# Air Quality Impacts on Crop and Ecosystem health

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***What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?***

Crop yields, ecosystem health, and carbon cycling substantially depend on ground-level ozone concentrations because ozone enters plant stomata and oxidizes tissue, thereby inhibiting photosynthesis and reducing stomatal conductance and carbon uptake [e.g., *Reich and Amundson,* 1985]. Likewise, enhanced nitrogen deposition is a primary cause of biodiversity loss [*Bobbink et al.*, 2010] and can perturb carbon sequestration [*Reay et al.*, 2008]. Satellite and other measurements of ozone and $NO_2$, which accounts for up to 1/3 of dry-deposited $NO_y$, show increasing concentrations in regions with large populations and significant biomass such as India, East Asia, and Africa. Levels of these pollutants are expected to continue to increase due to industrialization, population growth in conjunction with increased energy use per capita, and expansion of agricultural burning. Their impact on crop health (and thus food security) and ecosystems and the subsequent changes in carbon uptake are highly uncertain and represent a key gap in our knowledge of the Earth system. The challenge of understanding these relationships was endorsed as a critical research and applications need by the GEO-CAPE Atmospheric Science Working Group (ASWG) at a recent community workshop. This ASWG represents a broad cross-section of ~35 scientists from universities and government laboratories who have contributed to pre-formulation studies for the air quality component of the GEO-CAPE mission recommended by the 2007 Decadal Survey [http://geo-cape.larc.nasa.gov/].

Ozone has been shown to affect crop yields at concentrations as low as 40 ppb. However, up-scaling site-level findings to the regional and ultimately global scale is extremely challenging and fraught with uncertainty. Nevertheless, studies show substantial global economic consequences of ozone-induced crop damage, exceeding tens of billions of dollars annually [e.g. *Wang and Mauzerall*, 2004]. For example, *Ghude et al.* [2014] find that up to 9% of the Indian cereal crop, enough to feed over 94 million people, is lost due to ground-level ozone. Furthermore, *Sitch et al.* [2007] predict that the expected increase in ozone concentrations over the next century could reduce carbon uptake by plants to the extent that the resulting indirect radiative forcing would be as large as the direct forcing from tropospheric ozone. *Reay et al.* [2008], on the other hand, find that large increases in nitrogen deposition to both northern and tropical forests over the next few decades could help to sequester up to 10% of annual anthropogenic $CO_2$ emissions, but note that the caveats to the numerous extrapolations used to calculate the result are "legion". Reflecting in part the large uncertainties and potentially serious consequences of the impacts of changes in atmospheric composition on the terrestrial biosphere, the World Climate Research Programme recently endorsed "Biogeochemical forcings and feedbacks" as a Theme of Collaboration, similar in scope to the Grand Challenges.

Key questions that must be addressed to reduce these uncertainties are:

1. What controls near-surface ozone and $NO_2$ concentrations, particularly in tropical regions with large biomass concentrations?

2. What is the relationship between crop and ecosystem health and near-surface ozone and $NO_2$ levels across a range of vegetation types?
3. How does gross primary production, and thus carbon uptake, vary with surface ozone and $NO_2$ concentrations and deposition?

***Why are these challenges/questions timely to address now especially with respect to readiness?***

This is a critical time to address the issue of air quality impacts on crop and ecosystem health, given the expected rapid changes in ozone and $NO_2$ from changes in land use, population growth, and industrialization over the next several decades that threaten food security and may significantly impact terrestrial carbon uptake. There has been much progress in recent years toward using satellite data to quantify ozone pre-cursor emissions. Studies have successfully related changes in these precursors to changes in tropospheric ozone [e.g., *Verstraeten et al.*, 2015] and shown that these data can be combined with models to place constraints on near-surface ozone, particularly when augmented with in situ measurements [e.g. *Huang et al.* 2015]. New multispectral retrievals demonstrate the capability to directly measure near-surface ozone from space using a combination of reflected sunlight in the ultraviolet and visible with thermal IR radiances [e.g., *Worden et al.*, 2007; *Natraj et al.*, 2011; *Worden et al.*, 2010] and the first satellite-based estimate of global $NO_2$ dry deposition has recently been produced [Nowlan et al., 2014]. Our ability to use satellite measurements to understand the links between precursor emissions and near-surface ozone is expected to grow even more with the launch of the upcoming geostationary Earth orbit (GEO) missions TEMPO (NASA), GEMS (KARI), and Sentinel-4 (ESA), but assessing the impacts of air pollution on crops and ecosystems will continue to require massive extrapolation of site-level relationships between atmospheric concentrations and changes in plant physiology.

At the same time, our ability to gauge ecosystem health from space is growing rapidly. New measurements of photosynthesis using plant fluorescence in the near IR have been used to provide constraints on global and regional gross primary production [e.g., *Frankenberg et al.*, 2011; *Guanter et al.*, 2014]. The Earth Venture ECOSTRESS instrument will measure water stress, a potentially confounding factor with physiological effects similar to those of air pollution. Hyperspectral visible light measurements have been shown to provide key insights into vegetation health, including chlorophyll abundance and leaf relative water content [e.g., *Treitz and Howarth*, 1999]. New collocated $CO_2$ and fluorescence measurements from OCO-2 are advancing our understanding of the links between GPP, respiration, and carbon cycling. Currently, however, there is no way to relate any of these measurements to ozone and $NO_2$ concentrations with the spatial and temporal resolution required to understand the relationship between air quality and ecosystem health.

***Why are space-based observations fundamental to addressing these challenges/questions?***

While ground-based measurements have been key to understanding that ozone and $NO_2$ negatively affect plants and therefore impact carbon cycling, only a space-based observing strategy can provide the large numbers of measurements with high spatiotemporal resolution and regional or global coverage required to characterize the sources and transport of these pollutants and quantify their effects on different biomes in different regions. At the same time, aircraft and ground-based observations of $CO_2$ (such as those from FLUXNET), ozone, $NO_2$, and plant biomarkers will be critical to establish relationships between, for example, ozone concentrations and deposition rates and between plant damage and carbon uptake that can be used to calibrate and interpret the satellite measurements.

The new Decadal Survey offers the opportunity to develop a new satellite or system of satellites that measures the relationships between air quality and ecosystem function in an integrated way at the relevant scales required to address the fundamental yet unresolved science questions described above. While the technologies for the needed measurements are mature, the exact measurement requirements for such a mission (e.g. spatiotemporal resolution and precision) are not currently well-understood. Strong diurnal cycles in pollutant concentrations, stomatal conductance, and photosynthesis as well as high spatial variability in vegetation type and ozone and $NO_2$ abundance suggest a need for multiple measurements per day with contiguous mapping at scales of a few kilometers or less. These types of measurements are most easily accomplished from a GEO viewpoint, and would enable understanding of how pollution plumes are transported to and adsorbed by vegetation, how different biomes and crops respond to this pollution, and how these responses change their carbon uptake and ultimately atmospheric $CO_2$ abundances. Studies using ground networks, aircraft data, and regional and global models along with Observation System Simulation Experiments (OSSEs) will be required in advance of space-based measurements, however, to ensure that measurement requirements are established that will allow the satellite measurements to be exploited to their full potential. The NASA DISCOVER-AQ aircraft mission, which focused on air quality and helped to establish measurement requirements for GEO-CAPE, provides a blueprint for such studies. The suite of instruments from DISCOVER-AQ could be augmented with recently-developed airborne imaging spectrometers that measure plant fluorescence and visible imagers that measure biological markers of vegetation health to advance the scientific state-of-the-art with respect to characterizing the linkages between air quality, crop and ecosystem health, and carbon cycling.

An intriguing option that should be explored by the OSSE studies is a demonstration mission on the International Space Station. OCO-3 could potentially be timed to overlap with ECOSTRESS to provide a fairly comprehensive ecosystem mission. Additional air quality measurements from the same platform would provide the entire suite of concurrent measurements, though it is unclear whether the spatiotemporal resolution of the observations would be sufficient to provide substantial improvement in our understanding.

Given that much of the expected growth in emissions and most of the biomass occur in the tropics and subtropics, there is much to be gained from an ecosystem mission flying concurrently with a proposed air quality mission over these latitudes (see companion white paper on the “Future of Air Quality in the Developing World”), but measurements over any region would serve a wide range of science communities, including those interested in atmospheric composition and air-quality, ecosystem health and change, and the carbon cycle. The science would supply critical information to policy makers around the world concerned with food security, which can have enormous economic and political consequences not only regionally but globally.

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