Advanced Review

The climate–wildfire–air quality system: interactions and feedbacks across spatial and temporal scales

E. Natasha Stavros,[1,*] Donald McKenzie[2] and Narasimhan Larkin[2]

Future climate change and its effects on social and ecological systems present challenges for preserving valued ecosystem services, including local and regional air quality. Wildfire is a major source of air-quality impact in some locations, and a substantial contributor to pollutants of concern, including nitrogen oxides and particulate matter, which are regulated to protect public and environmental health. Since climate change is expected to increase total area burned by wildfire and wildfires affect air quality, which is regulated, there is a need to define and study climate, wildfire, and air quality as one system. We review interactions and feedbacks acting across space and time within the climate–wildfire–air quality system, providing a foundation for integrated modeling and for assessing the ecological and social impacts of this system and its broader ecological, social, and scientific implications. © 2014 John Wiley & Sons, Ltd.

How to cite this article:
WIREs Clim Change 2014. doi: 10.1002/wcc.303

INTRODUCTION

Many studies have shown warming temperatures and longer periods of drought will increase area burned by wildfire in North America.[1–3] Increased area burned will likely mean more fuel consumed and emissions produced. The latter contribute a positive feedback to greenhouse warming from greenhouse gases (GHGs) and both positive and negative feedbacks from aerosols.[4] From here forward, the term feedback is used when component A affects B, and B then affects A, whereas feedback loop refers to the bidirectional effect of A and B on one another such that A affects B concurrent to B affecting A.

Studying these types of feedbacks within the environment requires merging multiple scientific disciplines at multiple scales across space and time. Studies have focused on separate components of this system independently, but few have integrated the components,[5–8] and often this integration is solely in one direction without completing the feedback loop (i.e., how climate affects air quality degradation from wildfires and not how degraded air quality from wildfires affects climate). Existing research focuses mainly at characteristic spatial and temporal scales of understanding, e.g., how climate affects wildfire,[9] how wildfire affects air quality,[10–13] or how wildfire affects climate,[14] but does not incorporate cross-scale analysis necessary for quantifying feedbacks and interactions among system components (Figure 1).

Here we synthesize the latest research on climate, wildfire, and air quality to define interactions and feedbacks and propose a cross-scale approach to studying the system as a whole. We seek to identify the appropriate spatial and temporal domains for modeling the feedback loops between climate, wildfire, and air quality. We briefly discuss a modeling framework useful for investigating the climate–wildfire–air quality system. Finally, we discuss broader ecological, social, and broader scientific implications of applying a systematic approach to studying climate, wildfire, and air quality.

*Correspondence to: Natasha.Stavros@jpl.nasa.gov

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

[2]Pacific Wildland Fire Sciences Laboratory, USDA Forest Service, University of Washington, Seattle, WA, USA

Conflict of interest: The authors have declared no conflicts of interest for this article.
California Institute of Technology. Government sponsorship acknowledged.

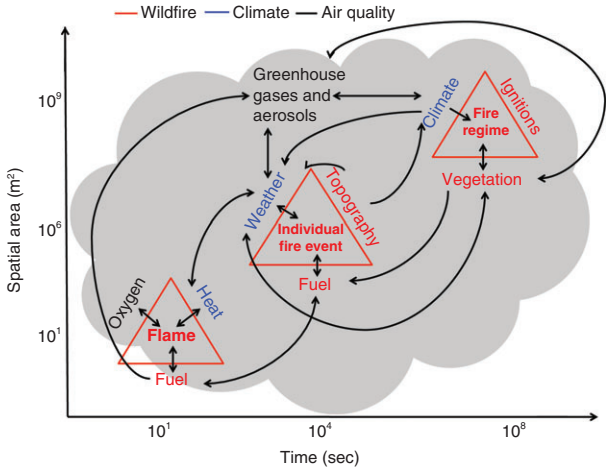

FIGURE 1 | Conceptual space–time diagram of the climate–wildfire–air quality system with components: air quality (black), climate (blue), and wildfire (red). This space–time diagrams have been modified with permission, to include the air quality and climate components, the feedback loops (double-pointed arrows), and effects (single-pointed arrows) of the climate–wildfire–air quality system across scales. (Reprinted with permission from Ref 12. Copyright 2005 National Academy of Sciences)

DEFINING THE SYSTEM: TERMINOLOGY

For discussion here, it is useful to define the terms needed to understand the climate–wildfire–air quality system (Figure 1). In the following discussion, components describe climate, wildfire, and air quality. Subcomponents are the terms in Figure 1 that are colored by each component and are defined below.

Climate describes daily, annual (e.g., seasons), and decadal (e.g., El Niño-Southern Oscillation or Pacific Decadal Oscillation) variation in *weather*, such as wind, rain, temperature, and relative humidity. A change in climate is defined as a long-term change in one or more of these variables. The term 'climate change' commonly applies to increasing global temperatures and changes in precipitation,[4] although the term can carry a broader meaning. Changes to temperature and precipitation can result from changes in radiative forcing, a metric of net energy balance within the Earth's system measured in watts per square meter.[4] Although radiative forcing is often used as a metric of climate change, it does not fully explain climate change.[15]

Wildfire is a cross-scale phenomenon (Figure 1).[16,17] At the finest temporal (seconds to hours) and spatial (10^{-3}–10^{3} m^2) scales, consider fire as the *flame*. To sustain combustion, a flame requires oxygen, fuel, and heat.[18] *Individual fire events* reside at intermediate temporal (days to months) and spatial (10^{4}–10^{8} m^2) scales, with fire behavior typically characterized in a triangle with legs for fuels, weather, and topography.[18] Each leg, and its interaction with the others, influences fire behavior. At broader spatial ($\geq 10^{9}$ m^2) and temporal (years to centuries) scales, wildfire can be characterized by the *fire regime*, which consists of many individual fire events over time and is defined by seven attributes[19]: fire frequency, seasonality, fireline intensity (the energy released), fire severity (effect of fire on biological and physical components of the system), fire type (e.g., crown fire, surface fire, ground fire), areal extent of fire perimeter, and spatial complexity (spatial variability of fire severity). These properties depend on interactions between climate, vegetation, and ignition source.[18]

At the broad scales associated with fire regimes—landscape (approximately 10^{6} m^2) to sub-continental—vegetation is aggregated into classes for modeling.[18] Ignition sources are either anthropogenic or natural (i.e., lightning). Anthropogenic ignitions are either by accident, arson, or a result of management. For example, in western North America, Native Americans burned the land for thousands of years to sustain food sources,[20,21] thereby altering fire regimes. Currently, managers use prescribed fire to reduce fuel loads, maintain ecological function, and control amount and seasonality of emissions.

Air quality is a measure or standard of the maximum acceptable pollutant concentrations in air. The air is composed of a 'cocktail' of compounds (e.g., oxygen and carbon dioxide); pollutants are enough of any one compound to have detrimental effects to both human and ecosystem health. The United States government has established national standards to regulate hazardous gases, some of which are greenhouse gases (GHGs), and others are aerosols. *GHGs* act as a blanket around the earth absorbing long-wave radiation and increasing global temperatures. *Aerosols* are solid or liquid microscopic particles dispersed in a gas.[22] An aerosol of particular concern for health is fine particulate matter (PM; see Section *Ecological, Social, and Scientific Implications*). Aerosols affect radiative forcing, and through changes in this process, climate. For example, aerosols can affect *albedo*, either through absorption of incoming short-wave radiation, and cloud formation and microphysical processes,[23] or more directly when deposited on snow and ice.[14]

INTERACTIONS AND FEEDBACKS

The feedback loop that defines the climate–wildfire–air quality system proceeds as follows: climate change caused by global warming from increased GHGs in the atmosphere increases annual

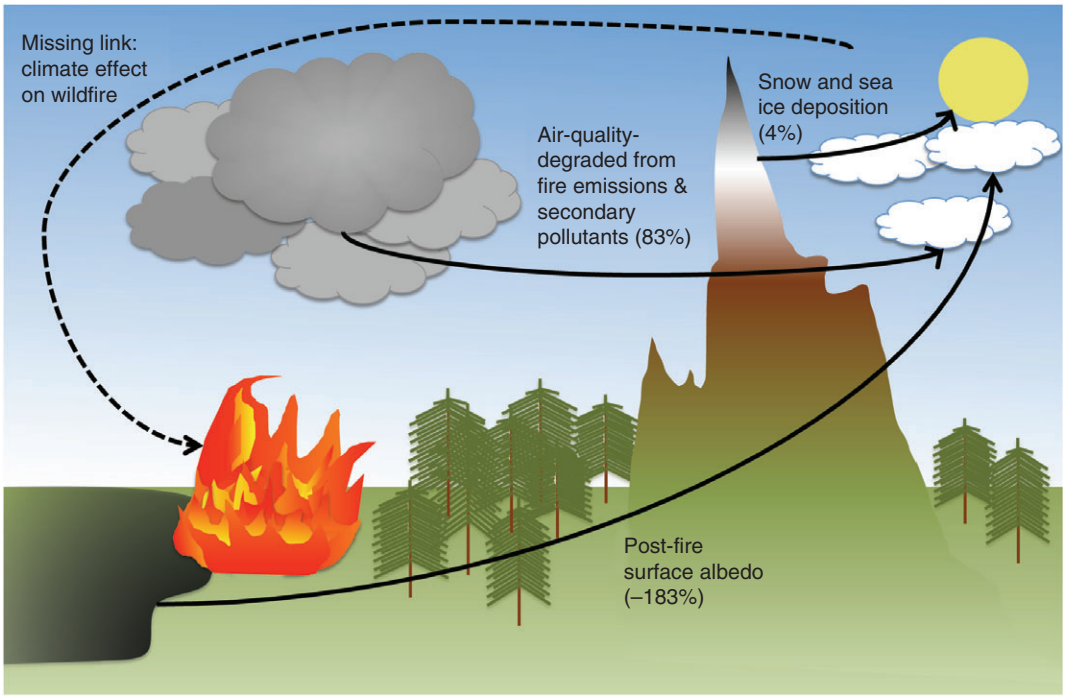

FIGURE 2 | Mean radiative forcing over an 80-year fire cycle in the boreal forest of interior Alaska.[14] Numbers are the percentage of total net radiative forcing from each component. Positive numbers represent increased forcing (i.e., positive feedback to climate change); negative numbers are decreased forcing. The dashed line represents the change in climatic forcing of fire regimes, thus closing the feedback loop.

wildfire area, which in turn affects the climate in many different ways (Figure 2). These include changes in the disturbance regime through vegetation shifts,[3,24,25] *albedo* changes due to surface changes within the fire perimeter,[26] and radiative and *albedo* feedbacks from increased emissions of GHGs and aerosols.[14,27] These effects feedback to climate, altering temperature and precipitation gradients and indirectly increasing the number of fire ignitions.[28]

Figure 2 illustrates the over-arching feedback loop in the climate–wildfire–air quality system. Using estimates of radiative forcing,[14] we convert estimates into a percentage of the total net radiative forcing on climate from a boreal forest wildfire in the interior of Alaska. The estimates used focus on one specific fire interval,[14] however, thereby quantifying only the effect on radiative forcing and not the complete feedback loop (represented by the dashed arrow), i.e., fire-caused forcing of climate in turn changes the fire regime. A more comprehensive analysis of the system involves this complete loop, along with resolving scale issues (e.g., radiative forcing is global, but local climate is what affects fire).

Wildfire Component

Feedback loops occur at fine and intermediate scales between individual fire events and fuels, and at broad scales between fire regimes and vegetation. Although many tree species' ecological niches are defined by climate,[29,30] disturbance regimes can affect the type of vegetation that regenerates.[3,25,31] Fire is an important disturbance regime to many communities, supporting ecosystem processes.[32,33] For example, fire affects gap dynamics for regeneration, which affect stand structure, composition, and age.[34,35] Some vegetation that depends on fire for recruitment is flammable (e.g., some chaparral species) and thus perpetuates fire-dependent communities.[36] Similarly, wildfire can affect soil through physical, chemical, and biotic processes and can alter erosion,[18,37] thereby affecting how vegetation grows and the available fuels.

The effect of vegetation on the type of fuels present (i.e., fuel type) acts across scales within the wildfire component of the climate–wildfire–air quality system. Fuel characteristics depend not only on the type of vegetation present (i.e., vegetation type), but also on the biophysical environment and the spatial patterns of biomass.[23] Vegetation type does affect the type and quantity of available live and dead fuels. Furthermore, different vegetation types have different chemical compositions, thus affecting the smoke chemistry and aerosol emissions from fires.[38] Hierarchical spatial variation exists across scales such that although vegetation types can be clumped at broad

scales (>10^9 m^2),[39] there is heterogeneous fuel composition at intermediate scales (10^6–10^9 m^2). Similarly, clustered fuel types at intermediate scales have heterogeneous spatial variation in fuel composition and structure at finer scales (10^1–10^6 m^2).[40,41]

Climate Component

There are two processes acting across temporal and spatial scales within the climate component. First is the effect of climate on weather. There are many feedbacks within the climate system that affect how the climate changes and consequently affects weather. For example, as the climate warms the overall locations of the jet stream change, causing different air masses to be transported into and out of a given region, thus affecting storm tracks and local weather variables like wind, temperature, and precipitation patterns.[4]

Second is the feedback loop between weather and heat from combustion. Weather typically provides the initial heat required for combustion at finer spatial and temporal scales, and heat from the flame affects local weather at intermediate scales. At the mesoscale (approximately 10^9 m^2) a heat release from wildfire of 10 Wm^{-2} has no detectable affect on local weather, but a heat release of 100 Wm^{-2} has a statistically noticeable influence on weather.[42] Further complicating the system, the amount of heat produced from the fire is not uniform (which affects the plume rise, vertical mixing, and emissions dispersal) and is largely dependent on the type and structure of fuel loadings.[11]

Interactions Between Climate, Wildfires, and Air Quality Components

Interactions between climate, wildfire, and air quality motivate studying the three components as one system. These interactions are shown in Figure 1 as arrows between components (between colored text). There exists one internal feedback loop between heat, oxygen, and fuel. Otherwise interactions are discussed in this section under three subcategories: wildfire and air quality, climate and air quality, and wildfire and climate. Wildfire and air quality includes the effect of fuels on air quality and the feedback loop between vegetation and air quality. Climate and air quality includes the feedback loop between weather and air quality and the feedback loop between air quality and climate. The last category, wildfire and climate, include the effect of climate on fire regime, the feedback loop between weather and individual fire events, the feedback loop between vegetation and weather, and the effect of topography on climate and weather.

Fine-scale, internal feedback loops among oxygen, heat, and fuel link all three components of the climate–wildfire–air quality system. The internal feedback loops are defined by the process of combustion, which has four phases: (1) preheating, (2) distillation and combustion of volatiles, (3) distillation and combustion of residual charcoal, and (4) cooling.[18,43] During the preheating phase, fuels trap heat. As the fuels heat up and moisture evaporates, the ignition process moves to phase (2). Fed by the fuel, the flame grows and produces more heat, thus drying any surrounding fuel in the preheating phase (1) and increasing flammability resulting in combustion (2). Provided there is enough oxygen, fuel, and heat to sustain a flame, the process of combustion will continue.

Wildfire and Air Quality

The effect of fuels on air quality depends on the moisture content, composition, and structure of fuels that determine the type of emissions.[23] The moisture content of the fuels not only affects flammability, but also the amount of water vapor produced during combustion. Also, the amount of methane emitted can affect the amount of water vapor from wildfire as oxidized methane can produce water vapor. Water (H_2O) is a GHG with substantial affects on radiative forcing.[4,44] The composition of the emissions that cocktail produced (Table 1) depends on the type, structure, and chemical composition of fuels burned as well as the completeness and efficiency of the combustion process.[11,23,45,46] For example, incomplete combustion of fuels, which is normally the case in wildfires, leaves behind carbonaceous materials,[18,46] as coarse PM, charcoal on the ground which can affect surface *albedo* and consequently radiative forcing[14,26] (Figure 2), or aerosols, which also affect radiative forcing through absorption and scattering of solar radiation,[27] cloud formation,[23] and deposition on snow and ice affecting surface *albedo*[14] (Figure 2).

The feedback loop between vegetation and air quality proceeds as follows: poor air quality can alter productivity of some plant species, while plant productivity can affect the quality of the air. For example, tropospheric ozone (O_3), a secondary pollutant formed in ultraviolet light through reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs), which are emissions from wildfire and fossil fuels,[47] can decrease productivity of some plant species, especially under high concentrations.[48] To complete the feedback, VOCs are also produced by vegetation,[49] while carbon dioxide (CO_2) is a key input for photosynthesis.

Climate and Air Quality

There is a feedback loop from air quality to weather. Ambient weather, fire-released energy, and moisture (atmospheric or from drying of fuels during

TABLE 1 | Some of the Emissions and Secondary Pollutants from Wildfire (Ref 18) as well as Classification as a Greenhouse Gas (GHG) or Aerosol and the Typical Spatial and Temporal Extent

Emission from Wildfire	GHG or Aerosol	Spatial Scale	Temporal Scale
Carbon monoxide (CO)	Neither	Fine	Fine
Carbon dioxide (CO_2)	GHG	Fine to broad	Broad
Methane (CH_4)	GHG	Fine to broad	Fine to intermediate
Water vapor (H_2O)	GHG	Fine to broad	Fine to intermediate
Nitrogen oxides (NO_x)	GHG	Fine to broad	Constant
Volatile organic compounds (VOCs)	Neither	Fine	Fine
Particulate matter (PM_{10})[2] 10 μm	Aerosol	Fine to intermediate	Fine
Particulate matter ($PM_{2.5}$)[2] 2.5 μm	Aerosol	Fine to broad	Fine
Secondary pollutants			
Tropospheric ozone (O_3)	GHG	Fine to broad	Fine to intermediate

Spatial and temporal scales are defined as fine (10^{-3}–10^3 m^2 or seconds-days), intermediate (10^4–10^8 m^2 or weeks-months), and broad ($\geq 10^9$ km^2 or years-centuries).

a fire) affect the injection height of emissions into the atmosphere and consequently emission's transport and diffusion.[11,42,50] Depending on the injection height[23] and the weather, emissions can have a shorter or longer life. Dry weather is conducive to longer life and farther transport of emissions, while wet deposition removes the aerosols and improves air quality. Aerosols emitted from wildfire can alter cloud formation both by acting as cloud-condensation nuclei (increasing) or absorbing light (decreasing), thus affecting precipitation,[23,27] while the amount of water vapor (which depends in part on temperature) affects the amount of moisture available for precipitation.[4] Furthermore, aerosol affects on cloud perturbations can absorb and scatter solar radiation,[27] thus affecting radiative forcing. These perturbations also affect the amount of available light, which is affected by cloud cover, which affects the photochemical reactions between CO, methane (CH_4), VOCs, and NO_x that form tropospheric ozone, a monitored and regulated GHG (Table 1 and Section *Ecological, Social, and Scientific Implications*).

Degraded air quality from wildfires is thought to be a substantial positive feedback to radiative forcing of the climate system.[21,46] As mentioned, the emissions such as CO_2 and CH_4 both from anthropogenic sources and wildfires, are GHGs. Aerosol emissions from wildfire have a less certain effect on the climate system as per the extent to which they absorb and scatter radiation both in the atmosphere and on the earth's surface.[26,51] Uncertainty exists not only because aerosol species' properties differ, but also because the effect of the source and injection height[23] of those species can produce net cooling or net warming.[4,21,46] In turn, climate can affect the spatial and temporal distribution of GHGs and aerosols such that it affects air quality.[21] For example, during times of high fire activity in Canada, transported emissions from wildfire increase background pollutant levels, tropospheric O_3 in particular, in the United States.[52] The transport and later deposition of aerosols can also alter sea ice and snow surface *albedo*, which affect radiative forcing and its consequent effect on climate (Figure 2).[14]

Wildfire and Climate

Climate affects the fire regime both directly and indirectly. Directly, climate influences fire regime by affecting flammability,[25] fuel availability, fire-season length, and ignitions. These direct effects are projected to increase annual area burned[1–3] and number of lightning-ignited fires[28] in a warming climate. Over time, there exists a nonlinear response between climate and fire climatology that is driven through significant interactions between climate, fire regime, and vegetation.[53] For example, at shorter time scales, in the dry southwestern United States, parts of Chile[54] and in the Mediterranean ecosystems of the Iberian Peninsula,[55] the strongest predictors of area burned are variables associated with the previous year's climate, which controls fuel availability and connectivity across landscapes.[9] Over longer temporal scales, through the Holocene in Alaska, vegetation type-mediated climatic controls on fire regimes.[53]

A feedback loop exists between weather and fire at both fine and intermediate scales. In the short term, weather controls wildfire behavior by affecting fine-fuel moisture, fireline intensity, and rate of spread. Fire behavior then affects weather because fire, air temperature, wind, and relative humidity (amount of water vapor in the air) change based on the airshed

characteristics and the amount of heat released from the fire.[42,56] For example, if a fire occurs in a basin and hot air rises during the fire, the relative humidity gradient in an air column changes because hot air can hold more moisture than cooler air. With warm air rising, vertical mixing and convective winds can change, with further consequences for fire behavior.[57]

The feedback loop between vegetation and weather proceeds as follows: vegetative surface cover influences local wind circulations and the amount of water transpired and evaporated in a region.[44,58] In turn, the local weather affects the composition, productivity, and mortality of vegetation that grows in the area.

Fire-climate dynamics are mediated globally by landforms, which influence climate at broad spatial scales and weather at intermediate spatial scales. For example, orographic controls on broad-scale atmospheric circulation over land produce continental climate, thus leading to very different fire regimes than those in maritime climates. At intermediate scales, topography affects weather by altering the length of time different aspects are shaded, consequently affecting fuel moisture, heat, and convective winds,[56] which are created by air flowing between high and low temperatures. Furthermore, local topography can affect the amount of rainfall received and changes in temperature affect relative humidity, the amount of moisture the air can hold. Finally, individual fire events at the intermediate scale affect climate through changes in surface *albedo*, which in turn affect radiative forcing and thus climate.[14,26]

MODELING THE SYSTEM: INTEGRATING MODELS ACROSS DISCIPLINES

Process-Oriented Scale Identification

Questions about climate, wildfire, and air quality are often addressed at characteristic scales of interest,[9–12,14] but neglect the complexity of the system and interactions among its (sub-)components. A complementary approach would be process-oriented by first identifying the multiple scales at which key processes in the climate–wildfire–air quality system interact. Once interactions and feedbacks within the system have been clearly articulated, five possible steps to a cross-disciplinary analysis might be: (1) pose a research question, (2) identify system (sub-)components pertinent to the research question (Figure 1), (3) identify spatial and temporal scales at which the processes of interest interact, (4) develop or apply models of key processes at these scales, and (5) integrate models from Step 4 into a model framework of the system.

Here we describe how to implement these steps using an example for the specific question or application of understanding the feedback loop defining the climate–wildfire–air quality system (Section *Interactions and Feedbacks*). Step 1: how does a changing climate affect wildfires, which affect air quality and feedback to affect climate (Step 1)? Step 2: the key (sub-)components of this question are climate, fire regime, aerosols, and GHGs (Figure 1). Step 3: Figure 1 shows that climate and fire regime interact at broad spatial and temporal scales, but aerosols and GHGs interact with climate and fire regime at a wide range of spatial and temporal scales. Ideally, in a world not limited by computational capacity, the system would be modeled at broad spatial and temporal domains with fine spatial and temporal resolution, capturing cross-scale interactions explicitly. Given the limitations, however, the scales of research domain and modeling resolution must be re-evaluated. Climate and wildfire interact at broad spatial and temporal resolutions and domain, whereas the effects of aerosols and GHGs on climate and fire regime occur at a broad spatial resolution and at fine temporal resolution. Consequently, the most appropriate scales of investigation for the research question posed in Step 1 are at broad spatial domain and resolution and broad temporal domain at fine temporal resolution. Now that the scales of key processes have been identified (Step 3), we can develop or apply models that simulate key processes at these scales (S4), and integrate them into a framework to address the research question (Step 5).

Modeling Frameworks and Sources of Uncertainty

To understand and quantify future wildland fire and degraded air quality, the use of models is necessary. Models by design are a simplification of reality from which we can draw inferences about the system being modeled. Each of these simplifications or underlying assumptions in the model can be used to tell us something about the system. There are three steps and considerations for modeling the climate–wildfire–air quality system: (1) identification of component parts, (2) assessment of available data and tools, and (3) identification of assumptions and simplifications that can cause error or uncertainty.

First, a diagrammatic illustration of the climate–fire–air quality system can help us to identify key components (Figure 3). Since each of these components is extremely complex, a modeling framework

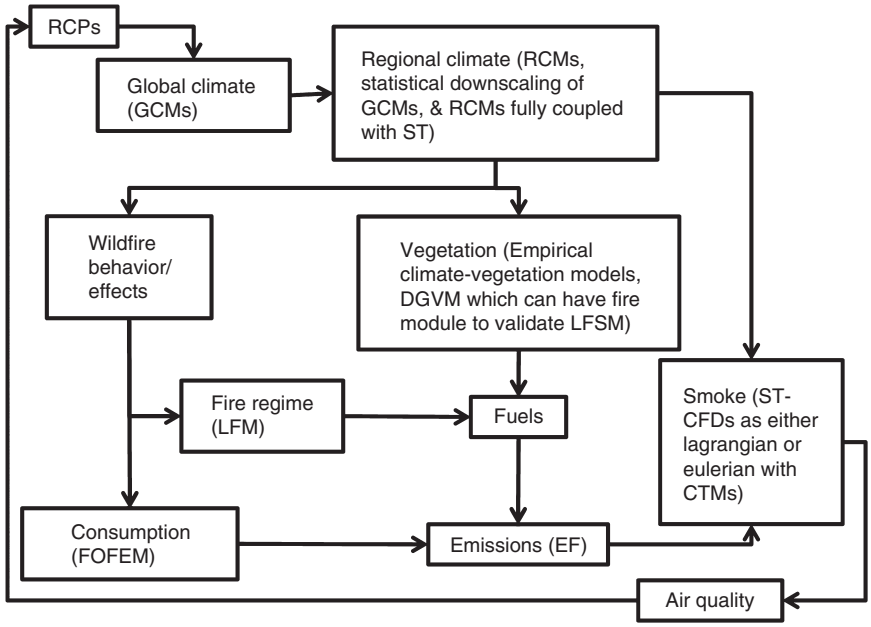

FIGURE 3 | Displayed are the modeling components of the climate–wildfire–air quality system and how the components connect to model the system as a whole. RCP = representative concentration pathway; GCM = global climate model; RCM = regional climate model; ST = smoke transport model; LFM = landscape fire model; DGVM = dynamic global vegetation model; LFSM = landscape fire succession model; CTM = chemical transport model; CFD = computational fluid dynamic model; EF = emissions factor; FOFEM = first-order fire effects model.

tocouple models of each component capturing key mechanisms is necessary. Some existing frameworks include the Bluesky Smoke Modeling Framework[11] and AIRFIRE.[42]

Second, we provide a brief overview of available models of each component and how to couple them creating a framework for studying the climate–wildfire–air quality system. Uncertainties are highlighted for each component. Other works have more detail than is provided here for modeling the system[59] and a comprehensive list of models has been developed and is available for each of these components.[54]

1. **Climate:** Global climate is simulated using global climate models (GCMs), which account for many feedbacks and processes at the highest affordable resolution. The spatial resolution from GCMs does not, however, meet the requirements for simulating wildfire. Consequently, modeling regional climate is necessary. There are two approaches, static and dynamic. The static approach uses gradient modeling to downscale GCMs statistically, while regional climate models (RCMs) provide a dynamic simulation of regional climate, using boundary conditions from a GCM.
2. **Vegetation:** At regional scales climate affects vegetation both directly through climate, and indirectly through disturbance regime, which can catalyze changes in the spatial pattern of vegetation.[1,60] Thus, although there exist empirically derived climate-vegetation models, these represent static relationships that do not integrate well with dynamic models such as RCMs. There are two types of dynamic climate-smart vegetation models: dynamic global vegetation models (DGVMs) and landscape fire succession models (LFSMs).[59] DGVMs use plant functional types (PFTs) and a fire module to simulate interactions between climate, vegetation, and fire as a disturbance. LFSMs create complex patterns across the landscape that influence fire spread, smoke, and vegetation succession post-fire. LFSMs, are computationally expensive, however, and therefore not feasible for the regional or sub-continental simulations required for studying the climate–wildfire–air quality system, thus they are more useful for validating DGVMs.[61]
3. **Fire:** Aggregate statistics of fire regime, such as annual area burned, are used to establish mean-field conditions and can be generated using statistical models[9] or simulation modeling.[5] One important uncertainty in modeling fire for the climate–wildfire–air quality system is in how heat transfer at fine temporal scales affects fuel conditions, weather, and

emissions dispersion. Although fuels do not drive fire behavior during extreme weather,[62] during nonextreme conditions, the heat from the fire can dry fuels ahead of the flaming front, thus increasing flammability and fire-spread rates. It could be argued that this feedback, affecting flammability and fire spread, may need to be incorporated in modeling at broad spatial scales.[63] For example, using a fire growth model, the Drossel and Schwabl Model (DSM[64]). Zinck et al.[63] demonstrate the importance of fuel mosaics in landscape diversity and confirm the interaction between disturbance and landscape diversity as proposed by the intermediate disturbance hypothesis.[65] By including fire-spread dynamics at a larger scales with finer scale variability of fuels and vegetation, we may improve estimates of fire regime at broad scales, however this requires more research.

4. **Fuels:** RCMs and DGVMs often operate at a relatively coarse spatial resolution, not optimal for capturing fine-scale variability of fuel types. Usually a Geographic Information System (GIS) layer is used as an initial fuel and vegetation map, which are developed from ground estimates, satellite data, and empirical or quasi-empirical models. Some examples of fuel maps include fuel classifications derived directly from vegetation,[40] PFTs extrapolated from plot-level data,[66] and fuel loadings derived from simulation modeling.[67] Using these models still has some uncertainty, which can affect the amount of heat produced, which is not uniform, therefore affecting plume rise, vertical mixing, and emissions dispersal as these are largely dependent on the specific choice of fuel loading.[11]
5. **Fuel consumption and emissions:** Fuel consumption and emissions are estimated using First-order-fire-effects models (FOFEMs), fuel loadings, fuel types, and fuel conditions. FOFEMs come in two varieties, which use either process-based heat-transfer equations to calculate combustion[68] or empirical models[11,42] derived from field and laboratory measurements of consumption. Emissions are then calculated using these estimates of consumption and emissions factors,[69] determined by how much and what type of biomass is consumed, the proportion of chemical species in a given fuel type, and the phase of combustion. An uncertainty to consider is how much variability in fire frequency or emissions factors, assigned over many different types of vegetation at coarse spatial resolution, affects the consumption rates and consequently emission estimates.[11] Different phases of combustion also have different chemical processes, which can occur over different time scales.[70] For example, flaming combustion happens within a few hours, while smoldering can continue for days or even weeks. This may bias estimates for emission factors depending on when and how (e.g., airborne versus field campaign) the estimate is derived. Separating flaming and smoldering emissions estimates is, however, incomplete because often the two phases happen simultaneously in a given patch.[69] Very often the type of combustion is assumed to be consistent between fuel type and structure, thus providing justification for implementing a smoldering fraction[13,71] to distinguish emission factors for the phase of combustion.[69]
6. **Smoke transport (ST):** ST models track pollutant-species evolution and development of secondary aerosols by simulating plume transport of gas and particulates through the atmosphere[72] using computational fluid dynamics (CFD). In general ST models are either Eulerian, which observe the passage of parcels or volumes of air with a specified amount of pollutant passed a fixed point, or Lagrangian, which follows the transport of the smoke plume through time and space. Lagrangian models are sometimes referred to as plume or puff-dispersion models and their simple forms can be useful for fast-screening air-quality assessments. More complex puff or particle dispersion models are used to track the smoke plume's complex and convoluted path, giving a better prediction of surface smoke concentrations, but are computationally expensive. On the other hand, Eulerian models are better used in modeling the airshed as a whole system because they better simulate actual atmospheric conditions by invoking submodels of atmospheric chemistry (chemistry transport models: CTMs). An uncertainty in this component occurs when modeling smoke dispersion at coarse spatial resolution because models either (1) assume a single source, and thus only simulate a single smoke column, which can substantially influence near-field concentrations[11] or (2) dilute the source, and consequently the smoke plume, to the size of the grid. Another uncertainty pertains to smoke composition and emission concentration level as this is dependent and sensitive to the smoke release height.[23,52,73,74] Plume rise or injection

height is largely dependent on heat release from the fire, atmospheric stability, and wind speed.[75] Goodrick et al.[72] provide an overview of the many modeling methods for estimating plume profiles including (1) assumptions of instantaneous, homogeneous mixing by assigning a predefined plume top and bottom based on fire size,[76] (2) conversion factors of heat flux to buoyancy flux[71] for input into parameterized pyrotechnical and metrological models,[75] and (3) the explicit numerical simulation based on fundamental atmospheric dynamics Although many methods exist for estimating the vertical distribution of pollutants, Goodrick et al.[72] suggest that more accurate modeling of the variability of plume dynamics must come from linking intermediate-scale processes with fine-scale fire behavior and canopy submodels. Nevertheless, uncertainty in ST is introduced by the tradeoff between computationally expensive modeling of fine scale dynamics over large areas and generalizing assumptions over an intermediate scale.

ECOLOGICAL, SOCIAL, AND SCIENTIFIC IMPLICATIONS

In an ecological context, fire as a disturbance alters the succession of vegetation,[3,31] and affects autotrophic productivity[77] and ecosystem resilience.[24] Fire can catalyze vegetation succession in communities adapting to a changing climate.[1,60] Alternatively, management can use fire in conservation and restoration efforts.[78] For example, fire affects gap dynamics for regeneration, which affect stand structure, composition, and age,[34,35] and can alter the disturbance regime. This produces a feedback between landscape pattern and processes like fire, depending on the strength of ecological memory.[24,79] Post-fire regeneration provides ecosystem services such as carbon sequestration by increasing growth[80] and nutrient cycling[81] and affects timber resources, biodiversity, and soil fertility.[77]

Wildfire effects on air quality can counteract the ecological benefits of fire, and emissions from wildfire that affect air quality depend on the type of vegetation system burned. For example, pollutants can have adverse effects on ecosystems,[77] including decreased forest growth, increased tree mortality, increased susceptibility to disease,[50] loss of sensitive species,[48,50] and increased presence of invasive species. At global scales, inter-annual variability in emissions follows that of area burned in forests,[82] thus demonstrating how the type of vegetation system can affect air quality.

Smoke from wildfires not only has ecological consequences but also social consequences, including respiratory illness,[83] heart attacks and mortality (Box 1), nuisance smoke on roadways,[84] and reduced visibility at scenic vistas (Figure 4).[4] Besides their effects on radiative forcing,[14,74] aerosols emitted from wildfires affect visibility (Figure 4), thereby contributing to nuisance smoke and regional haze. Aerosols can

BOX 1

HEALTH EFFECTS FROM WILDFIRES

The climate–wildfire–air quality system has social significance as wildfires can affect humans directly through emissions harmful to health. Emissions from wildfire in the form of CO, and PM less than 2.5 μm in diameter ($PM_{2.5}$), as well as secondary pollutants like tropospheric O_3, can have particularly grave consequences for human health. CO can alter pollutant levels, particularly of tropospheric O_3, across large distances.[23,52] Not only can CO affect tropospheric O_3 concentrations, but wildfires can directly affect both nearby and distant-downwind surface tropospheric O_3 levels, sometimes exceeding current health standards.[10] Surface tropospheric O_3 concentrations can irritate the respiratory system, reducing lung function, aggravating asthma, and increasing susceptibility to lung infection and inflammation of lung tissues. Besides tropospheric O_3, wildfires emit PM. The amount of $PM_{2.5}$ emitted is particularly important because when such small particles are inhaled, they can penetrate deep into the human lung causing similar symptoms as tropospheric O_3[45,83] and even mortality.[86] Furthermore, PM emitted from wildfire is more toxic than equal levels of PM concentration from ambient air without wildfire.[12] There are other less abundant, but still harmful, emissions from wildfire such as mercury, which can accumulate during dry and wet deposition and then be released into the atmosphere during combustion.[87] An overview of epidemiological studies of wildfire smoke and human health from around the world noted increased hospital attendance for asthma and other respiratory illnesses during periods impacted by wildfire smoke.[88] Although pollutants emitted from wildfire can also come from other sources (e.g., anthropogenic use of fossil fuels and volcanoes), the amount from wildfire can be substantial[13] as years with large-scale biomass burning increase annual emissions.[23]

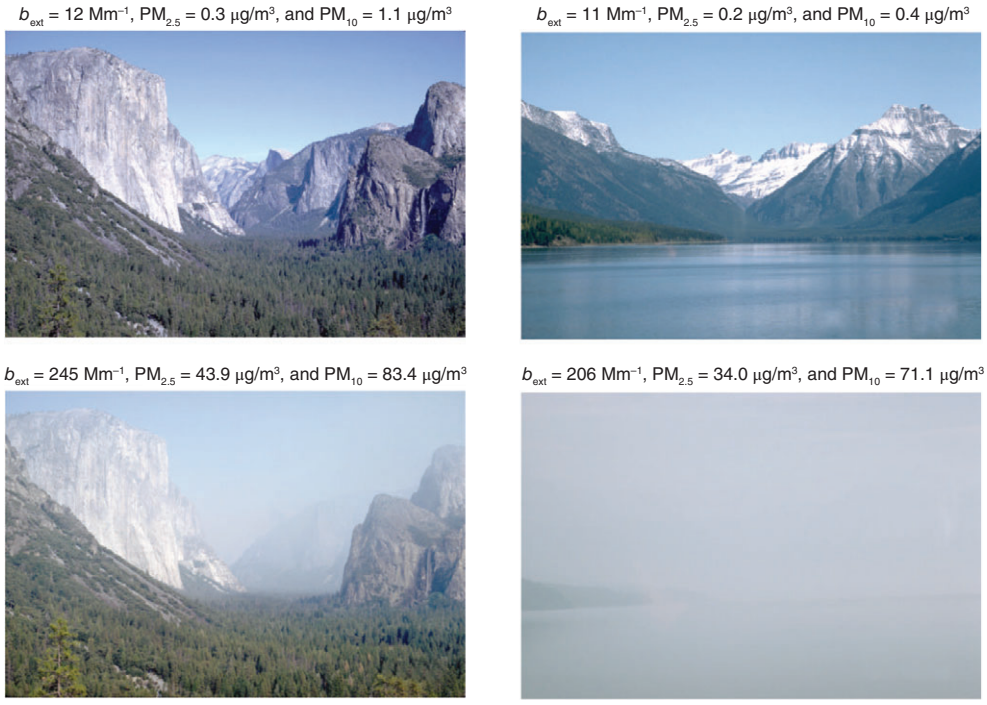

FIGURE 4 | Examples of pristine air quality (top panels) and degraded air quality (bottom panels) in Yosemite National Park (CA, USA; left) and Glacier National Park (MT, USA; right). b_{ext} represents light extinction whereby low values are typical for clear conditions and high are typical of degraded visibility. (Reprinted with permission from IMPROVE; http://vista.cira.colostate.edu/improve/)

come from many sources, but wildfires contribute substantially to annual aerosol emissions, particularly on the worst days. For example, in the western United States, wildfire emissions during summer constitute a significant fraction of the regulated annual NAAQS for $PM_{2.5}$, which reduces visibility.[85] At shorter time scales, following or during a burning a fire, there is nuisance smoke. Nuisance smoke is considered smoke that interferes with the rights or privileges of members of the public,[84] such as smoke that reduces visibility on roadways or for air traffic. At longer time scales, aerosols like $PM_{2.5}$ can reduce visibility by producing haze. Haze is the accumulation of microscopic aerosols, at sufficient concentrations to restrict visibility.[84] Haze obscures the view at scenic vistas in parks or when looking at a city from a distance.

A systems approach can help evaluate the success of meeting air-quality standards. Two national air-quality standards in effect for the United States are (1) the National Ambient Air Quality Standard (NAAQS), which regulates pollutants considered harmful to human health and the environment, and (2) the Regional Haze Rule, which requires national parks and other wilderness areas to reduce visibility impairment. Visibility provides ecosystem services such as esthetic appeal, which determines the value that many observers place on wilderness areas[22] and consequently the funding and political support required to maintain them.[89]

By studying climate, wildfire, and air quality as one system, managers, and political decision makers can make informed strategies for mitigating smoke effects and meeting air-quality regulations. Direct management strategies include prescribing fires during seasons and conditions that reduce smoke effects,[90] mechanical thinning of fuels to reduce emissions,[91] and fire suppression when expected emissions endanger health. Indirect management strategies include restricting emissions from anthropogenic pollution sources, such that more emissions from wildfire must occur before exceeding air quality standards. There is a need for integrative research across disciplines as management in one area such as wildfire may affect air quality in undesirable ways. For example, decades of fire suppression may cause fuel to accumulate and exacerbate air-quality degradation when a fire occurs.[91–93]

There are other, more subtle anthropogenic influences on the system besides direct and indirect management of fire at fine and intermediate scales. One example is the effect of land management on fire regime,[20,21,94,95] such as old growth conservation for Northern Spotted Owl habitat.[96] Another

example is the influence of anthropogenic land fragmentation caused by infrastructure, which can break fuel connectivity and impede fire spread.[97] Finally, the influence of urban sprawl with a growing wildland urban interface can affect ignition and fire-growth potential.[98] Although the framework we describe here does not account for these influences directly, anthropogenic influences can be indirectly linked to climate models implementing the radiative forcing AR5 scenarios.[99] In summary, these scenarios allow for different radiative forcing targets, while allowing flexible 'spending' of different contributors like technological development, population growth, and land management to meet the budget. Integrating these scenarios into the proposed framework may provide some insight into anthropogenic influence of the climate–wildfire–air quality system. However, caution should be taken as forcing agents may counterbalance each other while still meeting the same budget.[15] Nevertheless, the proposed framework and future research of sensitivities and uncertainties will provide insight into the temporal tradeoffs between proactive and reactive wildfire management.

In a broader scientific context, studying climate, wildfire, and air quality as one system can improve understanding of the carbon cycle and the climate system as a whole. The climate–wildfire–air quality dynamic influences the carbon cycle by (1) releasing carbon to the atmosphere[45]; (2) changing successional patterns that influence biomass carbon storage[100]; (3) providing improved soil nutrients and gaps for regeneration[101]; and (4) affecting fire frequency, which determines the amount of total carbon sequestered.[37] Furthermore, because some wildfire emissions have substantial feedbacks to the climate system,[21,82] future studies can integrate modeling frameworks not only by quantifying the impact of climate on air quality from wildfires, but also by including feedbacks to the climate system explicitly, thereby improving the predictive capabilities of climate models.

CONCLUSION

This overview of recent literature and synthesis of system dynamics provides a foundation to link climate, wildfire, and air quality, a subject that has only just begun to be assessed. We propose first selecting appropriate scales to address specific research objectives. Choosing appropriate scales for studying the broad feedback loop between climate, wildfire, and air quality, which defines the climate–wildfire–air quality system (see Section *Interactions and Feedbacks*), requires data and models at broad spatial scales because climate, fire regime, and smoke can span long distances (e.g., regional). Models should also have fine temporal resolution as pollutants and fire can change in short time spans (e.g., hours; see Section *Process-Oriented Scale Identification*). By identifying the scales necessary for capturing specific interactions, new models can be developed and datasets merged to bridge knowledge gaps between disciplines such as climatology, meteorology, fire ecology and behavior, and atmospheric physics and chemistry. Using a modeling framework (see Section *Modeling Frameworks and Sources of Uncertainty* and Ref 59) and investigating uncertainties therein, we can improve understanding of the climate–wildfire–air quality system. Research is needed to quantify interactions among these components and their uncertainties to evaluate impacts such that managers and decision-makers have more information to address existing regulations or shape new policy. Lastly, by studying the climate–wildfire–air quality system as a whole, scientists can better understand carbon budgets and their potential effect on the climate system.

Adopting the systematic approach described in this article will enable future research to quantify uncertainties of the modeling systems[7,11,42] and provide confidence for implementing them as useful tools for understanding the climate–wildfire–air quality system. There are three components to calculating uncertainty: parameter sensitivity, choosing assessment criteria, and verifying data and algorithms.[102] On individual models within the modeling system, sensitivity analyses can quantify estimates of parameter uncertainty,[103,104] which may be particularly useful when applying models to areas for which they were not originally designed, e.g., assessing different scenarios or applying the model to a new geographic location. There are many criteria by which to assess models, and even more when assessing a modeling framework; fortunately, methods exist for assessing the ability of the framework for meeting multiple criteria such as traditional optimization by assigning weights and multi-criteria Pareto optimization.[102,105,106] Finally, uncertainty of data and algorithms can be quantified once we adopt a systematic approach to assessing climate, wildfire, and air quality. By adopting the systematic approach proposed in this article, we can overcome data limitations by applying data assimilation (i.e., fusion observation and system information to estimate the state of process[107]) techniques.

We synthesize the latest research on climate, wildfire, and air quality to define interactions and feedbacks and propose a cross-scale approach to studying the system as a whole. We seek to identify the appropriate spatial and temporal domains for modeling

the feedback loops between climate, wildfire, and air quality and briefly discuss a modeling framework useful for investigating the climate–wildfire–air quality system. Finally, we discuss broader ecological, social, and broader scientific implications for studying the system as a whole.

ACKNOWLEDGMENTS

Funding for this review has been provided by the Pacific Northwest Research Station, U.S. Forest Service; the EPA-STAR program; and the Joint Fire Science Program, project # 11-1-7-4 and # 12-S-01-2. Many thanks for constructive reviews from Ernesto Alvarado, Christian Torgersen, Tim Essington, David L. Peterson, and Tara Strand. The final stages of this research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Stocks BJ. Global warming and forest fires in Canada. *For Chron* 1993, 69:290–293.
2. Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM. Implications of changing climate for global wildland fire. *Int J Wildl Fire* 2009, 18:483–507.
3. Littell JS, Oneil EE, McKenzie D, Hicke JA, Lutz JA, Norheim RA, Elsner MM. Forest ecosystems, disturbance, and climatic change in Washington State. *USA Clim Change* 2010, 102:129–158.
4. Stocker TF, Qin D, Plattner G-K, Alexander L V., Allen SK, Bindoff NL, Bréon F-M, Church JA, Cubasch U, Emori S, et al. TS: technical summary. AR5. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. *Climate Change 2013 Physical Science Basis Contribution Working Group I to Fifth Assessment Report Intergovernmental Panel Climate Change*. Cambridge, UK and New York: Cambridge University Press; 2013 33–115.
5. Mckenzie D, Oneill SM, Larkin NA, Norheim RA. Integrating models to predict regional haze from wildland fire. *Ecol Modell* 2006, 199:278–288.
6. Chen J, Avise J, Lamb B, Salathe E, Mass C, Guenther A, Wiedinmyer C, Lamarque JF, O'Neill SM, McKenzie D, et al. The effects of global changes upon regional ozone pollution in the United States. *Atmos Chem Phys* 2009, 9:1125–1141.
7. Spracklen DV, Mickley LJ, Logan JA, Hudman RC, Yevich R, Flannigan MD, Westerling AL. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *J Geophys Res* 2009, 114(D20):D20301.
8. Carvalho A, Monteiro A, Flannigan M, Solman S, Miranda AI, Borrego C. Forest fires in a changing climate and their impacts on air quality. *Atmos Environ* 2011, 45:5545–5553.
9. Littell JS, McKenzie D, Peterson DL, Westerling AL. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecol Appl* 2009, 19:1003–1021.
10. Pfister GG, Wiedinmyer C, Emmons LK. Impacts of the fall 2007 California wildfires on surface ozone: integrating local observations with global model simulations. *Geophys Res Lett* 2008, 35:L19814.
11. Larkin NK, O'Neill SM, Solomon R, Raffuse S, Strand T, Sullivan DC, Krull C, Rorig M, Peterson JL, Ferguson SA. The BlueSky smoke modeling framework. *Int J Wildl Fire* 2009, 18:906.
12. Wegesser TC, Pinkerton KE, Last JA. California wildfires of 2008: coarse and fine particulate matter toxicity. *Environ Heal Perspect* 2009, 117:893–898.
13. Lavoue D, Gong S, Stocks BJ. Modelling emissions from Canadian wildfires: a case study of the 2002 Quebec fires. *Int J Wildl Fire* 2007, 16:649–663.
14. Randerson JT, Liu H, Flanner MG, Chambers SD, Jin Y, Hess PG, Pfister G, Mack MC, Treseder KK, Welp LR, et al. The impact of boreal forest fire on climate warming. *Science* 2006, 314:1130–1132.
15. Jones AD, Collins WD, Torn MS. On the additivity of radiative forcing between land use change and greenhouse gases. *Geophys Res Lett* 2013, 40:4036–4041.
16. Moritz MA, Morais ME, Summerell LA, Carlson JM, Doyle JC. Wildfires, complexity, and highly optimized tolerance. *Proc Natl Acad Sci USA* 2005, 102:17912–17917.
17. Falk DA, Miller C, McKenzie D, Black AE. Cross-scale analysis of fire regimes. *Ecosystems* 2007, 10:809–823.
18. Agee JK. *Fire ecology of Pacific Northwest forests*. Washington, DC: Island Press; 1993.
19. Sugihara NG, van Wagtendonk JW, Fites-Kaufman J. Fire as an Ecological Process. In: Sugihara NG, van Wagtendonk JW, Shaffer KE, Fites-Kaufman J, Thode AE, eds. *Fire California's Ecosystems*. Berkeley, CA: University of California Press; 2006, 58–74.
20. Wright HA, Bailey AW. *Fire Ecology*. New York: John Wiley and Sons; 1982.

21. Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, Defries RS, Doyle JC, Harrison SP, et al. Fire in the earth system. *Science* 2009, 324:481–484.
22. Malm WC. *Introduction to Visibility*. Fort Collins, Co: Air Resources Division, National Park Service; 1999.
23. Langmann B, Duncan B, Textor C, Trentmann J, van der Werf GR. Vegetation fire emissions and their impact on air pollution and climate. *Atmos Environ* 2009, 43:107–116.
24. Peterson GD. Contagious disturbance, ecological memory, and the emergence of landscape pattern. *Ecosystems* 2002, 5:329–338.
25. Kitzberger T, Aráoz E, Gowda JH, Mermoz M, Morales JM. Decreases in fire spread probability with forest age promotes alternative community states, reduced resilience to climate variability and large fire regime shifts. *Ecosystems* 2012, 15:97–112.
26. Bonan GB. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 2008, 320:1444–1449.
27. Liu Y. Enhancement of the 1988 northern U.S. drought due to wildfires. *Geophys Res Lett* 2005, 32:L10806.
28. Price C, Rind D. The impact of a 2 x CO2 climate on lightning-caused fires. *J Clim* 1994, 7:1484–1494.
29. Peterson DW, Peterson DL. Mountain hemlock growth responds to climatic variability at annual and decadal time scales. *Ecology* 2001, 82:3330–3345.
30. Mckenzie D, Peterson DW, Peterson DL, Thornton PE. Climatic and biophysical controls on conifer species distributions in mountain forests of Washington State. *USA J Biogeogr* 2003, 30:1093–1108.
31. Sprugel DG. Disturbance, equilibrium, and environmental variability: what is "natural" vegetation in a changing environment? *Biol Conserv* 1991, 58:1–18.
32. Stephens SL, Ruth LW. Federal forest-fire policy in the United States. *Ecol Appl* 2005, 15:532–542.
33. Duguy B, Alloza JA, Baeza MJ, De la Riva J, Echeverria M, Ibarra P, Llovet J, Cabello FP, Rovira P, Vallejo RV. Modelling the ecological vulnerability to forest fires in Mediterranean ecosystems using geographic information technologies. *Environ Manage* 2012, 50:1012–1026.
34. Stephens SL. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. *For Ecol Manage* 1998, 105:21–35.
35. Kolb TE, Agee JK, Fulé PZ, McDowell NG, Pearson K, Sala A, Waring RH. Perpetuating old ponderosa pine. *For Ecol Manage* 2007, 249:141–157.
36. Bond WJ, Keeley JE. Fire as a global "herbivore": the ecology and evolution of flammable ecosystems. *Trends Ecol Evol* 2005, 20:387–394.
37. Kasischke ES, Christensen NL, Stocks BJ. Global warming and the carbon balance of boreal forests. *Ecol Appl* 1995, 5:437–451.
38. Yamasoe MA, Paulo A, Miguel AH, Allen AG. Chemical composition of aerosol particles from direct emissions of vegetation fires in the Amazon Basin: water-soluble species and trace elements. *Atmos Environ* 2000, 34:1631–1653.
39. Neilson RP. A Model for predicting continental-scale vegetation distribution and water balance. *Ecol Appl* 1995, 5:362–385.
40. McKenzie D, Raymond CL, Kellogg L-KB, Norheim RA, Andreu AG, Bayard AC, Kopper KE, Elman E. Mapping fuels at multiple scales: landscape application of the fuel characteristic classification system. *Can J For Res* 2007, 37:2421–2437.
41. Keane RE, Gray K, Bacciu V, Leirfallom S. Spatial scaling of wildland fuels for six forest and rangeland ecosystems of the northern Rocky Mountains. *USA Landsc Ecol* 2012, 27:1213–1234.
42. Miranda AI. An integrated numerical system to estimate air quality effects of forest fires. *Int J Wildland Fire* 2004; 1999:217–226.
43. Macias Fauria M, Michaletz ST, Johnson EA. Predicting climate change effects on wildfires requires linking processes across scales. *WIREs Clim Change* 2011, 2:99–112.
44. Swann AL, Fung IY, Levis S, Bonan GB, Doney SC. Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proc Natl Acad Sci USA* 2010, 107:1295–1300.
45. Ward DE, Hardy CC. Smoke emissions from wildland fires. *Environ Int* 1991, 17:117–134.
46. Bond TC, Doherty SJ, Fahey DW, Forster PM, Berntsen T, DeAngelo BJ, Flanner MG, Ghan S, Kärcher B, Koch D, *et al*. Bounding the role of black carbon in the climate system: a scientific assessment. *J Geophys Res Atmos* 2013, 118:5380–5552.
47. Hu YT, Odman MT, Chang ME, Jackson W, Lee S, Edgerton ES, Baumann K, Russell AG. Simulation of air quality impacts from prescribed fires on an urban area. *Environ Sci Technol* 2008, 42:3676–3682.
48. Reich PB, Amundson RG. Ambient levels of ozone reduce net photosynthesis in tree and crop species. *Science* 1985, 230:566–570.
49. Guenther A, Geron C, Pierce T, Lamb B, Harley P, Fall R. Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. *Atmos Environ* 2000, 34:2205–2230.
50. Wohlgemuth PM, Hubbert K, Abbaugh MJ. *Fire and physical environment interactions: soil, water and air. Fire California's ecosystems*. Berkeley, CA: University of California Press; 2006, 75–93.
51. Anderson TL, Charuon RJ, Schwartz SE, Knutti R, Boucher O, Rodhe H, Heintzenberg J. Climate

forcing by aerosols—a hazy picture. *Science* 2003, 300:1103–1105.

52. Wotawa G. The influence of Canadian forest fires on pollutant concentrations in the United States. *Science* 2000, 288:324–328.
53. Higuera PE, Brubaker LB, Anderson PM, Hu FS, Brown TA. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range. *Alaska Ecol Monogr* 2009, 79:201–219.
54. Holz A, Kitzberger T, Paritsis J, Veblen TT. Ecological and climatic controls of modern wildfire activity patterns across southwestern South America. *Ecosphere* 2012, 3:103.
55. Pausas JG, Paula S. Fuel shapes the fire-climate relationship: evidence from Mediterranean ecosystems. *Glob Ecol Biogeogr* 2012, 21:1074–1082.
56. Rothermel RC. *How to Predict the Spread and Intensity of Forest and Range Fires (GTR-INT143)*. Ogden, UT: USDA Forest Service; 1983.
57. Heilman WE, Bian X. Turbulent kinetic energy during wildfires in the north central and north-eastern US. *Int J Wildl Fire* 2010, 19:346–363.
58. Pielke RA, Walko RL, Steyaert LT, Vidale PL, Liston GE, Lyons WA, Chase TN. The Influence of anthropogenic landscape changes on weather in South Florida. *Am Meteorol Soc* 1999, 127:1663–1673.
59. McKenzie D, Shankar U, Keane RE, Stavros EN, Heilman WE, Fox DG, Riebau AC. Smoke consequences of new wildfire regimes driven by climate change. *Am Geophys Union Earth's Future* 2014, 1–25:35–59. doi: 10.1002/2013EF000180.
60. Barrett K, McGuire AD, Hoy EE, Kasischke ES. Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity. *Ecol Appl Ecol Soc Am* 2011, 21:2380–2396.
61. McKenzie D, Shankar U, Keane RE, Heilman WE, Stavros EN, Fox DG, Riebau AC, Bowden JH, Eberhardt E, Norheim R. Smoke consequences of new wildfire regimes driven by climate change. Joint Fire Science Program, Final Report 12-S-01-2. 2013.
62. Bessie WC, Johnson EA. The relative importance of fuels and weather on fire behavior in sub-alpine forests. *Ecology* 1995, 76:747–762.
63. Zinck RD, Johst K, Grimm V. Wildfire, landscape diversity and the Drossel—Schwabl model. *Ecol Modell* 2010, 221:98–105.
64. Drossel B, Schwabl F. Self-organized criticality in a forest-fire model. *Phys Rev Lett* 1992, 69:1629–1632.
65. Connell JH. Diversity in tropical rain forests and coral reefs. *Science* 1978, 199:1302–1310.
66. Ruefenacht B, Finco MV, Nelson MD, Czaplewski R, Helmer EH, Blackard JA, Holden GR, Lister AJ, Salajanu D, Weyermann D, et al. Contermonious U.S. and Alaska forest type mapping using forest inventory and analysis data. *Photogramm Eng Remote Sens* 2008, 74:1379–1388.
67. Lutes DC, Keane RE, Caratti JF. A surface fuel classification for estimating fire effects. *Int J Wildl Fire* 2009, 18:802–814.
68. Albini FA, Reinhardt ED. Improved calibration of a large fuel burnout model. *Int J Wildl Fire* 1997, 7:21–28.
69. Andreae MO. Emission of trace gases and aerosols from biomass burning. *Glob Biogeochem Cycles* 2001, 15:955–966.
70. Lobert JM, Warnatz J. Emissions from the combustion process in vegetation. In: Crutzen PJ, ed. *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires: Report of the Dahlem Workshop, Held in Berlin, 15–20 March 1992*. Hoboken, NJ: John Wiley & Sons, Inc.; 1993, 15–37.
71. Pouliot G, Pierce T, Benjey W, Neill SMO, Ferguson SA. Wildfire emission modeling: integrating BlueSky and SMOKE. In: 14th International Emission Invent Conference 'Transforming Emission Invent Meet Future Challenges Today.' Las Vegas, Nevada; 2005, 1–8.
72. Goodrick SL, Achtemeier GL, Larkin NK, Liu Y, Strand TM. Modelling smoke transport from wildland fires: a review. *Int J Wildl Fire* 2012, 22:83–94.
73. Stein AF, Rolph GD, Draxler RR, Stunder B, Ruminski M. Verification of the NOAA smoke forecasting system: model sensitivity to the injection height. *Weather Forecast* 2009, 24:379–394.
74. Jeong JI, Park RJ, Youn D. Effects of Siberian forest fires on air quality in East Asia during May 2003 and its climate implication. *Atmos Environ* 2008, 42:8910–8922.
75. Briggs GA. Optimum formulas for buoyant plume rise. *Philos Trans R Soc Lond Ser A Math Phys Sci* 1969, 265:197–203.
76. WRAP. 2002 fire emission inventory for the WRAP region: Phase I—Essential Documentation. Western Governors Association/Western Regional Air Partnership, 2004.
77. Fenn ME, Lambert KF, Blett TF, Burns DA, Pardo LH, Lovett GM, Haeuber RA, Evers DC, Driscoll CT, Jeffries DS. Setting limits: Using air pollution thresholds to protect and restore U.S. ecosystems. Issues Ecology. Ecological Society of America, Washington DC, 2011, esa 1–esa 21.
78. Reinhardt ED, Keane RE, Calkin DE, Cohen JD. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For Ecol Manage* 2008, 256: 1997–2006.
79. McKenzie D, Littell JS. Climate change and wilderness fire regimes. *Int J Wilderness* 2011, 17:22–31.

80. McDowell N, Brooks JR, Fitzgerald SA, Bond BJ. Carbon isotope discrimination and growth response of old *Pinus ponderosa* trees to stand density reductions. *Plant Cell Environ* 2003, 26:631–644.
81. Ghimire B, Williams CA, Collatz GJ, Vanderhoof M. Fire-induced carbon emissions and regrowth uptake in western U.S. forests: documenting variation across forest types, fire severity, and climate regions. *J Geophys Res* 2012, 117(G3):G03036.
82. van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano AF. Interannual variability of global biomass burning emissions from 1997 to 2004. *Atmos Chem Phys Discuss* 2006, 6:3175–3226.
83. Delfino RJ, Brummel S, Wu J, Stern H, Ostro B, Lipsett M, Winer A, Street DH, Zhang L, Tjoa T, et al. The relationship of respiratory and cardiovascular hospital admissions to the Southern California wildfires of 2003. *Occup Environ Med* 2009, 66:189–197.
84. Hardy CC, Ottmar RD, Peterson JL, Core JE, Seamon P. *Smoke Management Guide for Prescribed and Wildland Fire 2001 Edition*. USDI, USDA and, editor. Boise, ID: National Wildfire Coordination Group; 2001. Available at: http://www.nwcg.gov.
85. Jaffe D, Hafner W, Chand D, Westerling AL, Spracklen DV. Interannual variations in PM2.5 due to wildfires in the Western United States. *Environ Sci Technol* 2008, 42:2812–2818.
86. Johnston FH, Henderson SB, Chen Y, Randerson JT, Marlier M, Defries RS, Kinney P, Bowman DMJS, Brauer M. Estimated global mortality attributable to smoke from landscape fires. *Environ Health Perspect* 2012, 120:695–701.
87. Friedli HR, Radke LF, Lu JY. Mercury in smoke from biomass fires. *Geophys Res Lett* 2001, 28:3223–3226.
88. Bowman DMJSJS, Johnston FH. Wildfire smoke, fire management, and human health. *Ecohealth* 2005, 2:76–80.
89. Hyslop NP. Impaired visibility: the air pollution people see. *Atmos Environ* 2009, 43:182–195.
90. Bytnerowicz A, Cayan D, Riggan P, Schilling S, Dawson P, Tyree M, Wolden L, Tissell R, Preisler H. Analysis of the effects of combustion emissions and Santa Ana winds on ambient ozone during the October 2007 southern California wildfires. *Atmos Environ* 2010, 44:678–687.
91. Hurteau MD, Koch GW, Hungate BA. Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. *Front Ecol Environ* 2008, 6:493–498.
92. Covington WW, Everett RL, Steele R, Irwin LL, Daer TA, Auclair A. Historical and anticipated changes in forest ecosystems of the inland west of the United States. *Assess For Ecosyst Heal Inland West* 1994, 13–63.
93. Breshears DD, Allen CD. The importance of rapid, disturbance induced losses in carbon management and sequestration. *Glob Ecol Biogeogr* 2002, 11:1–5.
94. Veblen TT, Kitzberger T, Donnegan J. Climatic and human influences on fire regimes in Ponderosa Pine forests in the Colorado Front Range. *Ecol Appl* 2000, 10:1178–1195.
95. Gallant AL, Hansen AJ, Councilman JS, Monte DK, Betz DW. Vegetation dynamics under fire exclusion and logging in a Rocky Mountain watershed, 1856–1996. *Ecol Appl* 2003, 13:385–403.
96. Thomas JW, Franklin JF, Gordon J, Johnson KN. The northwest forest plan: origins, components, implementation experience, and suggestions for change. *Conserv Biol* 2006, 20:277–287.
97. Parisien M-A, Moritz MA. Environmental controls on the distribution of wildfire at multiple spatial scales. *Ecol Monogr* 2009, 79:127–154.
98. Jiang Y, Zhuang Q. Extreme value analysis of wildfires in Canadian boreal forest ecosystems. *Can J For Res* 2011, 41:1836–1851.
99. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, et al. The next generation of scenarios for climate change research and assessment. *Nature* 2010, 463:747–756.
100. Lorenz K, Lal R. *Effects of Disturbance, Succession and Management on Carbon Sequestration. Carbon Sequestration Forest Ecosystem*. New York: Springer; 2010, 103–157.
101. Kashian DM, Romme WH, Tinker DB, Turner MG, Ryan MG. Carbon storage on coniferous landscapes with stand-replacing fires. *Bioscience* 2006, 56:598–606.
102. Turley MC, Ford ED. Definition and calculation of uncertainty in ecological process models. *Ecol Modell* 2009, 220:1968–1983.
103. Steel EA, Mcelhany P, Yoder NJ, Purser MD, Malone K, Thompson BE, Avery KA, Jensen D, Blair G, Busack C, Bowen MD, Hubble J, Kantz T. Making the best use of modeled data: multiple approaches to sensitivity analysis of a fish-habitat model. *Fisheries* 2009, 34:330–339.
104. Green EJ, MacFarlane DW, Valentine HT. Bayesian synthesis for quantifying uncertainty in predictions from process models. *Tree Physiol* 2000, 20:415.
105. Kim K-J, Smith RL. Systematic procedure for designing processes with multiple environmental objectives. *Environ Sci Technol* 2005, 39:2394–2405 Available at: http://www.ncbi.nlm.nih.gov/pubmed/15871282.
106. Kennedy MC, Ford ED, Singleton P, Finney MA, Agee JK. Informed multi-objective decision-making in environmental management using Pareto optimality. *J Appl Ecol* 2008, 45:181–192.
107. Wikle CK, Berliner LM. A Bayesian tutorial for data assimilation. *Phys D Nonlin Phenom* 2007, 230:1–16.