BAMS
Essay

# Interactions between Air Pollution and Terrestrial Ecosystems

## Perspectives on Challenges and Future Directions

Cenlin He, Olivia Clifton, Emmi Felker-Quinn, S. Ryan Fulgham,
Julieta F. Juncosa Calahorrano, Danica Lombardozzi, Gemma Purser, Mj Riches,
Rebecca Schwantes, Wenfu Tang, Benjamin Poulter, and Allison L. Steiner

**ABSTRACT:** Interactions between air pollution and terrestrial ecosystems play an important role in the Earth system. However, process-based knowledge of air pollution–terrestrial ecosystem interactions is limited, hindering accurate quantification of how changes in tropospheric chemistry, biogeochemical cycling, and climate affect air quality and its impact on humans and ecosystems. Here we summarize current challenges and future directions for advancing the understanding of air pollution–ecosystem interactions by synthesizing discussions from a multidisciplinary group of scientists at a recent Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) early-career workshop. Specifically, we discuss the important elements of air pollution–terrestrial ecosystem interactions, including vegetation and soil uptake and emissions of air pollutants and precursors, in-canopy chemistry, and the roles of human activities, fires, and meteorology. We highlight the need for a coordinated network of measurements of long-term chemical fluxes and related meteorological and ecological quantities with expanded geographic and ecosystem representation, data standardization and curation to reduce uncertainty and enhance observational syntheses, integrated multiscale observational and modeling capabilities, collaboration across scientific disciplines and geographic regions, and active involvement by stakeholders and policymakers. Such an enhanced network will continue to facilitate the process-level understanding and thus predictive ability of interactions between air pollution and terrestrial ecosystems and impacts on local-to-global climate and human health.

**KEYWORDS:** Atmosphere-land interaction; Vegetation-atmosphere interactions; Air pollution; Air quality; Biosphere-atmosphere interactions

https://doi.org/10.1175/BAMS-D-20-0066.1

Corresponding author: Cenlin He, cenlinhe@ucar.edu

In final form 15 September 2020

**AFFILIATIONS: He**—Research Applications Laboratory, National Center for Atmospheric Research, Boulder, Colorado; **Clifton**—Atmospheric Chemistry Observations and Modeling, and Modeling and Mesoscale and Microscale Meteorology, National Center for Atmospheric Research, Boulder, Colorado; **Felker-Quinn**—Air Resources Division, National Park Service, Denver, Colorado; **Fulgham and Riches**—Department of Chemistry, Colorado State University, Fort Collins, Colorado; **Juncosa Calahorrano**—Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado; **Lombardozzi**—Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, Colorado; **Purser**—U.K. Centre for Ecology and Hydrology, Penicuik, Midlothian, and School of Chemistry, University of Edinburgh, Edinburgh, United Kingdom; **Schwantes* and Tang**—Atmospheric Chemistry Observations and Modeling, National Center for Atmospheric Research, Boulder, Colorado; **Poulter**—Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland; **Steiner**—Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan
*** CURRENT AFFILIATION: Schwantes**—Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and Chemical Sciences Laboratory, National Oceanic and Atmospheric Administration, Boulder, Colorado

The exchange of reactive trace gases and particulate matter (PM) between the atmosphere and terrestrial ecosystems influences air pollution, ecosystems, and climate. Even though land–atmosphere exchanges of reactive gases and PM are expected to evolve with climate and human activities, they are poorly understood from a mechanistic perspective (e.g., Barth et al. 2005; Fowler et al. 2009; Fiore et al. 2015; Kanakidou et al. 2018). Advances in the fields of atmospheric chemistry and land–atmosphere interactions over the past decades have largely proceeded independently [e.g., Oliphant, 2012; Melamed et al. 2015; Suni et al. 2015; National Academies of Sciences, Engineering, and Medicine (NASEM); NASEM 2016], with limited focus on the interdisciplinary topic of air pollution–terrestrial ecosystem interactions (hereinafter only terrestrial ecosystems are referred to when mentioning ecosystems). Building process understanding of air pollution–ecosystem interactions is key for identifying past, present, and future changes in air quality, terrestrial ecosystems, and their impacts on human and natural systems. Key science questions where the current knowledge is limited by poor mechanistic understanding of air pollution–terrestrial ecosystem interactions include the following:

- How does air pollution affect terrestrial ecosystems, and how do terrestrial ecosystems influence air pollution?
- What are the chemical, meteorological, biophysical, and biogeochemical feedbacks influencing air pollution–terrestrial ecosystems interactions?
- How does climate internal variability influence these interactions and feedbacks?
- How do human-induced changes in emissions of greenhouse gases and air pollutants, land use and land cover, fires, and meteorology alter these interactions and feedbacks?

The recent Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) early-career workshop held in Boulder, Colorado, during 16–17 October 2019 discussed current challenges and future directions for advancing process understanding of air pollution–ecosystem interactions. Here, we argue that addressing the key science questions outlined above requires a coordinated network of long-term chemical flux measurements together with related meteorological and ecological observations spanning diverse regions and ecosystems. We emphasize that it is critical that the network also focuses on data standardization and curation, multiscale syntheses of observations, laboratory and field experiments, and process modeling, as well as collaborations across different scientific communities, geographic regions, and among scientists, stakeholders, and policymakers.

### Key elements and processes in air pollution–ecosystem interactions

There are myriad connections between air pollution and terrestrial ecosystems (e.g., Barth et al. 2005; Fowler et al. 2009; Arneth et al. 2011; Ainsworth et al. 2012; Kanakidou et al. 2018; Farmer and Riches 2020), but for many of the associated important elements and processes (Fig. 1) there is limited process understanding and hence predictive ability. Vegetation and soil are the interface between the atmosphere and terrestrial ecosystems through emissions and wet and dry deposition of air pollutants and related compounds.

Vegetation emits biogenic volatile organic compounds (BVOCs) (Guenther et al. 1991, 1995; Fuentes et al. 2000; Duhl et al. 2008), contributing to the formation of tropospheric ozone and PM. Vegetation also serves as sinks of air pollutants via dry deposition on plant surfaces (Wesely and Hicks, 2000; Fowler et al. 2009; Karl et al. 2010; Nguyen et al. 2015), which in some

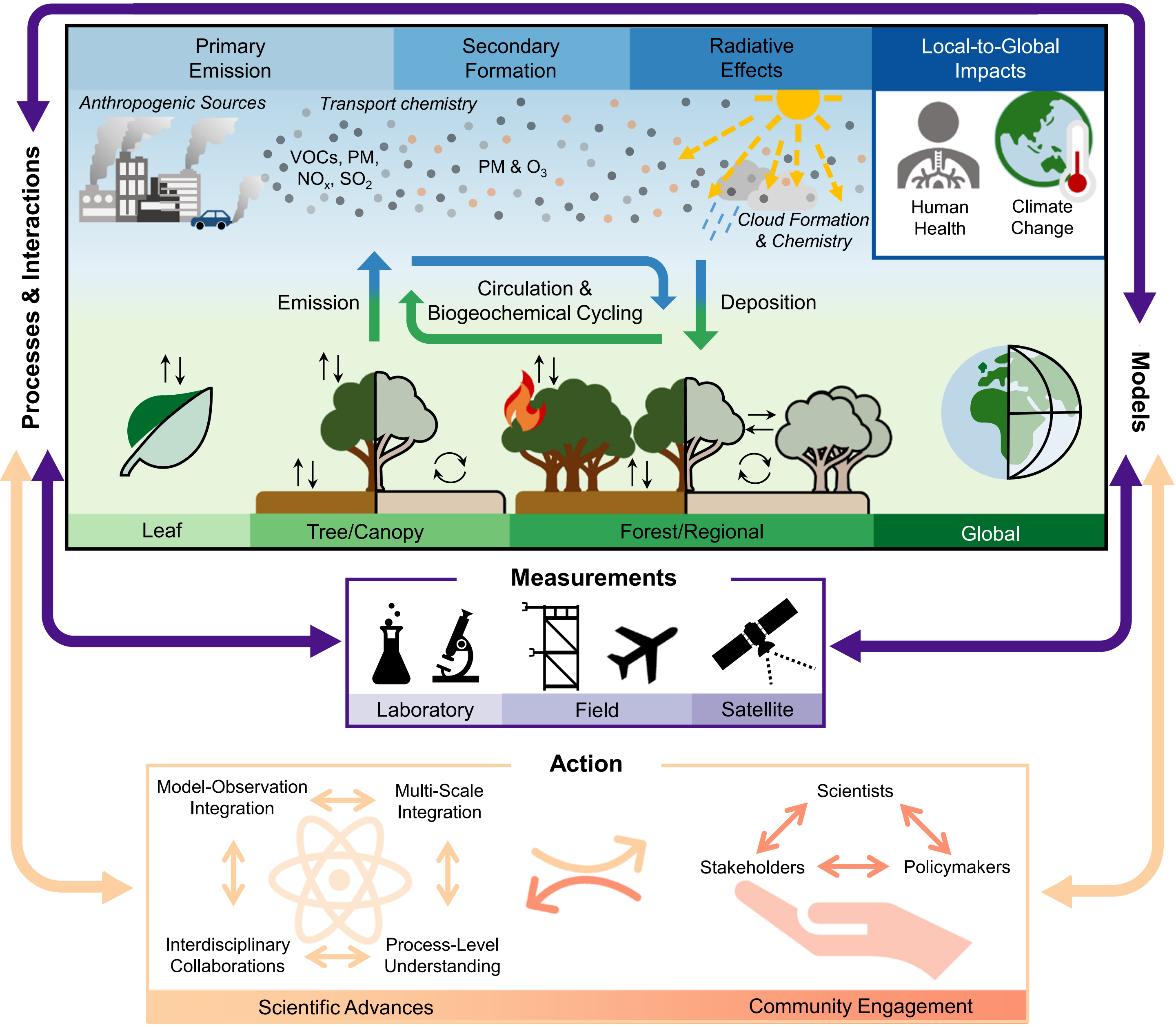

**Fig. 1. Demonstration of key elements and processes in air pollution–terrestrial ecosystem interactions, including vegetation and soil uptake and emissions of air pollutants and precursors, in-canopy turbulence, and effects of human activities, fires, and meteorology. To advance process knowledge of air pollution–ecosystem interactions, there is a need for a coordinated network of measurements (e.g., laboratory, field, and satellite), local-to-global modeling, and collaborations across scientific communities, geographic regions, and among scientists, stakeholders, and policymakers.**

cases is harmful to the plant. For instance, foliar damage is caused by dry deposition of ozone through plant stomata (Wittig et al. 2007; Lombardozzi et al. 2013). There is also evidence that dry deposition of ammonia (Krupa, 2003), nitrogen dioxide ($NO_2$) (Wingsle and Hällgren 1993), sulfur dioxide ($SO_2$) (Caporn et al. 2000), and PM (Grantz et al. 2003) changes stomatal conductance, water-use efficiency, and/or frost tolerance. Foliar damage from stomatal ozone uptake can change BVOC emissions (Loreto and Schnitzler 2010; Niinemets et al. 2010) and dry deposition, feeding back onto ground-level ozone concentrations (J. Li et al. 2016; Sadiq et al. 2017).

Besides dry deposition, wet deposition of air pollutants, particularly in the form of acid rain, also harms plant growth and productivity by damaging foliage (Sant'Anna-Santos et al. 2006) or reducing soil fertility (Singh and Agrawal 2007). Despite decades of mitigation efforts worldwide, acid rain is still a concern in some regions like Asia (Grennfelt et al. 2019), while wet deposition of reduced nitrogen has become increasingly important in the United States (Y. Li et al. 2016).

Soils are sources and sinks of air pollutants and precursors. For example, soils are sources of VOCs, nitric oxide, ammonia, and methane, and sinks of ozone, VOCs, $SO_2$, and PM (Fowler et al. 2009; Tang et al. 2019). Soil emissions are driven by chemical and microbial processes related to respiration, nitrification and denitrification, decomposition, and below-ground biomass. Dry and wet deposition to soil can affect soil chemistry (Singh and Agrawal 2007), the structure and function of microbial associations with roots (Bobbink et al. 1998; de Witte et al. 2017), biodiversity (Simkin et al. 2016), and biogeochemical and water cycling (Greaver et al. 2016).

Chemical reactions in canopy air spaces can influence vegetation and soil via dry deposition of air pollutants and related compounds, and affect regional-scale air quality and tropospheric chemistry when emitted compounds and chemical products are transported out of the canopy. For instance, certain BVOCs can react quickly with ozone inside forest canopies (Kurpius and Goldstein 2003; Goldstein et al. 2004) and hence enhance the formation of oxidized VOCs, oxidants (e.g., hydroxyl radical), and secondary organic aerosol (SOA) (Wolfe et al. 2011; Yee et al. 2018), which further impact climate (Unger 2014; Scott et al. 2018). BVOCs also react with the nitrate radical and subsequently change the production of oxidized compounds (Ng et al. 2017).

These processes (biogenic emissions, wet and dry deposition) and impacts on ecosystems and tropospheric chemistry can change with human activities, fires, and meteorology. This highlights the importance of understanding air pollution–ecosystem interactions from a mechanistic rather than empirical perspective. Building a process understanding of air pollution–ecosystem interactions will allow us to accurately estimate changes due to human activities and natural climate variability.

Anthropogenic emissions from fossil fuel and biofuel combustion in industrial, residential, transportation, power, and agricultural sectors directly produce large amounts of primary air pollutants (e.g., carbon monoxide, $NO_2$, $SO_2$, PM) and precursors contributing to secondary air pollutants (e.g., ozone and PM). Elevated air pollution due to high local-to-global anthropogenic emissions influences vegetation and soil health via dry and wet deposition as discussed above. The mixture of anthropogenic and biogenic emissions is also critical to estimate air quality accurately (Shilling et al. 2013; Zong et al. 2018). Some air pollutants, such as PM and ozone, are important short-lived climate forcers (IPCC 2013), which indirectly affect terrestrial ecosystems via altering meteorology and climate.

Increased atmospheric $CO_2$ concentrations due to anthropogenic emissions can enhance vegetation photosynthesis and leaf biomass (i.e., $CO_2$ fertilization effect; e.g., Cramer et al. 2001; Los 2013; Zhu et al. 2016; Mao et al. 2016), which influences dry deposition and biogenic emissions. $CO_2$ fertilization reduces emissions of BVOCs like isoprene and monoterpenes (e.g., Loreto and Schnitzler 2010; Feng et al. 2019), which is likely caused by changes in leaf metabolism (Rosenstiel et al. 2003) although the biochemical mechanism is not fully understood. This change in BVOCs emissions may affect ozone and PM formation (Tai et al. 2013; Hollaway et al. 2017). Elevated $CO_2$ also instantaneously reduces leaf stomatal conductance (Keenan et al. 2013; Feng et al. 2019) and hence alters stomatal uptake of air pollutants like ozone (Sanderson et al. 2007; Clifton et al. 2020b).

Changing land use and land cover through deforestation, land management, agricultural practices, and climate change directly alters ecosystem and land surface characteristics, such as vegetation type and cover, soil texture and structure, surface roughness and albedo. These surface changes can affect vegetation and soil emissions and dry deposition of air pollutants and precursors (Ganzeveld and Lelieveld 2004; Ganzeveld et al. 2010; Wu et al. 2012; Heald and Spracklen 2015; Fu and Tai 2015; Heald and Geddes 2016), some of which are short-lived climate forcers. Impacts on short-lived climate forcers and land–atmosphere exchanges of water and energy can alter meteorology and hence air pollution.

Fires contribute to air pollution by releasing a suite of reactive trace gases and smoke aerosols (Bond et al. 2004; Langmann et al. 2009; Akagi et al. 2011). These fire emissions influence climate, and fires also change ecosystem structure and composition by altering plant communities, carbon sequestration, and soil properties (Bowman et al. 2009; Pellegrini et al. 2015), therefore impacting dry deposition and vegetation and soil emissions. Changes in air pollution and the structure and composition of terrestrial ecosystems can create feedbacks with fires by altering land surfaces. For example, nitrogen deposition can fertilize soils making invasive grasses more competitive, intensifying fire cycles (Rao et al. 2010; Pyke et al. 2016). Deposition of smoke aerosols can accelerate snow melting by reducing albedo (Gleason et al. 2019; He and Flanner 2020), while earlier snow disappearance further causes moisture deficits, favoring fire occurrence and spread (Westerling et al. 2006).

Changes in meteorology from climate change can also alter air pollution–ecosystem interactions, because air pollution, vegetation and soil emissions, dry and wet deposition, and in-canopy chemistry strongly depend on meteorology (e.g., Kurpius and Goldstein 2003; Fowler et al. 2009; Andersson and Engardt 2010; Emberson et al. 2013; Fiore et al. 2015; Kavassalis and Murphy 2017; Zhao et al. 2017; Ding et al. 2019). Not only do large-scale transport patterns and turbulence influence the distribution of reactive gases and particles in the atmosphere and within plant canopies, respectively, but there are physical, chemical, plant physiological, and microbial controls on biogenic and soil emissions, deposition, and chemical reactions, all changing with temperature, humidity, solar radiation, and/or wetness.

## A call for a coordinated network of measurements, modeling, and collaboration

Predictive ability of air pollution–ecosystem interactions requires process understanding of chemical exchanges between the atmosphere and terrestrial ecosystems. Current process-based knowledge has been mainly gleaned from short-term flux data for only a few chemical species and sites around the world. For example, for ozone, arguably the most well-studied reactive trace gas in terms of land–atmosphere exchange, there are only ~10 sites with ozone flux data longer than five years (Clifton et al. 2020a). There are still many polluted regions without either short-term or long-term constraints on even ozone fluxes (Fig. 2a), including South and East Asia, Middle East, and South Africa, hindering understanding of how chemical fluxes influences air pollution over these locations. For other chemical species (e.g., $SO_2$, VOCs, and reactive nitrogen species), long-term flux observations are extremely limited. Given that chemical fluxes tend to vary strongly in time, datasets spanning longer periods (e.g., multiple years, until a climatological signal emerges from the noise of interannual variability) are necessary to quantify variability and trends accurately.

Identifying and building knowledge of the processes controlling chemical exchanges requires measurements to be well characterized in terms of ecology, biogeochemical cycling,

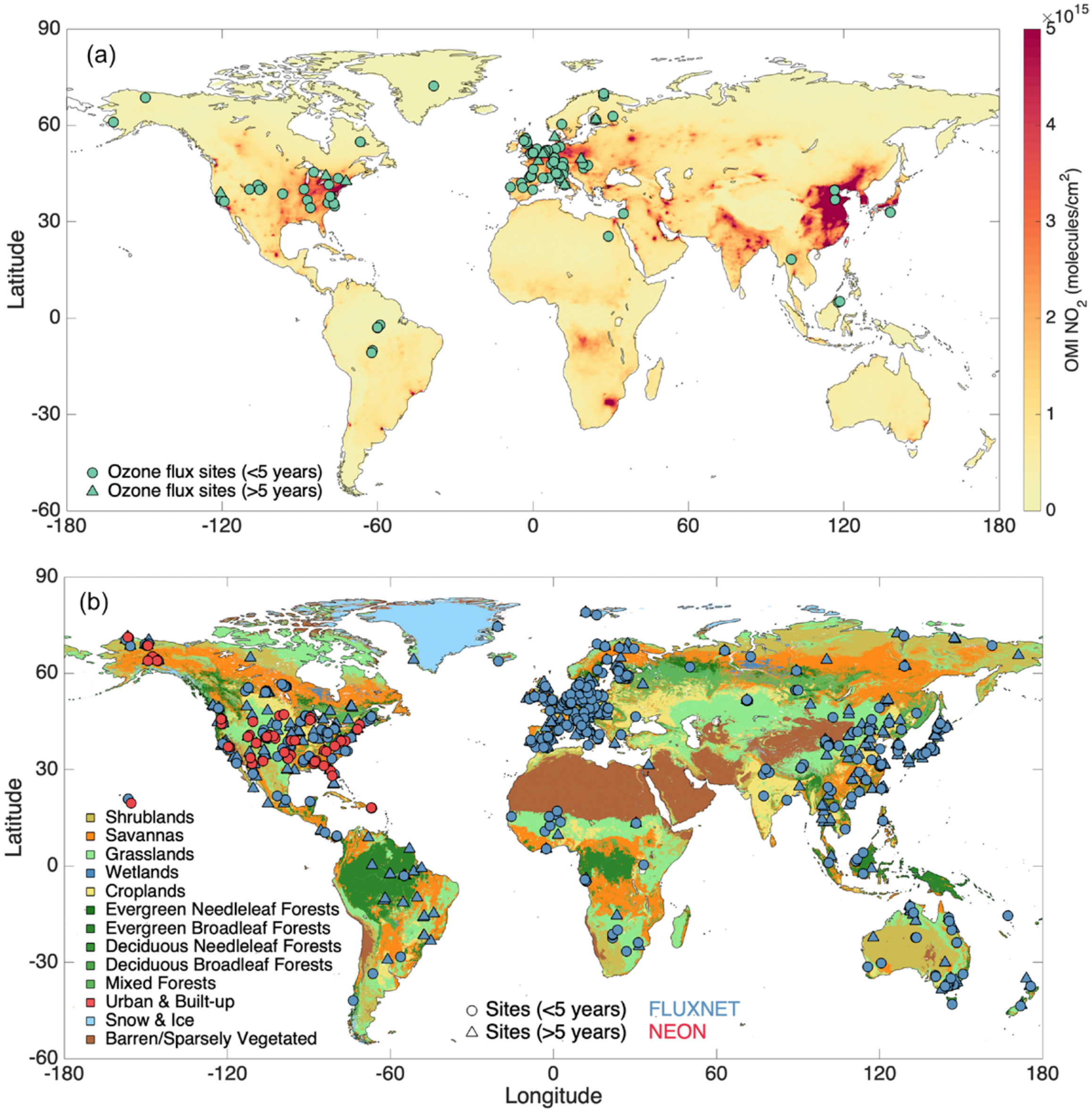

**Fig. 2. (a) Sites with ozone ecosystem-scale fluxes with monitoring time shorter (circles) or longer (triangles) than 5 years (Clifton et al. 2020a). The background of this map shows the 15-yr (2005–19) mean global $NO_2$ column burden from the Ozone Monitoring Instrument (OMI) satellite data (https://aura.gsfc.nasa.gov/omi.html) as an indicator for local air pollution. (b) Sites with ecosystem-scale energy, water, and/or carbon flux measurements with monitoring time shorter (circles) or longer (triangles) than 5 years, including FLUXNET (blue; Chu et al. 2017) and U.S. NEON (red; www.neonscience.org/field-sites/field-sites-map/list). The background of this map is 2019 global MODIS land cover (https://lpdaac.usgs.gov/products/mcd12c1v006).**

meteorology, and ambient composition (hereafter, sites with "a multidisciplinary set of measurements"). Building robust parameterizations in regional-to-global models, our best tools for advancing predictive ability of air pollution–ecosystem interactions, requires understanding of the generality of different processes and characteristics controlling land–atmosphere exchanges across climates, regions, and ecosystems (Fig. 1). This generality can be informed by a set of long-term comprehensive observations designed strategically within a network enabling robust comparison of flux data across individual sites.

The idea for sites with a multidisciplinary set of measurements (sometimes referred to as "flagship stations" or "supersites"; e.g., Hari et al. 2009; Mikkelsen et al. 2013) or sites that should be operated long term and coordinated across a network (e.g., Guenther et al. 2011) has been proposed in community discussions. However, a network of long-term chemical flux "supersites" or "flagship stations" has not been executed. A substantial impediment to executing a long-term network of chemical flux sites with a multidisciplinary set of measurements may be the lack of funding sources providing long-term investment. We see a continued need for long-term core funding from international government funding agencies worldwide and a diverse set of supplemental funding from nongovernment and private organizations.

The infrastructure of a coordinated network of observations is important to promote (i) strategic design of sites and set of measurements, (ii) data curation and standardization, (iii) syntheses of observations, experiments, and process modeling, (iv) collaborations across different scientific communities and geographic regions, and (v) connections among scientists, stakeholders and policymakers. We view these strategies i–v as critical to advance process understanding and predictive ability of air pollution–ecosystem interactions, and thus to address the key science questions outlined in the first section.

Detailed plans to implement our strategies/recommendations ("Strategic design of sites and set of measurements"–"Connections between scientists, stakeholders, and policymakers" sections) are presented in Table 1. Briefly, in the short term, we suggest synthesizing and archiving available observations (particularly for chemical fluxes) processed with standard data protocols, seeking out funding for short-term chemical flux measurements complementary to existing ecological and meteorological networks, and holding workshops to initiate comprehensive model evaluation and improvement projects and foster interdisciplinary collaborations on air pollution–ecosystem interactions. Agency and organization funding and support from stakeholders worldwide are key in establishing and maintaining a long-term measurement network to characterize air pollution–ecosystem interactions, continuously improving related data quality and model parameterizations, and maintaining collaborative projects and effective communication platforms across disciplines.

***Strategic design of sites and set of measurements.*** Prioritizing site locations and specific measurements within the network is fundamental for ensuring maximum knowledge gain from investment. There are several existing networks for ecological or atmospheric measurements [e.g., FLUXNET, https://fluxnet.fluxdata.org; National Ecological Observatory Network (NEON), https://neonscience.org], but they are not specifically designed for investigating air pollution–ecosystem interactions. Coordination among atmospheric and ecological research communities will be required to determine site locations and designs for targeted observables, including how existing networks such as FLUXNET or NEON can be leveraged. This is particularly important when funding and/or other resources are limited. When sites are not designed strategically with respect to atmospheric chemistry, it could be that sites included do not represent the full suite of chemical regimes (e.g., biogenic versus anthropogenic influences) or do not have the observables (e.g., fluxes for certain chemical species) required to advance the process understanding necessary to address the science questions outlined in the first section with confidence. On the other hand, when sites within a given network are not designed strategically with respect to ecology, it could be that the ecosystems represented among the sites are too similar, which limits process understanding of ecosystem–air pollution interactions at regional-to-global scales.

It is important to note that the majority of datasets from existing atmospheric or ecological networks, and current datasets related to air pollution–ecosystem interactions, are mostly from the northern midlatitudes. For instance, there are only a few FLUXNET sites in regions like Africa, South America, northern Russia and Canada, and Middle East (Fig. 2b). The lack of observations in many locations of the world hinders understanding of ecosystem–air pollution interactions at local-to-global scales, as the conditions and processes observed in northern

**Table 1. Implementation plans for a coordinated network of measurements, modeling, and collaborations recommended in this study to advance process knowledge of interactions between air pollution and terrestrial ecosystems.**

| Recommendations | Short-term implementations | Long-term implementations |
|---|---|---|
| Strategic design of the measurement network and a multidisciplinary set of measurements | • Collect and synthesize available observations on atmospheric chemistry, ecology, and meteorology, particularly chemical fluxes<br>• Archive data in a publicly available repository<br>• Explore the synthesized datasets to identify additional complementary measurements required in the future<br>• Seek out short-term funding opportunities to conduct complementary short-term measurements at or near existing ecological and/or meteorological sites/networks<br>• Establish site locations and multidisciplinary set of core measurements | • Obtain funding from agencies/organizations and support from stakeholders worldwide in establishing and maintaining a long-term measurement network for air pollution–ecosystem interactions |
| Data standardization and curation for measured chemical fluxes and state quantities | • Hold workshops/conferences to discuss standard data protocols on chemical flux measurements<br>• Standardize and curate available datasets and archive in a public repository<br>• Conduct uncertainty analysis for available datasets | • Implement and maintain the standard data protocol<br>• Continually improve data curation and quality control methods to reduce uncertainty |
| Multiscale syntheses of observations, experiments, and process modeling | • Hold workshops to gather observationalists, experimentalists, and modelers to discuss emergent science questions and needs to advance knowledge of air pollution–ecosystem interactions<br>• Initiate comprehensive model intercomparison and evaluation projects using the aforementioned synthesized available observations<br>• Improve parameterizations and reduce uncertainties for model processes across scales<br>• Upscale site measurements to regional-to-global using models and remote sensing data | • Seek out funding opportunities for comprehensive process-oriented model intercomparison and evaluation as well as improvements of model parameterizations |
| Collaborations across different scientific communities | • Initiate interdisciplinary reports to address key science questions related to air pollution–ecosystem interactions and the collaborative ways required to solve the questions<br>• Hold workshops to foster networking and collaborations among scientists from different fields and regions of the world<br>• Seek out funding opportunities for interdisciplinary projects, particularly involving scientists in understudied regions | • Obtain funding from national and international agencies and organizations to foster interdisciplinary and international programs |
| Connections among scientists, stakeholders, and policymakers | • Hold workshops to gather scientists, stakeholders, and policymakers to discuss emergent scientific, societal, and policy-related questions and collaborations<br>• Establish platforms for continuous and effective communications<br>• Seek out funding opportunities to establish collaborative projects among scientists, policymakers, and stakeholders | • Maintain the platforms for continuous and effective communications<br>• Obtain funding from agencies and stakeholders for more resources to establish collaborative projects among scientists, policymakers, and stakeholders |

midlatitudes may not be generalizable to other places. While leveraging existing networks of long-term chemical flux sites would likely lead to knowledge gains, they would exclude locations that have been historically understudied (e.g., South America, Africa, and Oceania). Many understudied locations in developing regions also have poor air quality (Fig. 2a), and thus there is the potential for air pollutants to impact the local environment and the need to understand the impact of local ecosystems on air quality for human health purposes.

In prioritizing site locations for observations related to air pollution–ecosystem interactions, attention should be paid to understudied regions, places with strong air pollution–ecosystem interactions, and places where changes in human activities and/or meteorology may lead to strong air pollution–ecosystem interactions. We note that global-scale analyses of observations (e.g., satellite data) and Earth system models (ESMs) are needed to identify regions with strong air pollution–ecosystem interactions.

It is important to leverage aircraft campaigns and satellite observations when designing ground measurement networks. Aircraft and satellite data can complement individual site measurements by providing regional-to-global constraints for some key land surface, meteorological, and chemical quantities. Coordination across different communities is needed to pursue short-term field campaigns to measure quantities that are infeasible for long-term observations.

- Takeaway: Strategic design of observational networks to represent different regions and ecosystems and measure chemical fluxes in the long term along with related meteorological and ecological quantities will allow for the comprehensive datasets needed to enhance predictive ability of land–atmosphere chemical exchanges.

***Data curation and standardization.*** Advancing process-based knowledge of chemical fluxes requires accessible standardized data across different sites and quantification of data uncertainty. Efforts to standardize and curate data and quantify data uncertainty are challenging, especially without funding, coordination, and oversight offered by a network. Currently, there is hardly any standardization, or common framework for review (e.g., quality control) and archival, across existing chemical flux datasets. Many older chemical flux datasets are not available online, hindering community awareness and access. Limited access to datasets, as well as insufficient metadata and nonstandardized data archival across available datasets, prevents the syntheses that are needed to build robust understanding of air pollution–ecosystem interactions. Metadata must include clarification of measurement processes, data uncertainty, and quality control. Overall, there is a strong need to establish a standard data protocol (e.g., data formatting, filtering, and correction) across sites.

- Takeaway: Network funding, coordination, and oversight will support the creation and maintenance of an accessible online repository for standardized chemical flux data, uncertainty, and metadata, enhancing understanding of chemical exchanges and changes in space and time.

***Multiscale syntheses of observations, experiments, and process modeling.*** Modeling and experimental studies should play a central role in the network of long-term chemical flux sites (Fig. 1). Involving laboratory scientists and modelers in designing the sites and the multidisciplinary set of measurements will help to identify the full suite of field observations needed to advance knowledge. In addition, complementary modeling and laboratory or chamber experiments that allow for testing hypotheses from flux tower data are essential for identifying the drivers of observed chemical fluxes, which for a given species represent the net effect of several uncertain and complex processes.

Current regional-to-global-scale models have large uncertainties and deficiencies in representing key parts of air pollution–ecosystem interactions (IPCC 2013; Dentener et al. 2006; Fowler et al. 2009; Hudman et al. 2012; Grote et al. 2014; Hardacre et al. 2015; Vivanco et al. 2018; Franz et al. 2018), including plant physiology, leaf biomass, soil properties, emission and uptake of chemical species by vegetation and soil, wet deposition, and the responses of ecosystems to air pollution and meteorology. Biogenic emission and dry deposition representations are largely empirical, with myriad tuning parameters, and thus it is uncertain how well these model treatments can represent changes with human activities and climate, or over ecosystems and regions where there are not a lot of data. Together with process modeling and laboratory or chamber experiments, field measurements can provide constraints on some key uncertain processes, hence facilitating the improvement of current model parameterizations related to air pollution–ecosystem interactions. Combining airborne and satellite data with process modeling is also necessary, specifically to translate the knowledge gleaned at the site level to regional-to-global scales and hence advance predictive ability across scales.

- Takeaway: A network can bring together field scientists with laboratory scientists and modelers to effectively use process understanding to interpret observations, build hypotheses that can be tested at other field sites or in the laboratory, and move across local-to-global scales.

***Collaborations across diverse scientific communities.*** Building an understanding of air pollution–ecosystem interactions requires initiating and sustaining connections among traditionally disparate scientific communities (Fig. 1). For example, designing network site locations, developing the multidisciplinary set of observations for the sites, and translating the knowledge gleaned from the site level to regional-to-global scales require expertise from a variety of disciplines. Universities and other research institutions, funding sources, journals, and conferences are often arranged by disciplines rather than scientific questions, limiting collaborative research and even exposure to the knowledge in fields other than one's own. Interdisciplinary workshops, conferences, reports (e.g., NASEM 2016; Wendling et al. 2018), and networks of scientists like iLEAPS (Suni et al. 2015) allow scientists to discuss collaborative projects, but initiating and sustaining collaborative research requires infrastructure.

A network across different scientific communities will also facilitate connections among scientists around the world. There is a need to advance understanding of air pollution–terrestrial ecosystem interactions in regions historically underrepresented in atmospheric and ecological observational datasets. Here "underrepresented regions" are places with potentially unique air pollution–terrestrial ecosystem interactions but without any or sufficient observations, such as Africa, South America, and Oceania. While local scientists make observations in underrepresented regions, funding opportunities are not always accessible or sufficient to cover the costs (e.g., labor, instrumentation, data storage, computational time, publication and travel) necessary to publicly distribute datasets and disseminate findings.

- Takeaway: A network as a mechanism for initiating and sustaining connections among scientists across disciplines and geographic regions will enhance communication of scientific findings and availability of data, funding, and other resources, which are key to advance knowledge of air pollution–ecosystem interactions at local-to-global scales.

***Connections between scientists, stakeholders, and policymakers.*** Meaningful collaboration between scientists, the people creating policy related to anthropogenic emissions or land use/land cover change (policymakers), and the people inhabiting or protecting the human and natural communities affected by air pollution (stakeholders) can inspire new research questions, spur scientific discovery, and lead to evidence-based decision-making (Fig. 1). However, meaningful collaboration requires flexibility and sustained dedication to improving mutual communication and building understanding and trust (e.g., Rose et al. 2018; Anenberg et al. 2020).

- Takeaway: A network that can promote meaningful collaborations and mutual understanding between scientists, stakeholders, and policymakers will ultimately foster actionable process-based science in the field of air pollution–terrestrial ecosystem interactions.

## Conclusions

Limited process knowledge of air pollution–terrestrial ecosystem interactions hinders predictive ability of tropospheric chemistry, ecosystems, and impacts on human and Earth systems. To advance the mechanistic understanding, we, an interdisciplinary group of early-career scientists, highlight the urgent need for a coordinated network of measurements, modeling, and collaborations across the globe. Such a network should have the following core foci:

1) a multidisciplinary set of long-term chemical flux measurements spanning different regions and ecosystems;
2) data standardization, accessibility, and curation;
3) integration of observations, laboratory and field experiments, and modeling across scales;
4) collaborations across different scientific communities and geographic regions; and
5) active involvement with stakeholders and policymakers.

A coordinated network of measurements, modeling, and collaborations across the globe, implemented as suggested here, would allow us to confidently address the big-picture scientific questions related to interactions between air pollution and terrestrial ecosystems.

**Acknowledgments.** We acknowledge the support and encouragement of the iLEAPS International Project Office (U.K. NERC Research Grant NE/P008615/1). The authors thank the iLEAPS Scientific Steering Committee and team for their strong support and considerate arrangements in the 2019 iLEAPS early-career workshop. The authors thank all the workshop attendees for their valuable discussions at the workshop. This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement 1852977.

## References

Ainsworth, E. A., C. R. Yendrek, S. Sitch, W. J. Collins, and L. D. Emberson, 2012: The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annu. Rev. Plant Biol.*, **63**, 637–661, https://doi.org/10.1146/annurev-arplant-042110-103829.

Akagi, S. K., R. J. Yokelson, C. Wiedinmyer, M. J. Alvarado, J. S. Reid, T. Karl, J. D. Crounse, and P. O. Wennberg, 2011: Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmos. Chem. Phys.*, **11**, 4039–4072, https://doi.org/10.5194/acp-11-4039-2011.

Andersson, C., and M. Engardt, 2010: European ozone in a future climate: Importance of changes in dry deposition and isoprene emissions. *J. Geophys. Res.*, **115**, D02303, https://doi.org/10.1029/2008JD011690.

Anenberg, S. C., and Coauthors, 2020: Using satellites to track indicators of global air pollution and climate change impacts: Lessons learned from a NASA-supported science-stakeholder collaborative. *GeoHealth*, **4**, e2020GH000270, https://doi.org/10.1029/2020GH000270.

Arneth, A., and Coauthors, 2011: Global terrestrial isoprene emission models: Sensitivity to variability in climate and vegetation. *Atmos. Chem. Phys.*, **11**, 8037–8052, https://doi.org/10.5194/acp-11-8037-2011.

Barth, M., and Coauthors, 2005: Coupling between land ecosystems and the atmospheric hydrologic cycle through biogenic aerosol pathways. *Bull. Amer. Meteor. Soc.*, **86**, 1738–1742, https://doi.org/10.1175/BAMS-86-12-1738.

Bobbink, R., M. Hornung, and J. G. M. Roelofs, 1998: The effects of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation. *J. Ecol.*, **86**, 717–738, https://doi.org/10.1046/j.1365-2745.1998.8650717.x.

Bond, T. C., D. G. Street, K. F. Yarber, S. M. Nelson, J.-H. Woo, and Z. Klimont, 2004: A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.*, **109**, D14203, https://doi.org/10.1029/2003JD003697.

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

Caporn, S. J. M., T. W. Ashenden, and J. A. Lee, 2000: The effect of exposure to $NO_2$ and $SO_2$ on frost hardiness in *Calluna vulgaris*. *Environ. Exp. Bot.*, **43**, 111–119, https://doi.org/10.1016/S0098-8472(99)00050-7.

Chu, H., D. D. Baldocchi, R. John, S. Wolf, and M. Reichstein, 2017: Fluxes all of the time? A primer on the temporal representativeness of FLUXNET. *J. Geophys. Res. Biogeosci.*, **122**, 289–307, https://doi.org/10.1002/2016JG003576.

Clifton, O. E., and Coauthors, 2020a: Dry deposition of ozone over land: Processes, measurement, and modeling. *Rev. Geophys.*, **58**, e2019RG000670, https://doi.org/10.1029/2019RG000670.

——, and Coauthors, 2020b: Influence of dynamic ozone dry deposition on ozone pollution. *J. Geophys. Res. Atmos.*, **125**, e2020JD032398, https://doi.org/10.1029/2020JD032398.

Cramer, W., and Coauthors, 2001: Global response of terrestrial ecosystem structure and function to $CO_2$ and climate change: Results from six dynamic global vegetation models. *Global Change Biol.*, **7**, 357–373, https://doi.org/10.1046/j.1365-2486.2001.00383.x.

Dentener, F., and Coauthors, 2006: Nitrogen and sulfur deposition on regional and global scales: A multimodel evaluation. *Global Biogeochem. Cycles*, **20**, GB4003, https://doi.org/10.1029/2005GB002672.

de Witte, L. C., N. P. Rosenstock, S. Van Der Linde, and S. Braun, 2017: Nitrogen deposition changes ectomycorrhizal communities in Swiss beech forests. *Sci. Total Environ.*, **605–606**, 1083–1096, https://doi.org/10.1016/j.scitotenv.2017.06.142.

Ding, S., and Coauthors, 2019: Observed interactions between black carbon and hydrometeor during wet scavenging in mixed-phase clouds. *Geophys. Res. Lett.*, **46**, 8453–8463, https://doi.org/10.1029/2019GL083171.

Duhl, T. R., D. Helmig, and A. Guenther, 2008: Sesquiterpene emissions from vegetation: A review. *Biogeosciences*, **5**, 761–777, https://doi.org/10.5194/bg-5-761-2008.

Emberson, L. D., N. Kitwiroon, S. Beevers, P. Büker, and S. Cinderby, 2013: Scorched Earth: How will changes in the strength of the vegetation sink to ozone deposition affect human health and ecosystems? *Atmos. Chem. Phys.*, **13**, 6741–6755, https://doi.org/10.5194/acp-13-6741-2013.

Farmer, D. K., and M. Riches, 2020: Measuring biosphere–atmosphere exchange of short-lived climate forcers and their precursors. *Acc. Chem. Res.*, **53**, 1427–1435, https://doi.org/10.1021/acs.accounts.0c00203.

Feng, Z., X. Yuan, S. Fares, F. Loreto, P. Li, Y. Hoshika, and E. Paoletti, 2019: Isoprene is more affected by climate drivers than monoterpenes: A meta-analytic review on plant isoprenoid emissions. *Plant Cell Environ.*, **42**, 1939–1949, https://doi.org/10.1111/pce.13535.

Fiore, A. M., V. Naik, and E. M. Leibensperger, 2015: Air quality and climate connections. *J. Air Waste Manage. Assoc.*, **65**, 645–685, https://doi.org/10.1080/10962247.2015.1040526.

Fowler, D., and Coauthors, 2009: Atmospheric composition change: Ecosystems–atmosphere interactions. *Atmos. Environ.*, **43**, 5193–5267, https://doi.org/10.1016/j.atmosenv.2009.07.068.

Franz, M., and Coauthors, 2018: Evaluation of simulated ozone effects in forest ecosystems against biomass damage estimates from fumigation experiments. *Biogeosciences*, **15**, 6941–6957, https://doi.org/10.5194/bg-15-6941-2018.

Fu, Y., and A. P. K. Tai, 2015: Impact of climate and land cover changes on tropospheric ozone air quality and public health in East Asia between 1980 and 2010. *Atmos. Chem. Phys.*, **15**, 10093–10106, https://doi.org/10.5194/acp-15-10093-2015.

Fuentes, J. D., and Coauthors, 2000: Biogenic hydrocarbons in the atmospheric boundary layer: A review. *Bull. Amer. Meteor. Soc.*, **81**, 1537–1576, https://doi.org/10.1175/1520-0477(2000)081<1537:BHITAB>2.3.CO;2.

Ganzeveld, L., and J. Lelieveld, 2004: Impact of Amazonian deforestation on atmospheric chemistry. *Geophys. Res. Lett.*, **31**, L06105, https://doi.org/10.1029/2003GL019205.

——, L. Bouwman, E. Stehfest, D. P. van Vuuren, B. Eickhout, and J. Lelieveld, 2010: Impact of future land use and land cover changes on atmospheric chemistry-climate interactions. *J. Geophys. Res.*, **115**, D23301, https://doi.org/10.1029/2010JD014041.

Gleason, K. E., J. R. McConnell, M. M. Arienzo, N. Chellman, and W. M. Calvin, 2019: Four-fold increase in solar forcing on snow in western US burned forests since 1999. *Nat. Commun.*, **10**, 2026, https://doi.org/10.1038/S41467-019-09935-Y.

Goldstein, A. H., M. McKay, M. R. Kurpius, G. W. Schade, A. Lee, R. Holzinger, and R. A. Rasmussen, 2004: Forest thinning experiment confirms ozone deposition to forest canopy is dominated by reaction with biogenic VOCs. *Geophys. Res. Lett.*, **31**, L22106, https://doi.org/10.1029/2004GL021259.

Grantz, D. A., J. H. B. Garner, and D. W. Johnson, 2003: Ecological effects of particulate matter. *Environ. Int.*, **29**, 213–239, https://doi.org/10.1016/S0160-4120(02)00181-2.

Greaver, T. L., and Coauthors, 2016: Key ecological responses to nitrogen are altered by climate change. *Nat. Climate Change*, **6**, 836–843, https://doi.org/10.1038/nclimate3088.

Grennfelt, P., A. Engleryd, M. Forsius, Ø. Hov, H. Rodhe, and E. Cowling, 2019: Acid rain and air pollution: 50 years of progress in environmental science and policy. *Ambio*, **49**, 849–864, https://doi.org/10.1007/S13280-019-01244-4.

Grote, R., and Coauthors, 2014: A fully integrated isoprenoid emissions model coupling emissions to photosynthetic characteristics. *Plant Cell Environ.*, **37**, 1965–1980, https://doi.org/10.1111/pce.12326.

Guenther, A. B., R. K. Monson, and R. Fall, 1991: Isoprene and monoterpene emission rate variability: Observations with eucalyptus and emission rate algorithm development. *J. Geophys. Res.*, **96**, 10799–10808, https://doi.org/10.1029/91JD00960.

——, and Coauthors, 1995: A global model of natural volatile organic compound emissions. *J. Geophys. Res.*, **100**, 8873–8892, https://doi.org/10.1029/94JD02950.

——, M. Kulmala, A. Turnipseed, J. Rinne, T. Suni, and A. Reissell, 2011: Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) assessment of global observational networks. *Boreal Environ. Res.*, **16**, 321–336, www.borenv.net/BER/archive/pdfs/ber16/ber16-321.pdf.

Hardacre, C., O. Wild, and L. Emberson, 2015: An evaluation of ozone dry deposition in global scale chemistry climate models. *Atmos. Chem. Phys.*, **15**, 6419–6436, https://doi.org/10.5194/acp-15-6419-2015.

Hari, P., M. O. Andreae, P. Kabat, and M. Kulmala, 2009: A comprehensive network of measuring stations to monitor climate change. *Boreal Environ. Res.*, **14**, 442–446, www.borenv.net/BER/archive/pdfs/ber14/ber14-442.pdf.

He, C., and M. Flanner, 2020: *Snow Albedo and Radiative Transfer: Theory, Modeling, and Parameterization*. Springer Series in Light Scattering, Springer, 67–133.

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

——, and J. A. Geddes, 2016: The impact of historical land use change from 1850 to 2000 on secondary particulate matter and ozone. *Atmos. Chem. Phys.*, **16**, 14 997–15 010, https://doi.org/10.5194/acp-16-14997-2016.

Hollaway, M. J., S. R. Arnold, W. J. Collins, G. Folberth, and A. Rap, 2017: Sensitivity of midnineteenth century tropospheric ozone to atmospheric chemistry-vegetation interactions. *J. Geophys. Res. Atmos.*, **122**, 2452–2473, https://doi.org/10.1002/2016JD025462.

Hudman, R. C., and Coauthors, 2012: Steps towards a mechanistic model of global soil nitric oxide emissions: Implementation and space based-constraints. *Atmos. Chem. Phys.*, **12**, 7779–7795, https://doi.org/10.5194/acp-12-7779-2012.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis.* Cambridge University Press, 1535 pp., https://doi.org/10.1017/CBO9781107415324.

Kanakidou, M., S. Myriokefalitakis, and K. Tsigaridis, 2018: Aerosols in atmospheric chemistry and biogeochemical cycles of nutrients. *Environ. Res. Lett.*, **13**, 063004, https://doi.org/10.1088/1748-9326/aabcdb.

Karl, T., and Coauthors, 2010: Efficient atmospheric cleansing of oxidized organic trace gases by vegetation. *Science*, **330**, 816–819, https://doi.org/10.1126/science.1192534.

Kavassalis, S. C., and J. G. Murphy, 2017: Understanding ozone-meteorology correlations: A role for dry deposition. *Geophys. Res. Lett.*, **44**, 2922–2931, https://doi.org/10.1002/2016GL071791.

Keenan, T. F., D. Y. Hollinger, G. Bohrer, D. Dragoni, J. W. Munger, H. P. Schmid, and A. D. Richardson, 2013: Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature*, **499**, 324–327, https://doi.org/10.1038/nature12291.

Krupa, S. V., 2003: Effects of atmospheric ammonia ($NH_3$) on terrestrial vegetation: A review. *Environ. Pollut.*, **124**, 179–221, https://doi.org/10.1016/S0269-7491(02)00434-7.

Kurpius, M. R., and A. H. Goldstein, 2003: Gas-phase chemistry dominates $O_3$ loss to a forest, implying a source of aerosols and hydroxyl radicals to the atmosphere. *Geophys. Res. Lett.*, **30**, 1371, https://doi.org/10.1029/2002GL016785.

Langmann, B., B. Duncan, C. Textor, J. Trentmann, and G. R. van der Werf, 2009: Vegetation fire emissions and their impact on air pollution and climate. *Atmos. Environ.*, **43**, 107–116, https://doi.org/10.1016/j.atmosenv.2008.09.047.

Li, J., A. Mahalov, and P. Hyde, 2016: Simulating the impacts of chronic ozone exposure on plant conductance and photosynthesis, and on the regional hydroclimate using WRF/Chem. *Environ. Res. Lett.*, **11**, 114017, https://doi.org/10.1088/1748-9326/11/11/114017.

Li, Y., and Coauthors, 2016: Increasing importance of deposition of reduced nitrogen in the United States. *Proc. Natl. Acad. Sci. USA*, **113**, 5874–5879, https://doi.org/10.1073/pnas.1525736113.

Lombardozzi, D., J. P. Sparks, and G. Bonan, 2013: Integrating $O_3$ influences on terrestrial processes: Photosynthetic and stomatal response data available for regional and global modeling. *Biogeosciences*, **10**, 6815–6831, https://doi.org/10.5194/bg-10-6815-2013.

Loreto, F., and J. P. Schnitzler, 2010: Abiotic stresses and induced BVOCs. *Trends Plant Sci.*, **15**, 154–166, https://doi.org/10.1016/j.tplants.2009.12.006.

Los, S. O., 2013: Analysis of trends in fused AVHRR and MODIS NDVI data for 1982–2006: Indication for a $CO_2$ fertilization effect in global vegetation. *Global Biogeochem. Cycles*, **27**, 318–330, https://doi.org/10.1002/gbc.20027.

Mao, J., and Coauthors, 2016: Human-induced greening of the northern extratropical land surface. *Nat. Climate Change*, **6**, 959–963, https://doi.org/10.1038/nclimate3056.

Melamed, M. L., and Coauthors, 2015: The International Global Atmospheric Chemistry (IGAC) project: Facilitating atmospheric chemistry research for 25 years. *Anthropocene*, **12**, 17–28, https://doi.org/10.1016/j.ancene.2015.10.001.

Mikkelsen, T. N., and Coauthors, 2013: Towards supersites in forest ecosystem monitoring and research. *Developments in Environmental Science*, Vol. 13, Elsevier, 475–496.

NASEM, 2016: *The Future of Atmospheric Chemistry Research: Remembering Yesterday, Understanding Today, Anticipating Tomorrow*. National Academies Press, 208 pp., https://doi.org/10.17226/23573.

Ng, N. L., and Coauthors, 2017: Nitrate radicals and biogenic volatile organic compounds: Oxidation, mechanisms, and organic aerosol. *Atmos. Chem. Phys.*, **17**, 2103–2162, https://doi.org/10.5194/acp-17-2103-2017.

Nguyen, T. B., and Coauthors, 2015: Rapid deposition of oxidized biogenic compounds to a temperate forest. *Proc. Natl. Acad. Sci. USA*, **112**, E392–E401, https://doi.org/10.1073/pnas.1418702112.

Niinemets, Ü., and Coauthors, 2010: The emission factor of volatile isoprenoids: Stress, acclimation, and developmental responses. *Biogeosciences*, **7**, 2203–2223, https://doi.org/10.5194/bg-7-2203-2010.

Oliphant, A. J., 2012: Terrestrial ecosystem-atmosphere exchange of $CO_2$, water and energy from FLUXNET; review and meta-analysis of a global in-situ observatory. *Geogr. Compass*, **6**, 689–705, https://doi.org/10.1111/gec3.12009.

Pellegrini, A. F., L. O. Hedin, A. C. Staver, and N. Govender, 2015: Fire alters ecosystem carbon and nutrients but not plant nutrient stoichiometry or composition in tropical savanna. *Ecology*, **96**, 1275–1285, https://doi.org/10.1890/14-1158.1.

Pyke, D. A., J. C. Chambers, J. L. Beck, M. L. Brooks, and B. A. Mealor, 2016: Land uses, fire, and invasion: Exotic annual *Bromus* and human dimensions. *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US*, Springer, 307–337.

Rao, L. E., E. B. Allen, and T. Meixner, 2010: Risk-based determination of critical nitrogen deposition loads for fire spread in Southern California deserts. *Ecol. Appl.*, **20**, 1320–1335, https://doi.org/10.1890/09-0398.1.

Rose, D. C., and Coauthors, 2018: The major barriers to evidence-informed conservation policy and possible solutions. *Conserv. Lett.*, **11**, e12564, https://doi.org/10.1111/conl.12564.

Rosenstiel, T. N., and Coauthors, 2003: Increased $CO_2$ uncouples growth from isoprene emission in an agriforest ecosystem. *Nature*, **421**, 256–259, https://doi.org/10.1038/nature01312.

Sadiq, M., A. P. K. Tai, D. Lombardozzi, and M. V. Martin, 2017: Effects of ozone–vegetation coupling on surface ozone air quality via biogeochemical and meteorological feedbacks. *Atmos. Chem. Phys.*, **17**, 3055–3066, https://doi.org/10.5194/acp-17-3055-2017.

Sanderson, M. G., W. J. Collins, D. L. Hemming, and R. A. Betts, 2007: Stomatal conductance changes due to increasing carbon dioxide levels: Projected impact on surface ozone levels. *Tellus*, **59B**, 404–411, https://doi.org/10.1111/j.1600-0889.2007.00277.x.

Sant'Anna-Santos, B. F., and Coauthors, 2006: Effects of simulated acid rain on the foliar micromorphology and anatomy of tree tropical species. *Environ. Exp. Bot.*, **58**, 158–168, https://doi.org/10.1016/j.envexpbot.2005.07.005.

Scott, C. E., S. R. Arnold, S. A. Monks, A. Asmi, P. Paasonen, and D. V. Spracklen, 2018: Substantial large-scale feedbacks between natural aerosols and climate. *Nat. Geosci.*, **11**, 44–48, https://doi.org/10.1038/s41561-017-0020-5.

Shilling, J. E., and Coauthors, 2013: Enhanced SOA formation from mixed anthropogenic and biogenic emissions during the CARES campaign. *Atmos. Chem. Phys.*, **13**, 2091–2113, https://doi.org/10.5194/acp-13-2091-2013.

Simkin, S. M., and Coauthors, 2016: Conditional vulnerability of plant diversity to atmospheric nitrogen deposition across the United States. *Proc. Natl. Acad. Sci. USA*, **113**, 4086–4091, https://doi.org/10.1073/pnas.1515241113.

Singh, A., and M. Agrawal, 2007: Acid rain and its ecological consequences. *J. Environ. Biol.*, **29**, 15–24, http://jeb.co.in/journal_issues/200801_jan08/paper_02.pdf.

Suni, T., and Coauthors, 2015: The significance of land-atmosphere interactions in the Earth system—iLEAPS achievements and perspectives. *Anthropocene*, **12**, 69–84, https://doi.org/10.1016/j.ancene.2015.12.001.

Tai, A. P., L. J. Mickley, C. L. Heald, and S. Wu, 2013: Effect of $CO_2$ inhibition on biogenic isoprene emission: Implications for air quality under 2000 to 2050 changes in climate, vegetation, and land use. *Geophys. Res. Lett.*, **40**, 3479–3483, https://doi.org/10.1002/grl.50650.

Tang, J., G. Schurgers, and R. Rinnan, 2019: Process understanding of soil BVOC fluxes in natural ecosystems: A review. *Rev. Geophys.*, **57**, 966–986, https://doi.org/10.1029/2018RG000634.

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

Vivanco, M. G., and Coauthors, 2018: Modeled deposition of nitrogen and sulfur in Europe estimated by 14 air quality model systems: Evaluation, effects of changes in emissions and implications for habitat protection. *Atmos. Chem. Phys.*, **18**, 10 199–10 218, https://doi.org/10.5194/acp-18-10199-2018.

Wendling, Z. A., J. W. Emerson, D. C. Esty, M. A. Levy, and A. De Sherbinin, 2018: Environmental performance index. Yale Center for Environmental Law and Policy, https://epi.yale.edu/.

Wesely, M. L., and B. B. Hicks, 2000: A review of the current status of knowledge on dry deposition. *Atmos. Environ.*, **34**, 2261–2282, https://doi.org/10.1016/S1352-2310(99)00467-7.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006: Warming and earlier spring increase western US forest wildfire activity. *Science*, **313**, 940–943, https://doi.org/10.1126/science.1128834.

Wingsle, G., and J. E. Hällgren, 1993: Influence of $SO_2$ and $NO_2$ exposure on glutathione, superoxide dismutase and glutathione reductase activities in Scots pine needles. *J. Exp. Bot.*, **44**, 463–470, https://doi.org/10.1093/jxb/44.2.463.

Wittig, V. E., Ainsworth, E. A., and Long, S. P. 2007: To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments. *Plant Cell Environ*, **30**, 1150–1162, https://doi.org/10.1111/J.1365-3040.2007.01717.X.

Wolfe, G. M., J. A. Thornton, M. McKay, and A. H. Goldstein, 2011: Forest-atmosphere exchange of ozone: Sensitivity to very reactive biogenic VOC emissions and implications for in-canopy photochemistry. *Atmos. Chem. Phys.*, **11**, 7875–7891, https://doi.org/10.5194/acp-11-7875-2011.

Wu, S., L. J. Mickley, J. O. Kaplan, and D. J. Jacob, 2012: Impacts of changes in land use and land cover on atmospheric chemistry and air quality over the 21st century. *Atmos. Chem. Phys.*, **12**, 1597–1609, https://doi.org/10.5194/acp-12-1597-2012.

Yee, L. D., and Coauthors, 2018: Observations of sesquiterpenes and their oxidation products in central Amazonia during the wet and dry seasons. *Atmos. Chem. Phys.*, **18**, 10 433–10 457, https://doi.org/10.5194/acp-18-10433-2018.

Zhao, B., and Coauthors, 2017: Enhanced $PM_{2.5}$ pollution in China due to aerosol-cloud interactions. *Sci. Rep.*, **7**, 4453, https://doi.org/10.1038/S41598-017-04096-8.

Zhu, Z., and Coauthors, 2016: Greening of the Earth and its drivers. *Nat. Climate Change*, **6**, 791–795, https://doi.org/10.1038/nclimate3004.

Zong, R., and Coauthors, 2018: Strong ozone production at a rural site in the North China Plain: Mixed effects of urban plumes and biogenic emissions. *J. Environ. Sci.*, **71**, 261–270, https://doi.org/10.1016/j.jes.2018.05.003.