ABSTRACT

LEIGH HAUGSETH. Measures of Sustainability in Land Use Decision-Making. (Under the direction of DOUGLAS CRAWFORD BROWN)

Sustainability and sustainable development are concepts that often surround land planning and development issues. Incorporating concrete sustainability principles into land use planning can be a challenge as sustainability tends to be an abstract concept in which several issues are intertwined. This thesis attempts to examine two measures, one ecological measure and one human health measure, and combine them so that they can be incorporated into land use decisions rooted in sustainability principles. Specifically, these measures are quality adjusted life years, which measure the health impact of air quality reductions, and net primary productivity, which measures the carbon absorbing potential of flora. A prototype methodology is then created which integrates these measures into a framework that can be followed during the decision-making process. As a test, this prototype methodology is applied to two counties in North Carolina to determine feasibility issues and limitations. Results indicate that this methodology can be useful in determining optimal locations for future land development in regards to net primary productivity and air quality. Feasibility can be an issue due to the potentially large percentage by which development must decrease in some cases in order to achieve a target QALY. This is due in part to the overestimation of decline in QALY's associated with development, which is a result of the precautionary assumptions built into the Hazard Index as this is used within the QALY equation.
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Introduction

Overview of Problem Area

In 1987 the Brundtland Commission defined sustainability as “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs”. Sustainability has since evolved into a buzzword that is being increasingly used by environmentalists, industry, world leaders, city and regional planners, and the general public. World conferences are held to discuss what countries can do to become more sustainable, businesses are beginning to incorporate sustainability principles into their management practices and city and regional planners are making land use decisions rooted in sustainability concepts. Some are even designing “green cities” aimed at being self-sufficient, pollution free, and ecologically sound (Green Cities, Gordon, 1990).

The concept of sustainability can encompass a wide variety of issues such as economic feasibility, social equity, environmental quality, and human health. It can be difficult to achieve a balance between them when making land-planning decisions. Human health considerations may be sacrificed for social equity concerns and environmental quality and/or human health risks may not be considered important issues when there are potential economic gains at stake. For example, if a large industrial plant wants to build in a poorer community, the local government of that community may consider the benefits of economic gain and an increase in jobs before considering any potential environmental degradation or human health risks that may occur.

While state and local planning groups in North Carolina have made significant progress in their efforts to achieve some measure of sustainability in their decision-
making, there is much to be done. Only a few counties in the state have a clear and
detailed written plan for achieving sustainability goals. Even for them, incorporating the
numerous issues pertaining to sustainability into the decision-making process can be
daunting, especially when there is a lack of resources to do so. For example, most state
and local planning boards in North Carolina have access to basic GIS software, whether it
is through their own database or through a statewide GIS database such the one created
through CGIA (Center for Geographic Analysis). However, their capabilities for putting
these data layers to use can be reduced due to lack of training or lack of sufficient data.
Better technology is needed as well as data that is accurate and up to date. In addition,
planning groups need user-friendly decision-support tools that can combine more than
one variable into the decision model so that incorporating sustainability principles into
the decision making process becomes easier.

Purpose

The purpose of this paper is to create a prototype methodology which combines
two measures, one an ecological measure and one a human health measure, that can be
incorporated into land use decision-making rooted in sustainability principles.
Specifically, these measures are net primary productivity (NPP) and the health impact of
reductions in air quality as measured in quality adjusted life years (QALY).

This paper begins with a background and literature review on sustainability and
land use planning in North Carolina presently, the health effects of air toxics and quality
adjusted life years, and net primary productivity and global warming. The methods
section then describes how I calculated quality adjusted life years and obtained net
primary productivity estimates for the state before mapping each of these measures onto a GIS map of North Carolina. I will then describe how the prototype methodology was constructed based on a ten-step process and how it was applied to two counties in North Carolina. I conclude with a description of the different ways in which counties can use this tool as a part of the land planning process within the context of sustainability as well as recommendations for future research that might incorporate a wider range of sustainability measures.

**Background and Literature Review**

*Sustainability and Land Use Planning in North Carolina*

North Carolina has made significant strides in their efforts for a more sustainable state, and for good reason. A beautiful and ecologically diverse state, North Carolina attracts hundreds of thousands of tourists every year. It ranks fourth in the country in overall biodiversity and its natural areas help make it a very attractive place to live. However, North Carolina is also the fourth fastest growing state in the nation and ranks sixth in the level of air pollution (Cumming, et.al. 2003). The growth rate of developed land from 1990-1997 was 23.4%, which is 11.4% faster than the rate of population growth (Save Our State, 2002). This trend has made automobile-dependant land use, commonly referred to as suburban sprawl, an immediate and pressing issue in North Carolina. Fortunately, groups throughout the state have begun to realize that urban sprawl is a problem and that our natural land areas are in jeopardy. Government agencies, academia, and NGO's throughout the state have initiated sustainability efforts which
address these issues. A literature review revealed several statewide and local sustainability and land planning efforts. The following is a description of the major statewide efforts taking place.

The North Carolina Department of Environment and Natural Resources has a sustainability committee which puts out a report on sustainability initiatives in the state, and provides checklists for individuals and organizations wishing to implement sustainability practices (NC DENR 2004). NC Project Green is a similar statewide initiative which operates under the Pollution Prevention department of DENR. They provide a comprehensive listing of sustainability reports from universities and state agencies on their website. They also host events to promote awareness and educate the public on sustainability (NC Project Green 2001). The North Carolina Progress Board, a non-profit organization established in 1995 to track the state's progress, has set goals for the preservation of the natural environment as well as the urban and economic environments. They wrote a comprehensive report evaluating North Carolina’s progress in eight areas: (1) healthy children and families, (2) safe and vibrant communities, (3) quality education, (4) high-performance workforce, (5) sustainable environment, (6) prosperous economy 21st century infrastructure, (7) active citizenship and (8) accountable government. In addition, the UNC-Chapel Hill Department of City and Regional Planning has developed a Triangle Regional Smart Growth Report Card in which letter grades are calculated for each of seven areas: (1) equity/affordability, (2) transportation, (3) open space/farmland, (4) economic vitality, (5) civic life, (6) environment/public health, and (7) growth management. In this report card, the Triangle region received a grade of C for environment/public health.
The Save Our State campaign, funded by the Z. Smith Reynolds Foundation, is another statewide initiative which campaigns for a better environment while at the same time promoting economic growth. The Save Our State campaign has helped to address land development issues by hosting a smart growth forum and using recommendations from this forum as a basis for the Legislative Commission on Smart Growth to establish goals for North Carolina (Save Our State, 2002).

In addition to these statewide sustainability initiatives, there are a couple of major land conservation efforts occurring simultaneously with sustainability efforts at the state level. The Department of Environment and Natural Resources set forth the Million Acre Initiative in 1998. The goal of this statewide collaborative effort is to preserve one million acres of farmland, open space and natural areas by 2009. In conjunction with this effort, the NC DENR has recently introduced the One North Carolina Naturally Initiative whose goal is to develop a comprehensive, state-wide conservation effort sustained by the current local efforts being made in order to effectively manage and protect North Carolina’s delicate natural areas.

At the local level, there are numerous ongoing land conservation/planning projects run by non-profit organizations and county planners. Since the prototype methodology discussed later in this paper deals with decisions made at the county level, the following section of the literature review focuses on the sustainability and land conservation efforts of two counties, Orange and Mecklenburg, to show how they organize their land use planning efforts.

Orange County has established a comprehensive sustainable planning effort by working with local conservation groups in the county to maximize the amount of natural
areas in the county. In 2001, the County Commissioners established the Environment and Resource Conservation Department (ERCD), which administers the county’s Land Legacy program. This program focuses on land acquisition and includes an extensive inventory of ongoing conservation efforts within the county, a GIS map including numerous data layers of the county’s natural resources (Table 1 below), and evaluation criteria which help them in prioritizing and choosing which lands are best to acquire.

**Table 1. Current and needed GIS data layers in Orange County, NC as of 2000**

<table>
<thead>
<tr>
<th>Current GIS Data</th>
<th>Data in Need of Update</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>Wetlands</td>
</tr>
<tr>
<td>Impervious surfaces</td>
<td>Aerial photography</td>
</tr>
<tr>
<td>Existing land use pattern</td>
<td>Soils</td>
</tr>
<tr>
<td>Land in active cultivation (farmland)</td>
<td>New building permits and development projects</td>
</tr>
<tr>
<td>Existing zoning and Land Use Element (parcel level)</td>
<td>Wetlands</td>
</tr>
<tr>
<td>Feedlots, pesticide application and animal waste lagoons</td>
<td>Aerial photography</td>
</tr>
<tr>
<td>Ground water recharge areas (ma)</td>
<td>Soils</td>
</tr>
<tr>
<td>Data from adjoining jurisdictions</td>
<td></td>
</tr>
<tr>
<td>Historic corridors</td>
<td></td>
</tr>
</tbody>
</table>

Since 2000, the department has acquired 794 acres for protection (Orange County, 2000). In addition, Orange County’s Planning Department encourages open space by requiring developers to submit two plans for the same parcel of land. The first and more conventional plan contains lots of similar sizes with minimal open space. The second more flexible plan clusters the house lots together and leaves at least 33 percent of the acreage as open space. The Planning Board then decides which plan would be better suited for the land being developed (Save our State, 2002).
Mecklenburg County houses one of the top ten fastest growing cities, Charlotte (Sierra Club, 2003). Transportation issues are at the center of land use planning in the greater Charlotte area. The 2005 General Land Use Plan was adopted in 1985 and is a detailed land use plan for the Charlotte-Mecklenburg area. The plan serves as a guide to many public decisions, especially land use changes as well as zoning enactments and related growth management legislation for the city of Charlotte and Mecklenburg County.

More recently, the 2015 Plan was adopted. This is essentially a policy document that establishes priority areas that the county should focus on in order to stay economically viable and maintain a high quality of life. The land use policies from the 2005 plan are used to help provide direction for the selection of priority areas in the 2015 plan (Charmeck Planning Commission, 2000). In addition to these countywide land use plans, there are several individual land use plans for specific areas in the Charlotte-Mecklenburg region (http://www.charmeck.org/Departments/Planning/Land+Use+Planning/Neighborhood+Planning/home.htm).

A problem facing such community planning efforts is how disparate measures of sustainability are to be combined in locating areas of future development and conservation. For example, if a county wants to improve human health by reducing air pollution and at the same time help to alleviate global warming by maximizing net primary productivity, how can they combine these two measures and incorporate them into the complex process of choosing areas for future development? This is the central problem motivating this thesis.
In considering the following material, it is essential to bear in mind the relationship between the methodology developed here and the larger process of decision that would take place in planning. While the motivation for the present work is sustainability as applied in development and planning, the methodology presented focuses solely on the two measures of human health and net primary productivity in a region. It does not focus on the remaining goals of sustainability: social justice and economic vitality. It also does not focus on the links between economic vitality and human health, such as the ability of a vibrant economy to improve health through both access to health care and access to increased financial resources to purchase pollution control measures. As a result, the term “development” as used in this paper does not reflect the full meaning of that term in planning, where it includes economic development that might lead to improvements in health. “Development” in this paper means only the creation of new sources of the air toxics producing the health risks calculated, with no mitigating effect of the accompanying economic development. This is an important caveat, and points further to the need to view the following methodology as only one of several tools that would be needed to produce complete planning decisions.

Health Outcomes and Quality Adjusted Life Years

The health effects due to the inhalation of toxic air pollutants are well documented (Koenig, 2000, Holgate, 1999, Health Effects Institute, 1999, American Lung Assoc. 1996, ICF and EPA, 1995, EPA 2000). Depending on the particular substance, the inhalation of toxic air pollutants can cause a variety of effects that may be cancerous or non-cancerous in nature. Examples of possible cancerous effects associated with inhaling
these pollutants include lung cancer, leukemia, kidney cancer, prostate cancer, nasopharyngeal cancer, and cancer of the trachea. Non-cancerous effects can include asthma, respiratory irritation, conjunctivitis, chronic bronchitis, kidney disease, and emphysema (EPA, 1994).

These effects or "outcomes", such as those resulting from toxic air pollutant exposure, can be measured in a number of different ways. One common way that health outcomes due to toxins are measured is to simply determine how much of the substance is in the body at elevated levels due to the exposure. Another common approach is to measure a health outcome such as cancer or non-cancer by calculating the probability of getting that outcome. This was done in the National Air Toxics Assessment conducted by the EPA in 1996 (EPA, 2002). Risk was characterized as the excess probability of getting cancer or non-cancer effects as a result of exposure to toxic substances, based on information collected from exposure assessments and dose response assessments.

An alternative and integrative method in which both cancer and non-cancer health outcomes can be measured is through a time-based measure known as Quality Adjusted Life Years (QALY). This health outcome measure is somewhat different from the previous two as it takes both quantity and quality of life into account as well as integrating the impact of cancer and non-cancer effects due to air toxics inhalation. Developed in the 1970's to measure the health states between perfect health and death, (usually represented by 1 and 0 respectively), quality adjusted life years is based on an individual's preference between living longer with disease or living a shorter period free of disease (McCulloch, 2003). While there is no standard formula for calculating QALY's, the basic method is well established. Each time period in a person's lifetime
receives a weight ranging from 0 to 1 corresponding to the quality of life during that period. This quality is affected by the presence and severity of disease in that period. Therefore the overall QALY represents the number of healthy years of life that are valued equivalently to the actual health outcome. For example, if a person was diagnosed with lung cancer at 60 years of age and the average life expectancy is 70 years of age, the QALY would depend on the person’s valuation of his or her own quality of life for those ten years in between. If a person rated their quality of life as a 1 from 0 to 60 years of age and as a 0.7 during the period where they had lung cancer, their Quality Adjusted Life Years would be 67 years \( (60 \times 1 + 10 \times 0.7 = 67 \) years).

While the QALY approach has been widely used over the past 20 years for evaluating medical policies and health interventions, experts in the environmental policy arena have only recently begun to pay special attention to this method for use in evaluating environmental policies (Gamo, Iwasa, Nakanishi, Tanaka, 1998). Their use in decision-making is still highly controversial and information on population preferences and disease latency and duration is still incomplete (Ponce et al. 2000). The use of QALY’s in environmental decision-making seems promising to many since they provide a single measure of overall health that can be compared against other goals of sustainability. A sustainable environment, with respect to human health, then is one for which the value of the QALY is acceptable even in the presence of environmental contaminants. However, there are some cons associated with their use such as possible bias, ethical considerations, legitimacy of preferences and implications for policy. Some of these pros and cons associated with the QALY approach are discussed in detail in the papers of Dolan et al. (2003), EPA (2001), and Bach (1994).
The following two studies summarize how two different approaches to the QALY method can be used in environmental health policy analysis. In the first study, the use of QALY’s in developing public health policies was advocated. In the second study, QALY’s were determined to be useful, but integrating them into cost-benefit analyses proved to be complicated and challenging.

In the first study conducted by Ponce et al. (2000), QALY weights and dose-response models were used to study the net health impacts of a lifetime of fish consumption. In this study, quality of life weights and life expectancy measures were combined with dose-response modeling to evaluate two health endpoints: developmental delay in offspring of mothers who consumed fish during pregnancy as the risk endpoint, and decreased risk of myocardial infarction from fish consumption among adults as the benefit endpoint. The net health impact was then estimated from the dose-response models as the sum of QALY’s gained or lost from developmental delay and MI fatality across a range of fish intakes and concentrations. Ponce et al. claim that this particular analysis allows one to compare risks when multiple endpoints such as cancer and non-cancer health effects are of interest as well as multiple exposures that result in both morbidity and mortality. They also state that the method used in this analysis can be generalized for use in comparative risk and health policy analysis, and that the use of QALY’s in public health policies is advantageous because by taking people’s preferences into account, better policies can be generated. A later paper by Ponce et al. examined the methodological considerations of this paper (Ponce et al. 2001).

In a second study conducted by Hubbell, B. (2002) of the EPA, QALY’s were examined in the analysis of air pollution regulations. Hubbell evaluated cost-benefit and
the willingness to pay methods and how they relate to QALY’s. He also used QALY’s to
evaluate the health impacts of air pollution regulations and then showed how monetary
values can be assigned to each QALY to determine the costs and benefits associated with
certain policies and regulations. Hubbell found that when QALY’s were evaluated
against the willingness to pay approach, the resulting monetized benefits were either
higher or lower than the WTP approach depending on the method used to value QALY’s.
He concluded that the QALY method can be advantageous because it allows mortality
and morbidity to be aggregated without the application of dollar values and because the
QALY method has been used extensively in public health economics literature.
However, he also added that when dollar values are assigned to each QALY,
complications arise. For example, it can be difficult to monetize acute symptoms such as
an asthma attack in an asthmatic child. He also stated that it can be a challenge to
integrate QALY’s into a cost-benefit framework in which other non-health benefits are
considered. He pointed out that doing so requires additional data as well as certain
assumptions about life expectancy, baseline health states for affected populations, life
years with chronic disease, and utility weights for chronic diseases. In the present thesis,
no monetary assignment is made to QALY’s.

Global Warming and Greenhouse Gas Emissions

While some refute evidence that global warming is occurring, the majority of
scientists and the public alike agree that it poses a serious global threat. The surface
temperature of the Earth has risen approximately 1 degree Fahrenheit in the past century
with accelerated warming occurring within the past two decades (EPA, 2000). In
addition, CO₂ levels have increased by 25% since 1850 due largely to the combustion of fossil fuels and ecologically destructive practices like deforestation (Boubel, 1994). Scientists expect this warming trend to continue unless there is a significant reduction in the amount of CO₂ emissions released into Earth’s atmosphere.

North Carolina may be especially vulnerable to global climate changes due to the large land area that sits just above sea level. Rises in sea level can cause serious flooding of the coastal areas and wreak havoc on the state’s economy. North Carolina is currently one of twenty-eight states that have a voluntary climate change action plan. This plan helps North Carolina to identify effective policies to reduce greenhouse gas emissions through a combination of public and private sector programs (EPA 2003). The converse of such policies are those that focus on increasing carbon sequestration, such as storage in flora. Under such a view, sustainability is measured by the ability of flora in a state to absorb the carbon dioxide emitted in that state (i.e. the degree to which the state is a carbon neutral system).

*Net Primary Productivity*

Plants help to combat global warming by converting atmospheric CO₂ into organic carbon and oxygen. One measure of the effect of this process is Net Primary Productivity. Net Primary Productivity (NPP) is defined as a measure of the amount of floral matter produced by green plants per unit time. It is the difference between gross primary production and respiration, where gross primary production is the total energy used by plants during photosynthesis and respiration is the process by which plants obtain the energy they need for basic metabolic processes. Net primary productivity is usually
expressed in energy or biomass per unit area per unit time, such as kcal/m²/yr or grams dry wt./m²/yr, and varies widely among ecosystems depending on a number of different factors including temperature, rainfall, plant species, and nutrient supply (Smith, 2001). A key measure of sustainability is the mean net primary productivity of flora in a state, with a higher mean being a higher state of sustainability (with respect to this one measure).

**Methods**

**Outline of Methodology**

In this section, two measures of sustainability, quality adjusted life years and net primary productivity, are combined into a methodology which can be utilized during the land planning process in conjunction with other measures of sustainability such as economic and social measures. Quality adjusted life years, in this thesis, provide a measure of human health with respect to air toxic inhalation and do not account for other quality of life indicators such as economic status or other health outcome measures. Therefore, this methodology can be used when one of the goals of the decision maker is to improve human health, with respect to air toxic inhalation only, by increasing quality adjusted life years while at the same time maximizing net primary productivity in a particular area. The following sections describe the data used in this methodology, show how I obtained these two measures of sustainability, provide a step by step methodology which examines how quality adjusted life years (with respect to air toxic inhalation) and net primary productivity can be combined for use as part of the decision making process, and provide two case studies at the county level as a demonstration.
Description of Data

National Air Toxics Assessment

Data used to calculate Quality Adjusted Life Years came from the National Air Toxics Assessment (EPA, 2004). This is the most recent comprehensive study involving air toxics and was conducted in 1996 by the Environmental Protection Agency. The National Air Toxics Assessment is a national scale assessment of 32 major urban air toxics\(^1\) that provides estimates of exposures and risks to health associated with these pollutants\(^2\). The 32 pollutants included in the assessment are shown in Table 2 below.

Table 2. Air pollutants included in the National Air Toxics Assessment of 1996

<table>
<thead>
<tr>
<th>1. acetaldehyde</th>
<th>18. formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. acrolein</td>
<td>19. hexachlorobenzene</td>
</tr>
<tr>
<td>3. acrylonitrile</td>
<td>20. hydrazine</td>
</tr>
<tr>
<td>4. arsenic compounds</td>
<td>21. lead compounds</td>
</tr>
<tr>
<td>5. benzene</td>
<td>22. manganese compounds</td>
</tr>
<tr>
<td>6. beryllium compounds</td>
<td>23. mercury compounds</td>
</tr>
<tr>
<td>7. 1, 3-butadiene</td>
<td>24. methylene chloride</td>
</tr>
<tr>
<td>8. cadmium compounds</td>
<td>25. nickel compounds</td>
</tr>
<tr>
<td>9. carbon tetrachloride</td>
<td>26. perchloroethylene</td>
</tr>
<tr>
<td>10. chloroform</td>
<td>27. polychlorinated biphenyls (PCBs)</td>
</tr>
<tr>
<td>11. chromic compounds</td>
<td>28. polycyclic organic matter (POM)*</td>
</tr>
<tr>
<td>12. coke oven emissions</td>
<td>29. propylene dichloride</td>
</tr>
<tr>
<td>13. 1, 3-dichloropropene</td>
<td>30. quinoline</td>
</tr>
<tr>
<td>14. diesel particulate matter</td>
<td>31. 1, 1, 2, 2-tetrachloroethane</td>
</tr>
<tr>
<td>15. ethylene dibromide</td>
<td>32. trichloroethylene</td>
</tr>
<tr>
<td>16. ethylene dichloride</td>
<td>33. vinyl chloride</td>
</tr>
<tr>
<td>17. ethylene oxide</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) 29 of these 32 pollutants were classified as carcinogens according to the 1990 Clean Air Act amendments.

\(^2\) This assessment provided risks associated with breathing pollutants only and not ingested pollutants. For example, the cancer risk associated with mercury is only the risk from breathing mercury although the majority of mercury in humans comes from eating contaminated fish.
To obtain measures of risk, the EPA first compiled a national emissions inventory from outdoor sources. The national emissions inventory was based on data from the 1996 National Toxics Inventory, which was compiled using data from state and local air pollutant inventories, EPA’s Toxic Release Inventory, estimates from a mobile source methodology, data from EPA’s air toxics regulatory program, and emissions estimates from activity data and emission factors. The national emissions inventory included the contribution from four major sources of emissions: major stationery sources, on-road mobile sources, non-road mobile sources, and area/other sources.

The national emissions were then inserted into an air dispersion model (the ASPEN model) to obtain ambient air concentrations. To obtain population exposures, the EPA ran an exposure model (HAPEM4) using these ambient air concentrations as input. Once population exposures were obtained, they then characterized the public health risks due to inhalation exposure by categorizing them into cancer and non-cancer effects. This was done by obtaining information on the health effects of air toxics, current EPA risk assessment and risk characterization guidelines, and estimated population exposures. The risk assessment data for cancer and non-cancer effects were generated at both the census tract and county levels in all states. Cancer risk was summarized as the lifetime excess probability of getting cancer, and non-cancer risk was summarized as a Hazard Index. The risk for both categories was based on contributions from major sources, mobile sources, non-mobile sources, area/other sources, and background sources (background sources were due to toxins blown into the state from activities elsewhere).
The present study uses the NATA-generated estimates of cancer probability and Hazard Index in developing the QALY measure, as described later.

MODIS data

Net Primary Productivity estimates for this paper came from The Land Processes Distributed Active Archive Center. The data were obtained by MODIS (Moderate Resolution Imaging Spectroradiometer). MODIS\(^3\) uses satellite based imagery and remote sensing to provide useful information for global warming research. MODIS has land surface, atmospheric, and oceanic data. Some examples of MODIS’s numerous data sets include vegetation production and net primary productivity, sea surface temperature, ocean primary productivity, and cloud cover fraction.

The MODIS data set used in this thesis is MOD17A3 or yearly Net Primary Production (which is the same as NPP). The MOD17A3 data utilize a concept called radiation use efficiency or RUE to obtain remote sensing estimates of Net Primary Production. Photosynthetically Active Radiation or PAR is solar radiation that is useful for photosynthesis; it is in the wavelength band 0.4 - 0.7 micrometers. Only about 45% of shortwave solar radiation that reaches Earth is in this PAR bandwidth region. Plants absorb some of this PAR energy and use it to convert CO\(_2\) to carbohydrate for respiration and growth. This amount of new growth is a measure of the plant’s RUE\(^4\).

A drawback to using the RUE approach to estimate NPP is that it can tend to ignore the complexity of ecosystem primary production processes. So that some of this

\(^3\)MODIS states that these products are still experimental in nature and their scientific validity is being investigated.

\(^4\)The RUE measure of a plant also depends on the type of plant and environmental conditions
complexity can be factored into the NPP estimates, MODIS set parameter values to be
used in its remote sensing algorithm based on the results of an ecosystem process model.
This ecosystem process model is called Biome-BCG and is a computer program that
estimates biogeochemical (BCG) cycles based on energy, water, carbon and nitrogen
fluxes for soil and vegetation. A daily time-step is used in the model which is then used
to create an 8-day photosynthesis product (MOS17A2) and also MOD17A3, annual
Primary Productivity.

The MODIS data used in this report are from the years 2001 and 2002, and
quantify the annual Net Primary Production in kilograms of carbon per square kilometer
(kgC/km²/yr). The area for each measure is 10° latitude by 10° longitude and the
resolution is 1 kilometer x 1 kilometer. The data are in 16-bit integer form with a scale
factor of 0.0001. Non-terrestrial fill values were assigned to areas where there is no land
cover such as water bodies, urban environment, snow or ice areas, sparse vegetation
(barren land, rock), and permanent wetlands. Since the MODIS data are coarser than
some other satellite data it is best to use the data for regional or global analysis rather
than for pixel-by-pixel comparisons (MODIS Users Guide).

Land Cover Data

Land cover data is needed in order to spatially determine which patterns of
development will maximize net primary productivity in each county. The land cover data
used in this paper came from the Center for Geographic Analysis in Raleigh, North
Carolina (CGIA). This data represents the amount and location of developed and
undeveloped land in each of the two counties examined as test cases. Units are in square meters and number of acres. See Tables 3 and 4 below:

Table 3. Area in square meters of developed and undeveloped land by county

<table>
<thead>
<tr>
<th>Land Cover for Developed Types by County (in square meters), 1996</th>
<th>Wake</th>
<th>Johnston</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Intensity Developed</td>
<td>88561242.3</td>
<td>28934319.3</td>
</tr>
<tr>
<td>Low Intensity Developed</td>
<td>75857651.8</td>
<td>111332381.1</td>
</tr>
<tr>
<td>Total Developed</td>
<td>164418894.1</td>
<td>39074305.4</td>
</tr>
<tr>
<td>Total Undeveloped</td>
<td>2932490540</td>
<td>2012196191</td>
</tr>
<tr>
<td>Total All Land Cover</td>
<td>3096909433.8</td>
<td>2051270496</td>
</tr>
</tbody>
</table>

Table 4. Area in acres of developed and undeveloped land by county

<table>
<thead>
<tr>
<th>Land Cover for Developed Types by County (in acres), 1996</th>
<th>Wake</th>
<th>Johnston</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Intensity Developed</td>
<td>21883.5</td>
<td>7149.8</td>
</tr>
<tr>
<td>Low Intensity Developed</td>
<td>18744.4</td>
<td>27510.7</td>
</tr>
<tr>
<td>Total Developed</td>
<td>40627.9</td>
<td>9655.4</td>
</tr>
<tr>
<td>Total Undeveloped</td>
<td>724618.4</td>
<td>497222.5</td>
</tr>
<tr>
<td>Total All Land Cover</td>
<td>765246.3</td>
<td>506877.9</td>
</tr>
</tbody>
</table>

This data is also available in the form of a GIS layer which is shown later in the thesis. This layer shows high intensity and low intensity development areas for each of the two counties. The imagery was taken in 1995 and released in 1996.
**Calculating Quality Adjusted Life Years**

Quality adjusted life years, with respect to diseases resulting from air toxic inhalation, provide a measure of sustainability that uses quality of life weightings for specific effects as well as data on the probability of those effects due to air toxin inhalation. The risk data for this calculation came from the National Air Toxics Assessment. Quality adjusted life years were calculated for each county in North Carolina using the following equation:

\[
\text{QALY} = (1 - P_c) \times [(1 - P_c) \times LE \times 1 + P_c \{ A_{\text{diag}} + (A_{\text{death}} - A_{\text{diag}}) \times QL_{4c} \}] + \\
\text{P}_{nc} \times [(1 - P_c) \times LE \times 1 \times QL_{\alpha} + P_c \{ A_{\text{diag}} + (A_{\text{death}} - A_{\text{diag}}) \times QL_{4c} \} \times QL_{\alpha}] 
\]

where:

\( P_c \) = probability of getting lung cancer

\( P_{nc} \) = probability of developing a non-cancer effect, quantified here as fraction of people with a HI >1

\( QL_{4c} \) = quality of life with lung cancer

\( QL_{\alpha} \) = quality of life with chronic asthma (taken here to be representative of non-cancer lung effects)

\( LE \) = Life expectancy

\( A_{\text{diag}} \) = Age at diagnosis of lung cancer

\( A_{\text{death}} \) = Age of death from lung cancer
QALY represents the total number of quality years of life (i.e. years free of disease) of an average person living in a specific county in NC in 1996 where the only effects considered are air toxics-induced lung cancer and non-cancerous effects such as asthma. Mean Life Expectancy was 76.1 years in NC in 1996 (Anderson 1998). Age of death from lung cancer for each county was obtained from the North Carolina Center for Vital Statistics (2003) and age of diagnosis from lung cancer for each county was obtained from the North Carolina Cancer Registry (2003). The excess lifetime probability of getting lung cancer by county came from the National Air Toxics Assessment described previously. This was also the data source for probability of getting a non-cancerous effect.

In risk assessment, a hazard index of 1 or above usually is assumed to indicate that there is a significant likelihood of the effect occurring. In the risk assessment data used here, the Hazard Indices were all above 1, with the range being between 1 and 5. However, the NATA study reported only the median Hazard Index in a county; in actuality, there is variability in this index across individuals in the county. In order to better determine the risk from non-cancer effects, risk was recalculated in each county as the fraction of people with a hazard index above one. This was done by assuming that the distribution of actual hazard indices in a county is lognormal with the median being the HI reported by NATA, and the GSD being 3. The Crystal Ball software was used to calculate the fraction of individuals with an actual hazard index above 1 when the median value for HI in a county is set at different values. Results are shown in the figure below as the points.
The data in this figure were then fit with a function of the form $P_{nc} = (1 - e^{-x^{0.7}HI})$, and the parameter “x” was determined to have a value of 0.7. If we plot a graph of hazard index versus fraction of people with a HI above 1 using the equation $P_{nc} = 1 - e^{-0.7HI}$, we can then determine the fraction of people above 1 for each median HI reported in NATA. This plot is shown as the line in Figure 1.

For quality of life estimates, I used health utilities associated with lung cancer because it is the most common cancerous effect from air toxins, and asthma because it is the most common non-cancerous effect. The quality of life from lung cancer was estimated to be 0.67 on a 0-1 scale. This number came from a study by Mahadevia (2003) that evaluated the merits of lung cancer screening. Quality of Life weights for this study were determined using information from published literature on health state utilities for lung cancer (Earle 2000, Trippoli, 2001). To get the quality of life measure for lung cancer, I used a weighted average of localized and advanced stage non-small cell lung cancer quality of life weights.

The quality of life with asthma was estimated to be 0.79 on a scale of 0-1 (Blumenschein, 1998). This number was obtained from a study that surveyed 69 patients
with asthma who rated their quality of life using three different methods: the rating scale method\(^5\), the standard gamble method\(^6\) and the time trade-off method.\(^7\) There was not a significant difference between the results of the standard gamble and time trade-off method, so an average of the two methods was taken, which was then averaged with the rating scale method to obtain a mean value of 0.79.

Next, the quality adjusted life years, with respect to air toxic inhalation, that were calculated for each county were mapped onto a GIS map of North Carolina. One data layer showing quality adjusted life years, one layer showing probability of cancer, one layer showing hazard index and fraction of people with a HI greater than 1, and one layer showing QALY’s lost due to air pollution (this is life expectancy, 76.1, minus quality adjusted life years for that county) were developed.

*Net Primary Productivity*

To map Net Primary Productivity by county and census tract, the MODIS data had to be converted into a shape file and then averaged across the two years (2001 and 2002). Non-terrestrial fill values were taken out. The census and county tract data are from the year 2000 and came from ESRI. I used a spatial join to join together census and county data with NPP data from MODIS to obtain an average of all the points in a tract.

*Prototype Methodology combining NPP and QALY factors*

By combining an ecological and human health measure (net primary productivity and quality adjusted life years), I created a prototype methodology that can be utilized to

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5 Subjects simply rate their quality of life on a scale, usually from 0-1  
6 Subjects decide between a certain outcome or a gamble that could result in a better or worse outcome  
7 Subjects must choose quality of life versus length of time alive
support land use decisions geared toward achieving sustainability. This methodology can be used when the goal is to ensure that the QALY value related to air pollution is held above a sustainable level while at the same time reducing global warming by maximizing net primary productivity. This methodology can be broken down into the ten-step process described below.

**Figure 2. Ten-Step Methodology Combining NPP and QALY**

- **Step 1**: Calculate current QALY for county

- **Step 2**: Calculate QALY for county under range of percent increases and decreases in development

- **Step 3**: Specify target level of sustainable QALY

- **Step 4**: Using steps 2 and 3 determine acceptable increase or decrease in development

- **Step 5**: Determine total amount of developed and undeveloped land currently in the county

- **Step 6**: Calculate the increase or decrease in developed and undeveloped land from Step 4

- **Step 7**: Allocate increase or decrease to a specific spatial pattern in the county

- **Step 8**: For this spatial pattern, calculate new mean NPP for the county

- **Step 9**: Repeat Steps 7 and 8 over all candidate spatial patterns

- **Step 10**: Select spatial pattern with optimal (highest) NPP if feasible

I have applied this ten-step methodology to two counties in North Carolina; Wake and Johnston. Wake County is one of the most developed counties in the state. The test methodology for Wake County examines how much development needs to
decrease (either move to another county or be eliminated completely) in order to achieve a specified target sustainable QALY in Wake County. By contrast, Johnston County is one of the 100 fastest growing counties in the country (US Census Bureau, 2002). The test methodology for Johnston County examines how much development can increase in order to stay within a specified QALY.

In the first and second steps, the current QALY's are determined and then new QALY's are calculated from these assuming a percent increase or decrease in development\(^8\). For Wake County, a 50% and 99% decrease in development were determined. For Johnston County, a 50% and 100% increase were determined. To calculate these new QALY's, new values were calculated for \(P_c\) and \(P_{nc}\) by increasing (Johnston) or decreasing (Wake) all emissions of air toxics uniformly by the corresponding percentage and then inserting the new resulting values of \(P_c\) and \(P_{nc}\) back into the original QALY equation\(^9\).

Wake County:

Current QALY: 60.75

50% decrease in development:

New \(P_c = 4.76 \times 10^{-5} \times 0.5 = 2.38 \times 10^{-5}\)

New Median HI = 4.63*0.5 = 2.32

New Fraction w/HI>1 (Pnc) = 1-EXP(-0.7*2.32) = 0.80

---

\(^8\) For purposes of this paper, I have assumed that an increase in development corresponds to the same increase in air polluting activities although this is not always the case.

\(^9\) A 50 or 99 percent increase or decrease in development means that the source terms (\(P_c\), HI, and fraction w/HI>1) have been increased or decreased by that factor, NOT quality adjusted life years.
New QALY = (1-0.80) * [(1-2.38*10^-5) * 76.1 + 2.38*10^-5 * (66.53 + (68.30 - 66.53)*0.67) + 0.80 * [(1-2.38*10^-5) * 76.1 * 0.79 + 2.38*10^-5(66.53 + (68.30-66.53) * 0.67 * 0.79] = 63.28

99% decrease in development:
New Pc = 4.76*10^-5 * 0.01 = 4.76*10^-7
New Median HI = 4.63*0.01 = 0.05
New Fraction w/HI>1 (Pnc) = 1-EXP(-0.7 * 0.05) = 0.03
New QALY = (1-0.03) * [(1-4.76*10^-7) * 76.1 + 4.76*10^-7 * (66.53 + (68.30 - 66.53)*0.67) + 0.03 * [(1-4.76*10^-7) * 76.1 * 0.79 + 4.76*10^-7(66.53 + (68.30-66.53) * 0.67 * 0.79] = 75.59

Johnston County:

Current QALY: 63.58

50% increase in development:
New Pc = 2.93*10^-5 * 1.5 = 4.40*10^-5
New Median HI = 2.19*1.5 = 3.28
New Fraction w/HI>1 (Pnc) = 1-EXP(-0.7 * 3.28) = 0.90
New QALY = (1-0.90) * [(1-4.40*10^-5) * 76.1 + 4.40*10^-5*(68.91 + (70.3 - 68.91)*0.67) + 0.90 * [(1-4.40*10^-5) * 76.1 * 0.79 + 4.40*10^-5(68.91 + (70.3-68.91) * 0.67 * 0.79] = 61.73

100% increase in development:
New $P_c = 2.93 \times 10^{-5} \times 2 = 5.87 \times 10^{-5}$

New Median HI = 2.19 * 2 = 4.38

New Fraction w/ HI > 1 (Pnc) = 1 - \text{EXP}(0.7 \times 4.38) = 0.95

New QALY = (1 - 0.95) \times [(1 - 5.87 \times 10^{-5}) \times 76.1 + 5.87 \times 10^{-5} \times (68.91 + (70.3 - 68.91) \times 0.67) + 0.79] \times [(1 - 5.87 \times 10^{-5}) \times 76.1 \times 0.79 + 5.87 \times 10^{-5} \times (68.91 + (70.3 - 68.91) \times 0.67 \times 0.79] = 60.87

The second step is graph construction for each county. These graphs were constructed from the new QALY's calculated above for a 50% and 100% increase in development (Johnston) and a 50% and 99% decrease in development (Wake). This graph allows the user to apply an acceptable QALY number for the county (specified in Step 3) and then determine the corresponding allowable percentage of increase/decrease in development. It can also work the other way. The user can determine what QALY results from a specific increase/decrease in development (in Step 4). See Figures 3 and 4 below to illustrate steps 2 and 4. The vertical lines in these figures represent a hypothetical target QALY of 62 years.
To demonstrate, consider the target QALY of 62 years for each county. For Wake county the current QALY is 60.75 as estimated from the NATA data. From the graph, it’s clear that in order to reach a target QALY of 62, there has to be approximately a 40% decrease in development. As estimated from the NATA data, the current QALY in Johnston County is 63.58. In order to reach the target QALY of 62, there can be approximately a 40% increase in development.

Step five involves determining how much land is already currently developed and undeveloped. This is done in the present study using land cover data from CGIA. These data (as shown previously in Table 2) give the areas of developed and undeveloped land in a county in square meters as well as acreage. In Wake County there is a total of 40627.9 acres of developed land and 724618.4 acres of undeveloped land. In Johnston County, there are a total of 9655.4 acres of developed land and 497222.5 acres of undeveloped land.

For the sixth step, the change in developed and undeveloped land must be determined. This indicates the number of acres that can be developed (Johnston county)
or number of acres that need to be returned to being undeveloped (Wake county) in order to reach the target QALY. To do this, the area of developed land is multiplied by the previously calculated percent change in development:

\[
\text{Wake county: } 40627.9 \text{ acres } \times (-0.40 \text{ change in development} = 16251.2 \text{ acres}
\]
\[
\text{Johnston county: } 9655.4 \text{ acres } \times (+0.40 \text{ change in development} = 3862.2 \text{ acres}
\]

The seventh and eighth steps involve determining the change in NPP from the simulated change in development. The goal is to develop in areas with a low net primary productivity (or move areas of high development into areas with lower NPP) so that the overall NPP in the county can be maximized. GIS maps have been created for each county with two layers overlaid on one another (Figures 5 and 6 below). One layer indicates where development has occurred in each county. The second layer shows net primary productivity in each county by census tract. The maps act as visual aids to help the user decide how the acreage for that county can be utilized if the goal is to maximize net primary productivity. Steps nine and ten involve allocating the land to certain spatial patterns and determining which spatial pattern will maximize net primary productivity.
Figure 5. Johnston County Map of Development with Census Tract NPP
Figure 6. Wake County Map of Development with Census Tract NPP
Results

Net Primary Productivity

The figures below indicate net primary productivity by county and census tract. Net primary productivity is the highest in the easternmost and westernmost counties of North Carolina. The lowest net primary productivity value was 0.2098 in Greene County and the highest was 1.2820 in Hyde County.

Figure 7. Net Primary Productivity in NC by County
**Figure 8. Net Primary Productivity in NC by Census Tract**

![Map showing net primary productivity in NC by census tract]

**Legend**
- Ave NPP in kgC/m²
- 0.00000 - 0.170417
- 0.170418 - 0.406139
- 0.406140 - 0.810663
- 0.810664 - 1.518220
- 1.518221 - 3.085214
- County data

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**Probability of Cancer**

Figure 9 shows excess lifetime probability of cancer from air toxins by county in North Carolina. Probability of cancer ranged from $2.15 \times 10^{-5}$ in Hyde County to $6.66 \times 10^{-5}$ in Guilford County, with the highest probabilities concentrated in the central region of the state and lowest probabilities in the far eastern and western areas. These numbers represent the average probability of cancer with contributions from major sources, on-road mobile sources, non-road mobile sources, area/other sources, and background sources.
Figure 10 indicates how much of the probability of cancer originates from on-road mobile sources, non-road mobile sources, major sources, and other. Background is approximately the same for each county. County planners can use this map to determine which sources contribute the most to the probability of cancer in their county. Reducing the amount of air toxins emanating from these specific sources will cause an increase in the QALY. For example, in Wake County, the largest contribution to the probability of cancer comes from on-road mobile sources. If the air toxins coming from these sources can be reduced, the QALY will increase as a result. If development must be curtailed, therefore, it might be curtailed preferentially in this source category.
**Hazard Index**

Figure 11 presents the Hazard Index in North Carolina by county. The Hazard Index ranges from 0.48 in Hyde County to 6.81 in Mecklenburg County. As with the probability of cancer, the highest Hazard Indices are in the central part of the state. On-road mobile sources, non-road mobile sources, major sources, background sources, and area/other sources contribute to the Hazard Index.
Figure 11. Hazard Index due to Air Toxic Inhalation by County

Figure 12 represents the contribution to the Hazard Index from on-road mobile sources, non-road mobile sources, major sources, and area/other sources. The contribution from background sources is approximately the same for each county. County planners can use this map to determine which sources contribute most to the Hazard Index in their county. Reducing the amount of air toxins emanating from these sources will increase the QALY. For example, in Wake County, the largest contributor to the Hazard Index is on-road mobile sources. If Wake County can reduce the air toxins coming from these sources, the QALY will increase as a result.
Quality Adjusted Life Years

Figure 13 indicates the quality adjusted life years for each county. Quality Adjusted Life Years by county ranged from 60.26 years in Mecklenburg County to 71.55 years in Hyde County. Quality Adjusted Life Years in the eastern part of North Carolina is higher than in the western portion of the state.

Loss of QALY is mapped in Figure 14. This is the number of quality adjusted life years subtracted from average life expectancy for North Carolina, 76.1 years.
Figure 13. Average Quality Adjusted Life Years due to Air Toxic Inhalation by County

Figure 14. Number of QALY's Lost due to Air Toxic Inhalation by County
Example Prototype Methodology Results

The prototype methodology was applied to the two case studies (Wake and Johnston counties) to assess feasibility and limitations.

Wake County

Steps 1, 2 and 3: Current QALY’s calculated, range of QALY’s under percentage increases and decreases calculated, and target QALY determined

In Wake County, the current QALY is 60.75 as estimated from the NATA data. With a 50% decrease in development, the new QALY was calculated to be 63.28. A 99% decrease in development increased the QALY value to 75.59. Table 5 summarizes what was calculated in the methods section.

Table 5. New Pc, HI, Fraction with HI>1, and QALY based on a 50% and 99% decrease in development

<table>
<thead>
<tr>
<th>Wake County</th>
<th>Pc</th>
<th>HI</th>
<th>Fraction with HI &gt; 1</th>
<th>Quality Adjusted Life Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>4.76 x 10^{-5}</td>
<td>4.63</td>
<td>0.96</td>
<td>60.75</td>
</tr>
<tr>
<td>50% Decrease in Development</td>
<td>2.38 x 10^{-5}</td>
<td>2.32</td>
<td>0.80</td>
<td>63.28</td>
</tr>
<tr>
<td>99% Decrease in Development</td>
<td>4.76 x 10^{-7}</td>
<td>0.05</td>
<td>0.03</td>
<td>75.59</td>
</tr>
</tbody>
</table>

I chose the target QALY as 62 years to use as an example of how this methodology can be used.
Step 4: Determine acceptable increase or decrease in development from Steps 2 and 3

By looking at the graph in the methods section constructed from the numbers in this table, in order for Wake county to increase it’s current QALY (as estimated from the NATA data) of 60.75 to the target QALY of 62, there must be approximately a 40% decrease in development.

Step 5: Determine amount of developed and undeveloped land

The total amount of developed land in Wake County was determined to be 40627.9 acres. The total amount of undeveloped land is 724618.4 acres.

Step 6: Calculate increase or decrease in developed and undeveloped land using Step 4

In Wake County, development needs to decrease by 16251.2 (40627.9 * 0.40) acres in order to reach the target QALY.

Step 7 and 8. Allocate increase or decrease to a specific spatial pattern and determine new mean NPP

According to the GIS map shown in the methods section, development in Wake County is concentrated in the central portion of the county and spreads outwards. Net primary productivity is higher in the western portion of the county with two census tracts in the northwest portion having the highest. One spatial pattern that could be considered is a pattern which decreases development in the western portion of the county by 16251.2 acres. This section of the county already has a significant amount of development within
an area of high NPP and a reduction in development here should result in an overall increase in NPP for the county.

*Steps 9 and 10:* Repeat Steps 7 and 8 over all candidate spatial patterns and select pattern with the highest NPP if feasible (There are numerous spatial patterns which can be considered here. I have chosen to consider one additional pattern and compared it to the first pattern, chosen in Step 7).

A second spatial pattern decreases development by 8126 acres (which is 50% of the 16251.2 acres) in the central portion of the county where development density is high but NPP is low and by 8126 acres in the western portion of the county where development is less dense but has a higher NPP. The NPP calculated for this spatial pattern would presumably be lower than the NPP in the first pattern (discussed in Step 7) because in this spatial pattern the acreage is taken from two areas (census tracts); one with a high NPP and one with a low NPP, but in the first pattern (in Step 7) all the acreage is taken from an area with high NPP resulting in a higher overall NPP.

Therefore, the first pattern should be chosen if feasible, all other factors being equal. By this, I mean factors other than quality adjusted life years due to air toxic inhalation and net primary productivity are considered when choosing a body of land for development. This tool allows to user to determine which spatial pattern will result in the highest NPP, but it is up to the decision maker to decide if this is the pattern that should be developed based on other factors, such as economic and social feasibility.
Johnston County

Steps 1, 2 and 3: Current QALY's calculated, range of QALY's under percentage increases and decreases calculated, and target QALY determined

In Johnston County the current QALY (as estimated from the NATA data) is 63.58. With a 50% increase in development, the new QALY was calculated to be 61.73. A 100% increase in development decreased the QALY value to 60.87. Table 6 summarizes the calculations from the methods section.

Table 6. New Pc, HI, Fraction with HI>1, and QALY based on a 50% and 100% increase in development

<table>
<thead>
<tr>
<th>Johnston County</th>
<th>Pc</th>
<th>HI</th>
<th>Fraction with HI&gt;1</th>
<th>Quality Adjusted Life Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>2.93 x 10^{-3}</td>
<td>2.19</td>
<td>0.78</td>
<td>63.58</td>
</tr>
<tr>
<td>50% Increase in Development</td>
<td>4.40 x 10^{-3}</td>
<td>3.28</td>
<td>0.90</td>
<td>61.73</td>
</tr>
<tr>
<td>100% Increase in Development</td>
<td>5.87 x 10^{-3}</td>
<td>4.38</td>
<td>0.95</td>
<td>60.87</td>
</tr>
</tbody>
</table>

I chose a target QALY of 62 years to demonstrate how this methodology works.

Step 4: Determine acceptable increase or decrease in development from Steps 2 and 3

By looking at the graph in the methods section constructed from the numbers in this table, in order for Johnston County to reach the target QALY of 62, from the current QALY (as estimated from the NATA data) of 63.58, there can be a 40% increase in development.
Step 5. Determine total amount of developed and undeveloped land

The total developed land in Johnston County was determined to be 9655.4 acres.
The total amount of undeveloped land is 497222.5 acres.

Step 6: Calculate increase or decrease in developed and undeveloped land using Step 4

In Johnston County, development can increase by 3862.2 (9655.4 * 0.40) acres to reach the target QALY.

Step 7 and 8. Allocate increase or decrease to a specific spatial pattern and determine new mean NPP

According to the GIS map of Johnston County shown in the methods section, there is a large cluster of development in the center of the county with two smaller clusters in the northwest and southwest sections of the county. Net primary productivity is varied throughout the county with a large section of high net primary productivity located in the southern central part of the county. One potential spatial pattern involves focusing all 3862.2 acres of future development away from the southern central portion of the state, since this area has a high NPP, and towards the area in the eastern section of the county that has the lowest NPP.

Steps 9 and 10: Repeat Steps 7 and 8 over all candidate spatial patterns and select pattern with the highest NPP if feasible (There are numerous spatial patterns which can be considered here. I have chosen to consider one additional pattern and compared it to the first pattern, chosen in Step 7).
A second spatial pattern could target 10% of development (965 acres) in the
central portion of the state within the census tract that has the next to lowest NPP and
90% (8690 acres) in the western portion of the county within the census tract which has
the lowest NPP. The resulting NPP for this spatial pattern would be slightly less than that
of the first spatial pattern (Step 7) since in this spatial pattern, 10% of development
occurs in an area with the next to lowest NPP where in the first spatial pattern, 100% of
the development occurs in the areas with the lowest NPP. Based solely on NPP and
quality adjusted life years due to air toxic inhalation, the first spatial pattern should be
chosen since it results in a higher overall NPP. But again, there are other issues at stake
when choosing areas of land to be developed, and it is up to the decision maker to
determine how important these two measures are in comparison to others such as
economic and social measures.

Conclusions and Recommendations

The methodology proposed in this paper gives an example of how two different
measures of sustainability can be combined so that each one contributes to a more
sustainable environment. This tool should be used in conjunction with other issues that
are to be considered when choosing an area of land for development purposes. While the
process of creating sustainable cities and therefore a more sustainable North Carolina can
be overwhelming at times, it is tools such as these that can help us transform abstract
concepts, such as sustainability, sustainable development and smart growth, into
achievable goals. This methodology simplifies the complex process of choosing future
areas for development, if only by a little (and incompletely), so that decision-makers
come closer to the goal of a sustainable North Carolina. Quality of life is important to the people in North Carolina and quality of life measures in regards to air pollution can be an important variable to consider when making decisions within the context of sustainability. The quality adjusted life years calculated here are somewhat subjective due to the subjective nature of the health utilities that were chosen for lung cancer and asthma. However, they provide a solid basis for comparisons between counties and give an overall picture of how the state is faring with regards to the health effects of air toxin inhalation.

The significant loss of QALY's in this paper is primarily due to non-cancer effects. Hazard Index values established in the NATA data were all above 1. However, these values have a built in margin of safety in order to protect humans, which causes the values to be higher than they would be if they were indicating actual thresholds of effect (as shown in laboratory studies with animals). Since a Hazard Index value of 1 was accepted as the threshold for effect in this paper, the loss of QALY's are significantly over-estimated as a result. In addition, quality adjusted life years have been depicted here as declining as a result of development This is a consequence of the assumption used in this methodology: that increased development results in increases in the mixture of sources of air toxics in a region, and that these increases are not mitigated by increasing economic resources that might both improve pollution control and lower the susceptibility of the population to diseases caused by the air toxics. A full accounting of the sustainability of a proposed pattern of development should account for this "feedback" between development, economic growth, pollution source terms, health, and the overall quality of life.
The maximization of net primary productivity is extremely important to the preservation of the ecological environment as well as human health and should be taken seriously. While North Carolina has a voluntary plan to limit greenhouse gases, there must be enough vegetation to reduce these gases and it is important that areas with high net primary productivity be preserved. The net primary productivity estimates shown in this paper are for the years 2001 and 2002. MODIS has just released their data for years 2000 and 2003. These should be averaged in with the 2001 and 2002 data to get a better estimate of the annual average of net primary productivity in the state.

There are some feasibility issues with the application of the prototype methodology to each county. For example, if Wake County wanted to raise it’s current QALY from 60.75 to the target QALY of 62, development would have to be reduced by 40%. Most planners would agree that this is not a feasible goal. In fact, for both counties, even a small increase or decrease in QALY results in a significant change in development. However, some decrease in development can be possible.

As stated earlier in the paper, the assumption has been made that a decrease/increase in development corresponds to that percentage decrease/increase in polluting activities. While this is most often the case, sometimes polluting activities and QALY can be reduced even if development is occurring. For example, in some counties\textsuperscript{11}, industry is the primary contributor to probability of cancer. If a large portion of that industry is moved to another county or eliminated completely, the QALY can increase without decreasing development. It should be noted that in my calculations for percent increase and decrease in development, the various sources that contribute to the

\textsuperscript{11} Includes Guilford, Davidson, Robeson, Person, Granville, Vance, Halifax, North Hampton, New Hanover, Washington, and Lee counties
probability of cancer and hazard index were assumed to increase or decrease proportionally. This is not necessarily the case. For example, if new development in an area consists mainly of major sources (industry), the contribution to probability of cancer and hazard index will be higher from major sources than the contribution from mobile sources or other sources. At the same time, if a neighborhood were developed in an area, the majority of the contribution to probability of cancer and non-cancer would probably come from on-road mobile sources rather than major sources. Therefore, depending on the type of development that is occurring, one could increase the probability of cancer and hazard index by the correct proportions of the sources, giving a more accurate depiction of the quality adjusted life years (with respect to air toxin inhalation) that result from increases and decreases in development. To do so requires use of the information on relative source contribution, examples of which were shown as bar charts in Figures 10 and 12.

Another example of reducing air pollution (therefore increasing QALY), while at the same time increasing development, is a compact city. In Europe, the move towards green urbanism has led municipalities to plan and build compact cities rooted in sustainability principles through ways such as preserving green space by keeping cities compact, and limiting air pollution by increasing the number of "car free" areas of the city. In cities such as these, QALY’s can increase even with an increase in development. While this may not be possible in extremely developed areas such Wake county, areas that are not as developed, but have high growth rates like Johnston county, can create more sustainable cities if carefully, and intelligently planned. In addition, it is important
to note that development can be left in place if emissions can be reduced through process change such as more fuel-efficient cars or filters on sources.

Future research should examine how this methodology can be automated and placed within a user-friendly GIS system. A decision software tool should be created that can systematically try placing development in different locations within a county (or any area) and find the optimal location given certain constraints (such as maximizing NPP). It would also be helpful to see if decision makers would find this tool useful and what impact it's use has on the decision making process.
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ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Douglas Crawford-Brown for his guidance during my study at Environmental Sciences and Engineering. I am also grateful to Dr. Whittington and Richard Rogers for taking the time to serve on my committee and give their constructive criticism and support. Jeff Brown at the Center for Geographic Analysis in Raleigh, NC helped with some of the GIS constructions in this report and Marta Chaves provided the data for net primary productivity.