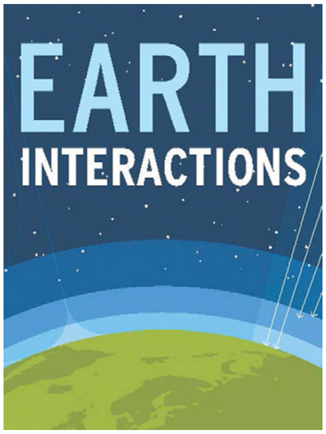

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# Grand Challenges in Understanding the Interplay of Climate and Land Changes

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**ABSTRACT:** Half of Earth's land surface has been altered by human activities, creating various consequences on the climate and weather systems at local to global scales, which in turn affect a myriad of land surface processes and the adaptation behaviors. This study reviews the status and major knowledge gaps in the interactions of land and atmospheric changes and present 11 grand challenge areas for the scientific research and adaptation community in the coming decade. These land-cover and land-use change (LCLUC)-related areas include 1) impacts on weather and climate, 2) carbon and other biogeochemical cycles, 3) biospheric emissions, 4) the water cycle, 5) agriculture, 6) urbanization, 7) acclimation of biogeochemical processes to climate change, 8) plant migration, 9) land-use projections, 10) model and data uncertainties, and, finally, 11) adaptation strategies. Numerous studies have demonstrated the effects of LCLUC on local to global climate and weather systems, but these putative effects vary greatly in magnitude and even sign across space, time, and scale and thus remain highly uncertain. At the same time, many challenges exist toward improved understanding of the consequences of atmospheric and climate change on land process dynamics and services. Future effort must improve the understanding of the scale-dependent, multifaceted perturbations and feedbacks between land and climate changes in both reality and models. To this end, one critical cross-disciplinary need is to systematically quantify and better understand measurement and model uncertainties. Finally, LCLUC mitigation and adaptation assessments must be strengthened to identify implementation barriers, evaluate and prioritize opportunities, and examine how decision-making processes work in specific contexts.

**KEYWORDS:** Climate change; Anthropogenic effects; Atmosphere–land interaction; Land use; Planning

# 1. Introduction

Land-cover and land-use change (LCLUC) resulting from human activities in the Anthropocene has altered an estimated 50% of Earth's land surface, mostly through conversion of forests to agricultural uses in the past century (Ramankutty and Foley 1999; Foley et al. 2011, Hurtt et al. 2011; Klein Goldewijk et al. 2011; Waters et al. 2016). These changes have substantially affected Earth's climate at local to global scales through altered biogeochemical and biogeophysical processes that change carbon, energy, and moisture fluxes to the atmosphere (Pitman et al. 2009; Pongratz et al. 2010; de Noblet-Ducoudré et al. 2012; Lawrence et al. 2012; Brovkin et al. 2013). Climate change in turn has affected land surface substances and processes such as carbon and water cycles, species composition and mortality (Allen et al. 2010b; Zhu et al. 2012; Dingle 2014), and LCLUC decisions (Jacobson and Ten Hoeve 2012; Georgescu et al. 2013; Bagley et al. 2015). Understanding, quantifying, and adapting to varying land–climate interactions at local to global scales is thus critical for Earth system sciences and sustainable development of our society (Pielke et al. 2011). Although considerable research has been done on land–atmospheric interactions from different perspectives at various scales, major challenges still remain. Here, we present an overview of 11 grand challenge themes, ranging from observation to modeling to adaptation, synthesizing and discussing the major research directions within each theme for the coming 5 to 10 years.

## 2. Overall and specific roles of LCLUC on climate

LCLUC resulting from both natural and anthropogenic forces has had major impacts on climate at the local to global scales. Especially during the past 10 years, efforts have been made to quantify the biogeochemical contribution of LCLUC-induced greenhouse gases acting at the global scale and analyze the biogeophysical effects of LCLUC on land–atmosphere coupling relevant at local to regional scales (e.g., changes in heat fluxes). The magnitude or even sign of these impacts remains highly variable and therefore uncertain (Pitman et al. 2009; de Noblet-Ducoudré et al. 2012; Brovkin et al. 2013; Boysen et al. 2014). Earth system models (ESMs) and dynamic global vegetation models (DGVMs) are powerful tools for the analysis of LCLUC effects on the Earth system because of the difficulties in observing the LCLUC-induced matter and energy fluxes directly over regional to global scales. However, the complexity of the underlying land–atmospheric interactions, the opacity and complexity of the models themselves, the influence of the implementation strategy of the underlying physical processes in models, and the lack of sufficient observational data still pose difficult challenges to the research community.

Climate is strongly affected by biogeochemical properties and processes such as $CO_2$ concentration in the atmosphere, and thus understanding the dynamics of land–atmospheric $CO_2$ exchange is critical (Myhre et al. 2015). LCLUC-induced $CO_2$ emissions have contributed about 50% to the atmospheric $CO_2$ increase since preindustrial times and about 10%–20% during the past decades (Pongratz et al. 2013; IPCC 2013; Le Quéré et al. 2015). Over the past decades, carbon uptake by the biosphere has increased due to $CO_2$ fertilization, the warming climate, and altered nutrient cycles (Pongratz et al. 2013), amounting to a land carbon sink of $3 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ between 2005 and 2014. Using bookkeeping methods (e.g., observations, inventories) and a set of DGVMs, recent studies have estimated the current net land-use flux to be an uptake of $1 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ (compared to $9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ fossil fuel emissions; Le Quéré et al. 2015). However, caution is needed, especially when analyzing future projections (Boysen et al. 2014) since models diverge in their representation of LCLUC effects (e.g., forest extents and/or land surface fluxes). Specific challenges with respect to the biogeochemical effects of LCLUC and climate change are presented in the two subsequent sections of this paper on carbon and other biogeochemical cycles and climatically relevant emissions from the land surface.

While the biogeochemical effects of LCLUC have affected climate at the global scale via greenhouse gas emissions (IPCC 2013), the biogeophysical effects of

LCLUC on weather and climate are likely limited to local to regional scales and only in areas of pronounced LCLUC (Lyons et al. 1993; de Noblet-Ducoudré et al. 2012; Lorenz et al. 2016). Some modeling experiments have found global climate effects resulting from large-scale tropical deforestation (Hasler et al. 2009; Medvigy et al. 2013), but others did not find such remote effects (Henderson-Sellers et al. 1993; Findell et al. 2006). The differences among these studies are likely caused by multiple factors, including the scale of deforestation, strength of land–atmosphere coupling, and the methods for statistical testing (Lorenz et al. 2016). Nevertheless, studies using models and satellite observations have shown that air masses passing over densely vegetated areas produce much more rain than those passing over sparse vegetation (Clark and Arritt 1995; De Ridder 1998; Spracklen et al. 2012), for example, and the atmosphere can be enriched by water vapor and convective potential energy after passing over a region of high evapotranspiration (ET). The replacement of this high ET surface with low ET cover (e.g., replacing rain forest with pasture) would lead to reduced atmospheric humidity and, as a result of this disturbance in moisture recycling, could potentially suppress precipitation downwind (Zemp et al. 2014). Replacing forest with crop or pasture might not only change these latent heat fluxes (e.g., induce local warming due to decreasing evaporation) but also increase surface reflectivity through an increased albedo, inducing local cooling (Davin and de Noblet-Ducoudré 2010; Brovkin et al. 2013; Davin et al. 2014). The strength of these competing effects depends on latitude, soil type, vegetation, topography, climatology, and physiography and may be coupled to different feedback mechanisms (Brovkin et al. 2003, 2009; Coe et al. 2009; Bathiany et al. 2010; Mahmood et al. 2014).

Although many modeling studies have attempted to investigate the climate impacts of past and projected LCLUC, they frequently do not concur on the magnitude or even sign of these impacts (Pitman et al. 2009; de Noblet-Ducoudré et al. 2012; Brovkin et al. 2013; Boysen et al. 2014; Lorenz et al. 2016), even though most coupled climate models include LCLUC in their land surface representation to fully capture carbon cycle dynamics (Le Quéré et al. 2014a). The reasons for this uncertainty are multifaceted. First, research depends highly on the use and performance of computer models that are subject to various uncertainties. Second, simplifications about biogeochemical and biogeophysical processes are often needed in the models to reduce the degree of complexity, keep computational costs low, and represent less-understood mechanisms, but we do not always understand the potential bias introduced by these assumptions. Third, climate and land-use datasets are needed as an input to these models, but again, these datasets might not be available or differ among climate model communities. Fourth, it is important to capture all land–atmosphere and ocean interactions to be able to fully represent the influence of pronounced LCLUC on local and regional climate (Davin and de Noblet-Ducoudré 2010; Pitman et al. 2011). All these factors add to the large uncertainty of research results on both biogeochemical and biogeophysical effects of LCLUC on climate.

Recent multimodel projects investigating the biogeophysical impacts of LCLUC on climate in standardized land-use and emission projections until 2100 allow for a comparison and analysis of the performance of all participating coupled ESMs (Arora et al. 2013; Brovkin et al. 2013; Boysen et al. 2014). These experiments show that additional systematic and simplified model comparison protocols are necessary to better understand the processes of land–atmosphere interactions driven by LCLUC, which are being implemented in the current generation of such projects [e.g., Land Use Model Intercomparison Project (LUMIP), https://cmip.ucar.edu/lumip]. Modeling initiatives like Land Use and Climate, Identification of robust impacts (LUCID, http://www.lucidproject.org.au/; de Noblet-Ducoudré et al. 2012), LUMIP, land-use change: assessing the net climate forcing, and options for climate change mitigation and adaptation (LUC4C; http://luc4c.eu/), and alternative benchmarking efforts (Best et al. 2015) point toward a better understanding of the processes involved in reality and the models. However, strategically deploying more observations and field experiments and making more effective use of their results remain a key challenge.

Overall, both observations and models have shown impacts of LCLUC on climate through locally relevant biogeophysical and globally relevant biogeochemical effects. However, uncertainties remain regarding the signs and magnitude of changes. This becomes even more of a challenge in view of increasing interest in mitigating the impacts of climate change on ecosystem functioning, and vice versa, through artificially altered land surfaces (Lenton 2010; Davin et al. 2014). A systematic reduction and simplification given in LCLUC scenarios could reduce some uncertainties arising from the different land-cover representations among the participating models (e.g., parameterization or dynamic representation of crops or pastures and gross versus net transitions). The challenge will be to 1) advance the collection and analysis of observational data to improve understanding of the land–atmosphere interactions and 2) improve representations of LCLUC processes and land–atmosphere interactions in current coupled ESMs (Abramowitz 2012; Gupta and Nearing 2014). To meet this challenge, it is necessary to conduct model–model and measurement–model intercomparisons using standardized protocols and benchmark frameworks.

## 3. The carbon cycle

Understanding the magnitude, patterns, and driving forces of terrestrial carbon sources and sinks, and their subsequent climate feedbacks with respect to LCLUC, is still a major challenge for Earth system science. Historical land-use changes, primarily deforestation, altered both regional (Kaplan et al. 2012) and global (Pongratz et al. 2010) carbon cycles, primarily via substantial emissions of carbon (C) to the atmosphere. As a result, it is estimated that deforestation and other land-use changes released huge amounts of $CO_2$ into the atmosphere from 1750 to 2011, equivalent to about half of the emissions from fossil fuel combustion and cement production during the same period (IPCC 2013). Current LCLUC is probably still causing C loss in the tropics (Don et al. 2011; Tyukavina et al. 2015), but post-disturbance regrowth in the temperate forests provides a strong C sink (Pan et al. 2011). Some of the most important and least-understood mechanisms in determining how LCLUC affects carbon and other biogeochemical cycles include fire and heterotrophic respiration.

Fire, closely linked to LCLUC in modern times, is the dominant global disturbance dynamic (Bowman et al. 2009), emitting $\sim 2\,\mathrm{PgC\,yr^{-1}}$ to the atmosphere in a variety of forms and trace gases (van der Werf et al. 2010) and can determine the C balance of very large regions (e.g., Bond-Lamberty et al. 2007). LCLUC is frequently associated with fire and pyrogenic emissions to the atmosphere (van der Werf et al. 2006)—an extreme example being the Indonesian peat fires of the late 1990s (Page et al. 2002)—and the fire record shifts from being precipitation- to anthropogenically driven with the industrial revolution (Pechony and Shindell 2010). This shift makes the modeling of fire and fire emissions particularly important (Cochrane 2003; Bowman et al. 2009). Recent fire models [summarized in Le Page et al. (2015)] are diverse, variously emphasizing physical processes, anthropogenic emissions, or particular regional characteristics in biota or climate, all for application at local to global scales (Pechony and Shindell 2009). Critical challenges include better representation of the interactions between fire, drought, and forest insect infestations; integrating more realistic treatments of anthropogenic ignitions into global vegetation models; and better understanding of how land-use management, fire, and species distributions interact at landscape scales (Liu et al. 2011; Ryan et al. 2013).

When LCLUC occurs, there is often an initial pulse of C to the atmosphere but then a long-lived and potentially much larger effect of soil heterotrophic respiration (HR). The HR response to disturbance and climate change has been poorly understood, and contested, for decades (Covington 1981; Harmon et al. 2011; Bradford et al. 2016). HR is critical because the global HR flux is ~51–57 Pg $\mathrm{yr}^{-1}$ (Hashimoto et al. 2015), 5–6 times larger than anthropogenic C emissions (Le Quéré et al. 2014b) and thus is a strong influence on the evolution of the global C cycle and climate system (Friedlingstein et al. 2014). Theoretical models (Harmon et al. 2011) generally posit a rising postdisturbance (e.g., post LCLUC) heterotrophic flux (and thus a weakening C sink overall), but surprisingly few empirical observations support this hypothesis (Luyssaert et al. 2007; Amiro et al. 2010; Gough et al. 2016). HR originates from a wide variety of sources, many of which are poorly understood or modeled using simplistic formulations that lack the mechanistic basis of, for example, photosynthesis models (Schimel 2013; Davidson et al. 2014). We also lack robust methods for upscaling HR or generating large-scale HR benchmarks (Bond-Lamberty et al. 2016). Such mechanistic models and upscaling methods will be critical to improve models' performance related to HR and soil carbon dynamics more generally (Todd-Brown et al. 2012). To reduce uncertainty in simulating soil carbon change, major progress has to be made on incorporating biogeochemical feedbacks and nutrient limitations (Arneth et al. 2010; Exbrayat et al. 2013) and updated knowledge on soil carbon decomposition and stabilization (Bradford et al. 2016), including the response functions of soil carbon decomposition to temperature and moisture (Exbrayat et al. 2013; Crowther et al. 2016).

In summary, historically LCLUC has exerted major effects on regional- to global-scale carbon cycles and climate. Understanding the current dynamics and future trajectory of these effects depends on progress in the challenge areas of 1) fire modeling, in particular with respect to human activities and climate-driven changes in fuel moisture, and 2) heterotrophic respiration dynamics in both organic and inorganic soils subjected to disturbance. Improving the mechanistic representation of these processes, testing improved models against robustly characterized fluxes at a variety of spatial and temporal scales, and leveraging improved observational networks and datasets should all be prioritized going forward.

## 4. Climatically relevant emissions from the land surface

The land surface emits a suite of gases and particles that can affect climate. As land-cover changes, shifting emissions provide an indirect pathway by which the land surface can exert a climate forcing [recently reviewed in Heald and Spracklen (2015)]. Terrestrial emissions include both the gas phase [e.g., greenhouse gases, volatile organic compounds (VOCs), or nitrogen oxides ($NO_x$)] and the particle phase (e.g., atmospheric aerosols). Many primary emissions of gases from the terrestrial biosphere (e.g., VOC, $NO_x$) do not directly exert a climate influence, but they can react in the atmosphere to form short-lived climate forcing agents such as ozone and aerosols (Myhre et al. 2013). Particles in the atmosphere have direct and indirect climate impacts and can be emitted primarily from the land surface (e.g., dust) or be formed via chemical reactions in the atmosphere [e.g., secondary organic aerosol (SOA), ammonium]. BVOCs can substantially affect regional and global climate through short-lived climate forcing agents such as ozone and SOA, and this effect has recently been shown to be comparable in magnitude to surface albedo changes or carbon effects (Unger 2014). Overall, the emissions of both long-lived greenhouse gases as well as short-lived species such as dust and other terrestrially derived aerosols are known to impact climate across local, regional, and global scales (Tegen et al. 2004; Henze et al. 2008; Mahowald et al. 2011; Unger 2014).

Natural vegetation is a key source of many of the trace gas constituents in the atmosphere that affect climate, and LCLUC affects the types and magnitude of these important emissions. These are dominated by VOCs, which include isoprene ($C_5H_8$), monoterpenes ($C_{10}$ compounds), sesquiterpenes ($C_{15}$ compounds), and a suite of oxygenated VOCs that contribute up to 80% of the global VOC budget (Guenther et al. 2006). Because many of these biogenic VOCs are reactive, they play an important role in tropospheric atmospheric chemistry (Goldstein and Galbally 2007). When nitrogen oxides and sunlight are present, BVOCs can play an important role in ground-level ozone formation (Chameides et al. 1988). Additionally, BVOCs can react to form lower-volatility products that can yield SOA (Hallquist et al. 2009). Natural landscapes also emit oxidized nitrogen due to microbial processes in soils, either through nitric oxide (NO) or greenhouse gases like nitrous oxide ($N_2O$; Holland et al. 1999). The $NO_x$ emissions influence gas-phase chemistry and ozone formation as well as particle formation in the presence of ammonia ($NH_3$) emissions (Zhang et al. 2012). Additionally, natural terrestrial landscapes emit a suite of particles, such as dust (Sokolik and Toon 1996; Mahowald and Kiehl 2003), that influence climate. Overall, these natural aerosols from terrestrial ecosystems are known to directly influence the amount of radiation reaching Earth's surface and in many cases indirectly affect the formation of clouds (Atkinson et al. 2013; Spracklen and Heald 2014; Steiner et al. 2015).

The transition from natural to managed landscapes alters the sources of climatically relevant emissions. LCLUC processes such as urbanization and increased agricultural and grazing lands alter the magnitude and composition of both gas- and particle-phase emissions. Urban growth triggers a large suite of anthropogenic emissions, derived from fossil fuel combustion releasing gas-phase species (e.g., $NO_x$ and a broader suite of VOCs than emitted naturally) and aerosols (typically in the form of nitrate, organic carbon, or elemental carbon). Urban aerosols have a broad range of physical and chemical properties depending on their location, as they represent the unique blend of industry, transportation, and human activity in each region (Zhang et al. 2015). Additionally, many anthropogenic VOCs such as aromatics are known to be high contributors to SOA (Henze et al. 2008). As noted above, natural nitrogen emissions from soils are accelerated by large-scale farming and fertilizer application. Concentrations of $N_2O$ have been increasing in the postindustrial era due to fertilizer applications in managed ecosystems, and food production is estimated to account for 80% of the increase in atmospheric $N_2O$ (Ciais et al. 2014). The transition to cropland and its accompanying fertilizer use can trigger large releases of ammonia, where 90% of ammonia emissions in the United States result from animal and crop agriculture (https://www.epa.gov/air-emissions-inventories). Ammonia is an important base in the atmosphere and can neutralize acidic compounds formed from $SO_2$ and $NO_x$ oxidation, thereby forming ammonium particles (either ammonium sulfate or ammonium nitrate) that can act as a direct forcing agent and indirectly affect cloud formation. Finally, grazing and livestock activities also release ammonia (Hiranuma et al. 2010) as well as contribute primary particles (Hiranuma et al. 2011) that influence climate.

LCLUC can also alter the emissions of biogenic volatile organic compounds (BVOCs) that control the loadings of multiple warming and cooling climate forcings (tropospheric $O_3$, $CH_4$, $N_2O$, and aerosols). In fact, LCLUC has to a large degree defined the BVOC emission variability over the past century (Lathière et al. 2010; Unger 2013). Recently, Unger (2014) showed that BVOCs have substantial impacts on regional and global climate in addition to the important flux of annual C emissions at 1.15 PgC each year (excluding $CH_4$; Goldstein and Galbally 2007). It is therefore necessary to consider the climate impacts of BVOCs in climate impact assessments of LCLUC, and this constitutes an important challenge in the coming decade.

Overall, the combination of gas- and particle-phase emissions provides a range of direct and indirect effects on climate that are strongly affected by land-cover change. Either through direct emissions of greenhouse gases or through indirect pathways (e.g., aerosols on clouds, the role of secondary pollutants such as $NO_x$ on greenhouse gas concentrations), the land surface–climate relationship is further complicated by the changing land surface. The intersection of natural and managed ecosystems plays an important role in understanding land-cover changes, as new mixtures of natural and anthropogenic compounds can accelerate gas-phase chemistry pathways (such as ozone formation) and the formation of secondary organic aerosols. As noted above, the presence of anthropogenic species influences the fate of many naturally emitted compounds such as BVOC, where higher urban $NO_x$ concentrations can facilitate more ozone formation. Thus, identifying emissions changes from LCLUC represents an important challenge in improving our understanding of the land surface on climate via emissions and their atmospheric pathways. Specifically, this includes 1) coupling dust emissions models with LCLUC, 2) improving databases of vegetation types to integrate with natural emissions models, and 3) developing flexible natural and anthropogenic emissions databases that can account for LCLUC.

## 5. The water cycle

Understanding the complex and variable interactions among climate, the water cycle, and LCLUC in space and time is a formidable challenge in Earth system science. The alteration of the water cycle, one of the principal and most influential effects of ongoing climate change and LCLUC, directly affects human populations, agriculture, forestry, and sustainability of natural ecosystems (Vörösmarty et al. 2013). Many region-specific studies have shown the impacts of LCLUC and climate on the water cycle. However, the impacts vary across time and space, and their scale dependence has only rarely been explicitly explored (Lorenz et al. 2016).

Climate and the water cycle can be altered by changes in land use and land cover mainly via two interrelated mechanisms. The first is the direct alteration of the hydrological pathways by LCLUC engineering works (e.g., reservoirs, canals, and irrigation and drainage systems). For example, large-scale irrigation has been shown to affect the water cycle and climate, particularly in downwind regions (Lo and Famiglietti 2013; Alter et al. 2015). Climate modeling at the global scale suggests that irrigation and impoundment of water in reservoirs enhance evapotranspiration and precipitation and can cool surface air temperatures (Milly and Dunne 1994; Puma and Cook 2010).

The second mechanism is the LCLUC-associated alteration of albedo, surface roughness, and properties of vegetation (e.g., stomatal conductance) resulting in effects on local climate and water fluxes (Bonan 2002; Lyons 2002; Bonan 2008). Many studies have shown the hydrological impacts of various LCLUC activities across the globe, but the spatial and temporal change and the scale dependence of the impacts are all poorly understood. For example, deforestation can lead to decreased evapotranspiration (Pierce et al. 1993; Coe et al. 2009) and increased local runoff (Coe et al. 2009) but may (Sampaio et al. 2007; Butt et al. 2011) or may not (Coe et al. 2009) change the characteristics of local precipitation. Urbanization strongly affects both the precipitation over and downwind of cities and the infiltration capacity of surfaces (Shepherd 2005; Pielke et al. 2007; Carrió et al. 2010; Niyogi et al. 2011; Bounoua et al. 2015), presenting a management challenge of storm water quantity and quality in urban areas (Carlson et al. 2015). Although region-specific studies have shown the LCLUC impacts on the water cycle, the scale dependence of the impacts remains unknown. Major challenges include understanding how local-scale LCLUC impacts are dampened across sequentially larger spatial scales and how impacts within a watershed or region vary with the scale or magnitude of LCLUC (i.e., the fraction of area being disturbed). Multiwatershed analysis and synthesis can be used to meet these challenges.

Large uncertainties remain regarding the hydrological responses to climate change. Some predicted hydrologic responses to climate warming (e.g., Held and Soden 2000) are consistent with an intensification of the water cycle in the observational record (Huntington 2006; Wentz et al. 2007; Syed et al. 2010; Giorgi et al. 2011; Durack et al. 2012), while others, such as the atmospheric moisture convergence (i.e., the so-called wet-get-wetter, dry-get-drier mechanism), have been strongly contested. Some climate projections and observation-based studies (Trenberth 2011; Boucher et al. 2013; Chou et al. 2013; Collins et al. 2013) suggest that precipitation events will become more intense but less frequent (Trenberth 2011; Chou et al. 2013; Collins et al. 2013). In some areas the changes in the character of precipitation could lead to seemingly contradictory effects: more frequent, heavier precipitation and potential flooding on the one hand and longer intervening dry periods, resulting in more frequent and severe droughts, on the other. Other studies, however, have shown different results (e.g., Sun et al. 2012;

Byrne and O'Gorman 2015). After analyzing observations of monthly precipitation (1940–2009) over the global land surface using a new theoretical framework, Sun et al. (2012) found that the global land precipitation variance over space and time has been reduced due to a redistribution where, on average, dry areas became wetter while wet areas became drier. A recent study with climate models showed that the simple thermodynamic scaling of the atmospheric moisture convergence is applicable to oceans but not land surfaces because changes in circulation cause deviations from the simple scaling (Byrne and O'Gorman 2015). Using an extended scaling that incorporates horizontal gradients of changes in temperature and fractional changes in relative humidity (not accounted for in the simple scaling), Byrne and O'Gorman found a robust drying trend at almost all latitudes. The effect of climate change on the water cycle is also complicated by seasonal (Chou et al. 2013) and regional (Marvel and Bonfils 2013) variability in evaporation and precipitation as well as by interannual variability, largely in response to ocean–atmosphere teleconnections (Avissar and Werth 2005; Schneck and Mosbrugger 2011), and the challenge is to separate them.

Climate warming is also likely to exacerbate naturally occurring droughts in some regions (Hayhoe et al. 2007; Williams et al. 2015), which in turn can affect many processes, including tree dieback (Allen et al. 2010a; Anderegg et al. 2013; Brando et al. 2014), geographic redistribution of various ecosystems (Pearson 2006; Feng and Fu 2013), and land-use activities (Hargreaves 1976; Brown et al. 2011). However, the intensification of droughts might be specific to certain climate regions. For example, increased tree mortality, induced by increasing drought and heat stress, has been observed in many parts of the globe (Allen et al. 2010a).

The change of the water cycle and climate will affect many ecological and economic processes with large regional variability. Regarding the impacts on the geographic redistribution of major ecosystems, Chan and Wu (2015) showed the global land area has shifted toward warmer and drier climate types from 1950 to 2010, with an expansion of arid climate and shrinkage of polar and midlatitude continental climates. Feng and Fu (2013) found that the expansion of drylands in the western United States from 1948 and 2008 was consistent with the trends in the dryness index, defined as precipitation divided by potential evaportranspiration (P/PET), and that increasing temperature will become progressively more important than changes in precipitation in further expansion of drylands, as indicated by an ensemble of climate model projections. Together, these studies point toward an increasing proportion of land areas experiencing drought and the consequent redistribution of the climate and ecosystems on landscapes. A major challenge is to understand and deal with the large regional variability in the analysis of causes and consequences of hydrological and climate change (Steinkamp and Hickler 2015). Well-coordinated synthesis activities that encompass many regions or watersheds with diverse LCLUC histories and climates are needed to tackle this challenge.

Overall, projected future warming is expected to result in continuing intensification of the water cycle with increasing rates of global average evaporation, transpiration, precipitation, and increasing atmospheric water vapor content (Collins et al. 2013). Climate change–induced alteration of the water cycle will likely have profound effects on land cover and land use (Hewitson et al. 2014; Settele et al. 2015), such as agricultural practices and planning and plant species redistribution, and vice versa. The interactions among climate, the water cycle, ecosystems, and LCLUC are complex, and understanding them is a grand challenge. Specifically, we need to understand how these interactions vary regionally and across spatial and temporal scales. In addition, understanding the impacts of future climate change on hydrology, such as the generality of the wet-get-wetter, dry-get-drier mechanism, remains a grand change going forward.

## 6. Agriculture and climate

Food production is a critical land-use activity of our society. Global demand for food production will rise in the future as human population and per capita food consumption increase and crop-based biofuel production likely expands (Bruinsma 2015). Increasing agricultural productivity is crucial for reducing poverty and achieving food security, and the Food and Agriculture Organization of the United Nations estimates that global production for cereals will have to increase at least 13% $\text{decade}^{-1}$ up to 2030 to keep per capita consumption the same (Ray et al. 2013). How to improve agricultural productivity in the face of climate change, and also understand the impacts of intensified agricultural activities to the climate system, is a major scientific and engineering endeavor for mankind (Wheeler and von Braun 2013).

The agricultural sector is sensitive and vulnerable to climate change. Many efforts have been devoted to investigating the impacts of observed climate change on food production, focusing primarily on three aspects of climate change: 1) mean climate change, 2) intra- and interannual climate variation, and 3) extreme weather events (Peng et al. 2004; Tao et al. 2006; Lobell et al. 2011; Zhang et al. 2016). These studies showed that past climate trends have negatively affected wheat and maize production for many regions (Porter et al. 2014) but have benefitted crop production in some high-latitude regions, such as northeastern China or Europe (Supit et al. 2010; Zhang et al. 2014). The relationship between climate trends and yield is often crop- and region-specific, depending on baseline climate, management practices, soils, and the timing and duration of crop exposure to various climatic conditions.

It is likely that climate variability and change will adversely impact food security in areas currently vulnerable to hunger and undernutrition (Wheeler and von Braun 2013). Variations in the production of annual and perennial crops and shifts in suitable production areas of agricultural crops are projected to increase and will impact food security in the future (Hatfield and Walthall 2015). Increased heavy precipitation will increase erosion and degrade soils to reduce their potential for production (Nearing 2001; Lal 2004; Nearing et al. 2004; Garbrecht et al. 2015). One challenge will be to determine if our current agriculture practices are adequate to protect against the increased occurrence of extreme precipitation events. Extreme temperature events on livestock systems will expose production systems to conditions that exceed their current minimum and maximum thresholds, and the challenge will be to assess the likelihood of these occurrences and the potential impact on plants and livestock (Walthall et al. 2012).

Agricultural land use will change with climate, with both land use and climate affecting productivity (Egli and Hatfield 2014b,a), leading to the need to understand how to enhance food production, given the regime of increasing variation in climate and greater likelihood of extreme events. Increasing the application of synthetic fertilizers and manure has been one effective measure to achieve higher crop yields on limited planting areas but can lead to non-carbon-dioxide greenhouse gas (GHG) emissions (Searchinger et al. 2008; Popp et al. 2010; Reay et al. 2012; Smith et al. 2012a; see section 4). The current understanding of the impacts of climate on agriculture has been summarized in recent reports (Walthall et al. 2012; Hatfield et al. 2014; Porter et al. 2014) discussing adaptation strategies for agriculture. These studies note that climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years, and crop and livestock production is expected to decline in many agricultural regions owing to increased climate-induced stresses (Hatfield et al. 2014).

In summary, the combination of global to local climate change, shifting land use, the need to increase productivity, and the necessity of protecting agricultural systems against increased extreme events is a grand challenge to scientists, farmers, and policymakers in the coming years and decades. To meet this challenge, it is necessary to 1) understand the agricultural effects on climate and vice versa and 2) integrate crop models with climate models to determine the most effective adaptation strategies for agricultural systems as described by Rosenzweig et al. (2014). In addition, optimizing agricultural land use and land cover in the face of ongoing climate change is critical for food security and agricultural sustainability, but such changes will be subject to diverse socioeconomic and environmental constraints.

## 7. Urbanization and climate

More than half of the world population now lives in cities, and this number is expected to increase over time (UN Population Division 2014), meaning that the interactions of climate and urban land surfaces have important implications for the environment and society at local to global scales. Cities are usually warmer than nearby rural areas due to 1) the high concentration of impervious surfaces that slowly reradiate during the night the heat absorbed during the day and 2) the anthropogenic heat from industrial activities and the heating and cooling of buildings (Bornstein 1968; Arnfield 2003; Imhoff et al. 2010). Urbanization-induced localized warming can be more important than greenhouse gas–induced climate change at local to regional scales, and the impacts may vary geographically (Georgescu et al. 2012; Georgescu et al. 2013; Zhou et al. 2014). In a modeling study, Georgescu et al. (2013) found that urban-induced warming could reach 4°C locally under a maximum development scenario for metropolitan areas in Arizona, yielding 3 times more impact on local climate than the warming associated with increased greenhouse gases. Another modeling study found that the impervious surfaces of U.S. cities are nearly 2°C warmer during summer than surrounding areas (Bounoua et al. 2015). In addition to the local impacts, urban expansion may contribute to temperature increases at the regional to global scale. For example, Kalnay and Cai (2003) showed that half of the observed decrease in the daily temperature range in the conterminous United States was due to urban and other land-use changes. Although urban areas currently account for less than 0.2% of the planetary surface, model simulations suggest that the urban heat island (UHI) effect may increase gross global warming by 0.06°–0.11°C (2%–4% of the total) in the next 20 years (Jacobson and Ten Hoeve 2012).

Urban environmental changes can affect a wide range of ecological processes. Impacts of urban warming on the seasonal development of vegetation have been observed using temperature networks (Schwartz et al. 2012), species composition in cities (Bechtel and Schmidt 2011), and remote sensing (Krehbiel et al. 2016; Melaas et al. 2013; Zhou et al. 2016). UHIs have been identified as causing earlier budding and blooming of flowers and trees and generally longer growing seasons for cities in Europe, Asia, and North America (Oke 1987; Jochner et al. 2012) as well as widely enhanced vegetation productivity (Zhao et al. 2016). Heat stress is a leading cause of human mortality in cities, particularly among the elderly (Baccini et al. 2008; Kovats and Hajat 2008). Environmental changes in urban environment such as $CO_2$ increase and UHI are considered the harbinger of future global change of other ecosystems (Grimm et al. 2008). Therefore, cities provide golden opportunities to study the possible interactions and feedbacks between land surfaces and climate futures. One key challenge is to attribute the observed environmental changes to a myriad of simultaneously changing driving forces (Zhao et al. 2016).

Effective representation of urban areas within land surface models that can be linked to mesoscale meteorological models remains a challenge due to the finescale spatial heterogeneity of urban infrastructure, including vegetation. Key information about urban canopies that is needed to improve modeling includes albedos, ratios of the heights of the buildings relative to the width of the streets, building roof area fractions, and vegetated surface fractions (Best and Grimmond 2015). Multiple efforts have been initiated to provide these urban parameters at local to global scales (Ching et al. 2009; Jackson et al. 2010). The typology of local climate zones (LCZ) addresses the problem of characterizing urban surfaces through a hierarchical classification scheme that is sensitive to structural arrangements that influence urban climate (Stewart and Oke 2012). The World Urban Database and Access Portal Tools (WUDAPT; http://www.wudapt.org/), inspired by the earlier National Urban Database and Access Portal Tools (NUDAPT; Ching et al. 2009), aims to produce LCZ classifications of global cities through curated crowdsourcing to advance urban climate modeling. Remote sensing is an important means through which to obtain some of these urban canopy data (Bechtel and Daneke 2012; Seto and Christensen 2013).

Improved representation of urban surface conditions within models is necessary but not sufficient (Best and Grimmond 2013). Current urban land surface models are not skillful enough to capture many of the complex interactions and feedbacks between urban surfaces and the atmosphere. A major urban land surface model intercomparison effort determined that for modeling latent and sensible heat fluxes throughout the year, three additional geophysical processes were identified as important to represent within the models: 1) shortwave radiation reflections within urban "street canyons," 2) amount of skyview within canyons modulating longwave emissions, and 3) the thermal contrasts between roof tops and street canyons (Best and Grimmond 2015). Mishra et al. (2012) evaluated the ability of regional climate models (RCMs) that were part of the North American Regional Climate Change Assessment Program to reproduce the historical statistics of precipitation extremes for 100 urban areas across the United States. The RCM performance was considered acceptable for storm water infrastructure design at only 12% and 25% of the 100 urban areas, respectively, for 3- and 24-h precipitation maxima at the 100-yr return period.

In summary, understanding land and climate processes in the urban environment represents both challenges and opportunities for advancing research on land–atmospheric interactions. In addition to improving model structure to represent urban-specific land and atmospheric processes and interactions, a substantial increase in information about the structures of cities, which are highly variable across the planet, will be required. It is also a grand challenge to effectively represent urban geophysical processes, climate impacts, and human mortality in large-scale models. To address this challenge, robust characterizations of urban metabolisms (Pataki et al. 2009; Kennedy et al. 2011) are necessary, but this will require different approaches at city (Gurney et al. 2012; McKain et al. 2015) to continental scales (Richter et al. 2005; Kennedy et al. 2009; Nassar et al. 2013).

## 8. Gradual acclimation of biogeochemical processes to climate change

In the face of atmospheric and climatic change, plants must acclimate, adapt, move, or die. The fate of plants, plant communities, and ecosystems is a primary determinant of the feedback between the atmosphere and the terrestrial biosphere, and predicting their responses under future conditions is a necessary component of climate change projections.

The primary responses of plants to increased atmospheric $CO_2$ are fairly simple, at least in theory: photosynthesis increases and stomatal conductance declines. Temperature affects all metabolic processes, so the primary responses to warming are more complex (Norby and Luo 2004). Nevertheless, with both elevated $CO_2$ and warming, it is the secondary, tertiary, and feedback effects that will have the largest influence on ecosystem responses over the long term. It is these effects that will determine the interaction between responses to atmospheric and climatic change and LCLUC. Many of the most important long-term effects and feedbacks revolve around biogeochemical cycling processes. Hence, the focus of many ongoing experimental and modeling research efforts is to describe the responses of carbon, water, and nutrient to atmospheric and climatic change, the interaction of different plant adaptations or functional traits to biogeochemical cycling, and how those biogeochemical responses shape the larger-scale responses of ecosystem structure and function.

The potential for nutrient dynamics to influence plant response to elevated $CO_2$ has long been recognized. Kramer (1981) questioned whether forests, which are frequently limited in their productivity by nitrogen (N) or water availability, would have the capacity to respond to rising $CO_2$ concentrations. Modeling studies (Comins and McMurtrie 1993) led to the hypothesis of progressive nitrogen limitation (PNL; Luo et al. (2004)), whereby N sequestration in wood and soil organic matter reduces N availability and creates a negative feedback to growth. Meta-analysis of experiments indicated a decline in N availability in response to $CO_2$ enrichment (Dieleman et al. 2012), but early results from free-air $CO_2$ enrichment (FACE) experiments in forests did not support the PNL hypothesis: enhanced tree growth was sustained in elevated $CO_2$ with no evidence of a negative feedback on N uptake (Norby and Iversen 2006; Finzi et al. 2007). However, as the experiments continued, PNL did develop in at least one FACE experiment, as indicated by declining N availability, declining net primary productivity (NPP), and a loss in response to elevated $CO_2$ (Norby et al. 2010). Hungate et al. (2006) also reported nutrient cycling responses to elevated $CO_2$ in a scrub oak ecosystem that were broadly consistent with PNL.

Many elements can limit plant responses to elevated $CO_2$ (van Groenigen et al. 2006), and the acclimation of nutrient cycles to elevated $CO_2$ or warming over time needs more attention. The occurrence of PNL discussed above emphasized the importance of time in consideration of ecosystem response to $CO_2$ (Norby and Zak 2011) as the N cycle acclimated to changing conditions. Acclimation of nutrient cycling processes can also be expected in response to warming. Increased soil temperature may increase nutrient cycling rates, counteracting nutrient limitation under elevated $CO_2$ (Dieleman et al. 2012), but warming effects on nutrient cycling are unlikely to be sustained as various soil carbon pools with different turnover rates come into equilibrium with the new temperature environment (Melillo 2002).

Understanding these long-term adjustments in biogeochemical cycling (and accurately representing them in predictive models) is a grand challenge. To meet this challenge, more experiments are needed that are sustained over many years, and new modeling approaches need to be developed to evaluate this potentially dominant influence on ecosystem responses to atmospheric and climatic change. Multiple confounding factors can affect biogeochemical processes, such as microbial activity that mediates carbon turnover in soils (Nie et al. 2013). It also can be difficult to separate different responses to co-occurring influences of $CO_2$ enrichment and warming (Dieleman et al. 2012). Hence, it is especially important to provide experimental data to inform and constrain models at the process level. Otherwise, there is a possibility of models correctly representing the net effect of multiple responses but doing so for the wrong reasons, thereby reducing their predictive power when confronted with new conditions (Zaehle et al. 2014a).

An important challenge in understanding biogeochemical acclimation to atmospheric and climatic change is to extend our understanding to other biomes beyond the temperate ecosystems that have heretofore been the focus of most experiments. A global perspective is required for addressing questions about the interactions between land use and land-use changes and climate change. A new generation of FACE experiments is needed to extend the inference space on elevated $CO_2$ effects into new biomes and climatic regions (Norby et al. 2016). In so doing, new issues about acclimation of biogeochemical cycles will undoubtedly arise. A prime example is a new focus on measurements and modeling of phosphorus (P) limitation, which is expected to be an important determinant of the responses of many tropical ecosystems (Reed et al. 2015). When a P cycle was included in the Community Land Model with Carbon, Nitrogen, and Phosphorus Cycling (CLM-CNP), model predictions of NPP of tropical forest sites in Amazonia were closer to measured values than predictions from a version of CLM with N but not P cycle (Yang et al. 2014). An exception was observed at one site with a history of disturbance showing P limitation was shifted to N limitation (Herbert et al. 2003). This result emphasized how land-use change and land-use history can alter biogeochemical feedbacks that are likely to influence response to atmospheric and climatic change. Yang et al. (2014) explored with CLM-CNP whether stimulation of fine-root production by $CO_2$ fertilization and associated phosphatase activity could alleviate P limitation to NPP. Such biogeochemical mechanisms will have a strong influence on whether responses to elevated $CO_2$ (and presumably warming as well) will be sustained.

Biogeochemical acclimation will have a dominant influence on the future productivity and carbon storage of terrestrial ecosystems (Wieder et al. 2015). Understanding long-term adjustment dynamics in biogeochemical cycling to climatic and atmospheric changes such as elevated $CO_2$ and warming is a grand challenge. To meet this grand challenge, it is essential that there be close coordination between measurements and process representation in models (Medlyn et al. 2015b). Our knowledge base needs to expand to incorporate a wide range of biomes, land-use histories, and plant adaptations. Furthermore, our analyses need to recognize that ecosystem responses to atmospheric and climatic change will change over time through biogeochemical process acclimation.

## 9. Plant biogeographical changes in response to climate change

Range migration is the primary strategy by which plants adapt to climate change (Aitken et al. 2008). Fossil pollen records and genetic data have indicated that climate-driven range shifts are common for plant species in the past glacial and postglacial period (Davis and Shaw 2001; Hamrick 2004). However, recent analyses have shown that velocity (both climate displacement rate and direction) of climate change (1880 to present) is much faster than what occurred in the past at any time since the Last Glacial Maximum and may substantially outpace many plant species' migration rates (Davis 1989; Loarie et al. 2009). Recent estimation of global mean velocities of change for mean annual temperature and rainfall from 2000 to 2100 are 420 and 220 m $yr^{-1}$, respectively (Davis 1989; Loarie et al. 2009). In contrast, the potential velocities of plant migration, estimated by combining routine maximum dispersal distances (50–1500 m) with typical times to maturity (1–30 yr) without consideration of habitat fragmentation and interactions with other species, are in the range of 1.7–1500 m $yr^{-1}$ (Corlett and Westcott 2013). As higher velocities of climate change are expected for the remainder of the twenty-first century, many plant species will need to move more than 1 km $yr^{-1}$ to keep up. It will thus be very challenging for many species to keep pace with climate change because of dispersal limitation, habitat fragmentation, potential novel climate and altered biotic competition, pests and pathogens, and invasive plants in the future.

Two types of predictive models are widely used to project plant species response to climate change. The first type is species distribution models (SDMs), also called habitat suitability models, ecological niche models, or climate envelope models (Thuiller et al. 2008). SDMs predict the future habitat range of species using the statistical relationships between species occurrence or abundance and environmental variables (including climate variables). However, SDM methods often assume that 1) the selected variables do in fact reflect the niche requirements of a species, 2) species are in equilibrium with their suitable habitat, 3) species will be able to disperse to their suitable locations, and 4) the effects of biotic interactions (including human interactions) are minimal. Recent analyses from SDMs have projected an average northward movement of 400–800 km of the climate habitat for more than 100 tree species in North America by the end of twenty-first century

(Iverson et al. 2008; McKenney et al. 2011). Such a range movement may be far beyond the actual migration capacity of most tree species.

Process-based models, which are usually simulations of vegetation dynamics at the taxonomic resolution of species or life-forms, represent the other tool used to predict plant species' responses to climate change in addition to SDMs (Thuiller et al. 2008). Process-based models are considered preferable to statistical-based models because they are better able to deal with factors such as the enhanced productivity possible via elevated $CO_2$ and increased water use efficiency (Keenan et al. 2011). However, trade-offs must be made between complexity and tractability in the realism of ecological processes. Dynamic global vegetation models (DGVMs) have been used to project vegetation pattern response to climate change at a global scale, but typically these models use a few plant functional types to represent vegetation at very coarse resolution ($>0.5°$), and they often lack several key ecological processes, including competition, fire disturbance, and land-cover change. Recently, a trait-based DGVM (aDGVM2) was developed to simulate growth, reproduction, and mortality and keep track of state variables such as biomass, height, and leaf area index (LAI) of each individual plant (Scheiter et al. 2013). The aDGVM2 represents a major advancement on simulating the individualistic response of plant species to climate change and therefore the potential novel community reassembly under the nonanalog environmental conditions at a global scale.

Improved understanding of plant response to climate change has been gained through predictive models, but major challenges and uncertainties still exist. First, future climate projection is highly uncertain. This uncertainty arises from our poor understanding of Earth systems, inadequate parameterization and representation of Earth system processes in the Earth system model, and unpredictable development and mitigation strategies (Meehl et al. 2007). As a result, future climate projections should be viewed as possible climatic conditions under various "what if" scenarios rather than as precise predictions. Second, most predictive models are useful for projecting climate-driven species' range shift but miss or oversimplify key processes, including habitat modification (Fahrig 2003), habitat refugia (Nogues-Bravo 2009), physical barriers to plant movement such as rivers and mountains (Burrows et al. 2014), novel biotic interactions (Blois et al. 2013), and nonanalog climate conditions (Garcia et al. 2014). Integrating these processes to predict plant response to climate change requires an interdisciplinary effort including ecologists, land change scientists, climatologists, sociologists, and other experts. Third, it is difficult to model the differential and interactive effects of light, temperature, nutrients, water, $CO_2$ concentration, and other factors on plant productivity. Nitrogen, a dominant regulator of vegetation dynamics, net primary production, and terrestrial carbon cycle, is rarely modeled mechanistically in process models (see section 8). Our understanding, and thus predictive ability, of plant responses to these key biogeochemical processes is still insufficient. Last, ecosystems respond to climate change nonlinearly with threshold behaviors. Irreversible state change can occur once a threshold is crossed (Scheffer et al. 2001). For example, climate-driven forest die-off from drought and heat stress has been observed, and the scale of such drought-related forest mortality will probably accelerate under warmer and drier climate in many parts of the world (Allen et al. 2010b; Anderegg et al. 2013). In addition, climate will interact with wildfires to influence forest distribution, structure, and composition that may completely change the state of the vegetation in the western United States

(Westerling et al. 2011) and elsewhere (Jolly et al. 2015). Our understanding of the mechanisms, the relative influence of specific climate variables for plant migration, and adaptation is limited, representing a knowledge gap and thus grand challenge for predicting plant biogeographical changes in response to climate change.

## 10. Land-use projections

Land-use activities are intrinsic to the development of human societies through time. Reliable projections of future land-use change are vital for understanding potential influences of land-use change on ecosystem services and climate change, and vice versa. Climate is an important, but not the only, factor that drives changes in land use (Rounsevell et al. 2012). Market demands, price, government programs, and infrastructure also drive land changes. Given the variety of socioeconomic factors that affect land use and their interplay with climate change, modeling the potential impacts of climate change on land use is complicated (Rindfuss et al. 2008; Brown et al. 2013). Ideally, a modeling framework would include feedbacks between climatological, economic, and policy driving forces from local to global scales (Sohl et al. 2010; Rounsevell et al. 2012; Meyfroidt et al. 2013). However, current land-use modeling efforts suffer from 1) an incomplete representation of processes affecting land-use change, 2) an inability to represent the feedbacks between driving forces operating at multiple scales, and 3) a limited ability to assess modeling uncertainties.

A wide variety of ecological and socioeconomic factors drive land-use change, and as a result, LCLUC models have originated from a wide variety of disciplines, including geography, economics, ecology, and social sciences. Models originating from different disciplines tend to focus on a specific aspect of landscape change, often neglecting other relevant driving forces (Verburg et al. 2004). Integrated assessment models (IAMs) were developed in an attempt to capture the variety of driving forces affecting climate and land-use change and are now a standard framework used by the Intergovernmental Panel on Climate Change (IPCC). For example, the IMAGE 2.2 model (Strengers et al. 2004) used for the IPCC Fourth Assessment Report (AR4) linked an agricultural economy model with land use, demographic, climate, energy, world economy, and other models to determine coarse-scale, land-use patterns. Similarly, multiple models were used for the IPCC's Fifth Assessment Report (AR5) to assess the feedbacks between natural and socioeconomic systems (Smith and Wigley 2006; Riahi et al. 2007; van Vuuren et al. 2007; Hijioka et al. 2008), including impacts on land use. However, one of the major shortcomings of traditional global-scale IAMs is the failure to account for local and regional driving forces (van Asselen and Verburg 2012; Rounsevell et al. 2012). Conversely, many models that attempt to address local and regional drivers of land-use change neglect to capture macroscale climatic or socioeconomic driving forces (Verburg et al. 2004; Rounsevell et al. 2012). For example, agent-based models (based on modeling land-use decision-making of various entities) have also been used to address land-use change at local and regional scales (Berger 2001; Brady et al. 2012; Ding et al. 2015), but they rarely account for macroscale driving forces, including climate change. Similarly, econometric models have been widely used within the U.S. to project regional-scale land use based on concepts of optimizing economic return (Murray et al. 2005; Lubowski et al. 2006; Radeloff et al. 2012), yet these too often neglect the impacts of climate change. Overall, it is impossible to perfectly represent all biophysical and socioeconomic processes that affect land-use change across all relevant spatial and temporal scales (Moreira et al. 2009; Sohl et al. 2010), and each of the modeling frameworks described here necessarily sacrifices the representation of some processes or geographic scale. The challenge for future applications is to include pertinent driving forces operating at multiple scales, while reducing model complexity to a reasonable level and maintaining the capability to quantify uncertainties (Sohl and Claggett 2013).

Related to a lack of model comprehensiveness is a limited ability to represent feedbacks between driving forces operating at multiple scales. In an attempt to link global-level driving forces to local-scale, land-use change, more recent modeling efforts have attempted to downscale IAMs and climate impacts on land-use systems to much finer spatial scales for both Europe (Verburg et al. 2008) and for the United States (Sleeter et al. 2012; Sohl et al. 2014; West et al. 2014). However, the direct modeling of feedbacks between the bottom-up and top-down drivers of land use and climate change remains a major challenge (Sohl and Claggett 2013). Integrated approaches that attempt to link models across disciplines typically do so in a "waterfall" approach (van Delden and McDonald 2010), where output from one model is used as input to another model, without any real-time linkage or feedback between models (Sohl and Claggett 2013).

Finally, one key shortcoming of nearly all IAMs and land use and climate modeling is a lack of comprehensive model validation efforts or attempts to quantify the myriad sources of model uncertainty (Sohl and Claggett 2013; Verburg et al. 2013). One of the greatest challenges facing land-use modelers is the need to represent important processes affecting landscape change while controlling model complexity (Messina et al. 2008; Rindfuss et al. 2008; Sohl and Claggett 2013). As modelers link models across disciplines in an attempt to build a more "complete" climate and land-use model, it becomes increasingly difficult to understand and quantify modeling uncertainties (see section 11). It has long been understood that an inability to quantify and communicate uncertainty is a hindrance to the adoption and use of models by decision-makers (Oreskes et al. 1994; Bradshaw and Borchers 2000). However, land-use models in general are moving toward more complex (and less transparent) frameworks, and many model applications do not even attempt to quantify modeling uncertainties (Sohl and Claggett 2013).

Progress has been made in recent decades in developing more comprehensive, integrated models of landscape and climate change. However, the issues and limitations outlined here must be addressed to facilitate the widespread use of these models for assessment, planning, and mitigation efforts. The grand challenge is to develop a comprehensive land-use modeling framework that 1) captures all major driving forces of land use, including both ecological, climatic, and socioeconomic factors; 2) addresses feedbacks between processes operating at scales from local to global; and 3) provides a quantitative accounting of modeling uncertainties while maintaining model transparency.

## 11. Reduction of uncertainty in models and data

Models are indispensable for understanding the interactions of LCLUC and climate and projecting the likely consequences of LCLUC activities and climate change. The skill of models in simulating biogeophysical and biogeochemical processes varies greatly in time and space. To improve model performance, common protocols are needed to compare different models, quantifying modeling uncertainties from input data and model structure to model output.

Model intercomparison exercises can provide intuitive and useful information on the agreement between model simulations and reference data (i.e., performance differences) and between models (i.e., structural differences). Several major model intercomparison efforts have been conducted in recent years in both the land and climate modeling communities (de Noblet-Ducoudré et al. 2012; Huntzinger et al. 2012; Taylor et al. 2012b; Walker et al. 2014; Schwalm et al. 2015b). For example, Zaehle et al. (2014b) studied the representations of the ecosystem C–N cycle responses to elevated atmospheric $CO_2$ in 11 models at two temperate forest ecosystems (the Duke and Oak Ridge National Laboratory FACE experiment sites). Although most of the models reproduced the observed initial enhancement of NPP at both sites, none were able to simulate both the sustained enhancement at Duke and the declining response at Oak Ridge, suggesting that these state-of-the-science models did not have the skill to predict the mid- to long-term effects of $CO_2$ enrichment. Nevertheless, this exercise was successful in identifying model assumptions that were consistent with data, important mechanisms that were missing from models, and mechanisms for which the data were insufficient for evaluation (Medlyn et al. 2015a). Current terrestrial biogeochemical models vary in their ability to simulate the impacts of climate extremes on C fluxes (Zscheischler et al. 2014), the regional patterns of mean surface runoff (Schwalm et al. 2015a), and mean carbon stocks and fluxes (Schwalm et al. 2015b). The poor performance of individual terrestrial ecosystem models suggests that ecosystem processes have predictability limits and/or that some models and reference data are not adequate (Schwalm et al. 2015b).

Global and regional climate models have not demonstrated skill at predicting multidecadal changes in regional and local climate in hindcast studies (Mishra et al. 2012). Even phase 5 of the Coupled Model Intercomparison Project (CMIP5), an integral part of the IPCC AR5 (Taylor et al. 2012b) representing the state of science in climate modeling, had obvious weaknesses. For example, model skills for regional and multidecadal scales were limited in simulating surface air temperature (Sakaguchi et al. 2012). Most of the CMIP5 models overestimated warming trends, compared to historical observations, and those models predicted less warming or even cooling in the earlier decades and then simulated too much warming in recent decades (Kim et al. 2012). Taylor et al. (2012a) studied the coupling between soil moisture and precipitation using global-scale observations and modeling. From satellite observations, they found no evidence of a positive feedback between soil moisture and precipitation (i.e., a preference for rain over wetter soils) at the spatial scale of 50–100 km, contrasting to positive feedback simulated by the six state-of-the-art models examined. This discrepancy suggests a fundamental failure in model representation of the land feedbacks on daytime precipitation, which may contribute to excessive simulated droughts in large-scale models.

Most of the existing exercises are heavily tilted toward revealing the performance differences of models without going into depth to explore why these differences exist. These model–data or model–model intercomparison exercises indicate an urgent and critical need to evaluate land surface and climate models more thoroughly. In particular, we have to objectively and systematically evaluate modeling uncertainties (model structure, parameterization, and reference data) and model capabilities in dealing with multifacet interrelated perturbations and feedbacks (de Noblet-Ducoudré et al. 2012; Knutti and Sedláček 2013; Schwalm et al. 2015b).

Research on the interactions between human and Earth systems has traditionally used one-way waterfall coupling between human-centered integrated assessment models and biophysical Earth system models. For example, CMIP5 uses outputs from human systems models to drive ESMs, while the Agricultural Model Intercomparison and Improvement Project (AgMIP; Nelson et al. 2014) feeds ESM outputs into human systems models. Such one-way couplings may be inaccurate, however, if feedbacks between human and Earth system models have strong and interactive effects (van Vuuren et al. 2012). An open question in modeling the Earth system's biogeochemical cycles and LCLUC revolves around whether and when a fully coupled human–Earth system is necessary. This problem has critical implications both for our approach to modeling (Schwaiger and Bird 2010; Smith et al. 2012b) and understanding of climate change dynamics because the answer can elucidate the likelihood that currently poorly constrained interactions will exert substantially positive or negative feedbacks over a variety of time scales.

Understanding and acknowledging the intrinsic and interrelated scale and heterogeneity dependencies of the interplay between land and atmospheric processes in models should be emphasized in the future (D'Almeida et al. 2007; Zhao and Liu 2014; Ma et al. 2015). Baidya Roy et al. (2003) compared the horizontal length scales of the simulated mesoscale circulations forced by land surface heterogeneity in the central United States and Amazonia and found that the scale of the organized mesoscale circulations was significantly different from the dominant length scale of the surface heterogeneity. Ma et al. (2015) found the Community Atmosphere Model performed differently at different horizontal resolutions because of the resolution sensitivities of aerosol indirect forcing and the resolution dependence of aerosol–cloud interactions, which in turn could be attributed to the resolution sensitivities of droplet nucleation and precipitation parameterizations.

Coordinated interdisciplinary efforts have been emerging in recent years to examine and reduce modeling uncertainties. Open, standardized benchmarking databases and systems are being built for model–model or model–measurement intercomparision (Abramowitz 2012; Wei et al. 2013; Best et al. 2015) such as the International Land–Atmosphere Model Benchmarking project (www.ilamb.org) and the Protocol for the Analysis of Land Surface models (http://pals.unsw.edu.au/). Ideas and methods are being explored for assessing model structural adequacy (Clark et al. 2008; Gupta et al. 2012; Gong et al. 2013; Gupta and Nearing 2014) in representing underlying processes (Clark et al. 2008; Foglia et al. 2013) and spatial variability structures (Zhao and Liu 2014).

More innovative, collective efforts are nonetheless necessary to detect, understand, and correct underlying epistemic uncertainties of models (Gupta et al. 2012; Foglia et al. 2013; Gong et al. 2013). Insights about model structure and the underlying processes may be gained by shifting the emphasis of modeling to more creative aspects of scientific investigation through comparing characteristic behaviors of the models and the data (Gong et al. 2013; Gupta and Nearing 2014;

Mendoza et al. 2015). Moving forward, it is necessary to integrate the strengths of the conventional process-based modeling philosophy (which relies on prior knowledge of underlying processes) with the strengths of the data-driven modeling philosophy through innovative model–data intercomparison (Gupta and Nearing 2014; Mendoza et al. 2015).

In summary, many model–measurement or model–model intercomparison exercises have shown that model skill varies greatly in predicting changes in global and local climate and land surface conditions. One major challenge is to evaluate land surface and climate models more thoroughly with improved understanding of their uncertainties and capabilities in dealing with multifacet, interrelated perturbations and feedbacks so that these models can be improved. Another challenge is to understand and then acknowledge the importance of scaling and representation of variability structures in many cross-scale land and atmospheric processes (Zhao et al. 2009; Gupta and Nearing 2014; Zhao and Liu 2014).

## 12. Human adaptation to climate and land change

Adaptation refers to policies, measures, and strategies designed to manage climate risks, avoid damage, and realize emerging opportunities with climate change (Moss et al. 2013). The importance of adaptation in climate policy is now widely recognized, reflecting the need to deal with changes in climate already occurring, commitment to some degree of future climate change, and present-day benefits that adaptations bring in term of reduced vulnerability (Moss et al. 2013; IPCC 2014). A wide range of potential LCLUC options can be employed to adapt to the effects of climate change (Kravitz et al. 2013). For example, heat wave impacts could be attenuated locally by increasing surface albedo through crop residue management (no-till farming; Davin et al. 2014) or promoting white roofs in urban settings (Georgescu et al. 2012), and dam construction and operations as well as associated LCLUC can be optimized to account for climate feedbacks (Hossain et al. 2012), while assisted migration can be used to help species whose natural ability to migrate cannot keep up with the velocity of climate change (Bell and Gonzalez 2011; Jones et al. 2012; Gonzalez et al. 2013; Williams and Dumroese 2013). Research on adaptation is rapidly expanding, but many gaps in understanding remain, framing a number of grand challenges for the adaptation research and practitioner community.

There is a need for practice-relevant adaptation science that provides a basis for preparing for climate change impacts (Lemos et al. 2012; Moss et al. 2013). There are many serious gaps, however, in addressing this challenge. Vulnerability assessments, for example, are needed to understand how land, atmospheric, and societal changes interact to affect critical ecosystem services (Turner et al. 2003; Smit and Wandel 2006; Stern et al. 2013). Understanding of the pathways through which future climate change will affect human systems through impacts on LCLUC is limited. Few studies have examined interdependencies between social and ecological systems, integrating future scenarios in the context of risk assessment and management or focusing on developing qualitative scenario planning approaches (Wu et al. 2013; Chapman et al. 2014; Wang et al. 2014; Tucker et al. 2015).

Adaptation assessments are needed to identify, evaluate, and prioritize adaptation opportunities, identify barriers that need to be overcome, and examine how adaptation decision-making processes work in specific contexts (Wise et al. 2014; Biesbroek et al. 2015; Champalle et al. 2015). While a variety of approaches and decision support tools have been developed to this end, few have been applied to support adaptation decision-making generally or in a LCLUC context, with an absence of ''usable'' or ''decision-orientated'' science noted to be a major constraint to adaptation (Dilling and Lemos 2011; Ford and King 2015; Lemos 2015; Taylor and McAllister 2015). Research is needed to assess adaptation performance in light of projected climate impacts and societal interactions, including identifying potential maladaptations, the displacement of impacts to other regions/future generations, and impacts on emissions (Bennett et al. 2009; Barnett and O'Neill 2010; Snorek et al. 2014). All LCLUC-centered adaptations have the potential to generate adverse or unintended effects across scales, including on the regional and global climate, and it is important that these adaptations are comprehensively evaluated to identify sustainable adaptation pathways (Bennett et al. 2009; Daily et al. 2009; Euliss et al. 2010; Jones 2012; Sovacool et al. 2015).

As adaptation increases in importance in climate policy across scales, a grand challenge will also be to measure whether investments made in adaptation are reducing vulnerability (i.e., monitoring and evaluation; Biesbroek et al. 2010; Berrang-Ford et al. 2011; Dupuis and Biesbroek 2013; Ford et al. 2013; Magnan et al. 2015). This measure of investments is needed to examine whether adaptation support is 1) translating into actions, 2) facilitating comparison of adaptations across regions and sectors, 3) ensuring resources are being invested in areas with the greatest need, and 4) informing governance systems on the current status and gaps in adaptation action (Ford et al. 2013; Berrang-Ford et al. 2014; Lesnikowski et al. 2015). There is an emerging scholarship examining specific adaptation initiatives and programs, developed mostly in the context of low-income nations by donors and development organizations (Lamhauge et al. 2012; Brooks et al. 2013; Lamhauge et al. 2013). These approaches provide a basis for monitoring and evaluation of specific LCLUC-focused adaptations, yet few have been applied in a land-cover, land-use change context.

There is much less research examining and comparing adaptation across nations and over time, with little consideration within the United Nations Framework Convention on Climate Change (UNFCCC) given on how to track adaptation across parties (Ford et al. 2015). This situation reflects conceptual, methodological, and empirical challenges of tracking adaptation at this scale. Ford et al. (2015) identified a number of key steps that will need to be taken to address this challenge, including 1) the need to determine an operational definition of adaptation, 2) decide what information needs to be tracked, 3) develop an adaptation baseline, and 4) create systematic reporting mechanisms on adaptation. An overarching challenge facing all adaptation work concerns the question ''what is adaptation?'' Answering this question will require much debate among practitioners, academics, and decision-makers on what adaptation looks like on the ground and how (or if) adaptation is distinct from traditional development activities (Ayers and Forsyth 2009; Eakin et al. 2014; Agrawal and Lemos 2015).

In summary, grand challenges on human adaptation to climate through land change activities include 1) a need for practice-relevant adaptation science; 2) adaptation assessments on adaptation opportunities, barriers, and effectiveness of adaptation decision-making processes; 3) cost-effectiveness analysis on investments in adaptation; and 4) examining and comparing adaptation across nations and over time. Meeting these grand challenges requires basic research that seeks to understand adaptation processes and needs as well as applied research that works with decision-makers to identify adaptation options, support adaptation planning, and guide implementation, monitoring, and evaluation (Rose 2014; Swart et al. 2014; Preston et al. 2015). An evolving institutional landscape of governments, research agencies, and organizations seeks to catalyze, support, and coordinate adaptation research (Bassett and Fogelman 2013; Swart et al. 2014; Preston et al. 2015). Yet, the field remains at a formative stage, especially in a LCLUC context, and the grand challenges identified herein provide strategic guidance of areas to prioritize in future work.

## 13. Summary

In this review and synthesis, we documented many challenges in the study of land–atmospheric interactions in the face of ongoing and projected LCLUC and climate change and in the pursuit of adaptation strategies and mechanisms. The overall and individual effects of various LCLUC activities on the atmosphere and climate vary greatly with space, time, and scale, and at present the magnitudes or even signs of LCLUC impacts remain highly uncertain. To improve our understanding of the interplay between LCLUC and climate, we have identified the following research priority areas:

1) LCLUC-induced changes in gas- and particle-phase emissions;
2) carbon consequences of altered fire regimes, heterotrophic respiration, and BVOC emissions and chemistry due to LCLUC and climate-driven changes;
3) location- and scale-dependent effects of LCLUC on the water cycle;
4) effects of increased extreme climate events on agricultural systems and impacts of agricultural LCLUC on climate and integrated crop–climate modeling to generate most effective adaptation strategies;
5) information about the structures of cities and effective representation of urban-specific geophysical structures and processes in large-scale land surface models;
6) biogeochemical process acclimations to atmospheric and climatic change across all biomes and mechanistic representation of these acclimations in models;
7) mechanisms governing climate-driven species' range shift and land-cover change and addition of the new understanding to extant biogeographical models;
8) land-use modeling frameworks with uncertainty measures that capture all major biogeophysical, climatic, and socioeconomic forces of LCLUC and address feedbacks between processes operating at scales from local to global;
9) systematic evaluation of the efficacy of alternative strategies on representing the underlying biophysical processes in models using standardized protocols and benchmark frameworks at a variety of spatial and temporal scales; vigorous measurement–model and model–model

(including data-driven modeling approaches) intercomparisons to identify and correct model structural errors; and
10) development of a practice-relevant adaptation science to support societal adaptation to climate change, particularly in the LCLUC context.

A consistent theme running through all our recommendations in these areas is the necessity for scale-aware modeling, integrated and innovative data–model comparison and syntheses for knowledge discovery and uncertainty reduction, and developing benchmark datasets and frameworks for model evaluation ensuring better reproducibility and data sharing.

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## References

Abramowitz, G., 2012: Towards a public, standardized, diagnostic benchmarking system for land surface models. *Geosci. Model Dev.*, **5**, 819–827, doi:10.5194/gmd-5-819-2012.

Agrawal, A., and M. C. Lemos, 2015: Adaptive development. *Nat. Climate Change*, **5**, 185–187, doi:10.1038/nclimate2501.

Aitken, S. N., S. Yeaman, J. A. Holliday, T. Wang, and S. Curtis-McLane, 2008: Adaptation, migration or extirpation: Climate change outcomes for tree populations. *Evol. Appl.*, **1**, 95–111, doi:10.1111/j.1752-4571.2007.00013.x.

Allen, C. D., and Coauthors, 2010a: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manage.*, **259**, 660–684, doi:10.1016/j.foreco.2009.09.001.

——, and Coauthors, 2010b: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manage.*, **259**, 660–684, doi:10.1016/j.foreco.2009.09.001.

Alter, R. E., Y. Fan, B. R. Lintner, and C. P. Weaver, 2015: Observational evidence that Great Plains irrigation has enhanced summer precipitation intensity and totals in the midwestern United States. *J. Hydrometeor.*, **16**, 1717–1735, doi:10.1175/JHM-D-14-0115.1.

Amiro, B., and Coauthors, 2010: Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *J. Geophys. Res.*, **115**, G00K02, doi:10.1029/2010JG001390.

Anderegg, W. R., J. M. Kane, and L. D. Anderegg, 2013: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nat. Climate Change*, **3**, 30–36, doi:10.1038/nclimate1635.

Arneth, A., and Coauthors, 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nat. Geosci.*, **3**, 525–532, doi:10.1038/ngeo905.

Arnfield, A. J., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.*, **23**, 1–26, doi:10.1002/joc.859.

Arora, V. K., and Coauthors, 2013: Carbon–concentration and carbon–climate feedbacks in CMIP5 Earth system models. *J. Climate*, **26**, 5289–5314, doi:10.1175/JCLI-D-12-00494.1.

Atkinson, J. D., and Coauthors, 2013: The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds. *Nature*, **498**, 355–358, doi:10.1038/nature12278.

Avissar, R., and D. Werth, 2005: Global hydroclimatological teleconnections resulting from tropical deforestation. *J. Hydrometeor.*, **6**, 134–145, doi:10.1175/JHM406.1.

Ayers, J., and T. Forsyth, 2009: Community-based adaptation to climate change: Strengthening resilience through development. *Environment*, **51**, 22–31, doi:10.3200/ENV.51.4.22-31.

Baccini, M., and Coauthors, 2008: Heat effects on mortality in 15 European cities. *Epidemiology*, **19**, 711–719, doi:10.1097/EDE.0b013e318176bfcd.

Bagley, J. E., J. Miller, and C. J. Bernacchi, 2015: Biophysical impacts of climate-smart agriculture in the Midwest United States. *Plant Cell Environ.*, **38**, 1913–1930, doi:10.1111/pce.12485.

Baidya Roy, S., C. P. Weaver, D. S. Nolan, and R. Avissar, 2003: A preferred scale for landscape forced mesoscale circulations? *J. Geophys. Res.*, **108**, 8854, doi:10.1029/2002JD003097.

Barnett, J., and S. O'Neill, 2010: Maladaptation. *Global Environ. Change*, **20**, 211–213, doi:10.1016/j.gloenvcha.2009.11.004.

Bassett, T. J., and C. Fogelman, 2013: Deja vu or something new? The adaptation concept in the climate change literature. *Geoforum*, **48**, 42–53, doi:10.1016/j.geoforum.2013.04.010.

Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler, 2010: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI Earth system model. *Biogeosciences*, **7**, 1383–1399, doi:10.5194/bg-7-1383-2010.

Bechtel, B., and K. J. Schmidt, 2011: Floristic mapping data as a proxy for the mean urban heat island. *Climate Res.*, **49**, 45–58, doi:10.3354/cr01009.

——, and C. Daneke, 2012: Classification of local climate zones based on multiple Earth observation data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, **5**, 1191–1202, doi:10.1109/JSTARS.2012.2189873.

Bell, G., and A. Gonzalez, 2011: Adaptation and evolutionary rescue in metapopulations experiencing environmental deterioration. *Science*, **332**, 1327–1330, doi:10.1126/science.1203105.

Bennett, E. M., G. D. Peterson, and L. J. Gordon, 2009: Understanding relationships among multiple ecosystem services. *Ecol. Lett.*, **12**, 1394–1404, doi:10.1111/j.1461-0248.2009.01387.x.

Berger, T., 2001: Agent-based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis. *Agric. Econ.*, **25**, 245–260, doi:10.1111/j.1574-0862.2001.tb00205.x.

Berrang-Ford, L., J. D. Ford, and J. Patterson, 2011: Are we adapting to climate change? *Global Environ. Change*, **21**, 25–33, doi:10.1016/j.gloenvcha.2010.09.012.

——, ——, A. Lesnikowski, C. Poutiainen, M. Barrera, and S. J. Heymann, 2014: What drives national adaptation? A global assessment. *Climatic Change*, **124**, 441–450, doi:10.1007/s10584-014-1078-3.

Best, M. J., and C. S. B. Grimmond, 2013: Analysis of the seasonal cycle within the first international urban land-surface model comparison. *Bound.-Layer Meteor.*, **146**, 421–446, doi:10.1007/s10546-012-9769-7.

——, and ——, 2015: Key conclusions of the First International Urban Land Surface Model Comparison Project. *Bull. Amer. Meteor. Soc.*, **96**, 805–819, doi:10.1175/BAMS-D-14-00122.1.

——, and Coauthors, 2015: The plumbing of land surface models: Benchmarking model performance. *J. Hydrometeor.*, **16**, 1425–1442, doi:10.1175/JHM-D-14-0158.1.

Biesbroek, G. R., R. J. Swart, T. R. Carter, C. Cowan, T. Henrichs, H. Mela, M. D. Morecroft, and D. Rey, 2010: Europe adapts to climate change: Comparing national adaptation strategies. *Global Environ. Change*, **20**, 440–450, doi:10.1016/j.gloenvcha.2010.03.005.

Biesbroek, R., J. Dupuis, A. Jordan, A. Wellstead, M. Howlett, P. Cairney, J. Rayner, and D. Davidson, 2015: Correspondence: Opening up the black box of adaptation decision-making. *Nat. Climate Change*, **5**, 493–494, doi:10.1038/nclimate2615.

Blois, J. L., P. L. Zarnetske, M. C. Fitzpatrick, and S. Finnegan, 2013: Climate change and the past, present, and future of biotic interactions. *Science*, **341**, 499–504, doi:10.1126/science.1237184.

Bonan, G. B., 2002: *Ecological Climatology: Concepts and Applications*. Cambridge University Press, 678 pp.

——, 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, **320**, 1444–1449, doi:10.1126/science.1155121.

Bond-Lamberty, B., S. Peckham, D. Ahl, and S. Gower, 2007: Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, **450**, 89–92, doi:10.1038/nature06272.

——, D. Epron, J. W. Harden, M. E. Harmon, F. M. Hoffman, J. Kumar, A. D. McGuire, and R. Vargas, 2016: Estimating heterotrophic respiration at large scales: Challenges, approaches, and next steps. *Ecosphere*, **7**, e01380, doi:10.1002/ecs2.1380.

Bornstein, R. D., 1968: Observations of the urban heat island effect in New York City. *J. Appl. Meteor.*, **7**, 575–582, doi:10.1175/1520-0450(1968)007<0575:OOTUHI>2.0.CO;2.

Boucher, O., and Coauthors, 2013: Clouds and aerosols. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 571–657.

Bounoua, L., and Coauthors, 2015: Impact of urbanization on US surface climate. *Environ. Res. Lett.*, **10**, 084010, doi:10.1088/1748-9326/10/8/084010.

Bowman, D. M., and Coauthors, 2009: Fire in the Earth system. *Science*, **324**, 481–484, doi:10.1126/science.1163886.

Boysen, L., V. Brovkin, V. Arora, P. Cadule, N. de Noblet-Ducoudré, E. Kato, J. Pongratz, and V. Gayler, 2014: Global and regional effects of land-use change on climate in 21st century simulations with interactive carbon cycle. *Earth Syst. Dyn.*, **5**, 309–319, doi:10.5194/esd-5-309-2014.

Bradford, M. A., W. R. Wieder, G. B. Bonan, N. Fierer, P. A. Raymond, and T. W. Crowther, 2016: Managing uncertainty in soil carbon feedbacks to climate change. *Nat. Climate Change*, **6**, 751–758, doi:10.1038/nclimate3071.

Bradshaw, G. A., and J. G. Borchers, 2000: Uncertainty as information: Narrowing the science-policy gap. *Conserv. Ecol.*, **4**, 7, doi:10.5751/ES-00174-040107.

Brady, M., C. Sahrbacher, K. Kellermann, and K. Happe, 2012: An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services. *Landscape Ecol.*, **27**, 1363–1381, doi:10.1007/s10980-012-9787-3.

Brando, P. M., and Coauthors, 2014: Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proc. Natl. Acad. Sci. USA*, **111**, 6347–6352, doi:10.1073/pnas.1305499111.

Brooks, N., S. Anderson, I. Burton, S. Fisher, N. Rai, and I. Tellam, 2013: An operational framework for Tracking Adaptation and Measuring Development (TAMD). IIED Climate Change Working Paper 5, 40 pp. [Available online at http://pubs.iied.org/10038IIED/?c=climate.]

Brovkin, V., S. Levis, M.-F. Loutre, M. Crucifix, M. Claussen, A. Ganopolski, C. Kubatzki, and V. Petoukhov, 2003: Stability analysis of the climate-vegetation system in the northern high latitudes. *Climatic Change*, **57**, 119–138, doi:10.1023/A:1022168609525.

——, T. Raddatz, C. H. Reick, M. Claussen, and V. Gayler, 2009: Global biogeophysical interactions between forest and climate. *Geophys. Res. Lett.*, **36**, L07405, doi:10.1029/2009GL037543.

——, and Coauthors, 2013: Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. *J. Climate*, **26**, 6859–6881, doi:10.1175/JCLI-D-12-00623.1.

Brown, D. G., P. H. Verburg, R. G. Pontius, and M. D. Lange, 2013: Opportunities to improve impact, integration, and evaluation of land change models. *Curr. Opin. Environ. Sustainability*, **5**, 452–457, doi:10.1016/j.cosust.2013.07.012.

Brown, I., L. Poggio, A. Gimona, and M. Castellazzi, 2011: Climate change, drought risk and land capability for agriculture: Implications for land use in Scotland. *Reg. Environ. Change*, **11**, 503–518, doi:10.1007/s10113-010-0163-z.

Bruinsma, J., 2015: *World Agriculture: Towards 2015/2030: An FAO Perspective*. FAO, 444 pp. [Available online at http://www.fao.org/3/a-y4252e.pdf.]

Burrows, M. T., and Coauthors, 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**, 492–495, doi:10.1038/nature12976.

Butt, N., P. A. de Oliveira, and M. H. Costa, 2011: Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *J. Geophys. Res.*, **116**, D11120, doi:10.1029/2010JD015174.

Byrne, M. P., and P. A. O'Gorman, 2015: The Response of precipitation minus evapotranspiration to climate warming: Why the ''wet-get-wetter, dry-get-drier'' scaling does not hold over land. *J. Climate*, **28**, 8078–8092, doi:10.1175/JCLI-D-15-0369.1.

Carlson, C., O. Barreteau, P. Kirshen, and K. Foltz, 2015: Storm water management as a public good provision problem: Survey to understand perspectives of low-impact development for urban storm water management practices under climate change. *J. Water Resour. Plann. Manage.*, **141**, 04014080, doi:10.1061/(ASCE)WR.1943-5452.0000476.

Carrió, G. G., W. R. Cotton, and W. Y. Y. Cheng, 2010: Urban growth and aerosol effects on convection over Houston. *Atmos. Res.*, **96**, 560–574, doi:10.1016/j.atmosres.2010.01.005.

Chameides, W., R. Lindsay, J. Richardson, and C. Kiang, 1988: The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study. *Science*, **241**, 1473–1475, doi:10.1126/science.3420404.

Champalle, M., J. D. Ford, and M. Sherman, 2015: Prioritizing climate change adaptations in Canadian Arctic communities. *Sustainability*, **7**, 9268–9292, doi:10.3390/su7079268.

Chan, D., and Q. Wu, 2015: Significant anthropogenic-induced changes of climate classes since 1950. *Sci. Rep.*, 13487, doi:10.1038/srep13487.

Chapman, S., K. Mustin, A. R. Renwick, D. B. Segan, D. G. Hole, R. G. Pearson, and J. E. M. Watson, 2014: Publishing trends on climate change vulnerability in the conservation literature reveal a predominant focus on direct impacts and long time-scales. *Diversity Distrib.*, **20**, 1221–1228, doi:10.1111/ddi.12234.

Ching, J., and Coauthors, 2009: National urban database and access portal tool. *Bull. Amer. Meteor. Soc.*, **90**, 1157–1168, doi:10.1175/2009BAMS2675.1.

Chou, C., J. C. H. Chiang, C.-W. Lan, C.-H. Chung, Y.-C. Liao, and C.-J. Lee, 2013: Increase in the range between wet and dry season precipitation. *Nat. Geosci.*, **6**, 263–267, doi:10.1038/ngeo1744.

Ciais, P., and Coauthors, 2014: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 465–570.

Clark, C. A., and P. W. Arritt, 1995: Numerical simulations of the effect of soil moisture and vegetation cover on the development of deep convection. *J. Appl. Meteor.*, **34**, 2029–2045, doi:10.1175/1520-0450(1995)034<2029:NSOTEO>2.0.CO;2.

Clark, M. P., A. G. Slater, D. E. Rupp, R. A. Woods, J. A. Vrugt, H. V. Gupta, T. Wagener, and L. E. Hay, 2008: Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models. *Water Resour. Res.*, **44**, W00B02, doi:10.1029/2007WR006735.

Cochrane, M. A., 2003: Fire science for rainforests. *Nature*, **421**, 913–919, doi:10.1038/nature01437.

Coe, M. T., M. H. Costa, and B. S. Soares-Filho, 2009: The influence of historical and potential future deforestation on the stream flow of the Amazon River—Land surface processes and atmospheric feedbacks. *J. Hydrol.*, **369**, 165–174, doi:10.1016/j.jhydrol.2009.02.043.

Collins, M., and Coauthors, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 1029–1136.

Comins, H. N., and R. E. McMurtrie, 1993: Long-term response of nutrient-limited forests to $CO_2$ enrichment: Equilibrium behavior of plant-soil models. *Ecol. Appl.*, **3**, 666–681, doi:10.2307/1942099.

Corlett, R. T., and D. A. Westcott, 2013: Will plant movements keep up with climate change? *Trends Ecol. Evol.*, **28**, 482–488, doi:10.1016/j.tree.2013.04.003.

Covington, W. W., 1981: Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. *Ecology*, **62**, 41–48, doi:10.2307/1936666.

Crowther, T. W., and Coauthors, 2016: Quantifying global soil carbon losses in response to warming. *Nature*, **540**, 104–108, doi:10.1038/nature20150.

Daily, G. C., and Coauthors, 2009: Ecosystem services in decision making: Time to deliver. *Front. Ecol. Environ.*, **7**, 21–28, doi:10.1890/080025.

D'Almeida, C., C. J. Vörösmarty, G. C. Hurtt, J. A. Marengo, S. L. Dingman, and B. D. Keim, 2007: The effects of deforestation on the hydrological cycle in Amazonia: A review on scale and resolution. *Int. J. Climatol.*, **27**, 633–647, doi:10.1002/joc.1475.

Davidson, E. A., K. E. Savage, and A. C. Finzi, 2014: A big-microsite framework for soil carbon modeling. *Global Change Biol.*, **20**, 3610–3620, doi:10.1111/gcb.12718.

Davin, E. L., and N. de Noblet-Ducoudré, 2010: Climatic impact of global-scale deforestation: Radiative versus nonradiative processes. *J. Climate*, **23**, 97–112, doi:10.1175/2009JCLI3102.1.

——, S. I. Seneviratne, P. Ciais, A. Olioso, and T. Wang, 2014: Preferential cooling of hot extremes from cropland albedo management. *Proc. Natl. Acad. Sci. USA*, **111**, 9757–9761, doi:10.1073/pnas.1317323111.

Davis, M. B., 1989: Lags in vegetation response to greenhouse warming. *Climatic Change*, **15**, 75–82, doi:10.1007/BF00138846.

——, and R. G. Shaw, 2001: Range shifts and adaptive responses to Quaternary climate change. *Science*, **292**, 673–679, doi:10.1126/science.292.5517.673.

de Noblet-Ducoudré, N., and Coauthors, 2012: Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: Results from the first set of LUCID experiments. *J. Climate*, **25**, 3261–3281, doi:10.1175/JCLI-D-11-00338.1.

De Ridder, K., 1998: The impact of vegetation cover on Sahelian drought persistence. *Bound.-Layer Meteor.*, **88**, 307–321, doi:10.1023/A:1001106728514.

Dieleman, W. I. J., and Coauthors, 2012: Simple additive effects are rare: A quantitative review of plant biomass and soil process responses to combined manipulations of $CO_2$ and temperature. *Global Change Biol.*, **18**, 2681–2693, doi:10.1111/j.1365-2486.2012.02745.x.

Dilling, L., and M. C. Lemos, 2011: Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environ. Change*, **21**, 680–689, doi:10.1016/j.gloenvcha.2010.11.006.

Ding, D., D. Bennett, and S. Secchi, 2015: Investigating impacts of alternative crop market scenarios on land use change with an agent-based model. *Land*, **4**, 1110–1137, doi:10.3390/land4041110.

Dingle, H., 2014: *Migration: The Biology of Life on the Move.* 2nd ed. Oxford University Press, 326 pp.

Don, A., J. Schumacher, and A. Freibauer, 2011: Impact of tropical land-use change on soil organic carbon stocks—A meta-analysis. *Global Change Biol.*, **17**, 1658–1670, doi:10.1111/j.1365-2486.2010.02336.x.

Dupuis, J., and R. Biesbroek, 2013: Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation policies. *Global Environ. Change*, **23**, 1476–1487, doi:10.1016/j.gloenvcha.2013.07.022.

Durack, P. J., S. E. Wijffels, and R. J. Matear, 2012: Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science*, **336**, 455–458, doi:10.1126/science.1212222.

Eakin, H. C., M. C. Lemos, and D. R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environ. Change*, **27**, 1–8, doi:10.1016/j.gloenvcha.2014.04.013.

Egli, D. B., and J. L. Hatfield, 2014a: Yield and yield gaps in central U.S. corn production systems. *Agron. J.*, **106**, 2248–2254, doi:10.2134/agronj14.0348.

——, and ——, 2014b: Yield gaps and yield relationships in central U.S. soybean production systems. *Agron. J.*, **106**, 560–566, doi:10.2134/agronj2013.0364.

Euliss, N. H., Jr., L. M. Smith, S. Liu, M. Feng, D. M. Mushet, R. F. Auch, and T. R. Loveland, 2010: The need for simultaneous evaluation of ecosystem services and land use change. *Environ. Sci. Technol.*, **44**, 7761–7763, doi:10.1021/es102761c.

Exbrayat, J.-F., A. Pitman, Q. Zhang, G. Abramowitz, and Y.-P. Wang, 2013: Examining soil carbon uncertainty in a global model: Response of microbial decomposition to temperature, moisture and nutrient limitation. *Biogeosciences*, **10**, 7095–7108, doi:10.5194/bg-10-7095-2013.

Fahrig, L., 2003: Effects of habitat fragmentation on biodiversity. *Annu. Rev. Ecol. Evol. Syst.*, **34**, 487–515, doi:10.1146/annurev.ecolsys.34.011802.132419.

Feng, S., and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmos. Chem. Phys.*, **13**, 10 081–10 094, doi:10.5194/acp-13-10081-2013.

Findell, K. L., T. R. Knutson, and P. Milly, 2006: Weak simulated extratropical responses to complete tropical deforestation. *J. Climate*, **19**, 2835–2850, doi:10.1175/JCLI3737.1.

Finzi, A. C., and Coauthors, 2007: Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated $CO_2$. *Proc. Natl. Acad. Sci. USA*, **104**, 14 014–14 019, doi:10.1073/pnas.0706518104.

Foglia, L., S. Mehl, M. Hill, and P. Burlando, 2013: Evaluating model structure adequacy: The case of the Maggia Valley groundwater system, southern Switzerland. *Water Resour. Res.*, **49**, 260–282, doi:10.1029/2011WR011779.

Foley, J. A., and Coauthors, 2011: Solutions for a cultivated planet. *Nature*, **478**, 337–342, doi:10.1038/nature10452.

Ford, J. D., and D. King, 2015: A framework for examining adaptation readiness. *Mitigation Adapt. Strategies Global Change*, **20**, 505–526, doi:10.1007/s11027-013-9505-8.

——, L. Berrang-Ford, A. Lesnikowski, M. Barrera, and S. J. Heymann, 2013: How to track adaptation to climate change: A typology of approaches for national-level application. *Ecol. Soc.*, **18**, 40, doi:10.5751/ES-05732-180340.

——, ——, R. Biesbroek, M. Araos, S. Austin, and A. Lesnikowski, 2015: Adaptation tracking for a post-2015 climate agreement. *Nat. Climate Change*, **5**, 967–969, doi:10.1038/nclimate2744.

Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti, 2014: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *J. Climate*, **27**, 511–526, doi:10.1175/JCLI-D-12-00579.1.

Garbrecht, J. D., M. A. Nearing, J. L. Steiner, X. J. Zhang, and M. H. Nichols, 2015: Can conservation trump impacts of climate change on soil erosion? An assessment from winter wheat cropland in the southern Great Plains of the United States. *Wea. Climate Extremes*, **10**, 32–39, doi:10.1016/j.wace.2015.06.002.

Garcia, R. A., M. Cabeza, C. Rahbek, and M. B. Araújo, 2014: Multiple dimensions of climate change and their implications for biodiversity. *Science*, **344**, 486–497, doi:10.1126/science.1247579.

Georgescu, M., A. Mahalov, and M. Moustaoui, 2012: Seasonal hydroclimatic impacts of Sun Corridor expansion. *Environ. Res. Lett.*, **7**, 034026, doi:10.1088/1748-9326/7/3/034026.

——, M. Moustaoui, A. Mahalov, and J. Dudhia, 2013: Summer-time climate impacts of projected megapolitan expansion in Arizona. *Nat. Climate Change*, **3**, 37–41, doi:10.1038/nclimate1656.

Giorgi, F., E. S. Im, E. Coppola, N. S. Diffenbaugh, X. J. Gao, L. Mariotti, and Y. Shi, 2011: Higher hydroclimatic intensity with global warming. *J. Climate*, **24**, 5309–5324, doi:10.1175/2011JCLI3979.1.

Goldstein, A. H., and I. E. Galbally, 2007: Known and unexplored organic constituents in the Earth's atmosphere. *Environ. Sci. Technol.*, **41**, 1514–1521, doi:10.1021/es072476p.

Gong, W., H. V. Gupta, D. Yang, K. Sricharan, and A. O. Hero, 2013: Estimating epistemic and aleatory uncertainties during hydrologic modeling: An information theoretic approach. *Water Resour. Res.*, **49**, 2253–2273, doi:10.1002/wrcr.20161.

Gonzalez, A., O. Ronce, R. Ferriere, and M. E. Hochberg, 2013: Evolutionary rescue: An emerging focus at the intersection between ecology and evolution. *Philos. Trans. Roy. Soc. London*, **B368**, 20120404, doi:10.1098/rstb.2012.0404.

Gough, C. M., P. S. Curtis, B. S. Hardiman, C. M. Scheuermann, and B. Bond-Lamberty, 2016: Disturbance, complexity, and succession of net ecosystem production in North America's temperate deciduous forests. *Ecosphere*, **7**, e01375, doi:10.1002/ecs2.1375.

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs, 2008: Global change and the ecology of cities. *Science*, **319**, 756–760, doi:10.1126/science.1150195.

Guenther, A., T. Karl, P. Harley, C. Wiedinmyer, P. Palmer, and C. Geron, 2006: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmos. Chem. Phys. Discuss.*, **6**, 107–173, doi:10.5194/acpd-6-107-2006.

Gupta, H. V., and G. S. Nearing, 2014: Debates—The future of hydrological sciences: A (common) path forward? Using models and data to learn: A systems theoretic perspective on the future of hydrological science. *Water Resour. Res.*, **50**, 5351–5359, doi:10.1002/2013WR015096.

——, M. P. Clark, J. A. Vrugt, G. Abramowitz, and M. Ye, 2012: Towards a comprehensive assessment of model structural adequacy. *Water Resour. Res.*, **48**, W08301, doi:10.1029/2011WR011044.

Gurney, K. R., I. Razlivanov, Y. Song, Y. Zhou, B. Benes, and M. Abdul-Massih, 2012: Quantification of fossil fuel $CO_2$ emissions on the building/street scale for a large U.S. city. *Environ. Sci. Technol.*, **46**, 12 194–12 202, doi:10.1021/es3011282.

Hallquist, M., and Coauthors, 2009: The formation, properties and impact of secondary organic aerosol: Current and emerging issues. *Atmos. Chem. Phys.*, **9**, 5155–5236, doi:10.5194/acp-9-5155-2009.

Hamrick, J. L., 2004: Response of forest trees to global environmental changes. *For. Ecol. Manage.*, **197**, 323–335, doi:10.1016/j.foreco.2004.05.023.

Hargreaves, M. W., 1976: Land-use planning in response to drought: The experience of the thirties. *Agric. Hist.*, **50**, 561–582. [Available online at http://www.jstor.org/stable/3741302.]

Harmon, M. E., B. Bond-Lamberty, J. Tang, and R. Vargas, 2011: Heterotrophic respiration in disturbed forests: A review with examples from North America. *J. Geophys. Res.*, **116**, G00K04, doi:10.1029/2010JG001495.

Hashimoto, S., N. Carvalhais, A. Ito, M. Migliavacca, K. Nishina, and M. Reichstein, 2015: Global spatiotemporal distribution of soil respiration modeled using a global database. *Biogeosciences*, **12**, 4121–4132, doi:10.5194/bg-12-4121-2015.

Hasler, N., D. Werth, and R. Avissar, 2009: Effects of tropical deforestation on global hydroclimate: A multimodel ensemble analysis. *J. Climate*, **22**, 1124–1141, doi:10.1175/2008JCLI2157.1.

Hatfield, J., and C. L. Walthall, 2015: Meeting global food needs: Realizing the potential via genetics × environment × management interactions. *Agron. J.*, **107**, 1215–1226, doi:10.2134/agronj15.0076.

——, G. Takle, R. Grotjahn, P. Holden, R. C. Izaurralde, T. Mader, E. Marshall, and D. Liverman, 2014: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 150–174.

Hayhoe, K., and Coauthors, 2007: Past and future changes in climate and hydrological indicators in the US Northeast. *Climate Dyn.*, **28**, 381–407, doi:10.1007/s00382-006-0187-8.

Heald, C. L., and D. V. Spracklen, 2015: Land use change impacts on air quality and climate. *Chem. Rev.*, **115**, 4476–4496, doi:10.1021/cr500446g.

Held, I. M., and B. J. Soden, 2000: Water vapor feedback and global warming. *Annu. Rev. Energy Environ.*, **25**, 441–475, doi:10.1146/annurev.energy.25.1.441.

Henderson-Sellers, A., R. E. Dickinson, T. Durbidge, P. Kennedy, K. McGuffie, and A. Pitman, 1993: Tropical deforestation: Modeling local-to regional-scale climate change. *J. Geophys. Res.*, **98**, 7289–7315, doi:10.1029/92JD02830.

Henze, D., J. Seinfeld, N. Ng, J. Kroll, T.-M. Fu, D. J. Jacob, and C. Heald, 2008: Global modeling of secondary organic aerosol formation from aromatic hydrocarbons: High- vs. low-yield pathways. *Atmos. Chem. Phys.*, **8**, 2405–2420, doi:10.5194/acp-8-2405-2008.

Herbert, D. A., M. Williams, and E. B. Rastetter, 2003: A model analysis of N and P limitation on carbon accumulation in Amazonian secondary forest after alternate land-use abandonment. *Biogeochemistry*, **65**, 121–150, doi:10.1023/A:1026020210887.

Hewitson, B., and Coauthors, 2014: Regional context. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*, V. R. Barros et al., Eds., Cambridge University Press, 1133–1197.

Hijioka, Y., Y. Matsuoka, H. Nishimoto, T. Masui, and M. Kainuma, 2008: Global GHG emission scenarios under GHG concentration stabilization targets. *J. Global Environ. Eng.*, **13**, 97–108.

Hiranuma, N., S. D. Brooks, D. C. Thornton, and B. W. Auvermann, 2010: Atmospheric ammonia mixing ratios at an open-air cattle feeding facility. *J. Air Waste Manag. Assoc.*, **60**, 210–218, doi:10.3155/1047-3289.60.2.210.

——, S. Brooks, J. Gramann, and B. Auvermann, 2011: High concentrations of coarse particles emitted from a cattle feeding operation. *Atmos. Chem. Phys.*, **11**, 8809–8823, doi:10.5194/acp-11-8809-2011.

Holland, E. A., F. J. Dentener, B. H. Braswell, and J. M. Sulzman, 1999: Contemporary and pre-industrial global reactive nitrogen budgets. *New Perspectives on Nitrogen Cycling in the Temperate and Tropical Americas*, A. R. Townsend, Springer, 7–43.

Hossain, F., A. M. Degu, W. Yigzaw, S. Burian, D. Niyogi, J. M. Shepherd, and R. Pielke Sr., 2012: Climate feedback–based provisions for dam design, operations, and water management in the 21st century. *J. Hydrol. Eng.*, **17**, 837–850, doi:10.1061/(ASCE)HE.1943-5584.0000541.

Hungate, B. A., and Coauthors, 2006: Nitrogen cycling during seven years of atmospheric $CO_2$ enrichment in a scrub oak woodland. *Ecology*, **87**, 26–40, doi:10.1890/04-1732.

Huntington, T. G., 2006: Evidence for intensification of the global water cycle: Review and synthesis. *J. Hydrol.*, **319**, 83–95, doi:10.1016/j.jhydrol.2005.07.003.

Huntzinger, D., and Coauthors, 2012: North American Carbon Program (NACP) regional interim synthesis: Terrestrial biospheric model intercomparison. *Ecol. Modell.*, **232**, 144–157, doi:10.1016/j.ecolmodel.2012.02.004.

Hurtt, G., and Coauthors, 2011: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, **109**, 117–161, doi:10.1007/s10584-011-0153-2.

Imhoff, M. L., P. Zhang, R. E. Wolfe, and L. Bounoua, 2010: Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sens. Environ.*, **114**, 504–513, doi:10.1016/j.rse.2009.10.008.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 1535 pp.

——, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. C. B. Field et al., Eds., Cambridge University Press, 1132 pp. [Available online at http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-PartA_FINAL.pdf.]

Iverson, L. R., A. M. Prasad, S. N. Matthews, and M. Peters, 2008: Estimating potential habitat for 134 eastern US tree species under six climate scenarios. *For. Ecol. Manage.*, **254**, 390–406, doi:10.1016/j.foreco.2007.07.023.

Jackson, T. L., J. J. Feddema, K. W. Oleson, G. B. Bonan, and J. T. Bauer, 2010: Parameterization of urban characteristics for global climate modeling. *Ann. Assoc. Amer. Geogr.*, **100**, 848–865, doi:10.1080/00045608.2010.497328.

Jacobson, M. Z., and J. E. Ten Hoeve, 2012: Effects of urban surfaces and white roofs on global and regional climate. *J. Climate*, **25**, 1028–1044, doi:10.1175/JCLI-D-11-00032.1.

Jochner, S. C., T. H. Sparks, N. Estrella, and A. Menzel, 2012: The influence of altitude and urbanisation on trends and mean dates in phenology (1980–2009). *Int. J. Biometeor.*, **56**, 387–394, doi:10.1007/s00484-011-0444-3.

Jolly, W. M., M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and D. M. Bowman, 2015: Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun.*, **6**, 7537, doi:10.1038/ncomms8537.

Jones, C. G., 2012: Grand challenges for the future of ecological engineering. *Ecol. Eng.*, **45**, 80–84, doi:10.1016/j.ecoleng.2012.02.023.

Jones, H. P., D. G. Hole, and E. S. Zavaleta, 2012: Harnessing nature to help people adapt to climate change. *Nat. Climate Change*, **2**, 504–509, doi:10.1038/nclimate1463.

Kalnay, E., and M. Cai, 2003: Impact of urbanization and land-use change on climate. *Nature*, **423**, 528–531.

Kaplan, J. O., K. M. Krumhardt, and N. E. Zimmermann, 2012: The effects of land use and climate change on the carbon cycle of Europe over the past 500 years. *Global Change Biol.*, **18**, 902–914, doi:10.1111/j.1365-2486.2011.02580.x.

Keenan, T., J. Maria Serra, F. Lloret, M. Ninyerola, and S. Sabate, 2011: Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: $CO_2$ matters! *Global Change Biol.*, **17**, 565–579, doi:10.1111/j.1365-2486.2010.02254.x.

Kennedy, C., and Coauthors, 2009: Greenhouse gas emissions from global cities. *Environ. Sci. Technol.*, **43**, 7297–7302, doi:10.1021/es900213p.

——, S. Pincetl, and P. Bunje, 2011: The study of urban metabolism and its applications to urban planning and design. *Environ. Pollut.*, **159**, 1965–1973, doi:10.1016/j.envpol.2010.10.022.

Kim, H. M., P. J. Webster, and J. A. Curry, 2012: Evaluation of short-term climate change prediction in multi-model CMIP5 decadal hindcasts. *Geophys. Res. Lett.*, **39**, L10701, doi:10.1029/2012GL051644.

Klein Goldewijk, K., A. Beusen, G. van Drecht, and M. De Vos, 2011: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecol. Biogeogr.*, **20**, 73–86, doi:10.1111/j.1466-8238.2010.00587.x.

Knutti, R., and J. Sedláček, 2013: Robustness and uncertainties in the new CMIP5 climate model projections. *Nat. Climate Change*, **3**, 369–373, doi:10.1038/nclimate1716.

Kovats, R. S., and S. Hajat, 2008: Heat stress and public health: A critical review. *Annu. Rev. Public Health*, **29**, 41–55, doi:10.1146/annurev.publhealth.29.020907.090843.

Kramer, P. J., 1981: Carbon dioxide concentration, photosynthesis, and dry matter production. *BioScience*, **31**, 29–33, doi:10.2307/1308175.

Kravitz, B., and Coauthors, 2013: Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **118**, 8320–8332, doi:10.1002/jgrd.50646.

Krehbiel, C. P., T. Jackson, and G. M. Henebry, 2016: Web-enabled Landsat data time series for monitoring urban heat island impacts on land surface phenology. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, **9**, 2043–2050, doi:10.1109/JSTARS.2015.2496951.

Lal, R., 2004: Soil carbon sequestration impacts on global climate change and food security. *Science*, **304**, 1623–1627, doi:10.1126/science.1097396.

Lamhauge, N., E. Lanzi, and S. Agrawala, 2012: Monitoring and evaluation for adaptation: Lessons from development co-operation agencies. Organisation for Economic Co-operation and Development Environment Working Papers, 49 pp., doi:10.1787/5kg20mj6c2bw-en.

——, ——, and ——, 2013: The use of indicators for monitoring and evaluation of adaptation: lessons from development cooperation agencies. *Climate Dev.*, **5**, 229–241, doi:10.1080/17565529.2013.801824.

Lathière, J., C. Hewitt, and D. Beerling, 2010: Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric $CO_2$ concentration, climate, and land use. *Global Biogeochem. Cycles*, **24**, GB1004, doi:10.1029/2009GB003548.

Lawrence, P. J., and Coauthors, 2012: Simulating the biogeochemical and biogeophysical impacts of transient land cover change and wood harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *J. Climate*, **25**, 3071–3095, doi:10.1175/JCLI-D-11-00256.1.

Lemos, M. C., 2015: Usable climate knowledge for adaptive and co-managed water governance. *Curr. Opin. Environ. Sustainability*, **12**, 48–52, doi:10.1016/j.cosust.2014.09.005.

——, C. J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nat. Climate Change*, **2**, 789–794, doi:10.1038/nclimate1614.

Lenton, T. M., 2010: The potential for land-based biological $CO_2$ removal to lower future atmospheric $CO_2$ concentration. *Carbon Manage.*, **1**, 145–160, doi:10.4155/cmt.10.12.

Le Page, Y., D. Morton, B. Bond-Lamberty, J. Pereira, and G. Hurtt, 2015: HESFIRE: A global fire model to explore the role of anthropogenic and weather drivers. *Biogeosciences*, **12**, 887–903, doi:10.5194/bg-12-887-2015.

Le Quéré, C., and Coauthors, 2014a: Global carbon budget 2014. *Earth Syst. Sci. Data*, **7**, 47–85, doi:10.5194/essd-7-47-2015.

——, and Coauthors, 2014b: Global carbon budget 2013. *Earth Syst. Sci. Data*, **6**, 235–263, doi:10.5194/essd-6-235-2014.

——, and Coauthors, 2015: Global carbon budget 2015. *Earth Syst. Sci. Data*, **7**, 349–396, doi:10.5194/essd-7-349-2015.

Lesnikowski, A. C., J. D. Ford, L. Berrang-Ford, M. Barrera, and J. Heymann, 2015: How are we adapting to climate change? A global assessment. *Mitigation Adapt. Strategies Global Change*, **20**, 277–293, doi:10.1007/s11027-013-9491-x.

Liu, S., and Coauthors, 2011: Simulating the impacts of disturbances on forest carbon cycling in North America: Processes, data, models, and challenges. *J. Geophys. Res.*, **116**, G00K08, doi:10.1029/2010JG001585.

Lo, M. H., and J. S. Famiglietti, 2013: Irrigation in California's Central Valley strengthens the southwestern U.S. water cycle. *Geophys. Res. Lett.*, **40**, 301–306, doi:10.1002/grl.50108.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly, 2009: The velocity of climate change. *Nature*, **462**, 1052–1055, doi:10.1038/nature08649.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333**, 616–620, doi:10.1126/science.1204531.

Lorenz, R., A. Pitman, and S. Sisson, 2016: Does Amazonian deforestation cause global effects; can we be sure? *J. Geophys. Res. Atmos.*, **121**, 5567–5584, doi:10.1002/2015JD024357.

Lubowski, R. N., S. Bucholtz, R. Claassen, M. J. Roberts, J. C. Cooper, A. Gueorguieva, and R. Johansson, 2006: Environmental effects of agricultural land-use change: The role of economics and policy. U.S. Department of Agriculture, Economic Research Service Economic Research Rep. 25, 82 pp.

Luo, Y., and Coauthors, 2004: Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. *BioScience*, **54**, 731–739, doi:10.1641/0006-3568(2004)054[0731:PNLOER]2.0.CO;2.

Luyssaert, S., and Coauthors, 2007: $CO_2$ balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biol.*, **13**, 2509–2537, doi:10.1111/j.1365-2486.2007.01439.x.

Lyons, T., 2002: Clouds form preferentially over native vegetation. *First Int. Congress on Environmental Modelling and Software*, Lugano, Switzerland, International Environmental Modelling and Software Society, 355–359. [Available online at http://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=3685&context=iemssconference.]

——, P. Schwerdtfeger, J. Hacker, I. Foster, R. Smith, and H. Xinmei, 1993: Land–atmosphere interaction in a semiarid region: The bunny fence experiment. *Bull. Amer. Meteor. Soc.*, **74**, 1327–1334, doi:10.1175/1520-0477(1993)074<1327:LIIASR>2.0.CO;2.

Ma, P.-L., and Coauthors, 2015: How does increasing horizontal resolution in a global climate model improve the simulation of aerosol-cloud interactions? *Geophys. Res. Lett.*, **42**, 5058–5065, doi:10.1002/2015GL064183.

Magnan, A., T. Ribera, and S. Treyer, 2015: National adaptation is also a global concern. IDDRI Working Paper 4/5, 16 pp. [Available online at http://www.iddri.org/Publications/National-adaptation-is-also-a-global-concern.]

Mahmood, R., and Coauthors, 2014: Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.*, **34**, 929–953, doi:10.1002/joc.3736.

Mahowald, N., and L. M. Kiehl, 2003: Mineral aerosol and cloud interactions. *Geophys. Res. Lett.*, **30**, 1475, doi:10.1029/2002GL016762.

——, and Coauthors, 2011: Aerosol impacts on climate and biogeochemistry. *Annu. Rev. Environ. Resour.*, **36**, 45–74, doi:10.1146/annurev-environ-042009-094507.

Marvel, K., and C. Bonfils, 2013: Identifying external influences on global precipitation. *Proc. Natl. Acad. Sci. USA*, **110**, 19 301–19 306, doi:10.1073/pnas.1314382110.

McKain, K., and Coauthors, 2015: Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *Proc. Natl. Acad. Sci. USA*, **112**, 1941–1946, doi:10.1073/pnas.1416261112.

McKenney, D. W., J. H. Pedlar, R. B. Rood, and D. Price, 2011: Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models. *Global Change Biol.*, **17**, 2720–2730, doi:10.1111/j.1365-2486.2011.02413.x.

Medlyn, B. E., and Coauthors, 2015a: Using ecosystem experiments to improve vegetation models. *Nat. Climate Change*, **5**, 528–534, doi:10.1038/nclimate2621.

——, and Coauthors, 2015b: Using ecosystem experiments to improve vegetation models. *Nat. Climate Change*, **5**, 528–534, doi:10.1038/nclimate2621.

Medvigy, D., R. L. Walko, M. J. Otte, and R. Avissar, 2013: Simulated changes in Northwest U.S. climate in response to Amazon deforestation. *J. Climate*, **26**, 9115–9136, doi:10.1175/JCLI-D-12-00775.1.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. Mitchell, 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.*, **88**, 1383–1394, doi:10.1175/BAMS-88-9-1383.

Melaas, E. K., M. A. Friedl, and Z. Zhu, 2013: Detecting interannual variation in deciduous broadleaf forest phenology using Landsat TM/ETM+ data. *Remote Sens. Environ.*, **132**, 176–185, doi:10.1016/j.rse.2013.01.011.

Melillo, J. M., 2002: Soil warming and carbon-cycle feedbacks to the climate system. *Science*, **298**, 2173–2176, doi:10.1126/science.1074153.

Mendoza, P. A., M. P. Clark, M. Barlage, B. Rajagopalan, L. Samaniego, G. Abramowitz, and H. Gupta, 2015: Are we unnecessarily constraining the agility of complex process-based models? *Water Resour. Res.*, **51**, 716–728, doi:10.1002/2014WR015820.

Messina, J., T. Evans, S. Manson, A. Shortridge, P. Deadman, and P. Verburg, 2008: Complex systems models and the management of error and uncertainty. *J. Land Use Sci.*, **3**, 11–25, doi:10.1080/17474230802047989.

Meyfroidt, P., E. F. Lambin, K.-H. Erb, and T. W. Hertel, 2013: Globalization of land use: Distant drivers of land change and geographic displacement of land use. *Curr. Opin. Environ. Sustainability*, **5**, 438–444, doi:10.1016/j.cosust.2013.04.003.

Milly, P. C. D., and K. A. Dunne, 1994: Sensitivity of the global water cycle to the water-holding capacity of land. *J. Climate*, **7**, 506–526, doi:10.1175/1520-0442(1994)007<0506:SOTGWC>2.0.CO;2.

Mishra, V., F. Dominguez, and D. P. Lettenmaier, 2012: Urban precipitation extremes: How reliable are regional climate models? *Geophys. Res. Lett.*, **39**, L03407, doi:10.1029/2011GL050658.

Moreira, E., S. Costa, A. P. Aguiar, G. Câmara, and T. Carneiro, 2009: Dynamical coupling of multiscale land change models. *Landscape Ecol.*, **24**, 1183–1194, doi:10.1007/s10980-009-9397-x.

Moss, R. H., and Coauthors, 2013: Hell and high water: Practice-relevant adaptation science. *Science*, **342**, 696–698, doi:10.1126/science.1239569.

Murray, B., and Coauthors, 2005: Greenhouse gas mitigation potential in U.S. forestry and agriculture. Environmental Protection Agency Rep. EPA 430-R-05-006, 154 pp.

Myhre, G., and Coauthors, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 659–740.

——, O. Boucher, F.-M. Bréon, P. Forster, and D. Shindell, 2015: Declining uncertainty in transient climate response as $CO_2$ forcing dominates future climate change. *Nat. Geosci.*, **8**, 181–185, doi:10.1038/ngeo2371.

Nassar, R., L. Napier-Linton, K. R. Gurney, R. J. Andres, T. Oda, F. R. Vogel, and F. Deng, 2013: Improving the temporal and spatial distribution of $CO_2$ emissions from global fossil fuel emission data sets. *J. Geophys. Res. Atmos.*, **118**, 917–933, doi:10.1029/2012JD018196.

Nearing, M., 2001: Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. *J. Soil Water Conserv.*, **56**, 229–232.

——, F. Pruski, and M. O'Neal, 2004: Expected climate change impacts on soil erosion rates: A review. *J. Soil Water Conserv.*, **59**, 43–50.

Nelson, G. C., and Coauthors, 2014: Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. USA*, **111**, 3274–3279, doi:10.1073/pnas.1222465110.

Nie, M., M. Lu, J. Bell, S. Raut, and E. Pendall, 2013: Altered root traits due to elevated $CO_2$: A meta-analysis. *Global Ecol. Biogeogr.*, **22**, 1095–1105, doi:10.1111/geb.12062.

Niyogi, D., P. Pyle, M. Lei, S. P. Arya, C. M. Kishtawal, M. Shepherd, F. Chen, and B. Wolfe, 2011: Urban modification of thunderstorms: An observational storm climatology and model case study for the Indianapolis urban region. *J. Appl. Meteor. Climatol.*, **50**, 1129–1144, doi:10.1175/2010JAMC1836.1.

Nogues-Bravo, D., 2009: Predicting the past distribution of species climatic niches. *Global Ecol. Biogeogr.*, **18**, 521–531, doi:10.1111/j.1466-8238.2009.00476.x.

Norby, R. J., and Y. Luo, 2004: Evaluating ecosystem responses to rising atmospheric $CO_2$ and global warming in a multi-factor world. *New Phytol.*, **162**, 281–293, doi:10.1111/j.1469-8137.2004.01047.x.

——, and C. M. Iversen, 2006: Nitrogen uptake, distribution, turnover, and efficiency of use in a $CO_2$-enriched sweetgum forest. *Ecology*, **87**, 5–14, doi:10.1890/04-1950.

——, and D. R. Zak, 2011: Ecological lessons from free-air $CO_2$ enrichment (FACE) experiments. *Annu. Rev. Ecol. Evol. Syst.*, **42**, 181–203, doi:10.1146/annurev-ecolsys-102209-144647.

——, J. M. Warren, C. M. Iversen, B. E. Medlyn, and R. E. McMurtrie, 2010: $CO_2$ enhancement of forest productivity constrained by limited nitrogen availability. *Proc. Natl. Acad. Sci. USA*, **107**, 19 368–19 373, doi:10.1073/pnas.1006463107.

——, and Coauthors, 2016: Model–data synthesis for the next generation of forest free-air $CO_2$ enrichment (FACE) experiments. *New Phytol.*, **209**, 17–28, doi:10.1111/nph.13593.

Oke, T. R., 1987: *Boundary Layer Climates.* Methuen, 435 pp.

Oreskes, N., K. Shrader-Frechette, and K. Belitz, 1994: Verification, validation, and confirmation of numerical models in the earth sciences. *Science*, **263**, 641–646, doi:10.1126/science.263.5147.641.

Page, S. E., F. Siegert, J. O. Rieley, H.-D. V. Boehm, A. Jaya, and S. Limin, 2002: The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**, 61–65, doi:10.1038/nature01131.

Pan, Y., and Coauthors, 2011: A large and persistent carbon sink in the world's forests. *Science*, **333**, 988–993, doi:10.1126/science.1201609.

Pataki, D. E., P. C. Emmi, C. B. Forster, J. I. Mills, E. R. Pardyjak, T. R. Peterson, J. D. Thompson, and E. Dudley-Murphy, 2009: An integrated approach to improving fossil fuel emissions scenarios with urban ecosystem studies. *Ecol. Complex.*, **6**, 1–14, doi:10.1016/j.ecocom.2008.09.003.

Pearson, R. G., 2006: Climate change and the migration capacity of species. *Trends Ecol. Evol.*, **21**, 111–113, doi:10.1016/j.tree.2005.11.022.

Pechony, O., and D. Shindell, 2009: Fire parameterization on a global scale. *J. Geophys. Res.*, **114**, D16115, doi:10.1029/2009JD011927.

——, and D. T. Shindell, 2010: Driving forces of global wildfires over the past millennium and the forthcoming century. *Proc. Natl. Acad. Sci. USA*, **107**, 19 167–19 170, doi:10.1073/pnas.1003669107.

Peng, S., and Coauthors, 2004: Rice yields decline with higher night temperature from global warming. *Proc. Natl. Acad. Sci. USA*, **101**, 9971–9975, doi:10.1073/pnas.0403720101.

Pielke, R. A., J. Adegoke, A. Beltran-Przekurat, C. A. Hiemstra, J. Lin, U. S. Nair, D. Niyogi, and T. E. Nobis, 2007: An overview of regional land-use and land-cover impacts on rainfall. *Tellus*, **59B**, 587–601, doi:10.1111/j.1600-0889.2007.00251.x.

——, and Coauthors, 2011: Land use/land cover changes and climate: Modeling analysis and observational evidence. *Wiley Interdiscip. Rev.: Climate Change*, **2**, 828–850, doi:10.1002/wcc.144.

Pierce, L. L., J. Walker, T. I. Dowling, T. R. McVicar, T. J. Hatton, S. W. Running, and J. C. Coughlan, 1993: Ecohydrological changes in the Murray-Darling Basin. III. A simulation of regional hydrological changes. *J. Appl. Ecol.*, **30**, 283–294, doi:10.2307/2404630.

Pitman, A., and Coauthors, 2009: Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophys. Res. Lett.*, **36**, L14814, doi:10.1029/2009GL039076.

——, F. Avila, G. Abramowitz, Y. Wang, S. Phipps, and N. de Noblet-Ducoudré, 2011: Importance of background climate in determining impact of land-cover change on regional climate. *Nat. Climate Change*, **1**, 472–475, doi:10.1038/nclimate1294.

Pongratz, J., C. Reick, T. Raddatz, and M. Claussen, 2010: Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change. *Geophys. Res. Lett.*, **37**, L08702, doi:10.1029/2010GL043010.

——, ——, R. Houghton, and J. House, 2013: Terminology as a key uncertainty in net land use flux estimates. *Earth Syst. Dyn.*, **5**, 177–195, doi:10.5194/esd-5-177-2014.

Popp, A., H. Lotze-Campen, and B. Bodirsky, 2010: Food consumption, diet shifts and associated non-$CO_2$ greenhouse gases from agricultural production. *Global Environ. Change*, **20**, 451–462, doi:10.1016/j.gloenvcha.2010.02.001.

Porter, J. R., L. Xie, A. J. Challinor, K. Cochrane, S. M. Howden, M. M. Iqbal, D. B. Lobell, and M. I. Travasso, 2014: Food security and food production systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, C. B. Field et al., Eds., Cambridge University Press, 485–533.

Preston, B. L., L. Rickards, and H. Fungeld, 2015: Towards reflexive climate adaptation research. *Curr. Opin. Environ. Sustainability*, **14**, 127–135, doi:10.1016/j.cosust.2015.05.002.

Puma, M., and B. Cook, 2010: Effects of irrigation on global climate during the 20th century. *J. Geophys. Res.*, **115**, D16120, doi:10.1029/2010JD014122.

Radeloff, V. C., and Coauthors, 2012: Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. *Ecol. Appl.*, **22**, 1036–1049, doi:10.1890/11-0306.1.

Ramankutty, N., and J. A. Foley, 1999: Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem. Cycles*, **13**, 997–1027, doi:10.1029/1999GB900046.

Ray, D. K., N. D. Mueller, P. C. West, and J. A. Foley, 2013: Yield trends are insufficient to double global crop production by 2050. *PLoS One*, **8**, e66428, doi:10.1371/journal.pone.0066428.

Reay, D. S., E. A. Davidson, K. A. Smith, P. Smith, J. M. Melillo, F. Dentener, and P. J. Crutzen, 2012: Global agriculture and nitrous oxide emissions. *Nat. Climate Change*, **2**, 410–416, doi:10.1038/nclimate1458.

Reed, S. C., X. Yang, and P. E. Thornton, 2015: Incorporating phosphorus cycling into global modeling efforts: A worthwhile, tractable endeavor. *New Phytol.*, **208**, 324–329, doi:10.1111/nph.13521.

Riahi, K., A. Grübler, and N. Nakicenovic, 2007: Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecasting Soc. Change*, **74**, 887–935, doi:10.1016/j.techfore.2006.05.026.

Richter, A., J. P. Burrows, H. Nuss, C. Granier, and U. Niemeier, 2005: Increase in tropospheric nitrogen dioxide over China observed from space. *Nature*, **437**, 129–132, doi:10.1038/nature04092.

Rindfuss, R. R., and Coauthors, 2008: Land use change: Complexity and comparisons. *J. Land Use Sci.*, **3**, 1–10, doi:10.1080/17474230802047955.

Rose, D. C., 2014: Commentary: Five ways to enhance the impact of climate science. *Nat. Climate Change*, **4**, 522–524, doi:10.1038/nclimate2270.

Rosenzweig, C., and Coauthors, 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci. USA*, **111**, 3268–3273, doi:10.1073/pnas.1222463110.

Rounsevell, M. D., and Coauthors, 2012: Challenges for land system science. *Land Use Policy*, **29**, 899–910, doi:10.1016/j.landusepol.2012.01.007.

Ryan, K. C., E. E. Knapp, and J. M. Varner, 2013: Prescribed fire in North American forests and woodlands: History, current practice, and challenges. *Front. Ecol. Environ*, **11**, e15–e24, doi:10.1890/120329.

Sakaguchi, K., X. Zeng, and M. A. Brunke, 2012: The hindcast skill of the CMIP ensembles for the surface air temperature trend. *J. Geophys. Res.*, **117**, D16113, doi:10.1029/2012JD017765.

Sampaio, G., C. Nobre, M. H. Costa, P. Satyamurty, B. S. Soares, and M. Cardoso, 2007: Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophys. Res. Lett.*, **34**, L17709, doi:10.1029/2007GL030612.

Scheffer, M., S. Carpenter, J. A. Foley, C. Folke, and B. Walker, 2001: Catastrophic shifts in ecosystems. *Nature*, **413**, 591–596, doi:10.1038/35098000.

Scheiter, S., L. Langan, and S. I. Higgins, 2013: Next-generation dynamic global vegetation models: Learning from community ecology. *New Phytol.*, **198**, 957–969, doi:10.1111/nph.12210.

Schimel, J., 2013: Soil carbon: Microbes and global carbon. *Nat. Climate Change*, **3**, 867–868, doi:10.1038/nclimate2015.

Schneck, R., and V. Mosbrugger, 2011: Simulated climate effects of Southeast Asian deforestation: Regional processes and teleconnection mechanisms. *J. Geophys. Res.*, **116**, D11116, doi:10.1029/2010JD015450.

Schwaiger, H. P., and D. N. Bird, 2010: Integration of albedo effects caused by land use change into the climate balance: Should we still account in greenhouse gas units? *For. Ecol. Manage.*, **260**, 278–286, doi:10.1016/j.foreco.2009.12.002.

Schwalm, C. R., and Coauthors, 2015a: How well do terrestrial biosphere models simulate coarse-scale runoff in the contiguous United States? *Ecol. Modell.*, **303**, 87–96, doi:10.1016/j.ecolmodel.2015.02.006.

——, and Coauthors, 2015b: Toward "optimal" integration of terrestrial biosphere models. *Geophys. Res. Lett.*, **42**, 4418–4428, doi:10.1002/2015GL064002.

Schwartz, M. D., J. L. Betancourt, and J. F. Weltzin, 2012: From Caprio's lilacs to the USA National Phenology Network. *Front. Ecol. Environ.*, **10**, 324–327, doi:10.1890/110281.

Searchinger, T., and Coauthors, 2008: Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240, doi:10.1126/science.1151861.

Seto, K. C., and P. Christensen, 2013: Remote sensing science to inform urban climate change mitigation strategies. *Urban Climate*, **3**, 1–6, doi:10.1016/j.uclim.2013.03.001.

Settele, J., R. Scholes, R. A. Betts, S. Bunn, P. Leadley, D. Nepstad, J. T. Overpeck, and M. A. Taboada, 2015: Terrestrial and inland water systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, C. B. Field et al., Eds., Cambridge University Press, 271–359.

Shepherd, J. M., 2005: A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interact.*, **9**, doi:10.1175/EI156.1.

Sleeter, B. M., and Coauthors, 2012: Scenarios of land use and land cover change in the conterminous United States: Utilizing the special report on emission scenarios at ecoregional scales. *Global Environ. Change*, **22**, 896–914, doi:10.1016/j.gloenvcha.2012.03.008.

Smit, B., and J. Wandel, 2006: Adaptation, adaptive capacity, and vulnerability. *Global Environ. Change*, **16**, 282–292, doi:10.1016/j.gloenvcha.2006.03.008.

Smith, K. A., A. R. Mosier, P. J. Crutzen, and W. Winiwarter, 2012a: The role of $N_2O$ derived from crop-based biofuels, and from agriculture in general, in Earth's climate. *Philos. Trans. Roy. Soc. London*, **B367**, 1169–1174, doi:10.1098/rstb.2011.0313.

Smith, P., and Coauthors, 2012b: Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: Current capability and future vision. *Global Change Biol.*, **18**, 2089–2101, doi:10.1111/j.1365-2486.2012.02689.x.

Smith, S. J., and T. Wigley, 2006: Multi-gas forcing stabilization with Minicam. *Energy J.*, 373–391. [Available online at http://www.jstor.org/stable/23297091.]

Snorek, J., F. G. Renaud, and J. Kloos, 2014: Divergent adaptation to climate variability: A case study of pastoral and agricultural societies in Niger. *Global Environ. Change*, **29**, 371–386, doi:10.1016/j.gloenvcha.2014.06.014.

Sohl, T. L., and P. R. Claggett, 2013: Clarity versus complexity: Land-use modeling as a practical tool for decision-makers. *J. Environ. Manage.*, **129**, 235–243, doi:10.1016/j.jenvman.2013.07.027.

——, T. R. Loveland, B. M. Sleeter, K. L. Sayler, and C. A. Barnes, 2010: Addressing foundational elements of regional land-use change forecasting. *Landscape Ecol.*, **25**, 233–247, doi:10.1007/s10980-009-9391-3.

——, and Coauthors, 2014: Spatially explicit modeling of 1992-2100 land cover and forest stand age for the conterminous United States. *Ecol. Appl.*, **24**, 1015–1036, doi:10.1890/13-1245.1.

Sokolik, I. N., and O. B. Toon, 1996: Direct radiative forcing by anthropogenic airborne mineral aerosols. *Nature*, **381**, 681–683, doi:10.1038/381681a0.

Sovacool, B., B. O. Linner, and M. E. Goodsite, 2015: The political economy of climate adaptation. *Nat. Climate Change*, **5**, 616–618, doi:10.1038/nclimate2665.

Spracklen, D., and C. L. Heald, 2014: The contribution of fungal spores and bacteria to regional and global aerosol number and ice nucleation immersion freezing rates. *Atmos. Chem. Phys.*, **14**, 9051–9059, doi:10.5194/acp-14-9051-2014.

——, S. Arnold, and C. Taylor, 2012: Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, **489**, 282–285, doi:10.1038/nature11390.

Steiner, A. L., S. D. Brooks, C. Deng, D. C. Thornton, M. W. Pendleton, and V. Bryant, 2015: Pollen as atmospheric cloud condensation nuclei. *Geophys. Res. Lett.*, **42**, 3596–3602, doi:10.1002/2015GL064060.

Steinkamp, J., and T. Hickler, 2015: Is drought-induced forest dieback globally increasing? *J. Ecol.*, **103**, 31–43, doi:10.1111/1365-2745.12335.

Stern, P. C., K. L. Ebi, R. Leichenko, R. S. Olson, J. D. Steinbruner, and R. Lempert, 2013: Managing risk with climate vulnerability science. *Nat. Climate Change*, **3**, 607–609, doi:10.1038/nclimate1929.

Stewart, I. D., and T. R. Oke, 2012: Local climate zones for urban temperature studies. *Bull. Amer. Meteor. Soc.*, **93**, 1879–1900, doi:10.1175/BAMS-D-11-00019.1.

Strengers, B., R. Leemans, B. Eickhout, B. de Vries, and L. Bouwman, 2004: The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. *GeoJournal*, **61**, 381–393, doi:10.1007/s10708-004-5054-8.

Sun, F., M. L. Roderick, and G. D. Farquhar, 2012: Changes in the variability of global land precipitation. *Geophys. Res. Lett.*, **39**, L19402, doi:10.1029/2012GL053369.

Supit, I., C. van Diepen, A. De Wit, P. Kabat, B. Baruth, and F. Ludwig, 2010: Recent changes in the climatic yield potential of various crops in Europe. *Agric. Syst.*, **103**, 683–694, doi:10.1016/j.agsy.2010.08.009.

Swart, R., R. Biesbroek, and T. C. Lourenco, 2014: Science of adaptation to climate change and science for adaptation. *Front. Environ. Sci.*, **2**, 29, doi:10.3389/fenvs.2014.00029.

Syed, T. H., J. S. Famiglietti, D. P. Chambers, J. K. Willis, and K. Hilburn, 2010: Satellite-based global-ocean mass balance estimates of interannual variability and emerging trends in continental freshwater discharge. *Proc. Natl. Acad. Sci. USA*, **107**, 17 916–17 921, doi:10.1073/pnas.1003292107.

Tao, F., M. Yokozawa, Y. Xu, Y. Hayashi, and Z. Zhang, 2006: Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agric. For. Meteor.*, **138**, 82–92, doi:10.1016/j.agrformet.2006.03.014.

Taylor, B. M., and R. R. J. McAllister, 2015: Editorial overview: Sustainability governance and transformation: Partnerships and sustainability governance: Progress, prospects and pitfalls. *Curr. Opin. Environ. Sustainability*, **12**, iv–vi, doi:10.1016/j.cosust.2014.12.003.

Taylor, C. M., R. A. de Jeu, F. Guichard, P. P. Harris, and W. A. Dorigo, 2012a: Afternoon rain more likely over drier soils. *Nature*, **489**, 423–426, doi:10.1038/nature11377.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012b: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Tegen, I., M. Werner, S. Harrison, and K. Kohfeld, 2004: Relative importance of climate and land use in determining present and future global soil dust emission. *Geophys. Res. Lett.*, **31**, L05105, doi:10.1029/2003GL019216.

Thuiller, W., and Coauthors, 2008: Predicting global change impacts on plant species' distributions: Future challenges. *Perspect. Plant Ecol. Evol. Syst.*, **9**, 137–152, doi:10.1016/j.ppees.2007.09.004.

Todd-Brown, K. E., F. M. Hopkins, S. N. Kivlin, J. M. Talbot, and S. D. Allison, 2012: A framework for representing microbial decomposition in coupled climate models. *Biogeochemistry*, **109**, 19–33, doi:10.1007/s10533-011-9635-6.

Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Res.*, **47**, 123–138, doi:10.3354/cr00953.

Tucker, J., M. Daoud, N. Oates, R. Few, D. Conway, S. Mtisi, and S. Matheson, 2015: Social vulnerability in three high-poverty climate change hot spots: What does the climate change literature tell us? *Reg. Environ. Change*, **15**, 783–800, doi:10.1007/s10113-014-0741-6.

Turner, B., and Coauthors, 2003: A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. USA*, **100**, 8074–8079, doi:10.1073/pnas.1231335100.

Tyukavina, A., and Coauthors, 2015: Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environ. Res. Lett.*, **10**, 074002, doi:10.1088/1748-9326/10/7/074002.

Unger, N., 2013: Isoprene emission variability through the twentieth century. *J. Geophys. Res. Atmos.*, **118**, 13 606–13 613, doi:10.1002/2013JD020978.

——, 2014: Human land-use-driven reduction of forest volatiles cools global climate. *Nat. Climate Change*, **4**, 907–910, doi:10.1038/nclimate2347.

UN Population Division, 2014: World urbanization prospects: The 2014 revision highlights. United Nations Rep. ST/ESA/SER.A/352, 32 pp.

van Asselen, S., and P. H. Verburg, 2012: A land system representation for global assessments and land-use modeling. *Global Change Biol.*, **18**, 3125–3148, doi:10.1111/j.1365-2486.2012.02759.x.

van Delden, H., and G. McDonald, 2010. Towards the integration of economic and land use change models. *Proc. iEMSs Fifth Biennial Meeting: Modelling for Environment's Sake*, Ottawa, Canada, International Environmental Modelling and Software Society, 1540–1548.

van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, P. S. Kasibhatla, and A. F. Arellano Jr., 2006: Interannual variability in global biomass burning emissions from 1997 to 2004. *Atmos. Chem. Phys.*, **6**, 3423–3441, doi:10.5194/acp-6-3423-2006.

——, and Coauthors, 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys.*, **10**, 11 707–11 735, doi:10.5194/acp-10-11707-2010.

van Groenigen, K.-J., J. Six, B. A. Hungate, M.-A. de Graaff, N. van Breemen, and C. van Kessel, 2006: Element interactions limit soil carbon storage. *Proc. Natl. Acad. Sci. USA*, **103**, 6571–6574, doi:10.1073/pnas.0509038103.

van Vuuren, D. P., M. G. Den Elzen, P. L. Lucas, B. Eickhout, B. J. Strengers, B. van Ruijven, S. Wonink, and R. van Houdt, 2007: Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, **81**, 119–159, doi:10.1007/s10584-006-9172-9.

——, and Coauthors, 2012: A comprehensive view on climate change: Coupling of Earth system and integrated assessment models. *Environ. Res. Lett.*, **7**, 024012, doi:10.1088/1748-9326/7/2/024012.

Verburg, P. H., P. P. Schot, M. J. Dijst, and A. Veldkamp, 2004: Land use change modelling: Current practice and research priorities. *GeoJournal*, **61**, 309–324, doi:10.1007/s10708-004-4946-y.

——, B. Eickhout, and H. van Meijl, 2008: A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *Ann. Reg. Sci.*, **42**, 57–77, doi:10.1007/s00168-007-0136-4.

——, A. Tabeau, and E. Hatna, 2013: Assessing spatial uncertainties of land allocation using a scenario approach and sensitivity analysis: A study for land use in Europe. *J. Environ. Manage.*, **127**, S132–S144, doi:10.1016/j.jenvman.2012.08.038.

Vörösmarty, C. J., C. Pahl-Wostl, S. E. Bunn, and R. Lawford, 2013: Global water, the Anthropocene and the transformation of a science. *Curr. Opin. Environ. Sustainability*, **5**, 539–550, doi:10.1016/j.cosust.2013.10.005.

Walker, A. P., and Coauthors, 2014: Comprehensive ecosystem model-data synthesis using multiple data sets at two temperate forest free-air $CO_2$ enrichment experiments: Model performance at ambient $CO_2$ concentration. *J. Geophys. Res. Biogeosci.*, **119**, 937–964, doi:10.1002/2013JG002553.

Walthall, C. L., and Coauthors, 2012: Climate change and agriculture in the United States: Effects and adaptation. USDA Tech. Bull. 1935, 193 pp.

Wang, B., S.-Y. Pan, R.-Y. Ke, K. Wang, and Y.-M. Wei, 2014: An overview of climate change vulnerability: A bibliometric analysis based on Web of Science database. *Nat. Hazards*, **74**, 1649–1666, doi:10.1007/s11069-014-1260-y.

Waters, C. N., and Coauthors, 2016: The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, **351**, doi:10.1126/science.aad2622.

Wei, Y., and Coauthors, 2013: The North American carbon program multi-scale synthesis and terrestrial model intercomparison project—Part 2: Environmental driver data. *Geosci. Model Dev.*, **7**, 2875–2893, doi:10.5194/gmd-7-2875-2014.

Wentz, F. J., L. Ricciardulli, K. Hilburn, and C. Mears, 2007: How much more rain will global warming bring? *Science*, **317**, 233–235, doi:10.1126/science.1140746.

West, T. O., Y. Le Page, M. Huang, J. Wolf, and A. M. Thomson, 2014: Downscaling global land cover projections from an integrated assessment model for use in regional analyses: Results and evaluation for the US from 2005 to 2095. *Environ. Res. Lett.*, **9**, 064004, doi:10.1088/1748-9326/9/6/064004.

Westerling, A. L., M. G. Turner, E. A. H. Smithwick, W. H. Romme, and M. G. Ryan, 2011: Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proc. Natl. Acad. Sci. USA*, **108**, 13 165–13 170, doi:10.1073/pnas.1110199108.

Wheeler, T., and J. von Braun, 2013: Climate change impacts on global food security. *Science*, **341**, 508–513, doi:10.1126/science.1239402.

Wieder, W. R., C. C. Cleveland, W. K. Smith, and K. Todd-Brown, 2015: Future productivity and carbon storage limited by terrestrial nutrient availability. *Nat. Geosci.*, **8**, 441–444, doi:10.1038/ngeo2413.

Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook, 2015: Contribution of anthropogenic warming to California drought during 2012-2014. *Geophys. Res. Lett.*, **42**, 6819–6828, doi:10.1002/2015GL064924.

Williams, M. I., and R. K. Dumroese, 2013: Preparing for climate change: Forestry and assisted migration. *J. For.*, **111**, 287–297, doi:10.5849/jof.13-016.

Wise, R. M., I. Fazey, M. S. Smith, S. E. Park, H. C. Eakin, E. R. M. A. Van Garderen, and B. Campbell, 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environ. Change*, **28**, 325–336, doi:10.1016/j.gloenvcha.2013.12.002.

Wu, Y., S. Liu, T. L. Sohl, and C. J. Young, 2013: Projecting the land cover change and its environmental impacts in the Cedar River basin in the Midwestern United States. *Environ. Res. Lett.*, **8**, 024025, doi:10.1088/1748-9326/8/2/024025.

Yang, X., P. E. Thornton, D. M. Ricciuto, and W. M. Post, 2014: The role of phosphorus dynamics in tropical forests—A modeling study using CLM-CNP. *Biogeosciences*, **11**, 1667–1681, doi:10.5194/bg-11-1667-2014.

Zaehle, S., and Coauthors, 2014a: Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperate free-air $CO_2$ enrichment studies. *New Phytol.*, **202**, 803–822, doi:10.1111/nph.12697.

——, and Coauthors, 2014b: Evaluation of 11 terrestrial carbon–nitrogen cycle models against observations from two temperate free-air $CO_2$ enrichment studies. *New Phytol.*, **202**, 803–822, doi:10.1111/nph.12697.

Zemp, D., C.-F. Schleussner, H. Barbosa, R. van der Ent, J. F. Donges, J. Heinke, G. Sampaio, and A. Rammig, 2014: On the importance of cascading moisture recycling in South America. *Atmos. Chem. Phys.*, **14**, 13 337–13 359, doi:10.5194/acp-14-13337-2014.

Zhang, L., and Coauthors, 2012: Nitrogen deposition to the United States: Distribution, sources, and processes. *Atmos. Chem. Phys.*, **12**, 4539–4554, doi:10.5194/acp-12-4539-2012.

Zhang, R., and Coauthors, 2015: Formation of urban fine particulate matter. *Chem. Rev.*, **115**, 3803–3855, doi:10.1021/acs.chemrev.5b00067.

Zhang, Z., P. Wang, Y. Chen, X. Song, X. Wei, and P. Shi, 2014: Global warming over 1960–2009 did increase heat stress and reduce cold stress in the major rice-planting areas across China. *Eur. J. Agron.*, **59**, 49–56, doi:10.1016/j.eja.2014.05.008.

——, X. Song, F. Tao, S. Zhang, and W. Shi, 2016: Climate trends and crop production in China at county scale, 1980 to 2008. *Theor. Appl. Climatol.*, **123**, 291–302, doi:10.1007/s00704-014-1343-4.

Zhao, S., and S. Liu, 2014: Scale criticality in estimating ecosystem carbon dynamics. *Global Change Biol.*, **20**, 2240–2251, doi:10.1111/gcb.12496.

——, ——, Z. Li, and T. Sohl, 2009: Ignoring detailed fast-changing dynamics of land use overestimates regional terrestrial carbon sequestration. *Biogeosciences*, **6**, 1647–1654, doi:10.5194/bg-6-1647-2009.

——, ——, and D. Zhou, 2016: Prevalent vegetation growth enhancement in urban environment. *Proc. Natl. Acad. Sci. USA*, **113**, 6313–6318, doi:10.1073/pnas.1602312113.

Zhou, D., S. Zhao, S. Liu, L. Zhang, and C. Zhu, 2014: Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. *Remote Sens. Environ.*, **152**, 51–61, doi:10.1016/j.rse.2014.05.017.

——, ——, L. Zhang, and S. Liu, 2016: Remotely sensed assessment of urbanization effects on vegetation phenology in China's 32 major cities. *Remote Sens. Environ.*, **176**, 272–281, doi:10.1016/j.rse.2016.02.010.

Zhu, K., C. W. Woodall, and J. S. Clark, 2012: Failure to migrate: Lack of tree range expansion in response to climate change. *Global Change Biol.*, **18**, 1042–1052, doi:10.1111/j.1365-2486.2011.02571.x.

Zscheischler, J., and Coauthors, 2014: Impact of large-scale climate extremes on biospheric carbon fluxes: An intercomparison based on MsTMIP data. *Global Biogeochem. Cycles*, **28**, 585–600, doi:10.1002/2014GB004826.