The Role of the Atmosphere in the Provision of Ecosystem Services

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Abstract

Solving the environmental problems that we are facing today requires holistic approaches to analysis and decision making that include social and economic aspects. The concept of ecosystem services, defined as the benefits people obtain from ecosystems, is one potential tool to perform such assessments. The objective of this paper is to demonstrate the need for an integrated approach that explicitly includes the contribution of atmospheric processes and functions to the quantification of air-ecosystem services. First, final and intermediate air-ecosystem services are defined. Next, an ecological production function for clean and clear air is described, and its numerical counterpart (the Community Multiscale Air Quality Model) is introduced. An illustrative numerical example is developed that simulates potential changes in air-ecosystem services associated with the conversion of evergreen forest land in Mississippi, Alabama and Georgia to commercial crop land. This one-atmosphere approach captures a broad range of service increases and decreases. Results for the forest to cropland conversion scenario suggest that although such change could lead to increased biomass (food) production services, there could also be coincident, seasonally variable decreases in clean and clear air-ecosystem services (i.e., increased levels of ozone and particulate matter) associated with increased fertilizer application. Metrics that support the quantification of these regional air-ecosystem changes require regional ecosystem production functions that fully integrate biotic as well as abiotic components of terrestrial ecosystems, and do so on finer temporal scales than are used for the assessment of most ecosystem services.

Keywords: ecosystem services; CMAQ; quantification of air-ecosystem services; air quality modeling; clean air services

1.0 Introduction

Solving the environmental problems that we are facing today requires holistic approaches to analysis and decision-making. Issues such as global climate change, land use change resulting from increasing human population, and long-term anthropogenic impacts on global biogeochemical cycles cannot be considered as isolated problems or individual research topics. To address the full implications of our decisions across local, national, and global scales and multiple human generations we must adopt a broad, systems perspective that incorporates social, environmental, and economic aspects. The U.S. National Research Council has referred to these as "the three pillars of sustainability" (National Research Council, 2011).

Recently the concept of ecosystem services, defined as the benefits people obtain from ecosystems, has been used to show how humans benefit from the natural capital provided by the earth (MEA, 2005). Valuing the benefits we receive from nature, and identifying the beneficiaries, allows for a more complete assessment of the social, environmental, and economic impacts of a given management action or policy decision leading to maximum benefits (including benefits to human health) and fewer unintended consequences**.** For example, quantification of wetland value based on the ecosystem services it provides to the local community may inform decision makers when evaluating the utility of that wetland relative to the benefits of urban development. The value of services provided by the atmosphere has rarely been considered in detail (Thornes et al., 2010). In response, Thornes et al. (2010) provide initial estimates for 12 atmospheric services; a total value that ranges from 100 to 1000 times the 2008 Gross World Product. These estimates are based on a value relative to Carbon Dioxide under the EUETS (European Union Emissions Trading Scheme), and value relative to compressed air. The authors note that additional research is needed to develop a more systematic approach to the valuation of specific atmospheric services. Challenges to the development of such an approach include those encountered when valuing any natural resource (see, e.g., Randall, 1987), but also include the tendency to treat the atmosphere as a source of hazard as opposed to benefit, and an artificial distinction between atmospheric and ecosystem services. In reality, ecosystems comprise biotic and abiotic components that cannot exist independent of one another, and together provide beneficial services to humans. The term air-ecosystem service is used throughout this discussion to emphasize that the integrated, co-dependent nature of this relationship must be considered. We begin by defining what is meant by the term "air-ecosystem service." This is followed by the exploration of a conceptual model detailing the tightly coupled nature of one specific air-ecosystem service; clean air. A crucial step towards the economic valuation of ecosystem services is the quantification of services using metrics that can be linked to economically valued benefits. A regional air quality model that quantitatively defines many aspects of the response of a tightly coupled atmosphere-biosphere system is used to illustrate connections between human behavior and preferences and the underlying ecological processes and functions leading to the production of clean air ecosystem services. This example is followed by a discussion of clean air-ecosystem services in the context of environmental economics and management.

2.0 Methodology

2.1 Defining and Classifying Air-Ecosystem Services

Two recent views regarding air-ecosystem interactions are presented in Berkowicz (2010) and Thornes et al. (2010). Both discussions treat the atmosphere and its processes as linked with, but external to, biological systems. However, these systems are, in fact tightly coupled, and failure to treat them as such in decision making can lead to unanticipated consequences. Pielke et al. (2007) provide examples of such consequences resulting from regional land-use and land-cover changes. Decreases in local temperature, increased cloud cover and, under some conditions, increased precipitation have been reported in response to the conversion of grassland to irrigated crop agriculture in the Great Plains of the U.S.; such changes can lead to greater biologic production in rainfed and irrigated systems. By contrast, observational studies of widespread tropical deforestation report rainfall decreases of 1 to 20% as the result of changes in evaporation, transpiration, surface albedo and aerodynamic roughness. These atmospheric interactions can exacerbate water quantity and quality problems resulting from altered surface runoff characteristics. Urbanization of natural landscapes restructures the local energy budget, leading to increased temperatures and modified diurnal temperature patterns, wind and humidity fields (Landsberg, 1981). These factors impact human health (e.g., heat- and air-quality related morbidity and mortality), local economies (e.g., energy, storage and transportation costs), and may further combine with anthropogenic changes in the aerosol environment to alter patterns of urban precipitation frequency and intensity (Shepherd and Burian, 2003). Studies such as these have led to a more holistic understanding of the tightly coupled interactions among the atmosphere, the biosphere and human society. We propose that same approach be applied to the quantification, valuation and sustainability of air-ecosystem services following the proposals of Constanza (2008) and Fisher et al. (2009), that any definition or classification of services should be context-dependent and should address issues of sustainability.

A holistic, systems-based approach begins by recognizing that an *ecosystem* comprises both biotic and abiotic (e.g., air, water, land) components. *Ecosystem services* are, therefore, outputs of ecological functions or processes of these interacting biotic and abiotic components that directly or indirectly contribute to social welfare or have the potential to do so in the future (USEPA, 2006c). Ecosystem services can be classified in many ways. The Millennium Ecosystem Assessment (MEA) defines and classifies ecosystem services into several categories:

> Ecosystem services are the benefits people obtain from ecosystems. These include *provisioning services* such as food, water, timber, and fiber; *regulating services* that affect climate, floods, disease, wastes, and water quality; *cultural services* that provide recreational, aesthetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling (MEA, 2005).

While useful, this definition is somewhat ambiguous and does not facilitate explicit linkage between ecological assessment and the economic valuation of changes in these services. Most importantly, it lends itself to double counting of benefits (Fisher et al., 2009). To avoid these pitfalls, Boyd and Banzhaf (2007) propose that an effective classification scheme should distinguish between *final ecosystem services*, *intermediate ecosystem services* and *benefits*. Since this paper focuses on exploring the biophysical quantification of air-ecosystem services in preparation for benefits assessment and valuation, this expanded classification is more appropriate. A *final ecosystem service* is a component of nature, directly enjoyed, consumed, or used to yield human well-being. That is, final ecosystem services are outputs or end products of ecological processes that either directly result in human benefits or, when combined with human, social or built capital, produce human benefits. Fisher et al. (2009) expand this definition to include ecosystem organization or structure if they are consumed or utilized by humanity. An *intermediate ecosystem service* is a service that is necessary for the production of final ecosystem services. For example, intermediate ecosystem services (endpoints) including habitat, biodiversity and clean water are necessary for the production of healthy recreational fish populations (final service). Benefits, however, do not accrue without the addition of roads, boat ramps, etc. to provide access to the service.

A hierarchy of air-ecosystem services utilizing these definitions is presented in Figure 1. In this hierarchy, clean air and climate and weather are final air-ecosystem services. Information regarding beneficiaries, atmospheric metrics, linkages to biologic components as well as example benefits and valuation metrics are provided in Tables 1 and 2.   Clear air (Table 1) focuses on issues of visibility with principal beneficiaries being the transportation and recreational sectors. Some metrics for these services include visual quality and range. Example benefits include reduced death/injury from accidents, improved delivery efficiency (e.g., can travel faster, fewer delays) and visitor viewing enjoyment (day and night). Clean air is closely related to clear air services, but in this case, beneficiaries include sensitive human and natural (e.g., vegetation, fish, wildlife, etc) subpopulations. Some metrics describing the quantity of clean air include hourly pollutant concentrations, air quality indices, the assimilative capacity of the atmosphere before unhealthy concentrations are experienced, and cumulative exposure metrics for humans, e.g. daily maximum 8 hr average ozone (MDA8), and for vegetation, e.g. W126 (USEPA, 2006a; USEPA, 2006c). Some metrics that quantify benefits derived from clean air for vegetation include appearance and biodiversity. Some metrics that quantify human benefits include reduced morbidity/mortality and hospital admissions in response to changes in pollutant concentration levels.

Climate and weather is the third major class of final air-ecosystem service (Table 2). Some components of climate and weather that are directly enjoyed and, therefore, are final services include a pleasant or livable environment and water quantity. The beneficiaries of a livable environment are the recreation sector, the general public and sensitive life-stages such as the very young or elderly. The quantity of pleasant environment directly experienced or enjoyed can be expressed through a number of human comfort indices that are a function of heat/cold, wind and humidity (see examples at. http://www.nws.noaa.gov/os/heat/index.shtml#heatindex and http://www.nws.noaa.gov/os/windchill/index.shtml). Some metrics that quantify the benefits of a livable climate are measured in terms of reduced heat/cold related morbidity, mortality and hospital admissions.

The final climate and weather service, water quantity, specifically applies to aspects of precipitation that are directly consumed or enjoyed such as maintenance of drinking water supplies and recreational activities requiring a specific volume or depth of water such as swimming, boating, snow skiing or snowmobiling. The beneficiaries are the general and recreating public. The service is measured in terms of precipitation depth or runoff volume. Such benefits are quantified by lake levels or the size of the recreational pool of a reservoir.

In addition to final services, Figure 1 indicates that there also can be climate and weather services such as the provision of temperature, precipitation and radiation conditions that are conducive (intermediate) to the production of clean water and biomass production final services. For example, returning to the earlier example of the conversion of grassland to irrigated cropland, the atmosphere provides intermediate services in the form of surface temperature and precipitation towards the provision of the final service “crop biomass” which is consumed in the form of food. The coupled interaction of the biologic community response to irrigation (i.e., seasonal changes, albedo, leaf area, surface roughness and moisture flux, in addition to additional moisture flux from the irrigation itself) are credited with the temperature and precipitation changes noted previously. Corn, an important food crop grown in the Great Plains, is particularly sensitive to high temperatures during flowering (anthesis). Any reduction from normal maximum daily temperatures at this critical crop stage can affect corn yield. Periodic increases in precipitation can result in reduced irrigation demand to stave-off yield losses associated with water stress. Table 3 contains selected examples in which climate and weather services are intermediate to the production of biomass and clean water final ecosystem services.

Another ecosystem characteristic that is particularly relevant for air-ecosystem services is the spatial relationship between service generation and beneficiaries. Fisher et al. (2009) propose three classes; *in situ* – where the services are generated and benefits are realized in the same location; *omi-directional* – where the services are generated in one location but benefit the surrounding landscape without directional bias; and *directional* – where the service generated benefits a specific location due to the flow direction. The turbulent, fluid nature of the atmosphere leads to the conclusion that air-ecosystem services are directional services. This characteristic is reflected in the concept of "airsheds" (Paerl et al., 2002), and is recognized in regulatory instruments such as the U.S. EPA Cross-State Air Pollution Rule (CSAPR, http://www.epa.gov/airtransport).

2.2 Ecological Production Functions

Quantifying the provision of ecosystem services and assessing the sustainability of these services under natural and human-induced stresses requires a comprehensive systems-level understanding of ecosystem component coupling. One means of describing the coupled system is through an *ecological production function (EPF)*. An EPF is a description of the type, quantity and interactions of natural features required to produce *ecological endpoints*, which are defined as any biophysical feature, quantity, or quality that requires little further translation to make clear its relevance to human well-being. Additionally, an EPF can be thought of as describing the relationship between intermediate services, final services and benefits (Ringold et al., 2009). Therefore, the outputs of EPFs, when combined with inputs that allow ecological goods or services to be used (e.g., roads or site accessibility) produce benefits (Wainger and Mazzotta, 2009; Wainger and Boyd, 2009).

As an example, the biophysical characteristics of a coastal wetland (flooding regimes, salinity, nutrient concentrations, plant species abundance, predator and prey abundances, climate, etc.) can influence the abundance of a population of watchable wading shorebirds (the ecological endpoint). An EPF describing these complex relationships would be useful for estimating the potential of different coastal wetlands to provide bird-watching recreational services, if other inputs (e.g., boardwalks or kayak launch points) were also present. Moreover, the relevance to sustainability of such an EPF would be increased if, (a) its dependent variables or outputs (i.e., the species predicted) aligned well to birdwatchers' preferences, (b) its independent variables or inputs (i.e., wetland characteristics) were feasibly measured, and (c) critical design factors for enhancing or restoring those characteristics, in cases where wetlands had been degraded or destroyed, were also incorporated into the EPF. There are several benefits and ecosystem services related to this example that are unidentified, unquantified, and unmonetized, ranging from clean water services and biodiversity to aesthetics and nonuse values (USEPA, 2006c). With these characteristics in mind, we describe an EPF for clean air-ecosystem services associated with clear and healthful air below.

2.3 A Conceptual Air-Ecosystem Service EPF

The tight coupling of biotic and abiotic ecosystem components required to produce the final air-ecosystem services of clean air and clear air that includes two-way feedbacks among the biosphere, atmosphere, weather and pollution is described conceptually in Figure 2. The primary processes involved in the provision of clean air services are the production (emission), transformation, dilution, and removal of harmful or potentially harmful (precursor) chemicals from the atmosphere. An EPF can be used to explore how differences in factors that affect these processes, such as land use, meteorology and emissions and interactions among these processes and factors can result in changes in the quantity of clean air, i.e., air quality experienced by humans. As in the previous example for wetlands, an EPF that is suited to addressing the sustainability of clean air services must be able to account for aspects of human and societal need or preference, as well as behaviors that can exacerbate or ameliorate threats to those services by affecting the magnitude of the underlying processes. An overview of processes that should be included in a clean air EPF follows.

Our EPF (Figure 2) begins with the introduction into our system of upstream or boundary air containing some level of natural and anthropogenic chemical constituents (upper left). Most unhealthful atmospheric constituents are either emitted directly into the atmosphere as the result of economic and social activity, e.g., power production, vehicular traffic, or are produced as the result of complex reactions within the atmosphere itself. Some of these emissions are deposited or transformed into other species near their sources, while the remainder may be transported out of the immediate area to later combine with additional downstream sources. Air pollutant emissions come from anthropogenic sources as well as managed and natural ecosystems. In Figure 2, sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxide (NO) and many volatile organic chemicals (VOC's) come primarily from anthropogenic sources, e.g., stationary sources (power plants) and mobile sources (gasoline and diesel fueled vehicles). The majority of ammonia (NH_3) emissions are due to livestock agriculture, but emission of NH_3, NO and nitrous oxide (N_2O), a powerful greenhouse gas, from agricultural soils represents a nexus of human activity (fertilizer application) and ecosystem function (nitrification and denitrification). Biogenic emissions from managed as well as natural sources are an important source of VOCs that can lead to the formation of secondary aerosols (haze) that can enhance (e.g., Blue Mountains of Australia and Smokey Mountains of the U.S.) or degrade (e.g., U.S. Grand Canyon) recreational viewing opportunities in natural areas(Geron et al., 1994; Lamb et al., 1993).

Interactions between the biosphere and atmospheric processes contribute to the production of atmospheric pollutants by natural and managed ecosystems. For instance, natural or man-altered land surfaces such as waterbodies, inundated wetlands and irrigated agricultural fields add large supplies of moisture (humidity) to the atmosphere through evapotranspiration. Moisture fluxes, combined with boundary layer mixing, can fuel the formation of clouds. Primary and secondary aerosols also play a key role in the formation of clouds, e.g., act as cloud nuclei, and can participate in cloud aqueous chemistry to form atmospheric acids. In addition, there are feedback effects of aerosols on radiative forcing. While these feedback effects are mainly important for climate applications, it is becoming evident that they have substantial effects on local meteorology and air quality in polluted regions (Jacobson et al., 1996; Wong et al., 2012). Production of oxides of nitrogen by lightning activity associated with convective clouds is recognized as an important pollutant source (DeCaria et al., 2005; Ott et al., 2007). While the presence of clouds may enhance some chemical transformation, many other important atmospheric chemical reactions such as those that produce ozone (O_3) are photolytic, i.e. driven by light energy and are inhibited by the presence of clouds. Isoprene, a VOC emitted by some vegetation species, is a precursor chemical for O_3, particulate matter (PM) and formaldehyde formation. Monoterpenes, another class of biogenic VOC produced by vegetation, can be oxidized by O_3, hydroxyl radical and nitrate radical to form products that readily partition into aerosols that can lead to haze and compromise visibility. Ammonia contributes to the formation of ammonium aerosol, which is a major constituent of fine particulate matter ($PM_{2.5}$) and VOCs, and NO can react with nitrogen dioxide (NO_2) to produce ozone and additional particulate matter. At sufficiently high levels, oxidized and reduced N species, O_3 and $PM_{2.5}$ are all detrimental to human health and well-being (McConnell et al., 2002; von Mutius, 2000; Wolfe and Patz, 2002).

Chemicals in the atmosphere are vertically or horizontally mixed into more or less reactive environments to either increase or dilute ambient concentrations. Two drivers of boundary layer mixing that link directly with ecosystem structure and function are convective and roughness-driven mixing. Convective mixing is driven by the flux of heat from underlying surfaces. Ecosystem features that directly impact surface temperature (as illustrated by the temperature values along the bottom of Figure 2) include overall surface reflectivity (e.g., snow cover *vs.* dark organic soils), and the heat capacity of the surface (e.g., leaves *vs.* water *vs.* soil). Roughness-driven mixing results when the free movement of air across a landscape is impeded by obstacles extending above an underlying surface. Some ecosystem features that can contribute to roughness-driven mixing include landscapes with varying patterns of vegetation heights and densities, and the extent and orientation of vegetated or non-vegetated corridors. Thus, both horizontal and vertical ecosystem structure contributes to the provision of clean air service through mixing-driven transport, dilution and deposition.

The underlying ecological structure and function also influence the removal of potentially harmful pollutants from the air. Precipitation can act to cleanse the atmosphere of harmful pollutants through wet deposition, but pollutants also are removed from the atmosphere through particle deposition to underlying surfaces and plant uptake of gases. The rate at which gases are removed is a function of surface wetness, strength of downward mixing, stomatal and cuticular vegetation conductance and leaf area. Stomatal and cuticular conductance can vary widely across vegetation species. For example, maximum stomatal conductance is much higher in grasses (0.01 m/s) than a broadleaf deciduous forest (0.005 m/s) (Xiu and Pleim, 2001). Forests, however, can have up to twice the intercepting leaf area per unit area leading to greater pollutant removal, and so the specific type of vegetation and vegetation density both contribute to the air pollutant removal efficiency. The rate of atmospheric particle deposition depends primarily on the particle size distribution and turbulence. (Grantz et al., 2003)

3.0 Analytical Framework

3.1 CMAQ as an Ecological Production Function

Since the coupled atmospheric and biosphere system is complex with competing and compensating sources and sinks of pollutants and processes, a numerical model is a useful tool to quantify and characterize clean air endpoints, thereby serving as an EPF. For this analysis, we applied the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006) version 4.7.1 as a clean and clear air EPF. CMAQ employs a 3-dimensional Eulerian modeling approach to address air quality issues such as tropospheric O_3, $PM_{2.5}$, air toxics, visibility and acid and nutrient deposition. The system comprises a meteorological modeling system for the description of atmospheric conditions, emission models for anthropogenic and natural emissions that are injected into the atmosphere, and a chemical-transport modeling system (CTM) to simulate chemical transformations and atmospheric fate and transport. CMAQ can be used for both retrospective studies as well as analysis of future scenarios, allowing the investigation of potential environmental outcomes regarding air quality management.

The meteorological model used in this example, the Weather Research Forecast model (WRF) (Skamarock et al., 2008), contains Land Surface Models (LSMs) that provide an interface between atmospheric processes and processes at the terrestrial surface. Land surface models simulate biophysical processes, soil hydrology, and surface heat and moisture fluxes to provide feedback to the atmosphere that, as described previously, may alter cloud, precipitation, and local and regional circulation. While current LSMs focus on surface fluxes affecting atmospheric processes with little regard for hydrology, they are becoming more sophisticated and are moving towards including dynamic vegetation modules, multi-layer vegetation canopy modules, terrestrial carbon and nitrogen cycling, irrigation treatment, surface and groundwater hydrology, transient land cover change and land-use change. The P-X land surface model is used in the present example (Pleim and Xiu, 2003).

Biogenic emissions are estimated within CMAQ using the Biogenic Emissions Inventory System (BEIS) version 3.09. BEIS estimates emission factors for NO and VOCs for a range of land use and land cover types (Guenther et al., 2000; Guenther et al., 1994).   The emission factors are the flux-rate that each species emits under standard environmental conditions. BEIS makes these estimates using the Biogenic Emissions Landcover Database version 3 (BELD3) as input (Pierce et al., 1998). The BELD3 comprises 1 km x 1 km rectangular grid cells to which are assigned 230 different vegetation and land use types. Anthropogenic emissions are estimated using emissions factors based on the 2005 U.S. EPA National Emissions Inventory (USEPA, 2006b).

The CMAQ model simulates horizontal and vertical chemical transport in the atmosphere including wet and dry deposition removal processes. Wet deposition is a function of the precipitation rate and cloud water concentration. Cloud water concentration is controlled by the scavenging ratio, which is calculated differently depending on whether the pollutant is absorbed into the cloud water and participates in the cloud water chemistry. Accumulation and coarse mode aerosols are assumed to have been the nucleation particles for cloud drop formation and are completely absorbed by the cloud and rain water. The Aitken mode aerosols are treated as interstitial aerosol and are slowly absorbed into the cloud/rain water. Dry deposition of gases and particles in CMAQ affects chemical species from the atmosphere as they adsorb to, absorb into or react with natural surfaces such as soil, water, vegetation and hardened surfaces such as roadways and structures. Deposition of gases such as O_3, SO_2, and N-species is a function of vegetation characteristics such as leaf area, canopy height, cuticular and stomatal resistance. Aerosol deposition is mainly dependent on particle size and microscale roughness characteristics of the surface. The size distribution of fine particles changes in response to deposition, coagulation between particles, growth by condensation from gas and/or vapor phase species, new particle production from vapor phase precursors, transport of particles and emision of new particles. Particle size is also affected by atmospheric moisture (humidity) conditions (Foley et al., 2010).

3.2 Application of the Analytical Tool

Numerical models such as CMAQ allow us to explore system-wide responses to possible future decisions. One scenario of interest involves the conversion of forested land to cropland to meet increased feedstock demand for biofuels and food to support a growing population. Using CMAQ as an EPF, we explore this scenario by constructing a land use data set in which 50% of the BELD3 evergreen forest area located in Mississippi, Alabama and Georgia is converted to rainfed cropland resulting in cropland increases ranging from 10 to 30% (Figure 3). The southeastern U.S. represents an area that is currently under-utilized (relative to the midwestern U.S.) with regards to cropland agriculture, and rainfall is usually sufficient to support rainfed crop agriculture enterprise. The cropland increase is assumed to be spread proportionally across the existing crop-species. The revised BELD3 data were used as input to both CMAQ and the meteorological model. In this scenario, biogenic emission changes will be the primary driver of air quality and ecosystem service change. Biogenic emissions are computed within the CMAQ model and so will respond to both the land use and meteorology changes. Ammonia emissions from nitrogen fertilizer applications and dust associated with tillage operations in the NEI are increased proportionally with the cropland area increase. All other anthropogenic emissions are assumed to be unchanged. The simulation is driven by 2006 WRF modeled weather for rectangular grid cells spanning 12km per side (144,000 ha).

First, consider the response of local (grid cell) weather variables to the imposed land use change. Figure 4 shows differences between base (current land use) and new (revised land use) scenarios for WRF variables during July 29 through August 4, 2002. The proposed land use change results in small decreases in mean hourly surface temperature (Figure 4A), precipitation (Figure 4B) and boundary layer height (4C). There is a small increase in mean hourly 10m windspeed (Figure 4D). These responses are all in keeping with the prescribed land use change.

Selected CMAQ results for April are presented in Figure 5 as ratios of new to base land use condition. Mean hourly atmospheric NH_3 concentrations (Figure 5A) exceed base concentrations by more than a factor of 6. NO (Figure 5B) and PM_{10} (Figure 5C) concentrations increase up to 20%, which reflects increased NEI fertilizer-related emissions and tillage-related dust. Nitrogen Oxide is an O_3 precursor whose emissions are the product of microbial-mediated denitrification. These emissions are computed within CMAQ as a function of fertilized land area and meteorology. Increased atmospheric concentrations reflect the scenario's greater agricultural land area. Total $PM_{2.5}$ (Figure 5D) increases in response to increased NH_3-related secondary particulate formation. Total (wet and dry, reduced and oxidized) N deposition (Figure 5E) increases up to a factor of 3, and is driven primarily by the increased atmospheric NH_3 concentrations.

Thus far we have focused on quantification of the environmental consequences of our land use change decision. Quantification of the economic and societal benefits (e.g. Table 1) that is needed to include sustainability in the decision making process requires relating these consequences to human and ecosystem health and well-being. One tool that facilitates such valuation is BenMap (http://www.epa.gov/air/benmap). BenMAP is a Windows-based computer program that uses a Geographic Information System (GIS)-based to estimate the health impacts and economic benefits occurring when populations experience changes in air quality. It requires input information regarding daily or monthly air pollution change, mortality effect, mortality incidence and exposed population. Results are presented in terms of mortality (number) or, with the introduction of the value of a statistical life, mortality value. Two additional exposure metrics for O_3 are the daily maximum 8 hr average ozone (MDA8) and W126 metrics. The MDA8, which requires hourly air pollution concentrations aggregated to an 8hr metricis used in acute epidemiological studies to link air pollutant exposure to health endpoints such as hospital admissions, morbidity and mortality, which contribute directly to tools such as BenMAP and are often used to support standard setting for human benefit analysis (Hubbell et al., 2009; Rothman, 2002). For instance, the U.S. National Ambient Air Quality Standards (NAAQS) is based on the 3yr running average of the annual fourth highest MDA8 average O_3 concentration. Increased MDA8 may suggest decreased healthy air services at a location quantified as increased hospital admissions *via* an epidemiological model. There may also be economic consequences associated with an increase in the number of days that exceed NAAQS standards.

The W126 is a cumulative metric used in the EPA Ozone Criteria Documents (USEPA, 2006a; USEPA, 2006c) for relating vegetation productivity losses with O_3 exposure. The W126 metric retains the mid and lower-level O_3 concentrations (40 ppb-65ppb), though it is weighted towards higher hourly average concentrations, i.e., greater than 65 ppb with maximum weight >100 ppb). The W126 can be used to quantify benefits or losses in agricultural productivity (biomass services) and associated estimated economic affects. Neither the MDA8 nor W126 metric rely purely on temporal averages and require hourly EPF information, which is a higher temporal resolution than most current ecosystem service estimates. For example, clean air services related to soil or lake acidification are calculated at a yearly time step; e.g. Hornberger and Cosby, 1989).

Returning to our land use change example, mean hourly O_3 concentrations during April increase slightly (not shown) with the new land use scenario. This response reflects the large increase in NO and reduced deposition velocity (not shown), coupled with slight decreases in isoprene (Figure 5F). Ozone deposition velocity is driven primarily by stomatal conductance so that decreased O_3 dry deposition velocity results from the replacement of higher stomatal conductance and leaf area species (evergreen forest) with lower conductance, lower leaf area species (crops). Isoprene, another O_3 precursor, declines in response to the shift from higher emitting species (evergreen forest with BEIS emission factor 70 gC/kg^2-h) to lower emitting species (crops with BEIS emission factors less than 20 gC/kg^2-h). This decrease would be very much greater if oak species (BEIS emission factor 26250 gC/kg^2-h) had been replaced with cropland. In spite of mean hourly increases, there is no significant change in April mean MDA8 (Figure 5G). W126 (Figure 5H), on the other hand, increases 4 to 8%. The contrast between MDA8 and W126 O_3 metrics suggests that simulated hourly O_3 changes occur primarily in low to mid-level ranges (40 ppb-65 ppb) as opposed to higher values (greater than 100 ppb).

In summary for April, a change in land cover from evergreen forest to managed agriculture could increase food and fiber service, but may also reduce healthful air final services associated with increased $PM_{2.5}$ concentrations and clear air services associated with PM_{10}. There is no apparent change in healthful air metrics associated with human exposure to O_3 based on the MDA8 metric. Delivery of additional N to aquatic and terrestrial systems associated with a change in clean air services is a negative final service relative to biodiversity, or intermediate service in support of clean water. It may be a positive intermediate service relative to food and fiber production. The W126 metric indicates that clean air final services related to vegetative appearance and intermediate services related to food and fiber production may be reduced.

Next, consider these same CMAQ results and clean and clear air metrics for July, 2006. There are larger areas of increased NH_3 (Figure 6A) and NO (Figure 6B) concentrations in response to warmer July temperatures. Changes in PM_{10} (Figure 6C) are much smaller and more localized than those noted in April, commensurate with the timing being well beyond the peak of agricultural activity in this area. The spatial extent of July $PM_{2.5}$ (Figure 6D) change is somewhat reduced from Figure 4D, reflecting reduced secondary particle production under warmer temperature conditions. Daily maximum 8 hr average ozone concentrations (Figure 6G) and W126 values (Figure 6H) increase from 4 to 8% over base July values suggesting mean hourly increases occur throughout the distribution of hourly O_3 values, including higher values.

In summary, final ecosystem services during July, as measured by metrics for human health and vegetation O_3 exposure, are reduced. Clean and clear air final services associated with $PM_{2.5}$ and PM_{10} are reduced as well, but perhaps not to the extent noted in April. Final and intermediate clean air service changes associated with N deposition are likely to be greater during July than April and have greater geographic extent.

4.0 Discussion and Conclusions

We have emphasized that the ecosystem services concept applied to air-ecosystem services includes consideration of social, environmental, and economic impacts including current and future human well-being. In the terminology of environmental economics, efforts to improve human well being by protecting the environment are efforts to address sources of market failure. That is, markets theoretically enable both producers and consumers to make only those transactions that improve, or at least do not reduce, their own well being and thus improve the overall well being of society, except when conditions exist that hinder market functioning. Market failure conditions occur when, for example, information about the benefits or disbenefits of traded goods or services is incomplete; when information is asymmetric (trading parties do not have access to the same information); when there are externalities (benefits or disbenefits accrue to individuals not party to the trade); or when goods have the characteristics of public goods which are non-rival (i.e., use by one does not diminish availability to others) and non-excludable (not subject to control of an owner).

Viewed in this framework, environmental research and monitoring have long been used to help address incomplete information about air pollutants, including their associated externalities (such as health and environmental impacts). Monitoring and air quality forecasts address information asymmetries by ensuring that polluters and the public have similar information about pollution levels and abatement costs. Science, policy and regulation have been used together to overcome the public-goods characteristics of final ecosystem services related to clean air by making the atmosphere's regional assimilative capacity (which in the context of clean air may be considered an intermediate ecosystem service) both exclusive and rival. In this scheme, the issuance of carefully limited and tradable emission permits enables markets to regulate the opportunity to pollute, ensuring that more efficient producers will buy out the heavy emitters. Efforts are underway, though incomplete, to do the same for ecosystem services related to climate and weather at global scales through the establishment of carbon markets. Most of this has been accomplished without application of the ecosystem services concept to air pollution control; however, there are several benefits to be gained by introducing these concepts to this field. For instance, the science tools used for determining regional-scale or airshed assimilative capacity, e.g. the CMAQ model has, to date, focused mainly on an understanding of the physical-chemical processes regulating pollutant dynamics, while the representation of biospheric processes and interactions has been more limited. These relative deficiencies limit our ability to completely account for biospheric mediation of atmospheric pollutant assimilative capacity and, by extension, to use techniques of ecosystem conservation, management or restoration as a tool of air quality management. These limitations occur in two main categories: detail in the spatiotemporal characterization of ecosystems themselves, and detail in the spatiotemporal characterization of emissions related to ecosystem processes. Some of these limitations are already being addressed by improvements to CMAQ, while others require additional data or model development. The importance of any given improvement will vary by pollutant species and mode of human and ecosystem exposure. Implementation of additional improvements depend both on USEPA priorities and air quality modeling community.

4.1 Improving the Representation of Biospheric Processes in CMAQ

In describing ecosystems themselves, the 12 km x 12 km grid cell used to characterize the land surface in CMAQ, including that used in the present example (v4.7.1), is relatively coarse in comparison to spatial scales at which vegetative landscapes occur, so that important biological processes or ecosystem-atmospheric interactions may be inadequately accounted for. This can be addressed to some degree by running simulations at ever higher resolutions, e.g., 4km or 1km, and CMAQ 5.0 (2012 release) differentiates atmospheric deposition for specific land-cover types within the cell. These advances will improve the analysis of, e.g., urban or rural afforestation/deforestation scenarios as they affect goods such as pollutant assimilative capacity and subsequent production of food and fiber services.

Within a vegetation type, geographic and seasonal changes in vegetation growth affect multiple processes at the biosphere-atmosphere interface, including pollutant removal. However, CMAQ provides only limited characterization of vegetation canopy structure variability. For instance, the canopy height of an evergreen forest in the Northeastern U.S. is assumed to be the same as that in the Pacific Northwest. In the future, remotely sensed data such as the NASA lidar-based Global Forest Heights data set (http://www.nasa.gov/topics/earth/features/forest-height-map.html) could be used to address this limitation. In addition, CMAQ now provides only weak characterization of seasonal vegetation changes, such as in leaf-area index estimation; future improvements could be made based on seasonal remote sensing data sets or by coupling CMAQ and a plant growth model.

A second area in need of refinement is CMAQ's representation of relationships between biological processes and emissions. An important limitation for the assessment of anthropogenic impacts on regional and global dynamics of both carbon and nitrogen is the current use of generic emission factors. The Biogenic Emissions Inventory System (BEIS) used by CMAQ apportions fixed, species-specific annual emission factors over the year as functions of factors such as LAI, temperature, radiation or precipitation. While these apportionment processes respond to changes in land cover, they currently are not sensitive to potential changes in vegetation management, and therefore do not support examination of differing crop management practices and climate conditions resulting changes in biogeochemical fluxes of chemically or radiatively species such as VOCs and N_2O.

CMAQ5.0 addresses some of these limitations by incorporating input and process parameterizations from the USDA Environmental Policy Integrated Climate (EPIC) biogeochemical and farm management model that simulates soil transformation dynamics of nitrogen. CMAQ5.0 then simulates dynamic bidirectional flux of NH_3 between agroecosystems and the atmosphere (Cooter et al., 2012; Izaurralde et al., 2006; Williams et al., 1984; Williams et al., 2006). The Fertilizer Emission Scenario Tool for CMAQ (FEST-C), currently under development, provides the ability to compare crop management scenarios that differentially affect the soil environment, altering the need for nitrogen additions and associated losses as well as facilitating analysis of ecosystem variables such as soil carbon content that are not used directly by CMAQ (Potter et al., 2006). Eventually we will be able to estimate the atmospheric ecosystem services that are provided when crop rotation (especially involving nitrogen-fixing crops), application timing, crop residue management (increasing soil organic matter), or other best management practices (BMPs) are used to reduce NH_3 fertilizer application

4.2 Using Improved Atmosphere-Biosphere Modeling to Achieve More Sustainable Outcomes

CMAQ5.0 enhancements as well as future enhancements will foster the exploration of system-wide societal adaptation to variable weather, economic conditions, future climate trends and climate extremes. As the potential for providing atmospheric ecosystem services through (land-based) ecosystem management is better understood and valued, policies can be designed to compensate these beneficial practices, resulting in more sustainable outcomes. Such modeling advances that focus on the atmosphere-biosphere interface open up additional possibilities for stimulating public or private actions and decisions that increase assimilative capacity and thus provide clean air services and, by extension, indirect air-ecosystem contributions to biomass production and clean water. The atmosphere remains non-rival and non-excludable, but just as opportunities to pollute the air can be made marketable through a tradable permits policy, the enhancement of land-based ecosystems can also be made marketable through mechanisms such as reverse auctions in which farmers bid to provide quality-rated conservation services for a given payment (Vukina et al., 2008).

Many efforts are already being taken to better understand and compensate other societal benefits associated with ecological enhancement (such as benefits from improving water quality and wildlife habitat), and to incorporate this information into decision-making and policy. The addition of atmospheric ecosystem services to this mix, appropriately categorized and analyzed, can further improve overall environmental management. For example, enhanced modeling will make clear the respective spatial distributions of landholders (e.g. Figure 3), who bear certain kinds of costs or benefits of land use change, and beneficiaries of atmospheric ecosystem services (e.g., Figures 4 through 6).

While ecological implications for clean air services at regional scales may be just emerging, the importance of the atmosphere-biosphere nexus to climate and weather ecosystem services at the global scale is already well-established and the subject of intensive policy formation efforts related to deforestation (FAO, 2008; Gibbs et al., 2007). With further improvements in biogeochemical agro-ecosystem models enabling estimation of soil-carbon dynamics and soil microbially-mediated processes, e.g. denitrification, we may soon be able to improve climate and weather ecosystem services through improved management of agricultural soils, as well as through forest protection.

Incorporation of sustainability into decision making *via* ecosystem services requires consideration of social, environmental and economic issues (National Research Council, 2011). This discussion has addressed sustainability of the quantity of ecosystem services in light of an economic and policy-driven land use conversion decision (i.e., increased regional agricultural income and national food security) using metrics that can link these changes to human and ecosystem benefits. We have demonstrated the importance of air-ecology interactions, and argue for integrated regional analyses that require ecosystem production function information at relatively fine temporal scales. This temporal component is important not only to link environmental results to human benefits but, as demonstrated by the land use change example, air-ecosystem services themselves are temporally dynamic, with presence or decline of services dependent on seasonally-variable air-ecosystem interactions and patterns of human activity (e.g., tillage). A complete valuation analysis has not been performed, but by providing the higher resolution information needed to support a range of epidemiological models and existing valuation tools such as BenMAP, we have established an explicit pathway to these valuation (benefits) endpoints. Provision of such integrated analyses will result in a more accurate full-cost accounting of coupled air, water and terrestrial ecosystem services.

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References

Berkowicz SM. Perspectives on the Atmosphere's Role in Sustaining Ecosystem Services. In: Liotta PH, Kepner WG, Lancaster JM, Mouat DA, editors. Achieving Environmental Security: Ecosystem Services and Human Welfare. 69. IOS Press, Amsterdam, 2010, pp. 73-85.

Boyd J, Banzhaf S. What are ecosystem services? The need for standardiazed environmental accounting units. Ecological Economics 2007; 63: 616-626.

Byun DW, Schere KL. Review of the governing equations, computational algorithms, and other components of the models-3 Community Multiscale Air Quality (CMAQ) modeling system. Applied Mechanics Reviews 2006; 59: 51-77.

Constanza R. Ecosystem services: multiple classification systems are needed. Biological Conservation 2008; 141: 350-352.

Cooter E, Bash J, Benson V, Ran L. Linking Agricultural Crop Management and Air Quality Models for Regional to National-Scale Nitrogen Assessments. Biogeochemistry Discussions 2012; 9: 6095-6127.

DeCaria AJ, Pickering KE, Stenchikov GL, Ott LE. Lightning-generated NOx and its impact on tropospheric ozone production: A three-dimensional modeling study of a STERAO-A thunderstorm. Journal of Geophysical Research 2005; 110: D14303.

FAO. UN collaborative programme on reducing emissions from deforestation and forest degradation in developing countries (UN-REDD): Framework document, Food and Agriculture Organization, UN development Programme, UN Environmental Programme,Accessed: 12/05/2011, http://www.un-redd.org/Portals/15/documents/publications/UN-REDD_FrameworkDocument.pdf, 2008.

Fisher B, Turner RK, Morling P. Defining and classifying ecosystem services for decision making. Ecological Economics 2009; 68: 643-653.

Foley KM, Roselle SJ, Appel KW, Bhave PV, Pleim JE, Otte TL, et al. Incremental testing of the Multiscale Air Quality (CMAQ) modeling system version 4.7. Geoscientific Model Development 2010; 3: 205-226.

Geron CD, Guenther AB, Pierce TE. An improved model for estimating emissions of volatile organic comounds from forests in the eastern United States. Journal of Geophysical Research 1994; 99(D6): 12773-12791.

Gibbs HK, Brown S, Niles JO, Foley JA. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2007; 2: 045023.

Grantz DA, Garner JHB, Johnson DW. Ecological effects of particulate matter. Environment International 2003; 29: 213-239.

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. Atmospheric Environment 2000; 34: 2205-2230.

Guenther A, Zimmerman P, Wildermuth M. Natural volatile organic coumpound emissionr ate estimates for U.S. woodland landscapes. Atmospheric Environment 1994; 28: 1197-1210.

Hornberger GM, Cosby BJ. Historical reconstructions and future forecasts of regional surface water acidification in southern most Norway. Water Resources Research 1989; 25: 2009-2018.

Hubbell B, Fann N, Levy J. Methodological Considerations in Developing Local-Scale Health Impact Assessments: Balancing National, Regional, and Local Data. Air Quality, Atmosphere & Health 2009; 2: 99-110.

Izaurralde RC, Williams JR, McGill WG, Rosenberg NJ, Quiroga-Jakas MC. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling 2006; 192: 362-384.
Jacobson MZ, Lu R, Turco RP, Toon OB. Development and application of a new air pollution modeling system. Part I: Gas-phase simulations. Atmospheric Environment 1996; 30B: 1939-1963.
Lamb B, Gay D, Westberg H, Pierce T. A biogenic hydrocarbon emission inventory for the USDA using asimple forest canopy model. Atmospheric Environment Part A 1993; 27: 1673-1690.
Landsberg HE. The Urban Climate. Vol 28. NY: Academic Press, 1981.
McConnell R, Berhane K, Gilliland F, al. e. Asthma in exercising children exposed to ozone: a cohort study. Lancet 2002; 359: 386-391.
MEA. Ecosystems and Human Well-Being: Wetlands and Water. Synthesis. Washington, DC: World Resources Instititue, 2005.
National Research Council. Sustainability in the U.S. EPA. Washington DC: National Academies Press, 2011.
Ott LE, Pickering KE, Stenchikov GL, Huntreiser H, Schumann U. Effects of lightning NOx production during the 21 July European Lightning Nitrogen Oxides Project storm studied with a three-dimensional cloud-scale chemical transport model. Journal of Geophysical Research 2007; 112: D05307.
Paerl HW, Dennis RL, Whitall DR. Atmopsheric deposition of nitrogen: Implciations for nutrient over-enrichment of coastal waters. Estuaries 2002; 25: 677-693.
Pielke RS, Adegoke J, Beltran-Przekurat A, al. e. An overview of regional land-use and land-cover impacts on rainfall. Tellus 2007; 59B: 587-601.
Pierce T, Kinnee E, Geron C. Development of a 1-km resolved vegetation cover database for regional air quality modeling. American Meteorological Society's 23rd Conference on Agricultural and Forest Meterology. American Meteorological Society, Albuquerque, NM, 1998.
Pleim J, Xiu A. Development of a land surface model. Part II: Data assimilation. Journal of Applied Meteorology 2003; 42: 1811-1822.
Potter S, Andrews S, Atwood J, Kellogg R, Lemunyon J, Norfleet L, et al. Model simulation of soil loss, and change in soil organic carbon associated with crop production,United States Department of Agriculture NRCS, Conservation Effects Assessment Project, GAO. Retrieved from http://www.nrcs.udsda.gov/technical/nri/ceap/croplandreport/croplandreportapp.html, 2006.
Randall A. Resource Economics: An Economic Approach to Natural Resource and Environmental Policy, 2nd Edition. New York: John Wiley and Sons, 1987.
Ringold PL, Boyd J, Landers D, Weber M. Report from the Workshop on Indicators of Final Ecosystem Services for Streams. EPA/600/R-09/137. U.S. EPA,, 2009, pp. 26pp.
Rothman KJ. Epidemiology: An Introduction. New York City: Oxford University Press, 2002.
Shepherd JM, Burian SJ. Detection of urban-induced rainfall anomalies in a major coastal city. Earth Interactions. 7, 2003, pp. 17.
Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, et al. A description of the advanced research WRF version 3. NCAR Tech. Note. NCAR/TN-475_STR. National Center for Atmospheric Research, Boulder, CO, 2008, pp. 113.
Thornes J, Bloss W, Bouzarovski S, Cai X, Chapman L, Clark J, et al. Communicating the value of atmospheric services. Meteorological Applications 2010; 17: 243-250.
USEPA. Air Quality Criteria for Ozone and Related Photochemical Oxidants (2006 Final),United States Environmental Protection Agency, Office of Research and Development. Retrieved from http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923#Download, Accessed 08/16/2012, 2006a.

USEPA. Documentation for the final 2002 Nonpoint sector (Feb06 version) National Emissions Inventory for Criteria and Hazardous Air Pollutants,Agency USEP, USEPA. Retrieved from ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/2002nei_final_nonpoint_documentation0206version.pdf, Accessed 08/16/2012, 2006b.

USEPA. Ecological Benefits Assessment Strategic Plan, EPA-240-R-06-001,United States Environmental Protection Agency, Office of the Administrator. Retrieved from http://yosemite.epa.gov/ee/epa/eed.nsf/webpages/EcologBenefitsPlan.html, 2006c.

von Mutius E. Current review of allergy and immunology. J. Allergy Clin Immun 2000; 105: 9-19.

Vukina T, Zheng X, Marra M, Levy A. Do farmers value the environment? Evidence from a conservation reserve program auction. International Journal of Industrial Organization 2008; 26: 1323-1332.

Wainger L, Mazzotta MJ. Proposed framework for quantifying ecosystem services and their economic benefits. ESRP Working Paper, 2009.

Wainger LA, Boyd JW. Valuing ecosystem services. In: McLeod K, Leslie H, editors. Ecosystem-Based Management for the Oceans Island Press, 2009.

Williams JR, Jones CA, Dyke PT. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 1984; 27: 129-144.

Williams JR, Wang E, Meinardus A, Harman WL, Siemers M, Atwood J. Epic Users Guide v0509, Temple, TX, Texas AgriLife Research and Extension Center,Accessed: 12/12/2011, http://epicapex.brc.tamus.edu/downloads/user-manuals, 2006.

Wolfe AH, Patz JA. Reactive nitrogen and human health: acute and long-term implication. Ambio 2002; 31: 120-125.

Wong DC, Pleim J, Mathur R, Binkowski F, Otte T, Gilliam R, et al. WRF-CMAQ two-way coupled system with aerosol feedback: software development and preliminary results. Geoscientific Model Development 2012; 5: 299-312.

Xiu A, Pleim J. Development of a land surface model. Part I: Application in a mesoscale meteorological model. Journal of Applied Meteorology 2001; 49: 192-209.

Figure Captions.

Figure 1. Hierarchy of Air-Ecosystem Services.

Figure 2. Conceptual diagram of an ecological production function for clean air services. Blue arrows indicate air movement or transport, yellow arrows indicate emissions, black arrows indicate transformation.

Figure 3. The fractional increase of agricultural land in each model grid cell resulting from a 50% reduction in evergreen forest area in Mississippi, Alabama and Georgia.

Figure 4. Comparison of WRF weather with and without landuse change for July 29 through August 4, 2006. Mean hourly difference in A) temperature (K), B) precipitation (mm), C) boundary layer height (m) and D) 10 m wind speed (m/s) All differences are computed as (new – base) land use scenario.

Figure 5. CMAQ simulation of April ratio of mean hourly A) NH_3 concentrations, B) NO concentrations, C) PM_{10} concentrations, D) $PM_{2.5}$ concentrations, E) total (wet +dry + reduced + oxidized) nitrogen deposition, F) isoprene concentration, G) daily maximum 8hr average ozone (MDA8) and H) W126. All ratios are new/base land use.

Figure 6. CMAQ simulated July ratio of mean hourly A) NH_3 concentrations, B) NO concentrations, C) PM_{10} concentrations, D) $PM_{2.5}$ concentrations, E) total (wet +dry + reduced + oxidized) nitrogen deposition, F) Isoprene concentrations, G) daily maximum 8hr average ozone (MDA8) and H) W126.. All ratios are new/base land use.