MRI: Development of an Urban-Forest Gradients Research Laboratory: Blurring the Edge - Lateral Impacts of Urbanization on Remnant Forests

PROJECT DESCRIPTION

1.0 Introduction and Guiding Questions

This MRI proposal aims to deploy a coordinated system of advanced instrumentation to quantify, map, and model the extent to which atmospheric and hydrologic vectors of urban pollution penetrate forest boundaries and how these pollution vectors affect biophysical responses in the forest ecosystem.

The primary purpose of this proposal is to build an instrumentation and data-gathering platform, the Duke Urban-Pollution Gradients Research Laboratory, with which we will study the incursion of urban stressors into surrounding forests and how forest organisms and ecosystems affect and respond to urban pollutants. Our overall hypothesis is that urban-edge effects are not only stressor-dependent but affect forest ecosystems far more than is currently appreciated. We propose to use the Duke Forest to study urban heat and nitrogen loading as they affect remnant forest ecosystems in a rapidly urbanizing landscape in North Carolina.

The instrumentation platforms will allow us to ask:

1) How far do urban-heat islands and pollutant N extend beyond the urban-forest “edge”?
2) What biophysical factors influence spatial and temporal extents of urban-heat and N through “edges”?
3) What are organismal and ecosystem responses to localized heat and high N supply in terrestrial and aquatic habitats?

Scientific understanding of urban-generated heat islands and atmospheric N pollutants has developed over three to four decades (Oke 1976, Likens and Bormann 1974). Both urban-generated heat and N pollutants are today recognized to have a complexity in process and scaling, the details of which are only recently quantifiable (Arnfield 2003, Sparks et al. 2008). For example, Arnfield (2003) emphasizes how recent research reveals urban-heat islands to possess remarkable diversity, and Sparks et al (2008) using new instrumentation and modeling approaches estimate that atmospheric N deposition may be double rates previously estimated. Our proposal seeks to new high-resolution spatial-scale instrumentation and analytical and modeling expertise on the Duke Forest, to create a laboratory aimed at transformative measurements of interactions of urban-generated pollutants and ecosystem responses. The MRI and laboratory will focus most immediately on studies of urban-heat and N pollutants.

Funding will allow us to build a set of mobile instrumentation platforms with an ability to monitor temperature and nitrogen at multiple points along selected urban to forest transects. The mobile instrumentation platforms can be flexibly deployed to gain high resolution data on lateral and longitudinal gradients (across or along urban-forest boundaries) and to compare interior and exterior forest stands. Specifically, the two instrumentation platforms will measure urban-generated atmospheric and hydrologic pollutants and their effects on local and regional forests across a wide range of time scales (Figure 1).

The proposed MRI unites interdisciplinary research teams in a new research laboratory, with participants from Duke’s Nicholas School of the Environment, Pratt School of Engineering, and Trinity College, along with scientists from the US Environmental Protection Agency and Forest

Service. Most of these investigators have worked together in interdisciplinary teams many in projects based on the Duke Forest.

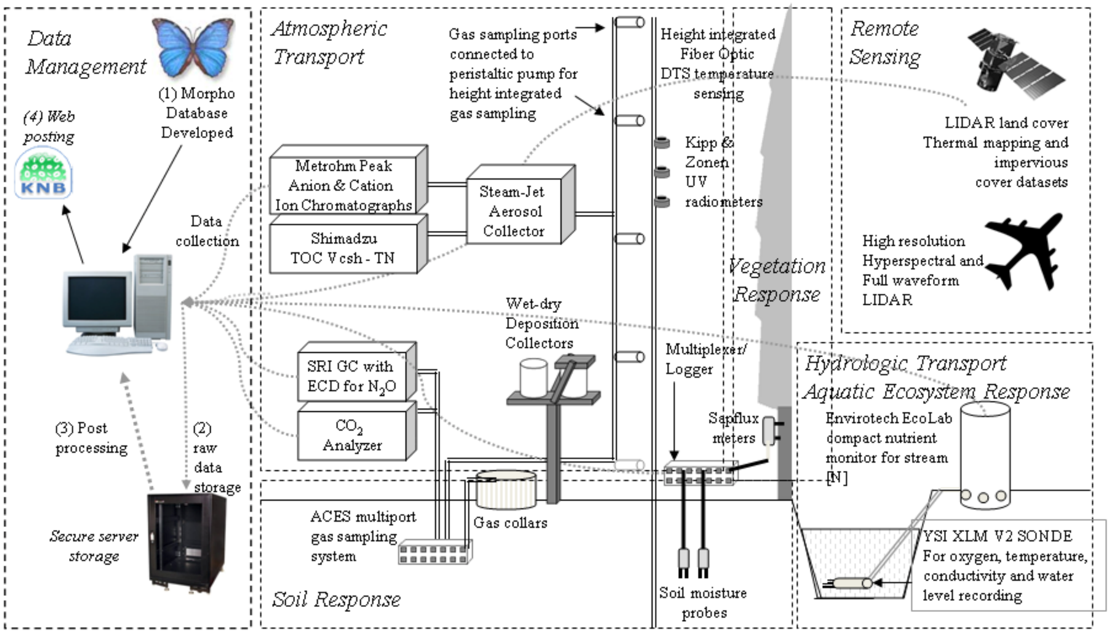

Figure 1. *The Duke Urban-Forest Gradients Research Laboratory will integrate potentially transformative N and heat measurements on mobile platforms to be deployed along strategically selected urban-to-forest N and heat gradients. Data are streamed, stored, and processed for real-time database assembly, analysis, modeling, and web posting.*

2.0 Conceptual Issues and Research Needs

In 1800 only five cities in the world exceeded 0.5 million people (Beijing, London, Guangzhou, Tokyo, and Istanbul), with only one (Beijing) that exceeded 1 million. Today there are more than 400 cities with more than a million inhabitants, and over these two centuries the proportion of the world's population living in large towns or cities has grown from ~5% to >50% (McMichael 2000, UNPD 2003). While the growth of the largest cities receives a great deal of attention, most of the Earth's population growth between 2000 and 2030 will occur in medium-sized cities of one to five million. By 2030, the majority of people on Earth will live in smaller cities of less than 1 million (UNPD 2003, Cohen 2004, Redman and Jones 2005a).

Durham along with nearby Chapel Hill and Raleigh are examples of such rapidly growing relatively small cities. In many urbanizing regions, as in central Carolina, forests provide the backdrop for urbanization. Of North Carolina's 18 million acres of forest, more than 1 million are being lost to urban development each decade (Schaberg et al. 2005). The Duke Forest, one of the world's leading experimental forests, contains more than 7000 acres of forest vegetation which are increasingly surrounded by urban areas, suburbs, roads, and industrial parks. We propose to use the Duke Forest to study how the stressors of urban heat and traffic-associated nitrogen loading are affecting and transforming remnant forest ecosystems in urbanizing landscapes.

Cities have long been associated with a lack of sanitation, infectious disease, and air pollution which together with crowding lead to high rates of infectious disease and mortality (Szreter 1997). Sanitary engineering in the developed world dramatically improved urban water supplies and waste removal starting in the late 19th century, but in nearly all modern cities pollution from carbon dioxide, nitrogen gases, ozone, and fine particulates continue to increase (McMichael 2000). Our ability to attain the UN Millenium Declaration's goal of ‘‘meeting human needs while conserving the earth's life support systems and reducing hunger" (UN 2005) will largely depend on our ability to understand how social organizations associated with urbanization impact with the environment (Alberti et al. 2003, Bettencourt et al. 2007).

The environmental impacts of this on-going urbanization are profound and not comprehensively studied. Rural to urban migration in the U.S. is resulting in the depopulation of the agricultural countryside. Over 100 acres of U.S. farmland each hour are transformed into other uses, with half of these acres urbanized, suburbanized, or industrially developed and the other half abandoned of agriculture and reverting to open space or less intensive uses (USDA 2001). As cities expand, local climate, air and water quality, and flows of energy and nutrients are greatly altered, stressing and transforming native biota, biodiversity, and ecosystems (Vitousek 1997a, Vitousek 1997b, Grimm et al. 2000, McMichael 2000, Alberti et al. 2003, Redman and Jones 2005a, Dudgeon et al. 2006). Thus the "ecological footprints" of cities will continue to expand far beyond their physical boundaries as new cities are created, existing cities expand, and urban residents continue to strive to improve their standards of living.

2.1 Impact 1 – Atmospheric Nitrogen Pollutants and Deposition As centers of human population, industry, and transportation, cities receive and disperse substantial amounts of biologically reactive N, derived mainly from fertilizers, fossil fuel combustion, city storm-runoff and organic wastes (Schlesinger 2007). As a result of their concentration of N-containing products, urban areas are particularly at risk from detrimental consequences of localized N pollution of air and water. Emissions of a variety of N species from vehicular traffic are increasing in nearly all cities of the world (Kennedy et al. 2007). Several decades of intensive research have steadily improved quantification of N deposition, even still major uncertainties still persist over the rates of regional and local N deposition. Recent work in the Duke Forest itself (Sparks et al. 2008), indicates that the deposition of pollutant N from the atmosphere may be occurring at two-fold previous estimates, at about 15 kg N ha^{-1} y^{-1}, rates that are ecologically very significant to functioning of terrestrial and aquatic ecosystems.

Organism and Ecosystem Responses: Because nitrogen limits primary productivity over much of the Earth, relatively low level, chronic N loading can stimulate increased plant growth and biomass with few detrimental consequences. Relatively moderate but sustained N deposition, however, can acidify soils, deplete soil micronutrient fertility, and eutrophy soil and surface waters (e.g., Aber et al., 1989; Aber et al., 1998). Ultimately, forest plant communities may show declines in productivity as a result of N loading. High N concentrations in surface waters degrade water quality and cumulatively can lead to significant coastal eutrophication and anoxia (e.g., Rabalais et al. 2002; Galloway, 2004).

2.2 Impact 2 – Urban-Heat Islands The urban heat island is the most well documented example of anthropogenic climate modification (Arnfield 2003). An extensive literature on urban heat islands has focused on the energetics of climatology from the perspective of the city, and for good reason (Crutzen 2004). Many cities are 5 to 10ºC warmer than non-urban environments through much of the day and night as well. Ground surface and subsurface heat islands follow spatial and temporal patterns that are distinctively different from those of atmospheric conditions, and can be expected to have ecologically significant effects in forest ecosystems that are immediately adjacent to cities.

Organism and Ecosystem Responses: Urban heat can significantly stress biological organisms, especially those living at the edges of their geographic distribution. Plant respiration, photosynthesis, evapotranspiration are closely tied to temperature, with direct and prominent effects also associated with drought stress. Microbial activity in soils and sediments are directly tied to temperature with more rapid rates of organic matter decomposition hypothetically resulting from locally elevated temperatures. Many aquatic organisms have narrow temperature optimum and changes as small as 1 °C can lead to the local extinction of regional taxa.

2.3 The Duke MRI and Other Urban-Edge Impacts Heat and N are two of many urban-generated pollutant stressors that are currently affecting landscapes surrounding cities. The purpose of this MRI is to accelerate research associated with urban-generated N and heat and to do so by creating a laboratory that in the future might explore any number of urban-forest issues such as atmospheric particulate emissions and depositions, methane emissions and deposition from urban landfills, and even invasions of plant and animal species.

3.0 The Duke Forest

The Duke Forest encompasses 7,060 acres of land in Alamance, Durham and Orange counties of North Carolina. Its six divisions are fully accessible through a network of roads and fire trails. A variety of ecosystems, forest cover types, plant species, soils, topography and past land use conditions are represented within its boundaries. The Forest has been managed for research and teaching purposes since the early 1930s. The original focus on forestry education and research has since expanded to include a broad range of studies in the ecological and environmental sciences. In terms of size, diversity, accessibility and accumulated long-term data, the Duke Forest is a resource for studies related to forest ecosystems and the environment that is unrivaled at any other university.

The Duke Forest supports mixtures of natural and planted pine, pine-hardwood and hardwood stands, as well as open fields on a variety of soils and topographic conditions in both the Carolina Slate Belt and Triassic Basin. Management practices for research on the Forest range from active silvicultural treatments including both natural and artificial regeneration, thinning and prescribed burning to areas reserved for study of natural processes without human disturbance. These practices can be tailored to meet emerging research needs. There are currently more than 1,450 acres of plantations and 1,200 acres of Natural Heritage Areas registered with the State of North Carolina. Flexibility in management options, stability of the land base, staffing and infrastructure facilitate a wide range of research opportunities in the Duke Forest. Because the Forest stretches into three counties and has areas adjacent to urban development as well as in rural landscapes, excellent opportunities exist for comparative effects of proximity to environmental change.

3.2 On-going Research on Duke Forest

More than 55 funded projects are currently underway on the Duke Forest with researchers from 30 research institutions and from most regions of the country. Its central location in the Research Triangle area fosters collaboration between Duke, UNC, NCSU, EPA, USDA Forest Service and other researchers. Examples of current projects from Duke and around the nation are:

- Examining the effects of Free Air CO_2 Enrichment (FACE) on a loblolly pine ecosystem, DOE FACTS-1 site, >30 investigators from >15 institutions
- Atmospheric N chemistry and N deposition, Duke & EPA
- Controls of net ecosystem exchange at an old field, a pine plantation, and a hardwood forest under closely similar climatic and edaphic conditions, UNC

- Suburban forest dynamics: succession, urbanization, and phenology of a Piedmont landscape, Duke
- Improving and evaluating dynamic models of natural and managed ecosystems over the central and southern US using AmeriFlux and MODIS data, University of Wisconsin
- Expression profiling of ecosystem response to climate change, Clemson
- Calibration of a regional ecosystem/atmosphere model to eddy-flux data, Harvard
- Implications of age-related variation in forest carbon cycling for atmosphere-biosphere carbon exchange, University of Illinois
- Insect responses to temperature manipulations, NCSU
- Effects of warming on tree species' recruitment in deciduous forests of the eastern United States, Duke
- Use of multispectral 3D aerial digital imagery to design, measure, and monitor land use and forestry carbon sequestration projects, Winrock and NASA

Until recently, nearly all research in the Duke Forest was intentionally sited in interior sections of the Forest to minimize edge effects from urban and roadway impacts. Investigators working in all parts of the Forest are recognizing a range of urban and suburban impacts (Figure 2). Higher temperatures, N deposition, tropospheric ozone, carbon dioxide and methane, particulates, urban-polluted runoff water, and exploding deer populations, all are associated with rapidly developing urban, suburban, and transportation systems immediately surrounding the Forest.

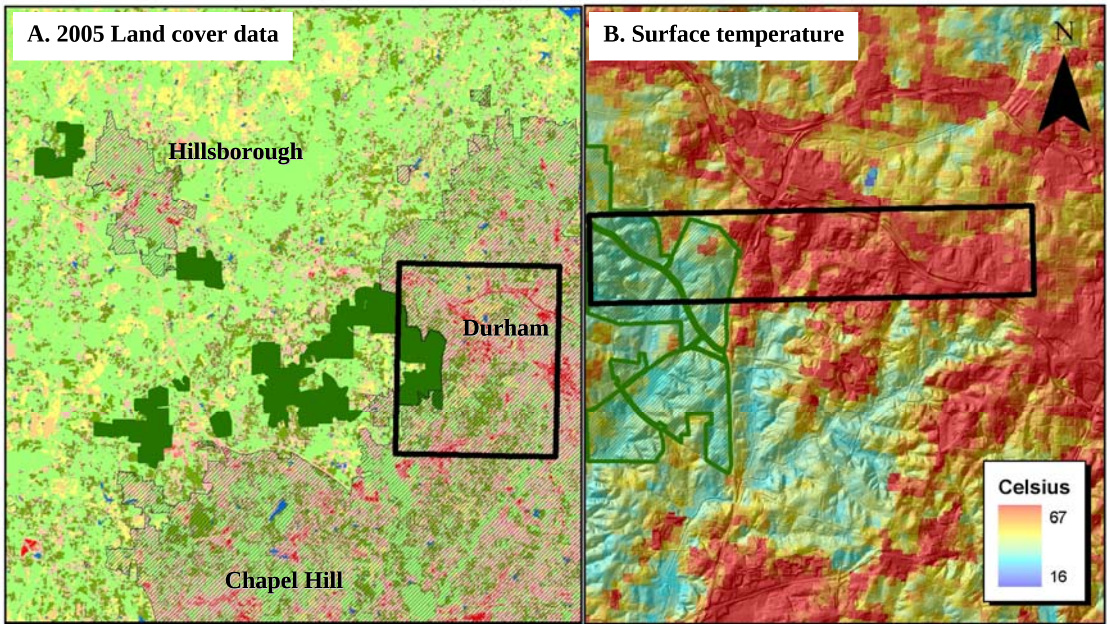

Figure 2. A) Land cover in 2005 in the vicinity of Duke Forest (dark green) and the rapidly urbanizing Durham, Chapel Hill, and Hillsborough. Intensity of red indexes % urbanized. B) Surface temperatures across Durham City and Duke Forest illustrate heating effects of Hwy 15-501, 147, & I-85 and surrounding city neighborhoods, July 2005 (Sexton & Urban, in prep.)

This proposal is motivated by the proliferation of recent Duke Forest research that investigates urban-forest interfaces, research that has important implications for public policy and education. Effects of an array of urban-associated pollutants are being studied on the Duke Forest, demonstrating that forests are highly responsive to rising atmospheric CO_2 (Finzi et al. 2007), and that atmospheric N deposition across the central Carolinas may well exceed 15 kg N $ha^{-1}y^{-1}$ (Sparks et al. 2008), the latter a result with major scientific and policy import. Forest “edges” are documented to have greatly altered tree-growth rates and to be gatekeepers for elevated numbers and densities of exotic plant species, some of which invade the forest interior (McDonald and Urban 2004, 2006). Hydrologic transport and management of Urban-generated pollutants are also transported hydrologically into the Duke Forest, the science and management of which is subject of recent and on-going study (Bernhardt and Palmer 2007, Kazezyilmaz-Alhan et al. 2007, Sutton-Grier et al. 2009). *This proposed MRI springs directly from the consolidating interests among Duke researchers from many scientific disciplines, and will without exaggeration help frame the next generation of research on the Duke Forest.*

4.0 What biophysical factors influence spatial and temporal extents of urban-heat and N through "edges"?

4.1 Strategic selection of terrestrial and aquatic sampling transects

To understand the contributing area for atmospheric and hydrologic transport of urban heat and N, we will initially use the National Land Cover Dataset (Homer 2004; http://www.mrlc.gov) and National Hydrography Dataset (NHD+, http://nhd.usgs.gov). The NHD+ has national coverage aimed at supporting watershed assessments based on land cover and hydrologic flow networks. As part of a recently completed study on ecosystem services in NC, we have collated the 2001 NLCD data products (land cover, impervious surface, and canopy closure) for all NHD+ catchments in North Carolina (Goodall et al., *in prep.*, Jenkins et al., *in prep.*, Urban *in prep*.).

We will use tactical approaches described by Urban (2000, 2002a) for efficient sampling of the study area. It is our intention to integrate remotely sensed data on vegetation and land use characteristics together with field observations to build statistical models that predict the permeability of urban/suburban edges to the hydrologic and atmospheric transfer of urban heat and N pollution. Currently sophisticated turbulent scalar transport modeling (e.g. via Large-Eddy Simulation methods) allows atmospheric scientists to predict wind driven dispersion of materials from complex source distribution, and these models are now beginning to confront the problem of how land surface and land cover heterogeneities affect fine scale transport (e.g Bertoldi et al., 2008). Cost surface modeling approaches have been used for determining habitat connectivity and dispersal distances, but current models fail to consider advective fluxes. We will link these approaches together – combining GIS layers describing impervious cover (heat source) and traffic volume (N source) with a hypothetical friction surface based on land cover and information on wind vectors to build a Hypothetical Cost Surface model describing variation in boundary permeability. This hypothetical model will be used to strategically select transects that vary in exposure and permeability to urban heat and N. For each transect we will contract for an overflight to collect high resolution hyperspectral and full waveform LIDAR – providing us with high resolution data on canopy temperatures and vegetation density to complement field measurements of heat and N distribution along each transect. Distributing samples over this decision tree effectively populates an ANOVA or regression design for subsequent analyses (Urban 2002a). In effect, a geographic information system (GIS; here, ArcGIS version 9.3, ESRI, Redlands, CA) will translate a distribution of samples from *parameter space* into *geographic space*. The approach can be extended to attend logistical concerns such as ease of access to candidate sampling locations (Urban 2000), or to enforce spacing of samples to minimize the effects of spatial autocorrelation (McDonald and Urban 2006b). Results of subsequent sampling will be used to calibrate and verify the hypothetical cost surface model – improving our predictions of buffer permeability and allowing us to extrapolate from limited field sampling.

4.2 Forest management "experiments."

We will take full advantage of ongoing stand management activities within the Duke Forest to provide strong tests of the statistical model for boundary permeability. We will compare model predictions to field measurements taken before and after stand thinning and stand harvest activities to directly determine how alterations in vegetation density and canopy height affect the transport of heat and N.

Annually on the Duke Forest approximately 50 acres are harvested and regenerated both naturally and with plantations. Operations such as pre-commercial thinning, commercial thinning and prescribed burning both in the understory and for site preparation are normally part of annual operations. These practices are often tailored to meet specific research goals.

5.0 MRI Question 1: How far and with what dynamics do pollutant N and urban heat islands extend beyond the urban-forest "edge"?

5.1 Nitrogen Deposition

Emissions of nitric oxide (NO) from combustion processes, particularly mobile sources, create an urban to rural gradient in atmospheric concentrations of oxidized nitrogen compounds ($NOx = NO + NO_2$; $NO_y = NO + NO_2 + HNO_2 + N_2O_5 + HNO_3 + PAN +$ other organic nitrates $+ NO_3^-$). Automobiles are also a significant urban source of ammonia (NH_3), equivalent to 10% of mobile NOx emissions (Durbin et al., 2002). Cumulatively, urban emissions of NO and NH_3 will enhance dry deposition rates locally (< 100 m from the source) and downwind into suburban and rural areas. For example, large gradients of NO_2, HONO, and NH_3 dry deposition have been observed along roadways (Fig 3, Cape et al., 2004).

Secondly, higher gas and aerosol reaction products of NOx, which include HNO_3, peroxy acetyl nitrates (PAN), other organic nitrates, NO_3^- aerosol, and organic aerosol, as well as aerosol products of NH_3 (NO_3^- and NH_4^+) will further enhance dry N deposition over a much larger area both within and downwind of the urban area. Figure 4 illustrates a dry N deposition budget for Duke Forest Blackwood Division, which is influenced by local NOx sources. Dry deposition of NO_y contributes significantly to ecosystem N inputs, particularly during the winter and fall when ground-level concentrations are higher.

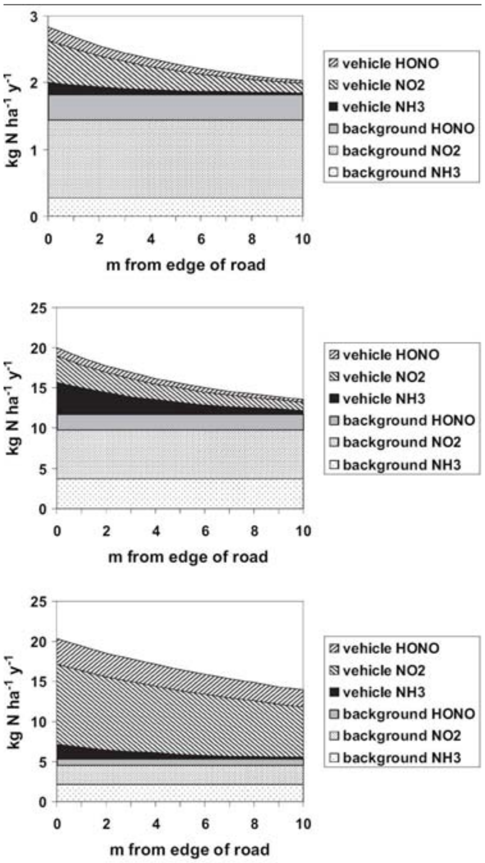

Fig. 3. N dry deposition vs distance from rural (top) and higher trafficked roads (Cape et al. 2004).

Additional measurements are needed at this site to determine the NO_2 fraction of the NOy flux and to quantify the contribution of organic N compounds, which may also contribute significantly to both wet and dry fractions. To accurately characterize the influence of urban N emissions on deposition to nearby forests, measurements must capture the microscale features of deposition near roadways and the more well mixed signal of primary emissions and reaction products further downwind.

Aerosol nitrogen species such as ammonium nitrate and some or all organo-nitrogen species are semi-volatile, i.e. their gas and aerosol phases are temperature-dependent. Because deposition velocities of aerosol particles are significantly lower than that of gases, dry N deposition can vary strongly with temperature, especially if the fraction of semi-volatile N in aerosol is high. This emphasizes the importance of quantifying N aerosol species and understanding their properties for accurate prediction of N deposition and the impact of urban sources on ecosystems.

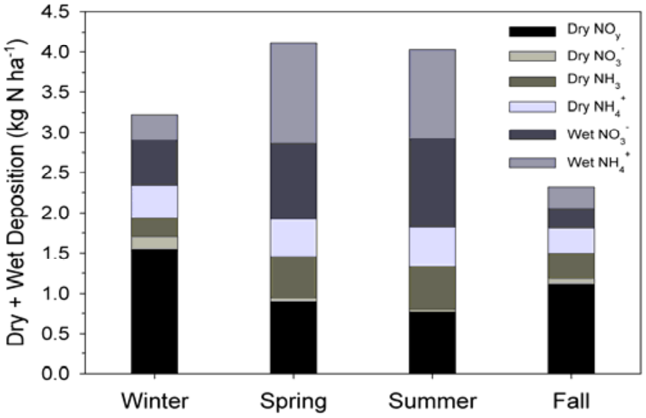

Fig. 4. Seasonal N deposition budget at Duke Forest (Sparks et al., 2008). Budget does not contain organic N species.

Nitrogen Deposition Measurements. Spatial and temporal patterns of nitrogen deposition will be characterized by combining highly temporally resolved direct flux measurements with highly spatially resolved time-integrated passive sampling. We anticipate relatively large gradients in nitrogen deposition (NOx, NH_3) immediately downwind of roadways adjacent to the forest. Such large spatial and temporal variability in air concentrations, as well as atmospheric turbulence and surface characteristics, preclude the use of standard micrometeorological techniques (i.e., eddy covariance and aerodynamic approaches) to quantify nitrogen dry deposition. Under these conditions, however, dry deposition rates can be estimated from highly spatially resolved time-integrated concentration measurements.

We propose to use badge-type passive samplers (Tang et al., 2001) to measure vertical and horizontal gradients of NOx and NH_3 concentrations along roadway-to-forest gradients, which, combined with standard meteorological variables, will be used to estimate dry deposition rates using resistance – based inferential modeling approaches (Meyers et al., 1998; Walker, et al., 2008). Because passive samplers are small and do not require power, they can be deployed in sufficient numbers to adequately characterize the expected complex spatial variability in air concentrations.

Further downwind, on the forest end of the urban to forest gradient, where air concentrations and surface characteristics are more spatially homogeneous, eddy covariance techniques will be used to directly quantify dry deposition fluxes of oxidized (NO_y) and reduced (NH_3) compounds to the forest canopy. Oxidized nitrogen species will be measured using a fast chemiluminescence approach (Sparks et al., 2008; Munger et al., 1996) and NH_3 will be measured by quantum cascade laser absorption spectroscopy (Whitehead et al., 2008). Both systems are capable of sampling frequencies of 1 – 10 Hz, which is a requirement of the eddy covariance technique. Direct flux measurements will be used to develop deposition budgets, examine the processes that regulate deposition (i.e., canopy physical and chemical characteristics), and parameterize the inferential models used to calculate fluxes from time integrated concentration measurements (passive samplers). A second chemiluminescence system will be used to measure in-canopy vertical profiles of oxidized nitrogen to partition net canopy-scale fluxes into foliage and soil components and examine the potential for in-canopy chemical loss or production. In addition to N deposition, N (as N_2O) emission from the soil will be quantified using an automated static chamber system interfaced to a portable gas chromatograph (GC/ECD). A second GC/ECD system will be used to quantify N_2O air concentrations within and above the forest canopy.

Concentration gradients of N species in aerosol particles will be measured using a set of three fully automatic instruments based on the Steam-Jet Aerosol Collector (SJAC) (Khlystov et al., 1995, Lin et al., 2009). The SJAC collects both soluble and insoluble particles into an aqueous solution/suspension, which is continuously directed to a set of on-line analytical instruments. Two Metrohm-Peak Ion Chromatographs are used to detect major inorganic aerosol constituents, including the nitrogen containing species (NH_4^+ and NO_3^-). A Shimadzu high sensitivity TOC/TN analyzer is used to detect the total (inorganic and organic) N content of the particles. The concentration of organic N in aerosol is determined as the difference between the total N and inorganic N concentrations. The high time resolution of the instrument (30 min) allows detection of the temperature dependence of concentrations due to diurnal variations and other transient phenomena.

5.2 Urban Heat

Urban heat islands are well documented examples of acute anthropogenic climate modification (Arnfield 2003). For over 30 years, urban heat islands have been studied, especially from the perspective of the energetics and climatology of the city. Climate change in urban environments is an important part of life in the Anthropocene (Crutzen 2004). Many cities are 5 to 10ºC warmer than surrounding non-urban environments through much of the day and night as well. Ground surface and and even subsurface heat islands follow spatial and temporal patterns that are distinctively different from those of atmospheric conditions. Urban heat islands are hypothesized in this MRI proposal to have important ecological effects on ecosystems adjacent and downwind from cities. As the Earth continues to be urbanized, rural ecosystems adjacent to cities are not only fragmented but are increasingly being altered by excess heat that spills out from the city limits. We hypothesize that this urban heat spillage is an important part of life in the Anthropocene and of ecological significance to forests that surround cities.

The proposed platforms will have two distributed temperature sensing (DTS) systems, instrumentation that provides the opportunity to monitor with high precision and accuracy and at high spatial and temporal frequencies. Though the technology is only beginning to be deployed to address environmental questions, its technical development is relatively advanced due to its use in fire prevention, mining, and industrial applications. Environmental scientists have very recently deployed DTS systems in marshes (Moffett et al. 2008), streams (Selker et al. 2006), agricultural fields (Hatch et al. 2008), snowpacks (Tyler et al. 2008), and in volcanoes down bore holes. Selker (2008) enthusiastically predicts that the technology is transforming the science of hydrology.

In our proposed MRI project, DTS systems will be used to measure air temperature, soil, and stream temperatures at fine spatial resolution longitudinally and vertically across a heated urban zone - forest edge (Figure 5). The

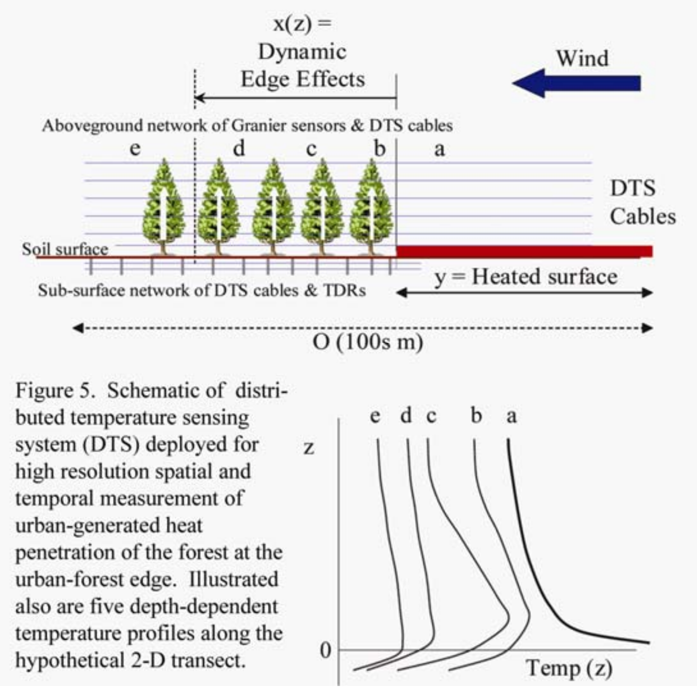

Figure 5. Schematic of distributed temperature sensing system (DTS) deployed for high resolution spatial and temporal measurement of urban-generated heat penetration of the forest at the urban-forest edge. Illustrated also are five depth-dependent temperature profiles along the hypothetical 2-D transect.

edge effect here is defined by the spatial distance starting from the heated urban zone to the point at which the mean air temperature profile equilibrated with the forest surface (e in Figure 5). This equilibration point can be defined from the data stream as the point at which the mean horizontal gradients in air temperature are small. This edge effect is illustrated as being two-dimensional inside the canopy and it is highly dynamic at short time scales. It is influenced by exogenous climatological forcings such the mean velocity and the radiation load arriving at the surface, and endogenous parameters such as leaf area density distribution of the forest stand, the radiative and physiological properties of the two surfaces, among others. The DTS system with its fast-sampling resolution will permit us to assess such expanation and shrinkage of the 'heat edge effect' initially in two dimensions and in the future in three. When combined with transpiration (Granier sap flow) data, the ecological consequence of this temporally integrated yet dynamic edge effect can be more fully quantified. The basic premise is that excess heat near the edge will increase vapor pressure deficit (VPD) thereby increasing transpiration rates as measured by a network of sap flow sensors and hypothetically depleting the root-zone soil moisture, as measured by a network of TDR probes. Over longer time periods, the vegetation in the edge-vicinity will hypothetically experience more prolonged moisture stress. The added moisture stress may even reduce photosynthesis, and make vegetation more susceptible to disease.

Urban heat can significantly stress biological organisms, especially those living at the edges of their geographic distribution. Plant respiration, photosynthesis, evapotranspiration are closely tied to temperature, with direct and prominent effects also associated with drought stress. Microbial activity in soils and sediments are directly tied to temperature with more rapid rates of organic matter decomposition hypothetically resulting from locally elevated temperatures. Many aquatic organisms have narrow temperature optimum and changes as small as 1 ºC can lead to the local extinction of regional taxa.

<u>6.0 What are organismal and ecosystem responses to localized heat and high N supply in terrestrial and aquatic habitats?</u>

6.1 Continuous measurement via instrumentation platforms. Prior work in the Duke Forest has documented significantly higher annual growth rates for two common NC Piedmont trees (*Pinus taeda* and *Liriodendron tulipifera*) within 5m of a forest edge (McDonald ad Urban 2004). With the instrumentation platforms proposed here we will be able to examine what aspects of the urban edge environment are associated with increased tree growth. Sap-flux sensors will provide continuous measurements of water moving up the transpiration stream; these values can be readily converted to crown level (tree) and canopy level (stand) transpiration, mean conductance, and CO_2 uptake. Oren lab and collaborators are currently measuring flux in a number of stands at the Duke Forest, and together with high school students from the North Carolina School of Science and Math are setting up a comparison site inside Durham to assess heat-island effects. However, there are many factors that could affect trees growing in urban environment differently from those growing in forests: Ozone, nitrogen oxides and other airborne pollutants may affect the ability of stomata to respond the water stress, negatively affecting plants, but when nitrogen is added to the soil, in many situations, the increased availability can positively affect photosynthetic rates (and thus conductance) and carbon partitioning to aboveground production. Such a shift results in decreased CO_2 efflux from the forest floor. The heat-island effect may increase the length of the growing season, as well as the vapor pressure deficit in each part of the season. A study along a transect, as opposed to a comparison between two points, will allow a better definition of causal (rather than corollary) relationship because the gradients in air pollution, soil pollution, and air temperature, are shaped differently, and the responses (combining information from sap-flux and soil CO_2 efflux) should map better to a subset of variables in each interval along the transect.

6.2 Follow-on measurements underpinned by MRI data support. Duke Forest is current the subject of a number of studies involving atmospheric change and climate, including the FACE experiment (Oren, PI), experimental warming (Clark, PI), and regional patterns of succession (Wright, PI). Response variables are tree physiology, demographic rates, and shifts in species identity. This proposal would provide opportunities for extending these studies to the overlooked problem of forests response to microclimate and atmospheric gradients in habitat fragments. We propose to implement transect studies for forest response including the ambient gradient 'control', coupled with manipulations that establish new forest fragments. To understand processes that have been impacted by existing urban gradients (UGs), we plan to document physiological, demographic, phenological and compositional variation along edges that have been in place for decades. Demographic rates estimated from longitudinal survey data will be used to test for how urban gradients differentially affect dynamics of different tree species. Surveys of invasive species will help us to determine how these edges function as corridors for invasion, for which types of species and at what rates. Prior work in the Duke Forest has shown that species composition in the forest edge is quantitatively different from the forest interior (McDonald and Urban 2006).

7.0. Project Management

7.1 Plans for Collaboration. This proposal was developed collaboratively by Duke faculty currently engaged in research in the Duke Forest. Most of our group are engaged in research collaborations with other group members and many have worked together for years on the highly collaborative and interdisciplinary Duke Free Air CO_2 Enrichment Experiment (PI Oren, current and previous co-investigators include Katul, Richter, Bernhardt, Johnsen, Clark, Jackson, Walker). We have a track record of productive, interdisciplinary science. Instrumentation platforms requested in this MRI will be developed as a shared mobile laboratory and will be managed through the Duke Forest office. PI Dan Richter will assume primary responsibility for hiring both the project technician and database manager and will take primary responsibility for the purchase, development and deployment of the DTS temperature systems. CoPI Emily Bernhardt will have primary responsibility for the purchase, development and deployment of the aquatic instrumentation platforms. CoPI Andrey Khlystov, together with John Walker will assume primary responsibility for the development and deployment of the atmospheric sampling platforms. Senior personnel Dean Urban will oversee a graduate RA in the first year of funding to finalize existing high resolution datasets on urban impervious cover and merge this with DOT data layers. Urban will assume primary responsibility for strategic site selection and for the acquisition and processing of high resolution LIDAR and hyperspectral imagery. Ram Oren and Kurt Johnsen will assume primary responsibility for the purchase, development and installation of soil respiration and sap flux measurement systems. Judd Edeburn, together with staff of the Duke Forest office will serve as the primary coordinator of outreach activities. This smaller team (Richter, Bernhardt, Khylstov, Urban, Oren, Johnsen and Edeburn) will meet weekly through the first year of funding as instruments are purchased and tested and the project database is developed. The entire MRI collaborative team (and affiliated students) will meet on a monthly basis to share progress reports and coordinate sampling and proposal writing.

7.2 Timeline

August 2009 – Funding awarded. Instruments ordered from suppliers. Advertisements posted for project technician.

September-December 2009 – Instruments arrive, project technician hired – calibration, field testing and protocol development by relevant faculty members. Advertisement posted for database developer.

January-April 2010 – Database developer hired, initial deployment of instrumentation platforms to test communication, data storage, data formats. Database developer generates user-friendly interface and efficient uploading approaches and together with relevant faculty begins to develop metadata and error checking macros.

May 2010 – Graduate RA begins compilation of GIS layers. Together with Dean Urban student produces a hypothetical cost surface model and strategically selects transects for comparison of traffic volume and upwind impervious surfaces.

7.3 Integration with existing monitoring networks. It is our intention to develop a data management system that is fully compatible with similar efforts under development through NSF's Long-term Ecological Research program and the National Ecological Observatory Network – facilitating data sharing and comparative analysis between research in the Duke Forest and NEON locations throughout the United States. Our current plan is to utilize the Morpho Data Management software developed by the Knowledge Network for Biocomplexity (KNB) as the starting point for developing our database infrastructure and for developing and compiling project metadata. We recognize that proper and efficient data management will determine the success of this project – our research plan requires the development of a database that compiles information from diverse instruments collected across a wide range of spatial and temporal resolution and in need of varying levels of post sample processing. We will hire a full time database manager ($80K) for 1.5 years whose time will be dedicated to building a user friendly relational database accessible to all project participants. We will post all data for public use within two years of collection through the KNB website.

8.0 Broader Impacts

8.1 Traditional Education The instrumentation platform will provide new collaborative, interdisciplinary opportunities for both current and future students through Duke's doctoral programs in Biology, Ecology, Environmental Science and Environmental Engineering Programs. The instrumentation platform would provide new information to support the ongoing research of current Duke PhD students each of whom is currently studying aspects of Duke Forest Ecosystems- Elizabeth Sudduth, Kayleigh Somers, Julie DeMeester, Siyi Wang, Joe Sexton, Chris Oishi, Eric Ward, Michelle Hersh, Dave Bell, Carl Salk, Emily Moran. The graduate programs in Environmental Science, Ecology and Biology all offer a guarantee of 5 years of TA funding upon admission and many of our students are successful at acquiring graduate fellowships from NSF, EPA, DOE, thus we anticipate that despite a lack of funding for graduate students through the MRI program we will be able to involve many students throughout the term of the grant and beyond.

In addition, we anticipate the data platform becoming an important foundation for numerous research initiatives by our undergraduate honors research programs and our professional environmental masters program (MEM students). We will introduce these students to the potential for independent research on urban edges by developing 2 courses in Urban Ecology. One will be taught as a freshman seminar while the second will be through an intensive field course designed for advanced undergraduates and MEM students. Because many Duke undergraduates and MEM students go on to pursue careers in environmental policy and medicine, we will have the opportunity to propagate information about urban stressors far beyond the academy.

8.2 Non-traditional Education. The PIs and many of the senior personnel have longterm relationships with municipal and state management agencies, and we will work with our colleagues at Durham Division of Stormwater services and Durham Department of Parks and Recreation and of City-County Planning to help bring the most recent science about urban impacts into ongoing discussions of infrastructure, zoning, and preservation planning in the Research Triangle. This study of urban heat and urban N represents an important opportunity to forge substantive and longlasting collaborations with the city of Durham.

To achieve broader impacts within our local region, we will work in partnership with Troy M. Livingston, Vice President for Innovation and Learning at Durham's Museum of Life and Science (http://www.lifeandscience.org/). The museum, which receives more than 340,000 annual visitors, is nationally recognized within the science center community for its work in developing new models for researcher/public engagement. In the first years of our project, we intend to have project researchers participate in the museum's Periodic Tables: Durham's Science Café to present the science-attentive public with an overview of our project so we can dialogue with them about their interests in or any potential concerns about our work. As the project matures, and within the period of the MRI grant, we will apply for supplemental grant funding through NSF's Community Research to Public Audiences (CRPA) program to fund more in depth programming that will enable us to reach historically underserved audiences cultivated by the museum. Initial discussions for the focus of this outreach involve our desire to work with Chewning Middle School, one of Durham's public middle schools where minority students constitute 86% of those enrolled. We'd like to purchase temperature, light and radiation sensors and data loggers that will allow students to compare diel and seasonal patterns of light, radiation and heat between impervious surfaces, open fields, and forest fragments—giving students real-time hands-on experience with the kinds of research our project conducts.

In association with the proposed research efforts we will mentor NC K-12 science teachers through the Kenan Teachers Fellows for Curriculum and Leadership Development (http://www.ncsu.edu/kenanfellows/) program administered through NC State University. We will also continue to work with faculty of the NC School of Science and Mathematics (a public, residential high school for talented students drawn from all over NC) in Durham. Since 2005 coPI Bernhardt has been working collaboratively with Dr. Christine Muth and Mrs. Leslie Brinson in developing a curriculum to address the effects of urbanization on aquatic ecosystems. We will extend this relationship to develop new learning modules focused on atmospheric chemistry and urban forestry. In both efforts our intention is to work with talented middle and high school teachers to develop curriculum and education materials appropriate for environmental science courses throughout the state of NC.

Informational signage, newsletters and web postings through the well established Duke Forest office. Currently, informational signage describing research projects and silvicultural activities is posted throughout the Duke Forest, which is visited by over 170,000 members of the general public each year. The Duke Forest LOG, a periodic newsletter is published 3 times a year and is distributed to over 2,000 recipients. In addition the Duke Forest staff conducts numerous field trips and educational programs annually, 23 in the past year alone, for almost 600 individuals including local K-12 schools, visiting international professionals from China and Indonesia and conference attendees from a Sustainable Agriculture meeting, the Forest Guild Society, Society of Economic Botany, and Ecological Society of America.

9.0 Details of Instrumentation

9.1 Detecting Pollutants

High resolution temperature sampling: Argilent fiber optic temperature sensor cable with DTS loggers will provide detailed data on longitudinal and vertical temperature profiles along each transect. Point estimates of incoming radiation will be measured at each sampling platform using Kipp & Zonen UV radiometers.

Nitrogen Gas Sampling: This is a two part system including a SRI greenhouse gase analyzer for N_2O analysis and a ECO PHYSICS CLD 88p NO Analzyer with CON 765 NO_y converter and PLC photolytic NO_2 converter and CLD 89 NO analyzer system for NO_y analysis. This instrumentation will be attached to a tower equipped with anemometer, height integrated gas sampling ports and a collection pump.

Aerosol collection and N analysis: This is a four part system consisting of a steam-jet aerosol collector (Khlystov 1995), 2 Metrohm Peak Ion Chromatographs (one for anions and one for cations) and a Shimadzu TOC-Vch with TN module. Aerosols will be sampled from height integrated air sampling ports collocated with ports for N gas collection.

Traditional wet dry N deposition collectors and passive N gas samplers will be deployed at all terrestrial sampling locations.

Hydrologic transport of inorganic N: Envirotech EcoLab compact nutrient monitor together with a YSI Sonde continuously recording water level for i*n situ* analysis of hydrologic transport of NH_4^+ and NO_3^-. The EcoLab performs wet chemistry in the field – providing unprecedented high resolution data during the critical times in which the bulk of urban N is transported through streams (during flood events). EcoLabs will directly interface with the YSI Sonde and will store data internally for periodic field retrieval.

9.2 Measuring Biological Responses

Soil Respiration: The Automated Carbon Efflux System (ACES, *US patent pending*) was developed by staff of the USDS Forest Service Southeast Research station (for details see supplemental documents). Briefly, the ACES system is a multiport, dynamic gas sampling system that utilizes an open flow-through design to measure carbon dioxide fluxes from the forest floor or woody tissue with a variety of chamber styles. In the current design, sixteen soil chambers are measured sequentially (fixed or variable time step) using a single infra-red gas analyzer (IRGA). The soil respiration chambers are constructed of pVC (25 cm diameter 10 cm height 4900 cm^3) with a lexan lid. Each chamber has an air and soil thermocouple, pressure equilibration with the atmosphere and reflective insulation that prevents "greenhouse" heating in the chamber even in full sunlight. A soil moisture reflectometer is used to take soil moisture readings in each chamber and can be installed in a common location for continuous measurement. The ACES is fully automatic requiring only calibration checks twice per week. Under AC power the system can run continuously, using a DC power supply the ACES can go up to 48 hours without recharging. We anticipate developing approaches to run the ACES system in conjunction with the SRI GC to simultaneously determine N_2O, CH_4 and CO_2 fluxes from both water surfaces and forest soils.

Sapflux and Soil Moisture: We will deploy 96 sapflux sensors (8 species X 6 individual trees x 2 sensor depths) at the endpoints of each characterized gradient. The sapflux sensors are constructed at cost from Granier parts and are connected to a Campbell CR1000 datalogger with multiplexer. Budgeted costs include sensor replacement and moving costs to reset the system in multiple locations.

Soil moisture monitoring: We will deploy 15 soil moisture smart sensors connected to a Campbell datalogger with multiplexer at all 10 terrestrial monitoring platforms.

YSI XLM V2 Optical SONDE with optical oxygen probe will be used to estimate whole-stream metabolism for each subreach along longitudinal transects.