterns are determined, in large part, by climate. In the past, correlational approaches have been used to link vegetation types with mean climate states (e.g., Holdridge 1967); however, these approaches do not encompass the rapid time scales required to predict vegetation structural and functional responses to global change, such as climate-induced forest die-off and associated alterations of vegetation-atmosphere energy exchange (e.g., Allen et al. 2010, 2015; Anderegg et al. 2013). For forest die-off, as well as some other key types of climate-driven vegetation change, the critical drivers are associated with extreme climate events rather than background climate trends alone (Jentsch et al. 2007). That is, drought compounded by warmer temperature ("global-change-type drought"; Breshears et al. 2005; or "hotter drought"; Allen et al. 2015) is a key driver of die-off events. Importantly, temperature increases are associated with nonlinear increases in atmospheric moisture demand during drought (Breshears et al. 2013) and this atmospheric demand component is a critical aspect of a new Forest Drought Severity Index that accurately predicts die-off events, shown for the Southwestern US (Williams et al. 2013) but likely relevant to other regions because of fundamental plant physiology (McDowell et al. 2008).

Progress related to patterns and mechanisms of mortality has recently been reviewed (McDowell et al. 2008, 2011; Allen et al. 2010, 2015; Anderegg et al. 2013), and we point readers to those reviews for additional details related to die-off processes. In brief, contemporary observational research suggests that tree die-offs impacting more than 30 % of the cover or of individuals are widespread in temperate regions around the world (Allen et al. 2010). Indeed, forests and woodlands of the Southwestern US have lost more than 20 % cover to drought-driven tree die-off events and wildfire (Williams et al. 2010). In the tropics, the Amazon forest carbon sink appears to be declining, attributed in part to increasing plant mortality (Brienen et al. 2015), with large trees experiencing higher mortality rates (Fisher et al. 2007; Nepstad et al. 2007; da Costa et al. 2010); this may be associated with drought related to tropical North Atlantic ocean anomalies (Aragão et al. 2007; Marengo et al. 2008; Phillips et al. 2009). However, increased mortality rates to date have not been at the scale of tree die-off there (i.e., loss of >30 % cover), except when associated with fire (Aragão et al. 2007).

Disturbances including forest die-off events fundamentally alter vegetation structure (Anderegg et al. 2013). The response of vegetation structure to variation in climate likely emerges primarily from impacts on plant demography—mortality, as well as growth and recruitment—which in the short term may impact the distribution and quantity of leaf area in the canopy (e.g., Medvigy et al. 2009; Stark et al. 2015). Even in relatively open semiarid woodlands, a reduction in tree cover due to die-off from ~14 to ~6 % of individuals yielded a nearly 10 % increase in incoming near-ground solar radiation (Royer et al. 2010, 2011). In the long-term, such effects may lead to changes in the composition and function of ecosystems. In more dense forests, such as in the Amazon, structural responses to climate-driven tree mortality are still evident even though these systems may have pronounced canopy resilience. For example, under severe multi-year experimental drought Leaf Area Index (LAI) dropped by >25 % from pre-drought levels of ~6 (Brando et al. 2008) even though tree loss was moderate and the canopy never completely collapsed (i.e., lost ~100 % cover). Gap fraction observed from LiDAR remote sensing in the Amazon was also correlated with mortality rates (Stark et al. 2012).

The persistence of vegetation structural changes varies with vegetation type. Such changes may persist for decades in semiarid woodlands and forests (Allen and Breshears 1998). Recovery could be comparably faster in parts of the Amazon (however see Saatchi et al. 2013) but may be related to the severity and duration of the extreme climate event. Increased light penetration following disturbance may promote recovery. For example, when light limitation is reduced by thinning the overstory in tropical forests, compensatory growth is typically observed in smaller individuals; forest management prescriptions and changes in tree growth following gap formation support this assertion (e.g., Miller et al. 2011; Stark et al. 2012). Such resilience, however, could be eroded if the regional scale-dependent feedback between forest cover and rainfall were disrupted by deforestation or climate change (Cox et al. 2004; Lawrence and Vandecar 2015), reducing net water input and possibly the potential for canopy recovery. Importantly, structural changes of vegetation in response to die-off are interrelated with the effects that vegetation has on the atmosphere on both short and long timescales.

The influence of vegetation on the atmosphere

The dynamics of vegetation affect radiation and energy-balance partitioning at the interface between land and atmosphere at multiple spatial and temporal scales; from the local effects of woody-canopies on surface energy balance, thermal emissivity, and surface properties—such as turbulence and aerodynamic-roughness structures—to synoptic scales where atmospheric circulation responds to surface forcings to the atmosphere—often associated with the presence and function of vegetation (Fig. 1a; Makarieva et al. 2013). At local scales, vegetation canopies, particularly trees and other woody plants, affect surface energy balance through interception of solar radiation and by influencing radiative properties of the surface—especially albedo and emissivity. Further, vegetation structure (e.g., the size, number, and spacing of tree crowns) affects surface roughness, modifying wind properties (Breshears et al. 2009). These combined effects have implications for the partitioning of net radiation into sensible and latent heat (i.e.,

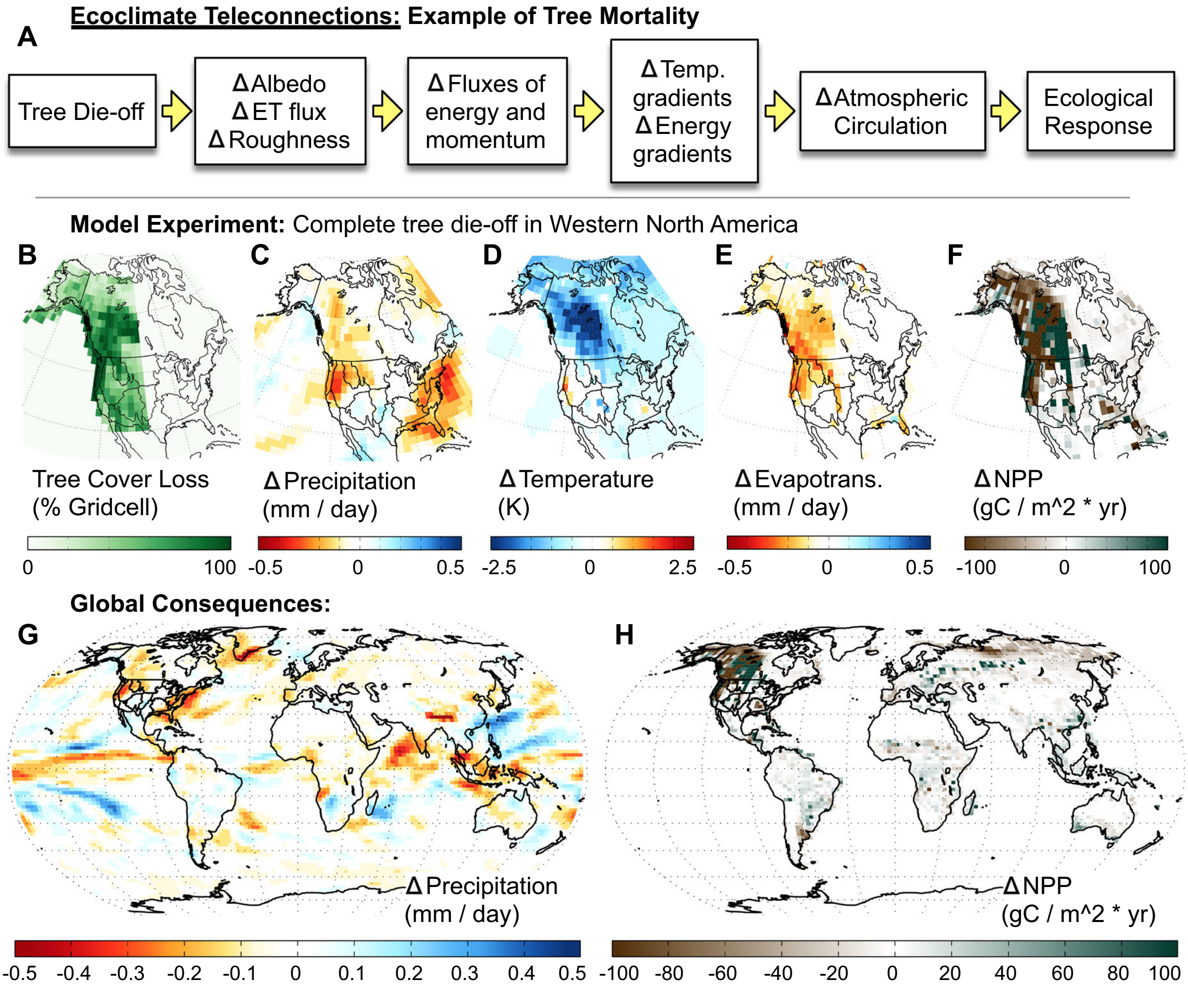

Fig. 1 Ecoclimate Teleconnections: concept and model-based example. **a** Conceptual diagram showing how tree mortality can lead to local changes in energy balance that create shifts in atmospheric circulation leading to teleconnection impacts. (Second and third rows) Climate modeling experiment representing complete die-off of western North American tree cover. Maps show the difference (present day minus forest loss scenario) due to the **b** change in tree cover for **c** annual mean precipitation, **d** temperature, **e** evapotranspiration, and **f**, **h** annual mean net primary production (NPP), and **g** precipitation globally. For panels **b** through **f** the delineated regions indicate NEON Domains. Note that the Southeastern United States is impacted by die-off in the Western US, as are the tropics, Siberia and other regions

evapotranspiration; Villegas et al. 2014, 2015). At the landscape-to-regional scale, evidence of these effects is captured by eddy flux measurement networks that directly measure the exchange of mass and energy between the biosphere and atmosphere (Baldocchi et al. 2001; da Rocha et al. 2009). These networks have enabled development of a broad understanding of the relationship between vegetation types and land-surface energy balance (Hasler and Avissar 2007; Fisher et al. 2009), but many areas that are undergoing rapid vegetation change (Allen et al. 2010, 2015) lack detailed assessments of energy balance. In particular, the effects of vegetation change such as tree die-off has typically not been addressed using eddy flux measurements, and more studies using paired tower arrays are needed to quantify energy balance effects of die-off (Goulden et al. 2006; Litvak et al. in prep). Given the scope of the challenge, additional measurement approaches to understand vegetation change impacts that can improve sampling globally are needed.

Vegetation changes such as forest die-off likely have important effects on regional as well as local atmospheric dynamics, although at larger scales there is currently greater uncertainty as to those effects. Regional modifications of atmospheric temperature, pressure and energy properties associated with vegetation changes lead to potential changes in atmospheric circulation (Dominguez et al. 2009; Swann et al. 2012). Current models assume rapid and complete transitions from one biome to another (e.g., forest to savanna) when climates become more favorable to the new biome according to present-day vegetation-climate relationships (e.g., Cox et al. 2004; Costa and Pires 2010). However, uncertainty in how ecological dynamics will actually play out following forest die-off or climate-driven disturbance creates uncertainty in the regional effects of vegetation change on the atmosphere. When such effects occur, though, they enable the potential for altered teleconnections (e.g., Swann et al. 2012) whereby climate in other regions can be affected, suggesting that a range of scenarios should be explored.

Global-scale responses: the "Teleconnection" component

Until recently, atmospheric teleconnections driven by changes in plant cover have received little attention as potential mechanisms that influence biosphere–atmosphere dynamics. However, modeled patterns of large-scale atmospheric circulation have been shown to link distant regions through the effects of the land surface on the atmosphere between regions, including feedbacks between regions (Avissar and Werth 2005; Feddema et al. 2005; Swann et al. 2012; Medvigy et al. 2013; Devaraju et al. 2015). Changes in vegetation cover and structure can alter climate locally in a given region and additionally have global effects on atmospheric circulation. For example, conversion of North American grasslands to forests via afforestation is predicted to shift the Intertropical Convergence Zone (ITCZ) by creating an energy imbalance between the northern and southern hemispheres that drives changes in the Hadley circulation (Swann et al. 2012). This shift in the ITCZ leads to drying over the southern flank of the Amazon, and a subsequent decrease in productivity and possible change in forest structure in locations far removed from the original forest cover change. This particular mechanism and others (i.e., Medvigy et al. 2013) suggest that the climate impacts of changes in forest structure and function are communicated widely by the atmosphere and can have implications for vegetation across the globe.

An approach for assessing ecoclimate teleconnections

Identifying ecoclimate teleconnections via modeling

Assessment of ecoclimate teleconnections requires specifically evaluating ecosystem-climate circulation feedbacks on global scales. Global climate simulations allow for the prediction of atmospheric circulation responses to land-surface forcing and are necessary for identifying plant-climate interactions for two primary reasons. First, we can use models to project the impacts of land-surface changes that have either not yet occurred (i.e., predicted tree die-off in the Amazon due to climate change) or that are not yet widespread. Second, global climate models can be used to help isolate and identify the effects of a single forcing factor on the climate system. The signal from a change in forest cover that has already occurred (e.g., North American forest die-off) may be identifiable locally (e.g., Maness et al. 2012), but the variability inherent in the global atmosphere will make any larger-scale signal very difficult to identify in observations without knowing where to look. Global-climate models can be used to identify the expected signal and enable hypothesis testing using direct observations.

In research that we have underway, we ask what possible ecoclimate teleconnections could arise from widespread tree die-off in Western North America and what mechanisms control them (Garcia et al. in prep.). Building from an analogous study on afforestation (Swann et al. 2012) and employing the Community Earth System Model with coupled atmosphere, land, and ocean models (V1.3 with interactive leaf area, static vegetation cover, and interactive ocean surface temperatures), we imposed 100 % tree loss across western North America (Fig. 1b) and tracked the response of surface-climate and ecosystem variables, including precipitation, temperature, evapotranspiration, and Net Primary Production (NPP) over a 50-year period (Fig. 1c–h). We found that widespread die-off is predicted to lead to local changes in climate through reductions in evapotranspiration, and decreasing temperatures from increased albedo. These local-scale changes force a global-scale atmospheric response that leads to widespread changes in precipitation (Fig. 1c, g) with consequences not just for climate elsewhere (Fig. 1c–e), but also for ecosystems (Fig. 1f, h) elsewhere. In particular, we see significant decreases in plant productivity (p value < 0.05) aligned primarily with regions experiencing a reduction in rainfall in mid and low latitudes, with some regions influenced more by temperature (not shown globally). For example, NPP decreases in northern Eurasia, due to statistically significant decreases in temperature and ice-driven declines in soil moisture and despite only small (non-significant) reductions in rainfall. Two scales of potential ecoclimate teleconnections appear important from these results. First, by highlighting the boundaries of the US National Ecological Observatory Network, we illustrate how changes in one or more Domains of that network can negatively impact another, such as the small (non-significant) drying and moderate yet significant reduction in NPP in the SE US (Fig. 1c, f). Second, we illustrate how the tropics and other non-local regions such as northern Eurasia could be negatively impacted by North American die-off (Fig. 1g, h). These examples demonstrate the types of ecoclimate teleconnections that could become increasingly important as global changes in climate and land use progress, but that to date are not generally accounted for. Understanding and better quantifying them will require improving our ability to link changes in surface energy balance to changes in vegetation structure.

Linking changes in energy balance to changes in vegetation structure: including rapid field assessment

Central to refining predictions of ecoclimate teleconnections is the prioritization—and subsequent measurement—of which aspects of vegetation structure and of energy balance are most influential (Fig. 2; see also Lou et al. 2012). Geometrical changes in vegetation structure that result from disturbances including tree die-off directly influence surface properties associated with energy balance partitioning—particularly latent and sensible heat flux partitioning, surface aerodynamic roughness, and radiative properties including surface albedo, which all directly influence atmospheric processes (Bonan 2008a; Swann et al. 2012). While leaf-level ecophysiological responses to changing climate (e.g., stomatal conductance) may also play an important role, the largest changes to ecosystem conductance and other factors impacting energy balance may occur when vegetation structure is altered by disturbances such as die-offs or land-use change. Consequently, digital characterization of vegetation geometry across disturbance gradients, such as with LiDAR remote sensing and hemispherical photography, can reveal changes to components of energy balance (Lefsky et al. 2002; Royer et al. 2010, 2011) that influence local through regional and interregional atmospheric dynamics. For energy balance, long-term fixed-location flux-tower observations of vegetation-atmosphere energy exchange serve as high-quality standards. However, methods that are quicker and more portable would enable more rapid and widespread assessment of these impacts of vegetation change and thus enable advances in understanding ecoclimate teleconnection responses to die-off and other disturbances.

A portable microclimate array could potentially enable rapid characterization of mean surface attributes relevant to energy and radiation balance partitioning and efficiently quantify surface energy budget change associated with actual tree die-off (Fig. 3a). These data could also offer opportunities to inform dynamic ecosystem approaches in Earth system models (e.g., Fisher et al. 2015) by directly linking forest structure to representations of surface energy fluxes. Here we illustrate such an array that incorporates a portable retractable mast instrumented with a net radiometer measuring down and upwelling radiation; an array of portable weather stations (Kestrel weather meter—Nielsen Kellerman 4500) to characterize near-surface wind/humidity/temperature profiles; soil temperature probes; and heat-flux plates to complete the description of the canopy boundary layer. This instrumental array allows short-term field observations in paired locations with and without tree cover change. With a 24–72 h observation period, albedo values can be derived from the short wave components of the net radiometer data. Canopy structural attributes are characterized by a combination of hemispherical photographs, ground-level net shortwave and photosynthetically-active radiation measurements, and a profiling LiDAR system that quantifies vertical vegetation structure (measurements along ~ 1 m wide transects arrayed in a 10 m × 10 m sampling grid in the radiometer footprint; Parker et al. 2004a; Stark

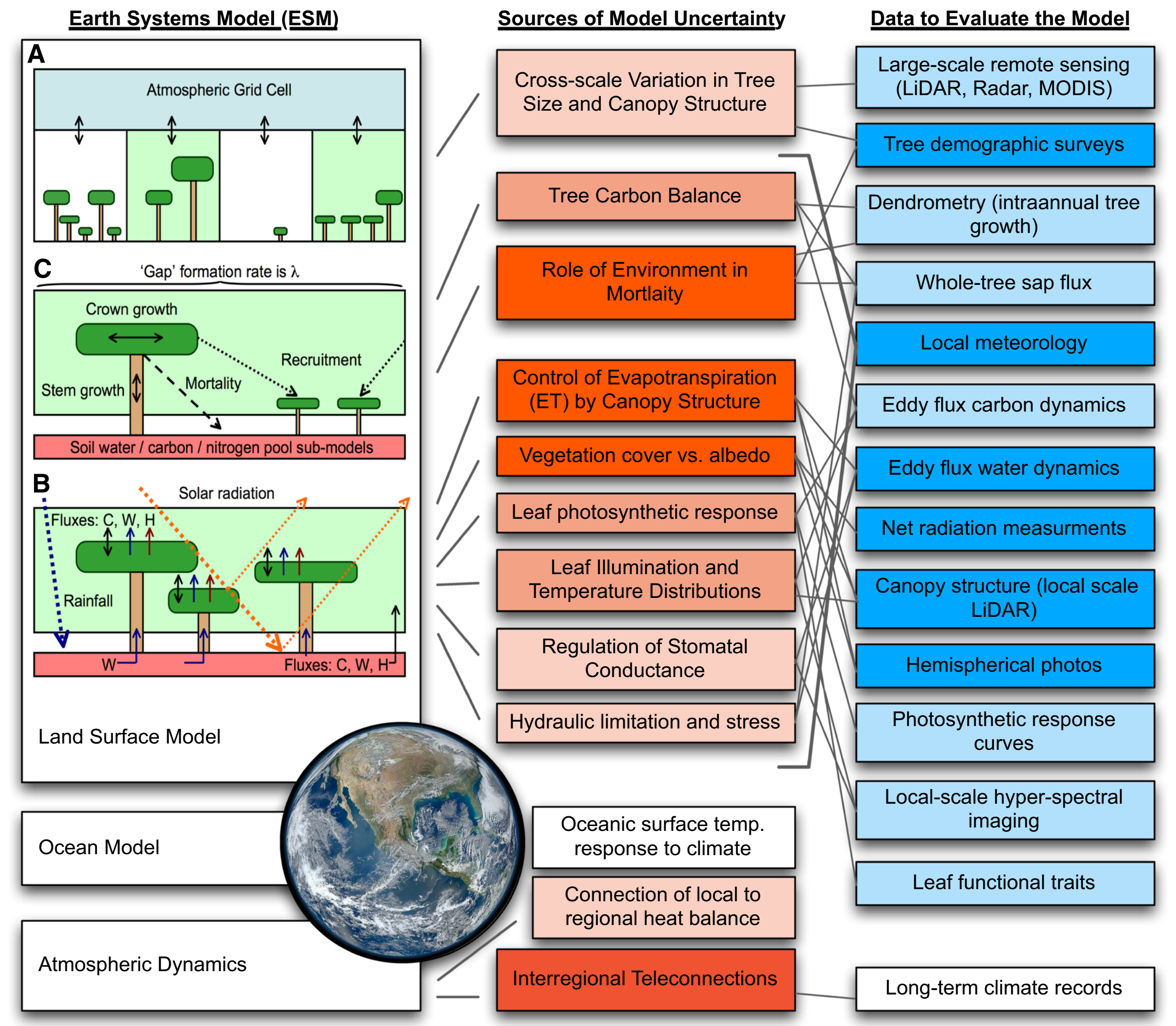

Fig. 2 Model structure and schema of data synthesis investigation. The *left column* of boxes depicts the components of an earth system model (ESM; modified from Medvigy et al. 2009). The land surface component of the ESM calculates the short-term fluxes of water, energy, momentum, and carbon from atmospheric inputs of climate variables such as incoming radiation and precipitation. *Center column* boxes indicate major sources of model uncertainty, while lines depict which component of the ESM model incorporates a representation of the process in question. *Right column* suggestions of prioritized data sources (e.g., Luo et al. 2012). The *strongest colored boxes* are the sources of uncertainty and indicate a suggested ranking of priority for synthesis activities and data collection. (Color figure online)

et al. 2012). Processing these measurements with simple assumptions about vegetation optical properties offers estimates of vertical and horizontal variation in leaf area and vertically incident radiation interception (Lefsky et al. 2002; Parker et al. 2004b; Stark et al. 2012).

With this approach, we calculate the proportion of direct solar radiation that reaches the ground surface relative to that for an open-sky situation at the same location (Direct Site Factor, DSF; Rich et al. 1999; Royer et al. 2010; Villegas et al. 2010). Solar radiation indices are quantified using hemispherical photographs taken at a fixed location (25–100 cm) above the ground using a horizontally leveled digital camera with a 180° field of view fish-eye lens. Images are analyzed using standard radiation simulation computational tools (Hemiview canopy analysis software version 2.1; 1999 Delta-T Devices, Ltd., Cambridge,

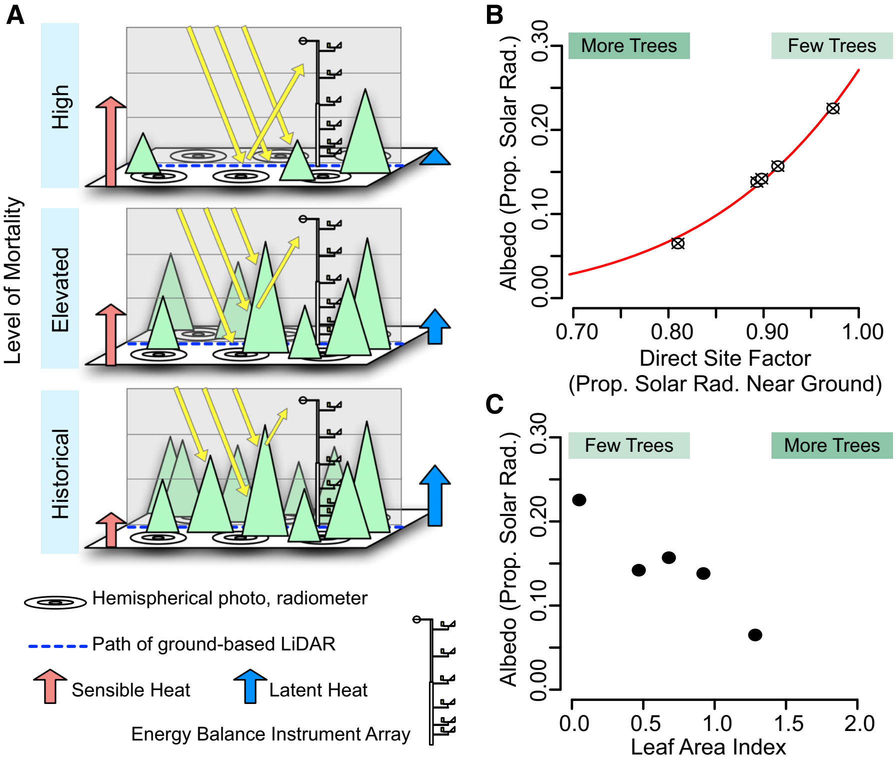

Fig. 3 Rapid assessment of the effects of vegetation change on energy balance: sampling scheme and field results. The diagram **a** depicts a rapid sampling scheme to quantitatively measure surface energy balance and vegetation structural impacts of tree die-off and other types of climate change related vegetation change. Panels **b** and **c** highlight results from an ongoing investigation of vegetation variability and tree die-off in the piñon-juniper woodland near Flagstaff Arizona. Comparing five sites, albedo is related to differences in radiation transmission Direct Site Factor (**b**) and leaf area index (**c**)

UK; Rich et al. 1999). Energy-balance partitioning can be estimated using the Bowen ratio energy budget method (Shuttleworth 2012), which combines measurements of net radiation, soil heat flux and estimates of the *Bowen ratio* (β, the ratio of sensible to latent heat flux) to partition available energy between sensible and latent-heat components, as a function of soil moisture condition (e.g., different behavior is expected in conditions when soil water is or is not limiting). To derive β from field observations, it is assumed that the processes that transport sensible and latent heat vertically are the same at the scale of meters to tens of meters from the ground. At these spatial scales, the transport of sensible heat is proportional to the difference in atmospheric-heat content between two levels of the atmosphere. Similarly, to estimate latent-heat flux, the rate of moisture transport is assumed proportional to the difference in humidity content between the two levels (Shuttleworth 2012). In our illustrated rapid-assessment approach, we use the vertical profiles of temperature and relative humidity derived from the portable weather station array to determine atmospheric gradients of virtual potential temperature and moisture content in the atmosphere and then calculate Bowen ratio β as a function of these variables (Shuttleworth 2012) for 30-min intervals throughout the entire observation period. We use these 30-min averages of β to partition net radiation into sensible and latent heat portions (after accounting for heat dissipation through the soil, measured with a heat flux plate).

To illustrate the characterization of vegetation-structure-vs-energy-balance-component relationships relevant for land-surface models, we draw on data from a 1-week field campaign in piñon-juniper woodland in northern Arizona, USA. We deployed our approach across a gradient of 5 sites of increasing tree cover, with each having recent tree mortality. Within this short field campaign, we were able to quantify how albedo changes using the amount of potential incoming near-ground solar radiation (DSF, described above; Fig. 3b) and how it changes as a function of change in LAI (Fig. 3c). The albedo-LAI relationship was associated with the hypothesized shifts (Fig. 3a) in the partitioning between sensible and latent heat (data not shown). These results combined with similar characterization in other forest types from both temperate and tropical regions could provide the basis for altering the forest structure-energy balance relationship in future model simulations to determine if they refine estimated ecoclimate teleconnections. More generally, this field approach is relevant across different types of vegetation change and could enable the rapid establishment of model-relevant relationships between changes in vegetation structure and energy balance, providing a practical supplement to measurements from eddy-flux installations for regions undergoing rapid vegetation change.

Toward accounting for ecoclimate teleconnections following vegetation change

The examples presented here illustrate a framework for advancing macrosystems ecology by assessing ecoclimate teleconnections. More generally, they highlight ecoclimate teleconnections as a fundamental aspect of macrosystems ecology needed to account for alterations to large-scale atmospheric-ecological couplings in response to major types of vegetation change. They also provide a roadmap for developing an approach that improves the integration of modeling and observational and experimental data (e.g., MODEX of the US DOE research program) from vegetation undergoing change for application to global-scale analysis. Although we have focused on tree die-off as an example of vegetation change, the concepts and approach presented here are also relevant to other major types of vegetation change, including losses of woody cover due to deforestation (Devaraju et al. 2015), or gains of woody cover due to afforestation (Swann et al. 2012) or shrub expansion (Walker et al. 2006).

In general, assessing ecoclimate teleconnections requires addressing the following: (1) *How does the land surface change in terms of vegetation structure?*; (2) *How does the vegetation-structure change influence albedo and other components of land surface energy balance?*; (3) *What are the consequences of the changes in vegetation structure and energy balance for the region?*; (4) *What climate teleconnections link the initially impacted region to other regions?*; and (5) *What type of secondary ecological impacts does this produce in another teleconnected region of interest?* Few studies consider more than one component of this list. We argue that a more comprehensive approach will enable us to effectively address problems that have an inherent component of connectivity through an ecoclimate teleconnection. Furthermore, the mismatch between spatiotemporal scales of ecological and climatological data sets will need to be reconciled with enhanced data acquisition—including multi-scale remote sensing and field sources—and upscaling approaches. Global-scale coupled land–atmosphere-ocean modeling approaches that are better informed by field and remote-sensing data are needed to identify key potential ecoclimate-teleconnection responses to vegetation change because, based on our current understanding, it is difficult to identify a priori where they will occur. Additionally, such a modeling approach can aid in targeting measurement efforts to reduce specific uncertainties in vegetation and ecosystems responses, including resilience, as well as enabling improvements in understanding of the associated ecological and atmospheric mechanisms driving ecoclimate teleconnections. To accurately predict ecoclimate teleconnections, it is necessary to consider two important aspects of uncertainty: (1) was the land surface forcing on the atmosphere correctly parameterized, and (2) is the atmospheric circulation response robust (while taking into account interactions between the atmosphere and ocean). State-of-the-art Earth systems modeling, robust field measurement approaches, and wide-spread remote sensing of vegetation structure and function offer the potential to rapidly address these questions.

We have also outlined an approach that can be applied to rapidly assess needed site characteristics in the field to then better inform models. This approach includes characterizing vegetation structure through traditional surveys and digital means (LiDAR and hemispherical photography) and deployment of portable masts with multi-height microclimate instrumentation, including portable weather stations and radiation sensors. These rapid field assessments, which do not require the long deployment times (years) associated with more detailed eddy-flux-tower studies, could become an integral and strategic complement of Earth systems modeling, continental scale observation networks such as the National Ecological Observatory Network (NEON; Keller et al. 2008), and detailed paired experiments of vegetation-structure-change effects on surface-atmosphere coupling (Litvak et al. in prep).

While recognition of the likely role of ecoclimate teleconnections has increased, we now need to move towards quantifying these ecoclimate teleconnections more explicitly. Teleconnections that modify major atmospheric circulation processes such as monsoons and convergence zones may be stronger or more widespread than currently appreciated. Although the largest effects are expected when forests undergo widespread die-off or deforestation, or when grasslands and semi-arid regions undergo conversion to forest, intermediate degrees of disturbance and conversion have the potential to drive ecoclimate teleconnections as well. However, predicting future or demonstrating present ecoclimate teleconnections remains difficult due in part to inadequate pairing between climate and ecological monitoring, an insufficient spatial scale of monitoring, and key uncertainties in Earth systems models in the response of energy balance to vegetation change. In summary, we argue that ecoclimate teleconnections are likely a fundamental aspect of macrosystems biology that are needed to account for alterations to large-scale atmospheric-ecological couplings in response to major types of vegetation change.

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