Integrating environmental sustainability efforts across community boundaries: A case study with Charlottesville City, Albemarle County, and the University of Virginia

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Abstract

Many entities use environmental footprint tools to help evaluate and improve environmental sustainability. The objective of my research was to build an integrated greenhouse gas (GHG), nitrogen (N), and phosphorus (P) footprint tool to estimate and spatially visualize the footprints of Charlottesville City (Charlottesville), Albemarle County (Albemarle), and the University of Virginia (UVA). The tool was then used to evaluate the impact of both planned and potential climate action strategies. The evaluation explored which strategies were co-beneficial with other footprint reductions and which were not as effective. The tool model is built from several existing tools, including the Community Nitrogen Footprint Tool (C-NFT) and the Integrated Environmental Footprint Tool (IEFT). The combined model produces a new framework for evaluating GHG, N, and P footprints side by side. Chapter 1 introduces previous work on integrated footprints and the unique characteristics of the study area (Charlottesville, Albemarle, and the University of Virginia).

Chapter 2 discusses the additions made to the original community nitrogen footprint tool (CNFT) presented in Dukes et al. (2020) and Stanganelli (2020). These additions captured sectors not needed for city level footprints such as crop and animal agriculture, septic systems, and airports. This section also built the framework for integrating a city, county, and large university each with separate data into the tool. The importance of having these sectors included for the N footprint was evident. In Albemarle, the N footprint from these additional three sectors and the addition of UVA increased from 40 kg N per capita annually to 77 kg N per capita annually. The Charlottesville N footprint also increased slightly due to the addition of a large university from 32 kg N per capita annually to 34 kg N per capita annually. Combining and collecting the inventory data set the framework to calculate the other two footprints and begin scenario analysis.

Chapter 3 discusses the integration of the GHG and P footprints into the C-NFT framework and how scenarios can be run to determine the impact of reduction scenarios on these three footprints. Integrating the GHG and P footprints used previously developed methodologies from Leach et al. (2017) (GHG) and Metson et al. (2020) (P) to first add the three footprints to

the analysis on a community basis. Then, scenarios were run using this combined tool to determine the impact on other footprints. There was a clear and direct relationship between the P and N footprints, likely due to the drivers of both these footprints being food purchased. The GHG and N and GHG and P footprints were not significantly correlated. However, most strategies produced co-benefit reductions. The only strategies that did not produce a co-reduction were with P and GHGs as energy strategies have no impact on the P footprint. Overall, a significant reduction the three footprints could be produced if strategies within climate action plans as well as some additional proposed strategies were employed.

The tool can be used as a model for other localities who have interconnect footprint reduction goals. The model used here for cities and counties can be used across the US as publicly available data are used for the majority of values calculated here. Many higher education institutions also track their GHG footprint (SIMAP, 2021). This means there is an opportunity here for integration of institutions within community footprint tracking. Using the integrated tool for community footprints allows for a broader footprint analysis of a community's environmental sustainability and can help stakeholders make decisions to benefit multiple footprints.

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Chapter 1

Background of the Nitrogen Footprint, Community Tools, Combined Indicators, and Plans for Institution N footprints

1. Introduction

Quantifying and reducing environmental impacts have become more and more of a focus for individuals, institutions, and communities. One increasingly popular form of quantifying these impacts is using footprint indicators which provide a quantitative way to display an entity's impact on resource use (Dizdaroglu et al., 2017). These resources can include food, energy, transportation, and material goods and services. Once entities can track their resource use, they are more able to make feasible, informed decisions to reduce impacts. The footprint methodology allows users to quantify and manage their footprints.

This chapter presents a research plan to 1) develop an integrated nitrogen (N), greenhouse gas (GHG), and phosphorus (P) footprint tool and to 2) use it to explore footprint reduction scenarios. The tool will not only integrate three footprints but also three jurisdictions within the same region: Charlottesville, Albemarle, and UVA. Each of these jurisdictions has separate sustainability goals and strategies to achieve these goals. However, actions within each jurisdiction have the ability to make broader, unintended positive and negative impacts. This research gives an example of how an integrated tool can be used to evaluate the impacts of sustainability strategies on the broader community.

A. Greenhouse Gas (GHG) footprints

The greenhouse gas (GHG) footprint is the total GHG emissions from an entity's activities, reported in units of carbon dioxide equivalents (MTeCO_2). The major sources are fossil fuel combustion (e.g., stationary fuels, transportation, purchased electricity), food purchased, refrigerants, animals, and fertilizer application. The GHG footprint is calculated by multiplying the activity data (e.g., kWh electricity purchased) by the carbon dioxide, methane, and nitrous oxide emissions factors, as appropriate. The footprint approach used here does not include GHG sequestration. Several sources of emissions factors include: Leach et al. (2017) which compiles US emission factors for fuel use (e.g., US EPA, 2019; Bureau of Transportation Statistics, 2020), food purchased (Keller & Heoleian, 2014), and refrigerants and chemicals

(IPCC, 2006). The average per capita GHG footprint in the US is 14.7 metric tons of carbon dioxide equivalent (MTeCO_2) per year in 2019 (World Data Bank). This average footprint includes energy use (ex: electricity use, natural gas use) and transportation (ex: kilometers driven, taken by bus) but does not include food. In the US, food can add ~0.5 MTeCO_2 per capita annually to this value, bringing the total to closer to 15.2 MTeCO_2 (Keller and Heoleian, 2014).

B. Nitrogen Footprints

The nitrogen footprint is the total reactive N released to the environment from an entity's activities, reported in units of metric tons of N. The major sources are food purchased, fossil fuel combustion, wastewater, animals, fertilizer application, and nitrogen-fixing crops. The N footprint is calculated by multiplying activity data (ex., kilowatt hours of electricity, weight of food purchased) by the appropriate emission factor or virtual nitrogen factor (VNF) (Dukes et al., 2020). For example, the total weight of beef purchased is multiplied by the nitrogen content of beef, a beef-specific VNF, and the N_2O and NOx emissions associated with transportation of beef (Leach et al., 2012). The average per capita N footprint is 41 metric tons of nitrogen (MT N) annually. This includes energy use, food purchased, and wastewater treatment (Leach et al., 2012).

C. Phosphorus footprints

The phosphorus footprint is the total P released to the environment from an entity's activities, reported in units of kg P (Metson et al., 2020). Sectors contributing to the P footprint are food purchased, wastewater, and fertilizer application. P emissions from fossil fuel combustion are negligible. All emission factors and virtual phosphorus factors (VPF) used are derived from Metson et al. (2020) which presents the P footprint of the US. The average P footprint in the US is 6.9 kg P annually and includes food purchased and wastewater treatment. It does not include energy use as there is no P associated with energy use (Metson et al., 2017).

D. The Community Scale

Evaluating environmental sustainability at the city and county levels is being done more frequently with the emergence of greenhouse gas (GHG) inventories focused at this level. Evaluating these footprints allows city planners and business managers to measure and set targets to reduce environmental impact. Many cities in the US are a part of organizations aiming to reduce environmental impact such as the Cities Climate Commitment Group (C40), which is a collection of mayors across the world working to implement strategies to meet the goals set out by the Paris Climate Agreement in their local communities (https://www.c40.org/cities). While most of these cities and counties are larger megacities throughout the world, an increasing number of small cities are setting goals to reduce environmental impacts and are tracking GHG emissions, with both Charlottesville and Albemarle being two of them. Alongside GHG emissions, cities are beginning to track other environmental indicators such as nitrogen (N) (Dukes et al., 2020; McCourt et al., 2021), water (Mahjabin et al., 2018), and ecological footprints (Wackernagel et al., 2006; Montoya et al., 2020). To evaluate these footprints, community-wide data need to be gathered. Determining how to gather and utilize city data is a challenging task. In the US, several studies have used census data and the scale of census track or block groups to evaluate their data sets (Demetillo et al., 2020; Dukes et al., 2020; Stokes et al., 2019)

Charlottesville and Albemarle are unique communities in many ways, one of these being the impact a large institution (UVA) has on their population, economies, and environmental health. Students make up a portion of the population in both Charlottesville and Albemarle and can be difficult to capture in census reports as many students reside in the city and county only during the academic year (Wrable et al., 2021). The university is a large employer (~28,000 student and staff employees) within the community which impacts the needs for housing, transportation, and other infrastructure to be built in and around the localities. With these entities so closely tied, there is an undeniable need for collaboration to meet climate goals. In 2018, these entities came together to collaborate to reach climate goals (Climate Action Together 2019). The Climate Action Together plan outlines initiatives each entity is taking to reduce environmental impacts under their jurisdiction.

The idea of an institution being integral to a town’s economy and sustainability efforts is not new. Many communities across both Virginia (Blacksburg, VA and Virginia Tech; Lynchburg, VA and Liberty University) and the United States (Durham, NH and the University of New

Hampshire; Clemson, SC and Clemson University) are tied to the presence of an academic institution in their town. The work done here could be an example to other communities with large institutions present and serve as a model on how to create sustainable plans together.

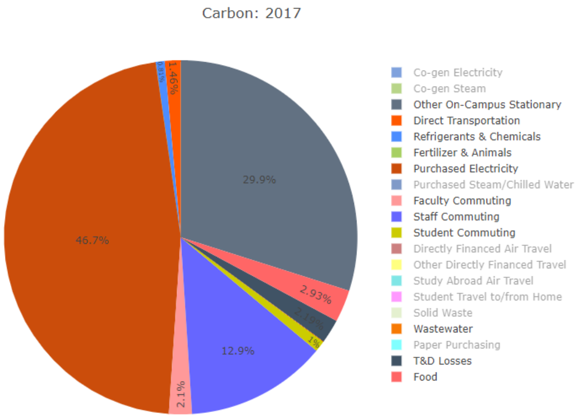
E. Integrating Footprint Indicators across Elements and Scales

Several entities have taken the approach of looking at multiple indicators (e.g., nutrients, biotic integrity, etc.) to assess environmental quality. Focusing on one indicator while ignoring the impacts on another could create unintended environmental consequences. These indicators have been used within watersheds (Flotemersch et al., 2015), protected areas (Cook et al., 2012) and endangered ecosystems (Mouillot et al., 2017), even the entire earth (Sherwood et al., 2020).

2. Previous Work

A. UVA's Nitrogen and Greenhouse Gas Footprints

UVA has tracked its GHG and N footprints since 2009 and 2010, respectively. The most recent calculation completed is for 2017 (figure 1.1). The UVA footprint includes inventory data from all buildings (electricity use, wastewater, refrigerants and chemicals, and on-site utilities) on UVA's grounds as well as food data from all dining and catering operations (excluding concessions). Inventory data points such as weight of food purchased, kilowatt hours of electricity used, and on-site heating fuels have been collected in SIMAP to account calculate UVA's GHG, N, and P footprints.



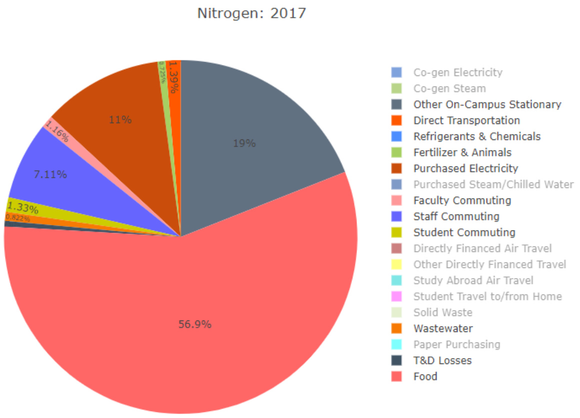


Figure 1.1: *UVA's greenhouse gas (GHG) and nitrogen (N) footprints. This is calculated by category for the calendar year 2017 (SIMAP, 2021).*

A team of UVA students has worked with stakeholders from dining, facilities management, and the health system to track these footprints within the Sustainable Indicators Management and Analysis Platform (SIMAP). SIMAP is used as the official tracking platform for UVA's GHG and N footprints (SIMAP, 2021). The UVA Greenhouse Gas Action Plan outlines the steps needed to reach the goal of a 25% GHG footprint reduction by 2025, and the UVA Nitrogen Action Plan outlines steps to reach the 25% N footprint reduction goal by 2025. The newest UVA goals include carbon neutrality by 2030, being fossil fuel free by 2050, and a 30% N footprint reduction by 2030. Currently, the university is working to prepare action plans outlining the steps the university needs to take to reach these more ambitious goals.

B. Charlottesville Nitrogen Footprint Calculations

In 2018, the first calculation of a community N footprint was completed for Baltimore City, MD (Milo et al., 2018; Dukes et al., 2020). This calculation used consumer purchasing data for food, energy usage, kilometers traveled, and wastewater consumption data from both businesses and residents to estimate the N footprint of census block groups (BG) within the city. BGs are the smallest geographical unit of measure the US Census Bureau publishes data and consist of populations from 600-3,000 (United States Census Bureau, 2010). This methodology used the Consumer Expenditure Report (CEX 2017) alongside city-specific data such as electricity use and wastewater to determine the N footprint of the community by BG. The result showed the spatially distributed N footprint of Baltimore City and a correlation with income.

The second iteration of a community N footprint was completed for Charlottesville in 2019/2020 (Stanganelli 2020) (figure 1.2). This version used the upgraded tool and worked with several Charlottesville Department of Planning members to create and model feasible reduction strategies. Stanganelli (2020) found that food in Charlottesville was the largest contributor to the N footprint, similar to Baltimore City, and transportation was the largest local source. Stanganelli (2020) also found that income correlated with N footprint, similar to the findings of Dukes et al. (2020).

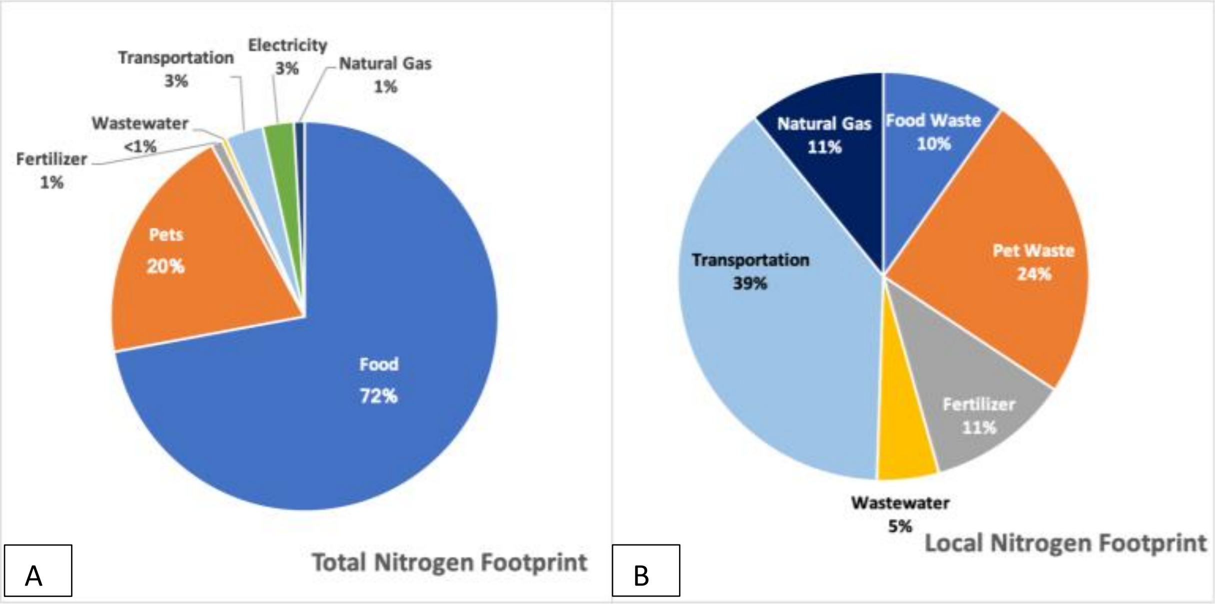


Figure 1.2: *The total (A) and local (B) N footprints of Charlottesville. The total footprint of Charlottesville City was 1,400 MT N and the local footprint was 114 MT N. The local N footprint refers to categories where the N emissions are occurring within the system bounds of the City of Charlottesville which include transportation, natural gas, food waste, pet waste, fertilizer, and wastewater treatment (Stanganelli 2020).*

C. Integrated Footprint Work

In 2017, the excel-based NFT tool was merged with the Campus Carbon Calculator to create a tool to integrate two environmental footprint indicators (C and N) in the Sustainable Indicators Management and Analysis Platform (SIMAP, 2021). This allowed institutions to use one dataset to calculate two footprints and evaluate synergies and tradeoffs between the two footprints (Leach et al., submitted) This tool was built with resources from the National Socio-Environmental Synthesis Center (SESYNC, 2020).

In 2020, the first integrated footprint tool for institutions (IEFT) was created to calculate GHG, N, P, and W footprints alongside social costs (C and N) (Dukes et al., in review). The tool uses data from several important sectors at the university level (food, water, electricity, and transportation) to calculate the footprints using emission factors from several papers (Leach et al., 2017; Leach et al., submitted; Metson et al., 2020; Natyzak et al., 2017; Compton et al., 2017). The integration of these tools was the first to integrate four footprints alongside a cost analysis intended to guide decisions surrounding solutions to complex environmental problems. This tool was used to evaluate the co-benefits of planned reduction strategies at UVA as well as changes to the social impacts of GHG and N footprints. The tool used UVA as a case study to evaluate several proposed reduction strategies from the UVA Nitrogen Action Plan (UVA Nitrogen Action Plan, 2019) and Greenhouse Gas Action Plan (UVA Greenhouse Gas Action Plan, 2017) (figure 1.3).

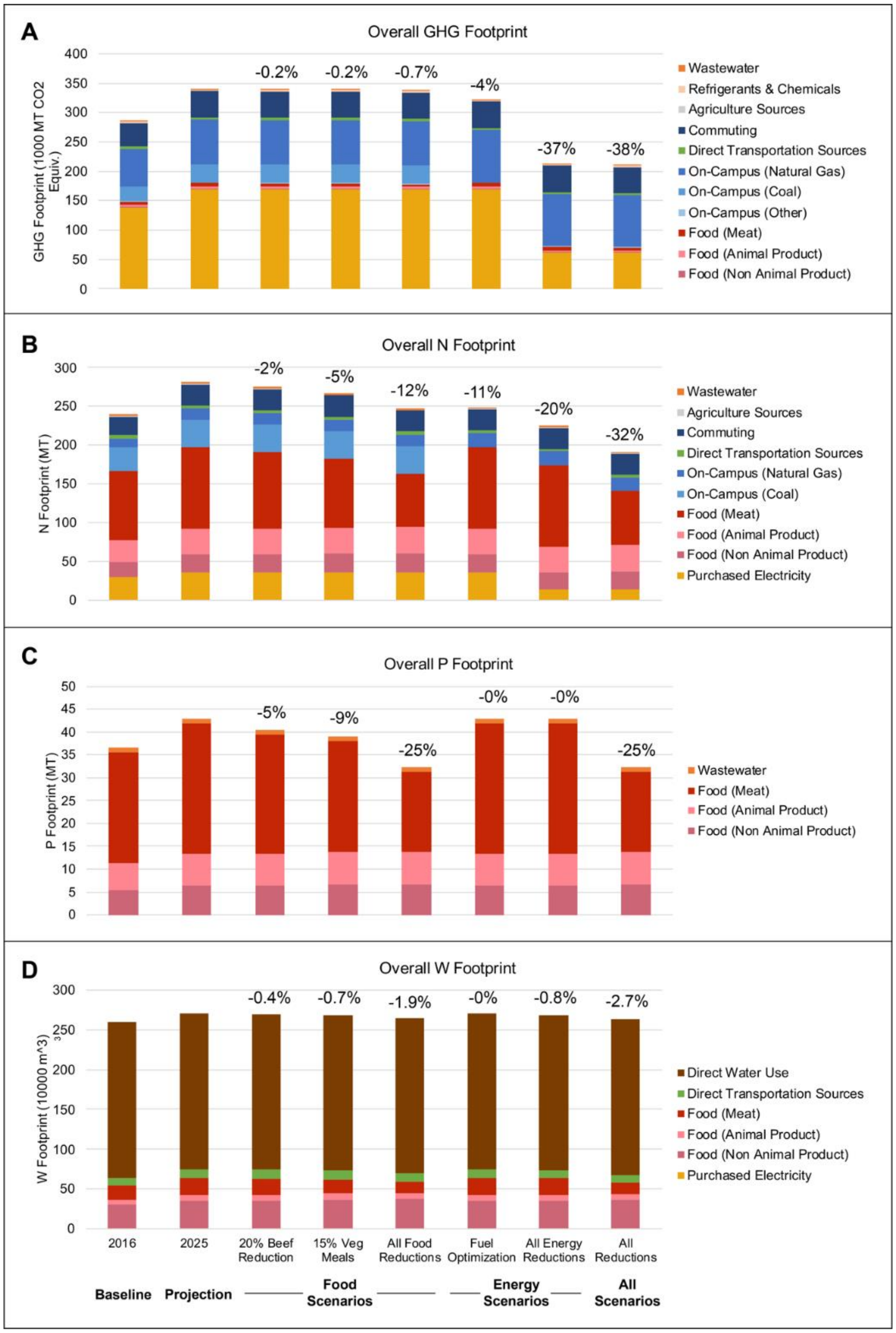


Figure 1.3: *The overall GHG (a), nitrogen (b), phosphorous (C) and water (d) footprints of UVA. Based on 2016 inventory data using the Integrated Environmental Footprint Tool (IEFT). The leftmost bar shows the baseline data while following bars evaluate strategies from the UVA Nitrogen and GHG Action Plans to determine the impact on subsequent footprints (Dukes et al., in review)*

3. Objective of Study

The objective of my research is to build an integrated greenhouse gas (GHG), nitrogen (N), and phosphorus (P) footprint tool to estimate and spatially visualize the footprints of Charlottesville, Albemarle, and UVA. The tool will evaluate the total footprint associated with activities happening within the city, county, and university bounds. For example, this will include upstream losses associated with the food purchased within the system bounds in the food sector and capture the losses due to human waste and wastewater treatment in the wastewater and septic systems sectors. The tool will be used to test scenarios to decrease the environmental footprints of these entities and serve as an example of how communities and institutions can work together to improve environmental outcomes.

4. Research Questions

1. What are the spatially defined N footprints of the integrated UVA, Charlottesville, and Albemarle community?
2. What are the three GHG, N, and P footprints and what actions can be taken to decrease footprints in the three jurisdictions?
    a. What is the impact of existing sustainability goals on the combined footprints of each jurisdiction?
    b. What additional strategies can be explored to reduce all three footprints simultaneously?

5. Addressing the Research Questions

Chapter 2 focuses on answering research question 1. To do this, there were several additions made to the current community nitrogen footprint (Dukes et al., 2020; Stangnelli, 2020) framework to address emissions from a rural county. This included adding frameworks to include N-related emissions due to crop, animal, airport, and septic tanks.

Chapter 3 focuses on incorporating greenhouse gases and phosphorus into the integrated tool framework and applying these tools to explore sustainability strategies. Based largely on Leach et al. (2017) and Metson et al. (2020), the framework for both greenhouse gases and phosphorus footprints was added to the tool. Then, I evaluated the potential reductions from 14 different strategies derived from the UVA Nitrogen and Greenhouse Gas Action Plans, the Albemarle Climate Action Plan, Stanganelli (2020) for Charlottesville's proposed Climate Action Plan, and several additional food, sewage, and agriculture strategies.

Chapter 4 presents the successes, limitations, and potential for future work with this tool. This section provides an analysis of the potential implications this tool could have on planning reduction goals for UVA, Charlottesville, and Albemarle. This section outlines the limitations of using this model as well as the potential impact sectors excluded from the system bounds could have on the tool. As is the case with most scientific works, there are many pieces that could be added to the analysis presented here. This chapter discusses potential next steps for the research.

Chapter 2

An integrated N footprint tool for a county, city, and university, designed for education and resource management.

1. Introduction

Environmental sustainability is essential for building a maintainable community structure. To assess environmental sustainability, communities often turn to footprint indicators as a method evaluate their impacts. Nitrogen (N) footprint indicators have recently gained popularity as an assessment tool as it encapsulates food as an essential part of the calculation (McCourt et al., 2021; Dukes et al., 2020; Stanganelli 2020). An N footprint is defined as the amount of reactive nitrogen released to the environment because of an entities resource use (Leach et al., 2012). N footprint tools have been developed at the individual (Leach et al., 2012; Gu et al., 2013; Shibata et al., 2014), institution (Leach et al., 2013; Castner et al., 2017; Liang et al., 2018; MacDonald et al., 2020), and community (Dukes et al., 2020; Stanganelli, 2020; McCourt et al., 2021; Xian et al., 2022) levels.

This chapter focuses on the community level N footprint indicator. The community level N footprint indicator uses Consumer Expenditure Report BG level data alongside public utility data to evaluate the spatially distinct N footprint of a community. Dukes et al. (2020) evaluates the N footprint of food, pets, wastewater, electricity, transportation, and natural gas in Baltimore City, Maryland. The study found that food was the largest driver (75%) with transportation (15%) following behind the per capita N footprint of Baltimore City residents. For food, beef was the highest N footprint category followed by pork. For transportation, the highest N footprint was for passenger cars (Dukes et al., 2020). This model works well for a cities like Baltimore City which includes little agricultural land.

Stanganelli (2020) used the methods presented in Dukes (2020) to evaluate the second community footprint for Charlottesville, Virginia. Stanganelli (2020), found the same top contributors to the per capita N footprint of residents within Charlottesville as Dukes et al., 2020 found in Baltimore. Charlottesville residents' N footprints were slightly higher (by 2 kg N or 6.6%) but within reasonable estimates for uncertainty. Stanganelli (2020) followed the same system bounds as the Charlottesville Greenhouse Gas Action Plan (2019) which excluded UVA, a large higher education and medical institution, from the N footprint calculations. UVA tracks it's GHG and N footprints separately from the city (Charlottesville) and county (Albemarle).

In 2017, UVA had a full-time equivalent student population of ~25,600 students and ~16,600 faculty and staff. Charlottesville has a population of ~47,500 people and Albemarle has a population of ~108,000. The university is the primary employer in the area and crosses both city and county lines (*Living in Charlottesville*, 2021). Since the university is an essential part of the community, evaluating the institution within the framework of the city and county would provide a more wholistic view of the total N footprint of the area.

Albemarle is a largely agricultural area with only ~5% of the county considered to be in the "urban ring". The urban ring of Albemarle is identified as Development Areas in Albemarle's master planning document (Albemarle County Master Planning Department, 2022). In order to add a rural or agricultural community, there are several missing pieces including agriculture and septic systems. Agriculture systems have a large impact on nitrogen losses (Bowels et al., 2018). While septic systems are less prevalent than municipal wastewater treatment plants in the US, they can make up a significant portion of the total N footprint in rural areas. Traditional septic systems convert less reactive nitrogen to N_2 captured within the tank than wastewater treatment facilities (Dowling et al., 2020). Therefore, to accurately assess the nitrogen footprint of a rural community, agriculture and septic systems need to be included.

Charlottesville, Albemarle, and UVA have worked to create a plan to integrate environmental sustainability efforts. The Climate Action Together Plan outlines steps taken by each separate entity to reduce GHG footprints. However, each entity both tracks their footprints separately and creates their own reduction goals and strategies. Interconnected tracking and goal setting among jurisdictions has been shown to have a greater potential to achieve positive climate outcomes (Youm and Feiock, 2019). This study presents an integrated N footprint analysis of the three entities is the first step to achieving desired outcomes of an environmentally sustainable community.

In this study, a methodology to answer the question: what is the spatially defined nitrogen footprint of Charlottesville, Albemarle, and UVA is presented. In order to do this the following chapter walks through the calculations completed to calculate the Albemarle footprint adding agriculture, septic systems, a small airport, and a large institution to both the city and county.

2.Methods

To answer these research questions and create an integrated nitrogen footprint tool, the following steps were completed. First, the original N footprint calculation for Albemarle was calculated. In the text below, the "original" N footprint calculation for Albemarle and Charlottesville indicates the values calculated based on solely the data categories in Dukes et al. (2020) and Stanganelli (2020) and excluded the additional data from agriculture, septic systems, airports, and UVA. In order to calculate the original N footprint of Albemarle, data were collected from several community organizations and the Community Expenditure Report (CEX) (table 1).

In the text below, the "revised" N footprint calculations for Albemarle and Charlottesville refers to the new N footprint based on the addition of sources proposed in this study. Then, additional N footprint sources of agriculture (crops and animals), septic systems, airports, and UVA were added to the calculations as well as emissions factors for crop production, animal agriculture, septic systems, and the airport within the county. Collecting UVA data also involved assigning census block groups (BGs) to each of the buildings within Charlottesville and Albemarle.

Since the goal of this work is to determine the impact of additional categories for Albemarle, the original N footprint calculation is compared to the revised calculation. The following section goes into further detail how these steps were completed.

A. Albemarle Nitrogen Footprint

First, data from Stanganelli (2020) on the Charlottesville nitrogen footprint were used. Then, data were collected from either the same or similar sources for the adjacent categories in Albemarle for 2017 to determine the original N footprint of Albemarle (table 2.1).

Table 2.1: *Inventory of data sources and years of data collected for the Albemarle Nitrogen Footprint calculations. The source column indicates where the raw data was obtained. The year column indicates the year of raw data available to use for the Albemarle N footprint calculation.*

Category	**Source- Charlottesville**	**Source- Albemarle**

Food purchased	Community Expenditure Report Data (CEX 2017)	Community Expenditure Report Data (CEX 2017)
Pet Food	Okin et al. (2017)	Okin et al. (2017)
Pet Waste	Okin et al. (2017)	Okin et al. (2017)
Fertilizer	Chesapeake Land Cover Data Project and Frasier et al. (2012)	Chesapeake Land Cover Data Project and Frasier et al. (2012)
Wastewater	Rivanna Sewer and Water Authority	Rivanna Sewer and Water Authority (2017) and Virginia Department of Health (PC: 2021)
Transportation	Virginia Department of Transportation (VDOT 2017)	Virginia Department of Transportation (VDOT 2017)
Electricity	Dominion Energy (2018)	Albemarle Department of Public Works (Dominion Energy and Shenandoah Electric)
Natural Gas	Charlottesville Department of Public Works	Albemarle Department of Public Works

To fully capture the N footprint of the three entities, data were collected from agriculture, airports, and septic systems as described in the following.

i. Crops

To begin adding crops into the community's N footprint, a clear set of system bounds needed to be established. Within the system bounds of Albemarle, most of the crop agriculture involved is growing and harvesting. Much of the processing is done outside of the county, which will not be included in this calculation. Figure 2.1 shows the steps from farm to plate and nitrogen losses that occur along the way. The percentage of nitrogen lost to the environment and not taken up by the crops themselves is a major source of losses of N captured in the Albemarle footprint. N losses due to processing for human and animal consumption are not included in this calculation. The food purchasing sector does include the losses along the entire chain listed here, except wastewater, for food purchased and eaten by residents within the county (Figure 2.1).

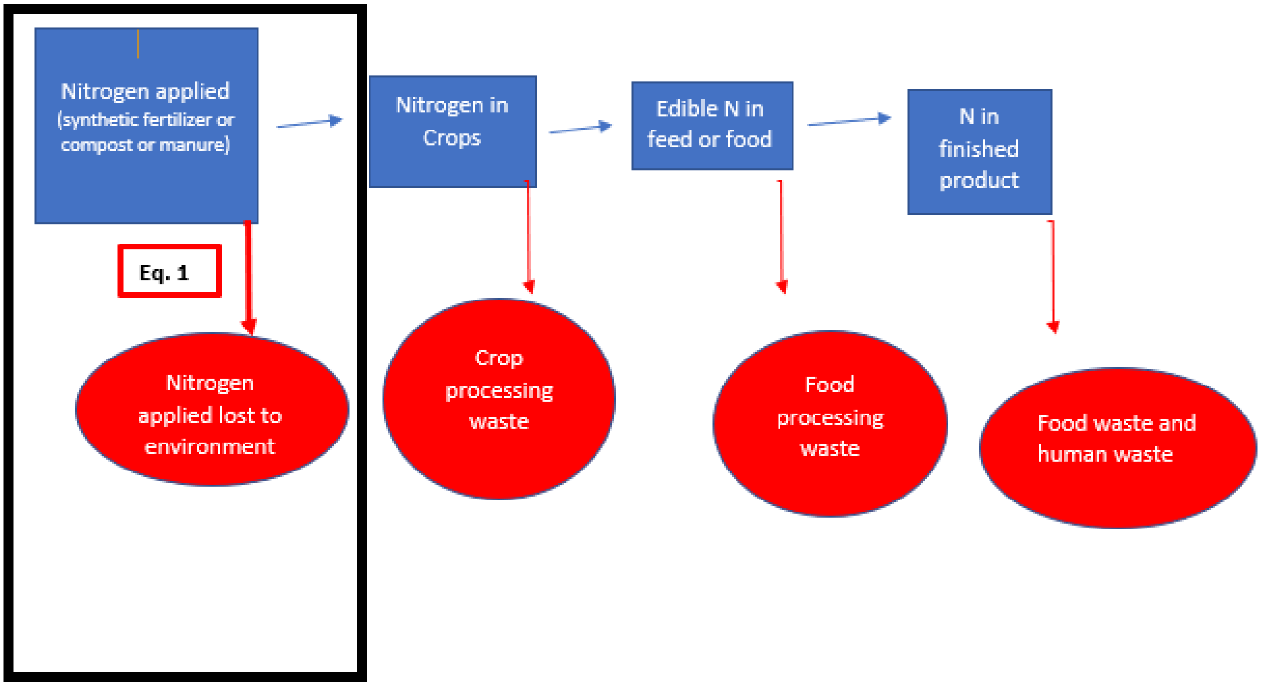


Figure 2.1: *Nitrogen (N) losses along the line of crop planting to human or animal consumption. The red arrows represent N losses along the production line. The blue arrows represent N that is contained in the product moving to the next step. The black box represents the portion of the N footprint included in the C-NFT of Albemarle. The red box shows where Equation 1 was applied within the footprint. Treatment of human waste is included in the "wastewater" sector of the footprint tool and the food waste portion is included in the food purchased sector.*

One potential overlap are crops both grown and purchased in the county. The N footprint of this food would be included in both the food purchased and agriculture portion of the footprints. To my knowledge, there are no datasets which capture the total amount of food both produced and sold locally without leaving the county for processing. Only 7% of the food produced for human consumption stayed within the county and city bounds. This estimate is consistent with the average amount of food locally produced and sold in grocery stores (Food and Facts 2021). This estimate is likely an overestimate of the locally purchased food as "local" is considered within 500 kilometers (Vogel and Low, 2015). Using this overestimate, the total potential overcalculation of an individuals per capita N footprint was ~0.1%.

To calculate the crop footprint, several datasets and emission factors were used. First, the total acreage of crops in each BG by type were obtained from the USDA Cropscape database as a raster file and processed using ArcGIS Pro (Cropscape 2018). Then, the average N fertilization rate was multiplied by the acres of crop in each BG (Kissel and Harris, 2008). Finally, a nitrogen use efficiency (NUE) factor was applied to these values to capture the N lost because of runoff or volatilization prior to uptake by crops (Lassaletta et al., 2014). This was done for each crop type in each BG of Albemarle where the N fertilization rate and NUE are specific to each crop type. (Eq. 1) (Appendix Table A2.1).

Equation 1:

$$\begin{aligned}&Crops\ Nitrogen\ Footprint\ \ (kg\ N)\\&\qquad = Acres\ of\ crop * average\ N\ fertilizer\ applied\ per\ acre\ (kg\ N)\\&\qquad * (1 - NUE)\end{aligned}$$

5% of the nitrogen fertilizer used was assumed to be manure or compost which is consistent with the national average in the US (MacDonald et al., 2009). All manure and compost used in crop fertilization was assumed to come from within the county. Since there is no difference in the crop calculations based on the source of N fertilizer (synthetic or organic), these calculations stay the same. To capture N re-use in terms of manure, the N losses from manure in the county were reduced by 5% of the total N needs of crops (~81,000 kgs). Using these initial assumptions, the distribution of crop production in Albemarle was made. By dollars in revenue to Albemarle, the largest crop within the county was fruit. By acreage, the largest crop was hay and forage within the county.

ii. Animals

The second sector added was animals. Like crops, to add animals to the community N footprint a clear set of system bounds needed to be established. Most animals by number and weight within the county are beef cattle (in the cow-calf stage) and horses (USDA 2021). These animals are grazed or hay-fed for most of their lives within the county. The assumption was made that all feed for cattle, sheep, goats, and horses came from within the county as either hay or pastureland. This assumption was made as there are not sufficient data to determine the total amount of feed coming from other localities. Albemarle produces ~4% more hay annually than needed to feed the total number of cattle, sheep, horses, and goats in the county (USDA 2021). This is assuming cattle are grazed. Using this assumption, most of the feed production N footprint for animals will be captured in the crop sector (Eq 1). There are no major beef, lamb, or hog meat processing plants within the county. An assumption was made that no meat processing occurred within the city or county limits as there are no large processing facilities within the system bounds (Figure 2.2).

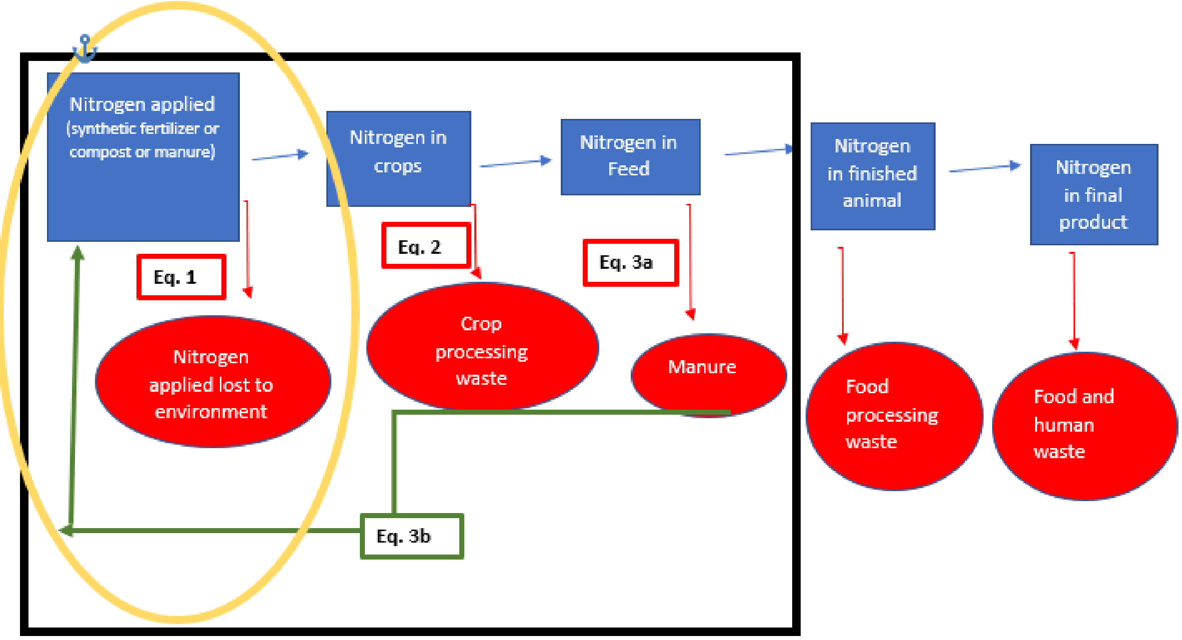


Figure 2.2: *System bounds of the N footprint for animals. Red arrows represent N lost to the environment, blue arrows represent the N retained in the product at that stage, and the green arrow represents the recycled manure used to produce crops (alfalfa and other hay) then used to feed animals within the county. The black box represents the footprint I want to include in the county footprint. The yellow circle includes factors assuming already included, which is the food purchased end of the N footprint, which is primarily hay production at ~350,000 bales annually. The boxes represent where the equations below were used to calculate the N footprint of each set within the flow diagram.*

The first data set used was the number of animals per census BG. The total number of animals by type are reported by the US Department of Agriculture (USDA 2021). These data are not available at the BG level, so the animals were split into BGs based on the amount of pastureland within each BG (Cropscape 2021). The average number of animals per acre was used to determine the concentration of animals on each acre of pastureland in the county. This was determined to be 2-3 cattle per acre per best practice guidelines (Jacob Gilley, personal communication, American Farmland Trust, 2021).

The main loss of nitrogen within the animal sector is manure as food has already been captured within the crops sector due to hay production. The losses of N by animal type and by average weight were used to estimate the total amount of manure by type in each census block group (USDA 2021). Waste management practices such as dredging, pooling, and collection influenced the nutrients lost to the environment because of animal production. The Virginia average waste management practices (WMS) from the Local Governments for Sustainability USA report (ICLIE 2013) were used to estimate any practices commonly used to reduce N leaching from waste. Most of these practices are present on hog and chicken farms but not cattle and horse farms which are a large portion of Albemarle’s animal agriculture system (ICLIE 2013). Horse and cattle manure were assumed to either be left on fields or dredged which resulted in no reduction in N leaching (Eq. 2a).

The manure re-used as fertilizer was assumed to be 5% of the total crop N needs for the county which is the US national average. This was subtracted from the total manure lost for chickens and cows which are the two commonly used sources of manure fertilizer (Foster and Andrews 2007).

Equation 2a:

$$
\begin{aligned}
&Animal\ Waste\ Nitrogen\ Footprint\ (kg\ N) \\
&\quad = ((number\ of\ animals * average\ weight\ of\ animal)\ (kg) \\
&\quad * annual\ estimated\ manure\ production\ (\frac{kg\ manure}{kg\ animal\ weight}) \\
&* N\ content\ of\ manure\ \left(\frac{kg\ N}{kg\ manure}\right) * WMS\ factor\ (chickens, cows, and\ hogs)) \\
&\quad - manure\ used\ as\ fertilizer\ (kg\ N)
\end{aligned}
$$

This was done for each animal type and BG using factors specific to each animal type (Eq 2a) (Appendix Table 2A). Finally, their recycled waste was subtracted from the crops N footprint to avoid double counting manure being used as fertilizer in the crops sector.

iii. Septic Systems

The third sector added to the C-NFT was septic systems. In Albemarle, some residents are connected to a municipal treatment plant, while others use septic systems. To determine the number and location of septic systems within the county, a map provided by Robert Woodside (Rivanna Water and Sewer Authority) was used to determine which areas of the county are connected to municipal treatment (Figure A2.2). All other residents living outside of this area were assumed to have septic systems. An average annual capacity of these septic systems was assumed to be 5,000 liters per day and each resident using 300 liters of water per day (Robertson et al., 2008). In these calculations, we are assuming an average denitrification rate of 40% for these septic systems and a 20% annual failure rate was assumed (Eq.3) (Robertson et al., 2008). In these failed systems, 100% of the N in wastewater is lost to the environment (Wood and Lee, undated).

Equation 3a:

$$\begin{aligned} &Functional\ Septic\ Systems\ Nitrogen\ Footprint\ (kg\ N) \\ &\quad = [(water\ treated\ by\ septic\ systems\ (liter) * 0.8) \\ &\quad * N\ in\ wastewater\ (kg\ N/liter) * (1 - N\ removal)] \end{aligned}$$

Equation 3b:

$$\begin{aligned} &Failed\ Septic\ Systems\ Nitrogen\ Footprint\ (kg\ N) \\ &\quad = [(water\ treated\ by\ septic\ systems\ (liter) * 0.2) \\ &\quad * N\ in\ wastewater\ (kg\ N/liter)] \end{aligned}$$

The functional and failed N footprints of septic systems are added and then added to the total wastewater N footprint. This calculation was done for each BG which is considered to be outside of the Rivanna Wastewater Treatment Plant’s breadth (Appendix Fig. 2.1).

iv. Airport

The fourth sector added was air travel. The Charlottesville-Albemarle Regional Airport (CHO) is located in Albemarle. To add an airport to the calculations, the number of flights leaving the CHO airport or liters of fuel CHO uses annually were obtained. To be consistent with the system bounds set of within-county emissions, only the takeoff fuel was accounted for, which is roughly 10% to 20% of the fuel used for the entire trip (US EPA; SIMAP 2022). Emission factors used here were from the *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2016* from table A-91 (US EPA). This is consistent with methodologies included for calculating the GHG footprint of a city. (US EPA; SIMAP 2022). (Eq. 4).

Equation 4:

$$Airport\ Nitrogen\ Footprint\ (kg\ N) = \Big(number\ of\ flights * \big(takeoff\ fuel\ used\ (\%) * fuel\ per\ flight(gal)\big) * (EF\ (\frac{N_2O}{gal}\Big) * (0.63\ N/N_2O)) + (number\ of\ flights * \big(takeoff\ fuel\ used\ (\%) * fuel\ per\ flight\ (gal)\big) * (EF\ \Big(\frac{NOx}{gal}\Big) * (0.3\ N/NOx)$$

This calculation was done for the BG where the airport was located within the county and added to the total N footprint of transportation for each BG.

B. Integrating UVA, Charlottesville, and Albemarle Footprints

UVA has computed its N footprint since 2010. The most recent calculation is for 2017. The UVA footprint includes inventory data from all buildings (electricity use, wastewater, refrigerants and chemicals, and on-site utilities) on UVA's grounds in Charlottesville and Albemarle, as well as food data from all dining and catering operations (excluding concessions which are discussed below). UVA tracks its inventory data in a platform called the Sustainable Indicators Management and Analysis Platform (SIMAP). SIMAP data was used to add the university to the C-NFT calculations alongside building specific electricity, natural gas, and water use data (Ethan Heil, UVA Office for Sustainability, PC, 2022)

UVA is located in both Albemarle and Charlottesville. In both Albemarle and Charlottesville, the previous N footprint calculations, UVA was excluded from the purchased electricity, wastewater, and natural gas values. This means UVA SIMAP inventory values for these categories will not overlap.

To integrate the university footprint into the community N footprint tool framework, several things were considered. First, the location of UVA facilities within the city and county by BG were identified. Second, resource use (both energy and food) by building was assessed. Third, there were some data overlaps and missing pieces which were considered when processing the data and interpreting the results.

i. Locating UVA Facilities

The first step in integrating UVA, Charlottesville, and Albemarle footprints was determining the location of UVA within the census block groups of Albemarle and Charlottesville. This was done using a point layer of UVA buildings overlayed with BGs in Charlottesville and Albemarle. Each UVA building was assigned to a particular BG. Some buildings overlapped BGs. In this case, BGs were assigned based on where most of the facility was located (Appendix Fig 2). A total of 552 buildings associated with UVA were added to 13 BGs across the city and county.

In order to determine the proportion of UVA's footprint that lies within each block group, the type of building (academic, residence hall, dining facility, health system) and their respective energy usage was obtained. The food purchased footprint was split up depending on the dining facilities within the BGs.

ii. Additional Categories

There are some categories that are present in the community nitrogen footprint tool (C-NFT) structure that are not included in the institution N footprint calculations and vice versa. These were captured in the revied C-NFT for the integrated university, city, and county tool (Table 2.2).

Table 2.2: *Combining categories for the C-NFT revised tool. The categories within two existing tools (C-NFT, UVA-SIMAP) and the proposed categories for the tool in development (C-NFT revised) are listed below. The integrated community tool adds two additional footprints and combines knowledge from three entities to create a detailed picture of environmental losses because of the categories listed. "Y" indicates the sector was included and "N" indicates the sector was not included.*

Categories	C-NFT original	UVA-SIMAP	C-NFT revised

Food purchased	Y: Community Expenditure Report (See Appendix Section 1)	Y: Vendor-specific reports from UVA Dine, Health System, and Darden	Y: Combination of both
Pet Food	Y: Estimate of Okin et al., 2017 per capita pets	N	Y: Okin et al., 2017 estimate with added student population
Pet Waste	Y: same as above	N	Y: same as above
Fertilizer	Y: estimated per capita fertilizer use on home lawns (Frazier et al., 2014)	Y: direct fertilizer applied to on-grounds grass	Y: Combination of both
Wastewater	Y: Wastewater treated by municipal plant	Y: Wastewater sent to municipal plant	Y: Septic systems (above) and total wastewater treated by Rivanna Water and Sewer annually
Transportation	Y: Vehicle kilometers traveled through the city and county	Y: Direct transportation as liters of fuel for buses and commuting as estimate of kilometers traveled by FTE staff and students	Y: Vehicle kilometers traveled through city and county and airport (above)
Electricity	Y: Total kwh used by businesses and residents	Y: total kwh used by UVA	Y: Combination of both

Natural Gas	Y: Total therms used by residents and businesses	Y: on-campus heat plant usage	Y: Combination of both
Agriculture- Crops	N	N	Y: See agriculture above
Agriculture- Animals	N	N	Y: See agriculture above

iii. Data Overlaps and Missing Pieces

As noted above (table 2.2), there were several areas of potential overlap and missing data that needed to be rectified within the integrated community tool structure. The areas of overlap are transportation and food purchased at dining halls by students living off-grounds. The missing piece of data is food purchased off-grounds by students living on-grounds.

Transportation is the first area of overlap. Distances traveled through the city and county are included in the C-NFT inventory dataset from information provided by the Virginia Department of Transportation. Kilometers traveled by university-owned vehicles are included in the “direct transportation” category, and kilometers travelled by commuters to the university are included in the “staff, faculty, and student commuting” categories in the UVA-SIMAP inventory. If both are included in the community footprint calculation, the kilometers traveled within the city and county by commuters and university owned vehicles would be counted twice. This was rectified by removing the direct transportation and commuting UVA inventory data and only including emissions from kilometers traveled within city and county limits.

Food Purchased is the second area of overlap and missing data. The Consumer Expenditure Report (CEX) does not include food purchasing data from businesses or institutions, so the food data inventory from UVA can directly be used in the N footprint calculation for Charlottesville and Albemarle. This overlap would occur when students living off-grounds purchase food on-grounds. These expenditures would be included in the CEX purchasing data as “Food Away from Home”. Including both the CEX report data and UVA food inventory would double count these purchases. An area of missing data is food purchased off-grounds by students living on-grounds.

Students living in dormitory housing are not included in the CEX survey since they are not considered "permanent residents". While food purchased on-grounds would be completely captured using the UVA inventory dataset, food purchased by these students off-grounds would not be included in any report. For this analysis, the assumption was made that the missing food data from UVA on-grounds residents eating off-grounds and off-grounds residents eating on-grounds would cancel each other out. As mentioned above, there are no additional datasets to capture the losses from students not included in the Consumer Expenditure Report. With ideal datasets, each students living on-grounds would record the food consumed somewhere other than UVA Dine locations but these data are not available nor was it feasible to ask students to do this for the scope of this project. Further discussion on the impact of this limitation is presented in Chapter 4.

Food served at UVA concession stands during sporting events is not included in the footprint. This is a minor omission because food served at concession stands only make up ~2% of the total weight of food served at UVA (personal communication: Caroline Baloga, UVA Dine, 2022).

3. Results

Using the methods from Dukes et al. (2020), excluding the additions of septic systems, agriculture, the Charlottesville Albemarle Airport, and UVA, the total N footprint of Albemarle was 4,400 MT N. On a per-capita basis it was 40 kg N per capita. This compares to a total of 1,500 MT N for Charlottesville and 32 kg N per capita, excluding UVA (Figure 2.3). Per unit area footprint calculations were completed but mostly tracked population density due to the methods of N footprint calculation (Appendix Fig A2.3).

Without the revisions suggested in the methods above, Albemarle residents have higher per capita N footprint than residents in Charlottesville. This is driven by both personal car travel (45% higher), electricity use (32% higher) and food purchased (13% higher). Both per capita footprints are consistent with the US average N footprint of 37 kg N per capita annually (Leach et al., submitted).

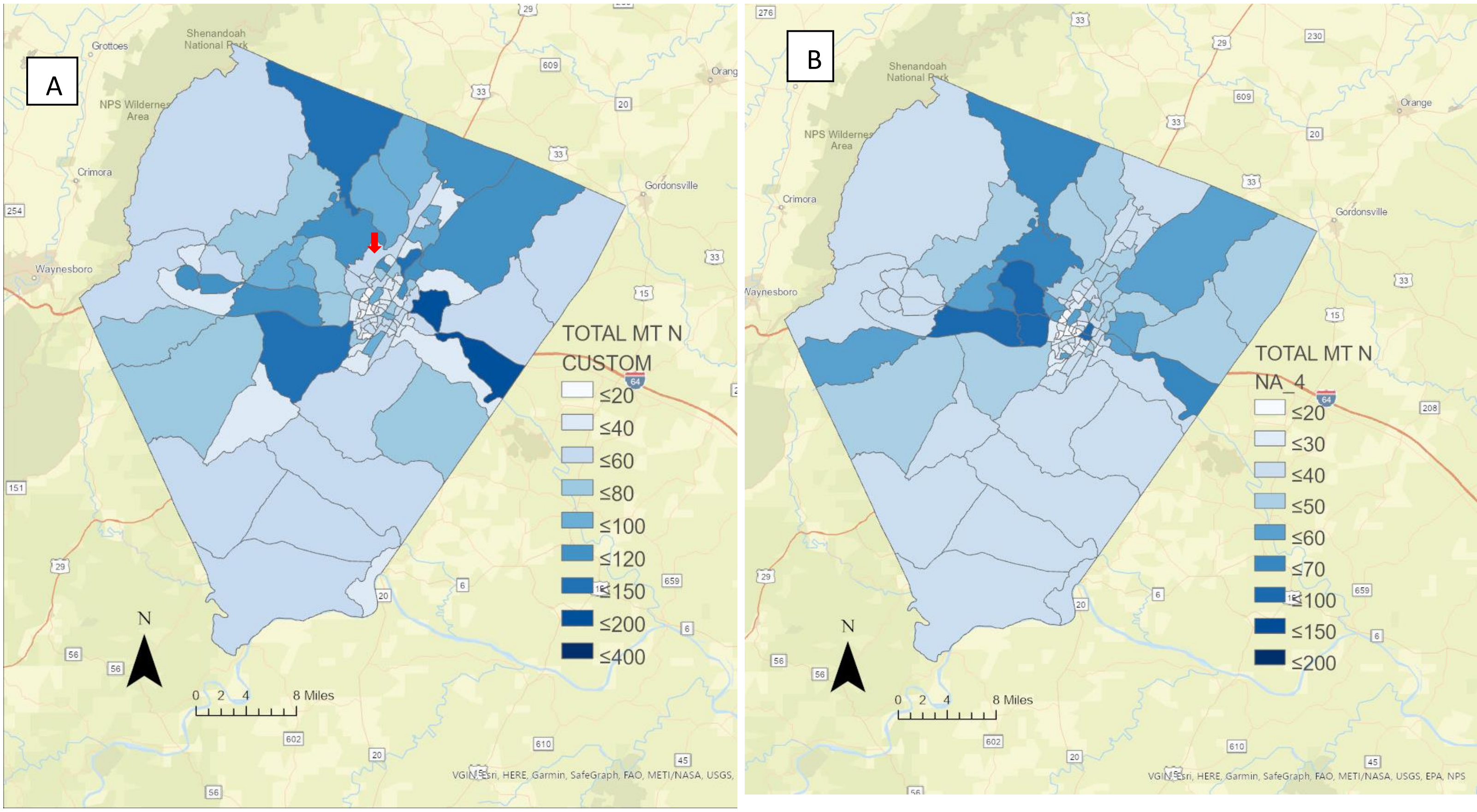


Figure 2.3: *Total and per capita original footprints. The total (MT N) (A) and per capita (kg N) (B) footprint of BGs in Albemarle and Charlottesville without added agriculture, septic systems, airports, or UVA. (A) The total N footprint scale starts at 30 MT and increases by increments of 30 MT N to 180 MT N. The scale ends at 350 MT N to capture the 14 BGs higher than 180 MT N (topping out at 322 MT N). (B) The per capita N footprint scale begins at 20 kg N and ranges to 80 kg N with increments of 10 kg N. The scale then jumps to 100, 150, and 400kg N. This is to capture the 4 BGs above 100 kg N per capita, 3 at 150 kg N, and 2 higher than 150 MT N (topping out at 360 kg N per capita). Red arrow indicates airport location.*

After adding the septic systems, agriculture, the Charlottesville Albemarle Airport, and UVA to the N footprint calculations, the total N footprint of Albemarle was 8,300 MT N and 77 kg N per capita. The total N footprint for Charlottesville was 1,600 MT N and 34 kg N per capita. The total N footprint of UVA was 210 MT N with ~7 kg N per full-time student. It should be noted that the full-time equivalent student footprint is likely lower than expected as students travel to and from home and some or all their food footprint would not be included in UVA total. The UVA footprint was distributed appropriately throughout the BGs in Charlottesville and Albemarle. (Figure 2.4).

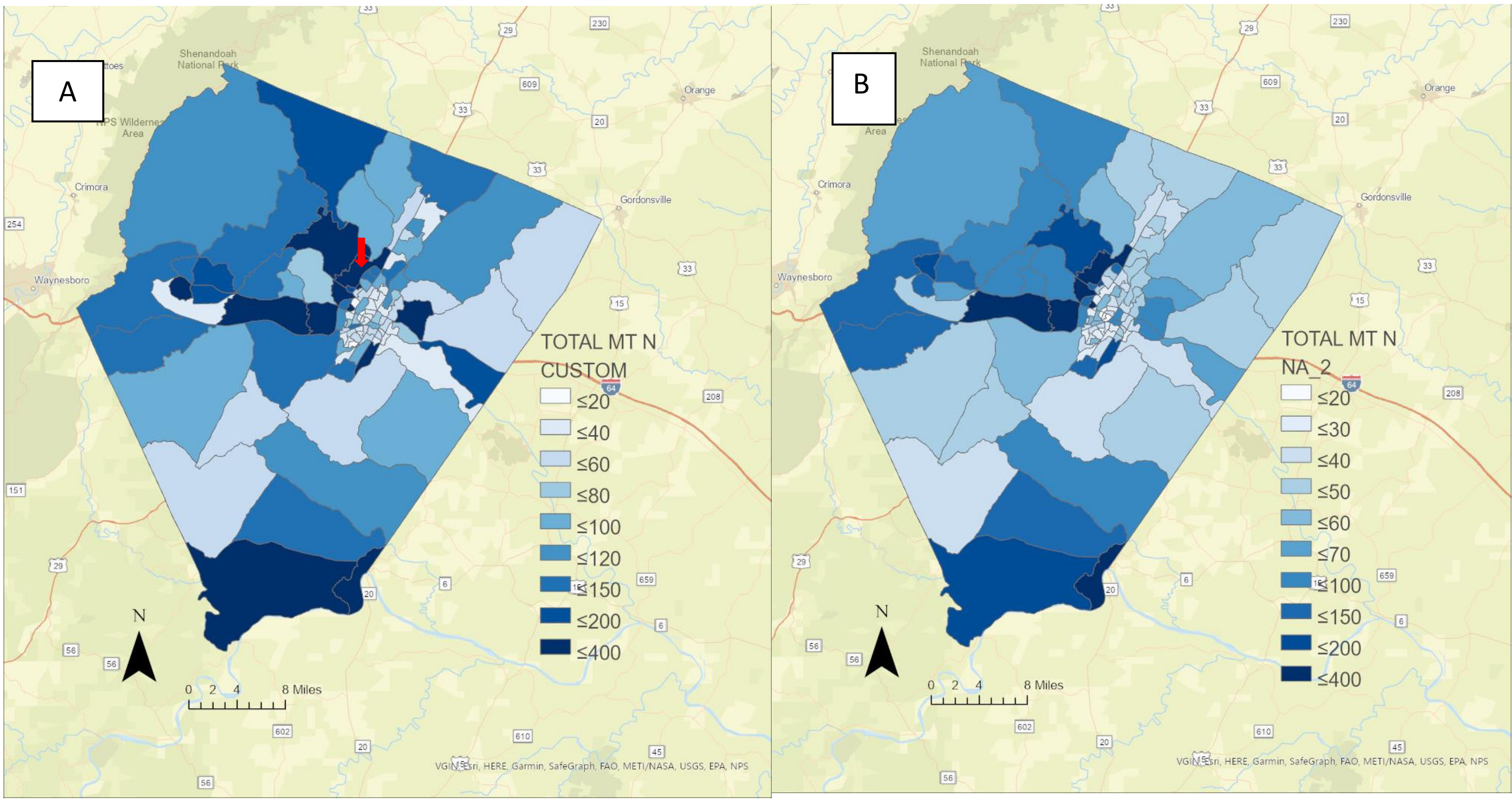


Figure 2.4: *Total and per capita revised footprints. The total (A) and per capita (B) N footprints of residents in Albemarle and Charlottesville after the addition of agriculture, septic systems, airports, and UVA. (A) The total N footprint scale starts at 20 MT and increases by increments of 20 MT N to 120 MT N. The scale ends at 400 MT N to capture the 14 BGs higher than 120 MT N (topping out at 356 MT N). (B) The per capita N footprint scale begins at 20 kg N and ranges to 80 kg N with increments of 10 kg N. The scale then jumps to 100, 150, and 400kg N. This is to capture the 5 BGs above 100 kg N per capita (topping out at 388 kg N per capita). Red arrow indicates where airport is located.*

One additional method used to evaluate the N footprint was a normalization by area. Since Charlottesville has a denser population than Albemarle, most of the BGs within the city were on the upper end of the per area footprint distribution. However, when agriculture was added to Albemarle, there were some BGs that began to stand out as higher contributors even with a low population and large area (Figure 2.5)

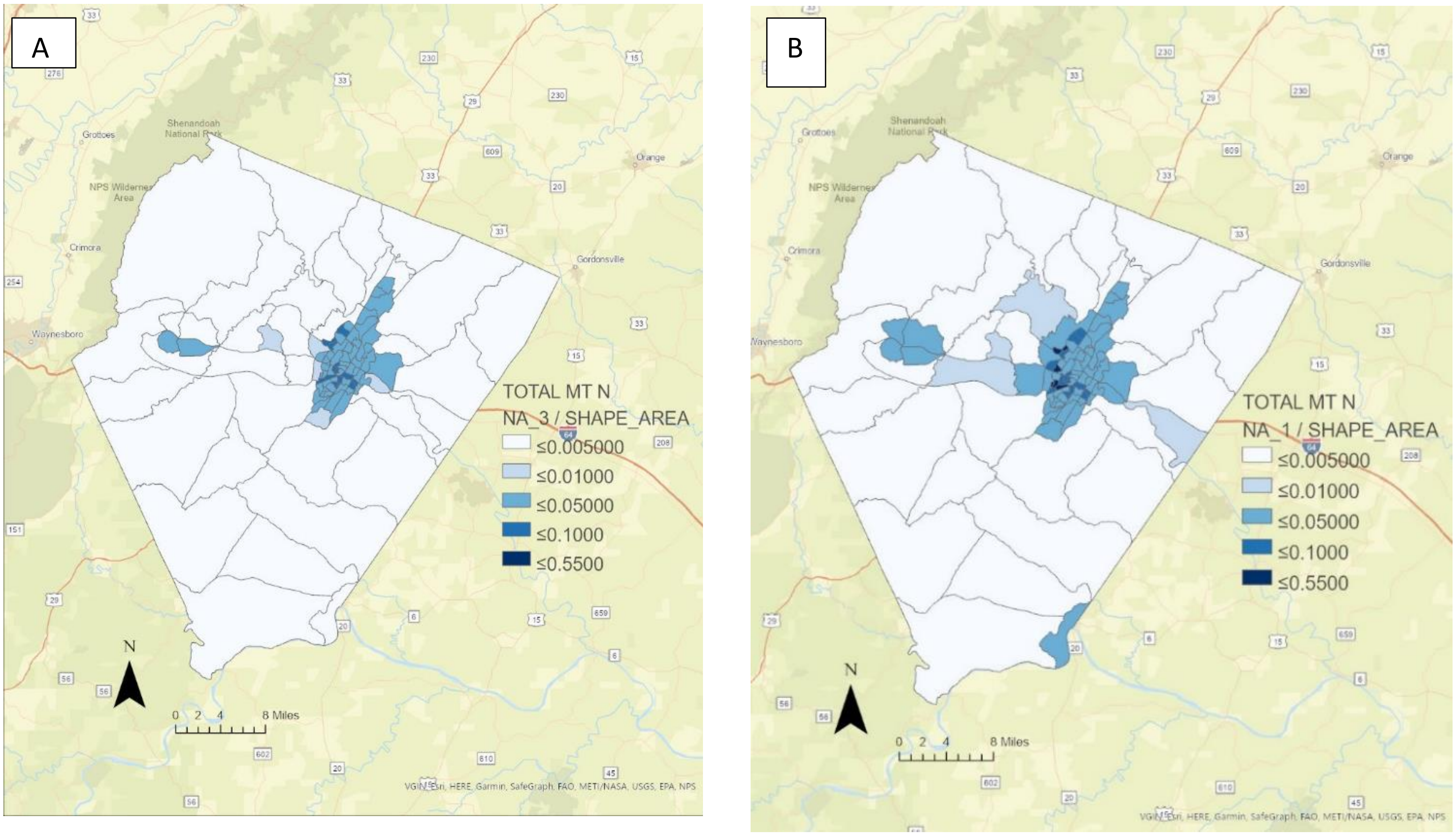


Figure 2.5: *N footprint per area. The total N footprint normalized by unit area (meters squared) in ArcGIS pro for the original (A) and revised (B) N footprints of UVA, Charlottesville, and Albemarle.*

The largest increase in per capita and total N footprint occurred for residents in Albemarle with the addition of the previously excluded sectors (e.g., agriculture). This was to be expected as Albemarle is an agriculture-based community with ~182,500 acres of farmland (crops and animals) and septic systems accounted for ~42% of the total liters of wastewater in the county.

There were 9 of 17 total census block groups containing UVA affiliated buildings in Albemarle and 8 of 17 total in Charlottesville (Figure 2.6).

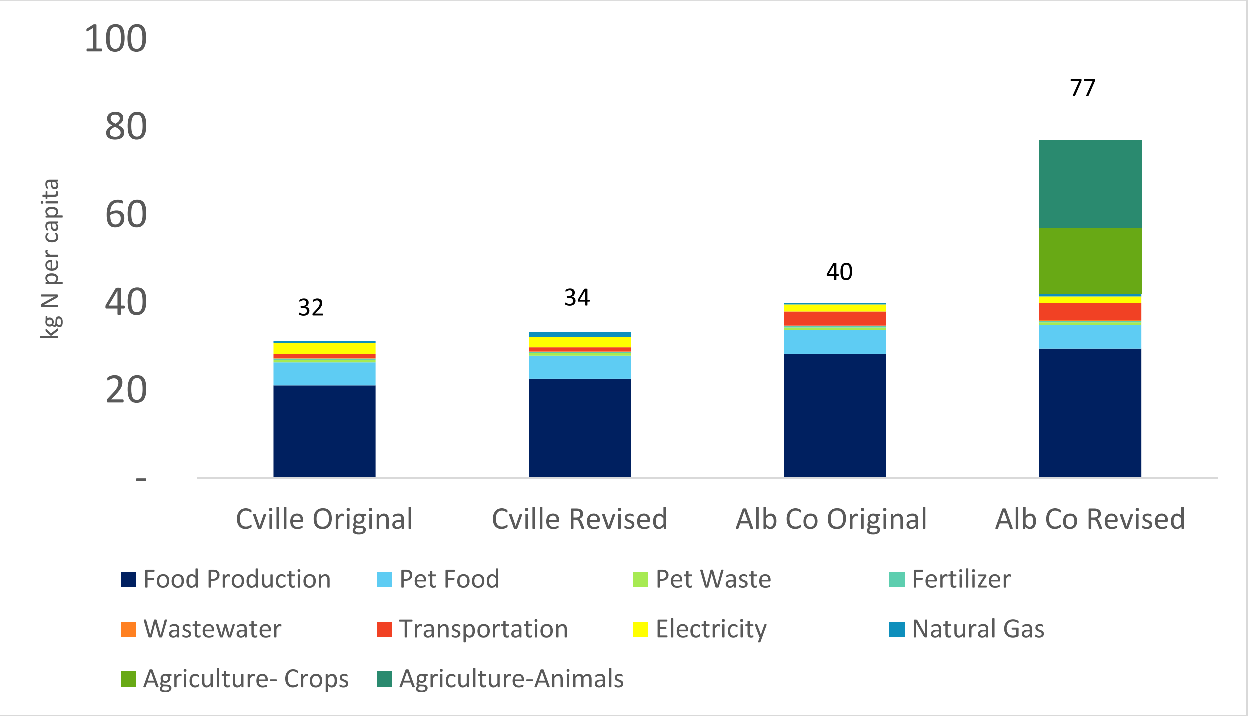


Figure 2.6: *Per capita footprint comparisons. The per capita N footprint of sectors within the CNFT for both Charlottesville and Albemarle, VA. Charlottesville and Albemarle both increased in N footprints after the "revised" calculation to include agriculture, septic systems, UVA, and airports. Albemarle had the largest increase per capita due to the agricultural nature of the community.*

4. Discussion

The revised C-NFT that included crop and animal agriculture, septic tanks, airports, and UVA increased the average per capita N footprint of both Charlottesville and Albemarle residents. The largest impact was seen on the average footprint of Albemarle residents (Figure 5).

Prior to the addition of the three new categories, Albemarle residents had slightly higher N footprints per capita than Charlottesville residents. The average per capita footprints of all sectors were higher, in particular food and transportation. Transportation being the largest difference in per capita footprints (45% higher) is likely due to the decentralization of community resources and limited public transportation. With limited public transportation options in the county, there are more single-passenger cars on the road. Residents living within the county have to travel longer distances to attend school, work, and purchase goods like groceries. Electricity use was also 32% higher per capita in Albemarle than Charlottesville. This could be due to the number of residents living in apartment style residences in Charlottesville. Apartments are likely to use less energy than single family homes for reasons such as smaller size and configuration of an apartment to be more energy efficient. Often, apartments are rented while townhomes and houses are often occupied by residents. This is reflected in the footprint results as the total percentage of renters in Charlottesville is ~60% compared to ~34% in Albemarle. Food purchased was also slightly higher (13%) per capita in Albemarle than in Charlottesville. This was present relatively equally across all food sectors with no one food sector being higher than another.

After adding agriculture, septic systems, airports, and UVA, the Albemarle N footprint almost doubled (48% increase) and Charlottesville N footprint increased by 6%. The only factor effecting the Charlottesville N footprint was the addition of UVA's buildings to 8 of the 36 BGs in the city. In Albemarle, crop agriculture was added to 59 of 65 BGs, animal agriculture to 52 of 65 BGs, septic systems to 20 of 65 BGs, airport data to 1 of 65 BGs, and UVA buildings to 9 of 65 BGs. Agriculture made up the largest portion of this increase by far with 41% of the increase coming from crop agriculture and 52% from animal agriculture. Septic systems caused an increase of 4% and the CHO airport an increase of 2%. The increase in the Albemarle footprint shows that the biggest contributor was agriculture (Figure 2.5).

Agriculture almost doubles the N footprint of Albemarle; it is important to note several considerations. The average Albemarle resident has a much higher N footprint than both residents of UVA or Charlottesville. On one hand, this can be viewed as inflated because the county person is not 'consuming' the N. However, by virtue of occupation of individuals within the county, the footprint of everyone else in the BG is elevated. While eliminating agriculture could "solve" the N footprint concerns within the county, this would not be sustainable. A nitrogen footprint of "zero" is impossible to obtain as all food requires nitrogen to be grown and nitrogen is an essential part of protein structure for animals, including humans. Albemarle is in the top 25% of counties in the state of Virginia in revenue coming from agriculture (USDA 2021). Albemarle produces food for individuals living in Charlottesville and other cities across the US. Additionally, ~15% of the total population of the county is employed by the agriculture sector (Albemarle County, Economic Development). Locally and sustainably produced food can be beneficial to the local environment and reduce kilometers traveled from food to plate and can enhance the local economy. However, considerations in the practices used are necessary. Farms that employ practices such as manure reuse or crop rotation can minimize N losses to the environment (Blesh and Drinkwater 2013). Evaluating these practices in Albemarle could impact the N footprint of the county. If other agriculture-based counties evaluated their N footprints, this study could be used to compare N footprints of agricultural systems. The N footprint should be considered along with other environmental and social factors to enable consumers to make decisions about the best products to purchase (Edwards-Jones 2010).

Including UVA in the analysis of the revised C-NFT directly increased the 13 BGs where UVA buildings were present. On average, the total N footprint of these BGs increase by 53% with a range of a 241% increase to a 0.7% increase. The university buildings and dining locations have a clear impact on the N footprint of both the city and county however, there is likely a spill-over effect of the presence of UVA on the surrounding community. Many students and staff residents travel from other communities to Charlottesville and Albemarle to work and study at UVA, increasing the resource demand and therefore the N footprint of the community. This is captured by the N footprints of individual BGs in the CEX report and community energy use reports but is not directly associated with UVA's N footprint. To fully assess the impact the university has on the community's N footprint, additional studies would need to be done to assess the off-grounds resource use of transient students and staff on the community. Then, the total N footprint of students living and eating off grounds could be parsed out and a decision made as to whether or not this should be associated with the community or university. As the tool stands, the off-grounds footprint of students and staff of the university are completely associated with the city or county.

Combining these three entities in to one N footprint tool has significant impacts on how the N footprint is assessed within the broader community. Tracking Albemarle, Charlottesville, and

UVA’s environmental footprints separately has been commonplace for several years (Climate Action Together, 2019). While these assessments are steps in the right direction, evaluating the integrated footprints on an annual basis can begin to determine the tradeoffs and co-benefits of city, county, and university policies.

This tool could be used to assess the tradeoffs and co-benefits of current greenhouse gas, climate, and nitrogen action plans. Plans such as UVA’s commitment to carbon neutrality in 2030 could be evaluated within this tool to determine the impact on city and county resident’s N footprints (UVA Sustainability Plan, 2020). Additional potential scenarios such as reducing beef consumption through resident education programs within the city and county could be assessed within the current tool framework as well. If these three entities were committed to tracking their integrated N footprints on a regular basis, the impact of these scenarios could be seen. For example, if UVA reduces beef served at dining locations, would students opt to eat at meat-based restaurants? Or if the city of Charlottesville incentivizes solar panel installation would this increase the number of rental homes with solar panels for students? Assessing the impact of scenarios across the three entities would provide useful insight into which scenarios could have the most co-benefits to assist each entity with their goals.

5. Conclusion

This study presents a tool for assessing an integrated nitrogen footprint of a city, an agricultural community, and a university. The model shows the importance of agriculture, septic systems, and airports on a rural community such as Albemarle. The model also shows the impact a large university has on certain areas of a city and county. The tool uses publicly available datasets alongside public utility and university supplied datasets to calculate the N footprint associated with residents on a per capita basis. The census block group specific datasets allow for a spatially defined footprint to be determined. With consistent annual tracking, the tool can be used to determine the tradeoffs and co benefits of each entities’ environmental sustainability policies on the broader community.

Chapter 3

An integrated N, C, P footprint tool across three combined landscapes: city, county, university to determine and manage impacts of resource use

1.Introduction

City and county governments are laden with many important tasks to keep their constituents safe, healthy, economically prosperous, and environmentally sustainable. Ideally, community leaders could assess all these aspects in an integrated manner to make the best decisions for their constituents. There are tools available to communities to assess different parts of these aspects but there are a limited number of tools that evaluate decisions with multiple indicators in parallel (Wiedmann et al., 2021). It is important for entities to measure multiple indicators to assess their environmental impact. Focusing on one pollutant while ignoring the impacts of another could create unintended environmental consequences. Several entities have taken the approach of looking at multiple indicators (e.g., nutrients, biotic integrity, etc.) to assess environmental quality. These indicators have been used within watersheds (Flotemersch et al. 2015), protected areas (Cook et al. 2012) and endangered ecosystems (Mouillot et al. 2017), and even the entire earth (Sherwood et al. 2020). In this study, a methodology is proposed to assess governance decisions on N, P and GHG footprint indicators within one tool.

Environmental sustainability has become an increasingly important aspect of community health, especially in locations vulnerable to climate change (Meerow 2019; Chakraborty et al., 2019). Many cities across the world assess their greenhouse gas (GHG) emissions through footprinting tools such as those provided by the Intergovernmental Panel on Climate Change (IPCC) or Life-Cycle Analysis (LCA) models (Ohms et al., 2022). Many cities and counties across the world use greenhouse gas (GHG) indictors to track, compare, and set reduction goals for GHG's. A GHG footprint is a measure of the CO_2, CH_4, N_2O, refrigerant emissions and other radiatively-active substances associated with an entity's activities. Cities and counties often produce reports for their constituents and to benchmark and collaborate with other cities on solutions to the ever-increasing GHG emissions worldwide (https://www.c40.org/research/).

. These analyses capture direct emissions from energy production within city limits (scope 1), and indirect emissions from electricity generation (scope 2) (SIMAP 2021). Often due to limitations in data, many cities do not include emissions from indirect sources (scope 3) such as emissions from food production. Some cities do capture transportation emissions within their city limits using reports from local branches of the department of transportation which is essential to understanding the scope of greenhouse gas emissions (Jiang et al., 2022). Food production is generally not captured in a city-level GHG footprint analysis as it often happens outside of city limits. Food production can have a large impact (20-30%) on a cities GHG footprint but it is often difficult to track and harder to influence (Mohareb et al., 2018).

In this study, the N, P, GHG footprint tools are combined to measure the environmental sustainability of three entities, Charlottesville, Albemarle, and UVA. An N footprint is a measure of the reactive nitrogen (Nr) released to the environment because of an entities' resource use. Nr is defined as any species of N except $N_{2.}$ (Galloway et al., 2003). Excess Nr in the environment has a cascade of negative environmental and human health effects. These include smog, forest die-backs, eutrophication, contribution to the greenhouse effect, and stratospheric ozone hole destruction (Galloway et al., 2003). These resources include energy use, wastewater, and food purchased and consumption. While the N footprint model follows the scopes laid out for GHGs, food is a much more important aspect to a communities' N footprint, making up 70-80% of a community's N footprint (Dukes et al., 2020, McCourt et al., 2021). A handful of cities across the world have calculated their N footprint including two spatially explicit calculations: Baltimore City, Maryland, USA (Dukes et al., 2020); and Charlottesville, Virginia, USA (Stanganelli, 2020); and two conglomerate footprints for Canadian provinces (McCourt et al., 2021), and the Yangtze River Delta (Xian et al., 2022).

In addition to the GHG and N footprint indicators, phosphorus (P) footprint indicators provide additional information on the environmental impact of excess P. Demand for P in agricultural systems is one of the key components of resource demands, especially for animal-based proteins (Metson et al., 2014). Runoff of P from agricultural fields can pollute natural water resources if applied in excess or because of erosion from agricultural fields (Smith and Schindler, 2009). P footprints for individuals at the country level were developed to help consumers make decisions. Food is the driving factor in an individual's P footprint with animal products making up most of the footprint. P losses from wastewater and fertilizer are also considered. Unlike the GHG and N footprints, there is no P footprint associated with energy use or transportation (Metson et al., 2020). A city level P footprint analysis has been done for Brussels, Belgium which evaluated the P footprint of individuals in the city by using a top-down approach of evaluating the total food consumed in the city using the Belgian Household Budget Survey to estimate the total amount of food consumed by residents (Papangelou et al., 2021).

Assessing several different facets of the environment can capture additional sectors of a community's resource use and identify potential unintended environmental consequences of policy change. In 2017, the excel-based Nitrogen Footprint Tool (NFT) tool was merged with the Campus Carbon Calculator to create a tool to integrate two environmental footprint indicators (GHG and N) in the Sustainable Indicators Management and Analysis Platform (SIMAP, 2021). This allowed institutions to use one dataset to calculate two footprints and evaluate synergies and tradeoffs between the two footprints (Leach et al., submitted). In 2020, the first integrated footprint tool for institutions (IEFT) was created to calculate GHG, N, P, and W footprints alongside social costs (GHG and N) (Dukes et al., in review). The tool uses data from several important sectors at the university level (food purchased, water use, electricity, and transportation) to calculate the footprints using emission factors from several sources (Leach et al., 2017; Leach et al., submitted.; Metson et al., 2020; Natyzak et al., 2017; Compton et al., 2017). The combination of these tools was the first to integrate four footprints alongside a cost analysis intended to guide decisions surrounding solutions to complex environmental problems.

In 2019, Charlottesville, Albemarle, and UVA joined forces to achieve environmental sustainability goals by creating a plan involving stakeholders for these three groups (Climate Action Together, 2019). The groups track their environmental footprints separately and have separate goals but come together to discuss strategies which could impact another entity. Charlottesville and Albemarle have both officially calculated and published their GHG footprints (Climate Action Plan, 2021). UVA officially tracks both its GHG and N footprints (A Great and Good University, 2019). These efforts are on-going with the intent to meet each entity's 2030 Climate Action Goals.

Albemarle and Charlottesville have also had their N footprints calculated based on methods from Dukes et al. (2020) and Stanganelli (2020) (see Chapter 2). UVA's P footprint was calculated in 2020 using a beta version of the Integrated Environmental Footprint Tool (IEFT) (Dukes et al., in review). The combined N footprint of the three entities has also been calculated (Chapter 2).

Based on the data used to calculate N footprints of Albemarle, Charlottesville and UVA in Chapter 2, the methodology presented here describes a tool to calculate the GHG, N, and P footprints of UVA, Charlottesville, and Albemarle and use this to evaluate the synergies and tradeoffs of each entities' separate Climate Action Plans.

This study addresses the questions:

1. What are the GHG, N, and P footprints of Albemarle, Charlottesville and UVA and what actions can be taken to decrease footprints in the three jurisdictions?
2. What is the impact of existing sustainability goals on the combined footprints of each jurisdiction, and what additional strategies can be explored to reduce all three footprints simultaneously?

The next section describes the steps taken to build P and GHG indicators into the existing N footprint framework created in Chapter 2 and evaluate strategies proposed in current sustainability plans alongside additional strategies to determine the impact on the integrated footprints.

2.Methods

In order to answer these research questions and create an integrated N, P, and GHG footprint to evaluate the impact of proposed strategies on the three entities footprints, the following steps were completed. First, the methodology of how to add both GHG and P footprints to the revised C-NFT framework is discussed. Then, the methods used to visualize the footprints on a spatial scale and evaluate synergies between the three footprints are presented. Finally, the list of scenarios and methods to evaluate each are presented.

A. Integrating the GHG and P Footprints within the revised C-NFT Framework

The same resource-use data used in the revised C-NFT framework (Chapter 2) were used to determine the GHG and P footprints. A summary of the emissions factors and key sources used to calculate the GHG, N, and P footprints are listed below (table 3). To summarize, the activity data for each category (e.g., coal, automobiles, beef, etc.) are multiplied by an emissions factor (e.g., CO_2, CH_4, N_2O) and are converted to a normalized unit.

Table 3.1. *The greenhouse gas, nitrogen and phosphorus footprints: Emissions types, normalized units, and key references.*

	Emissions types	Units	Key References
GHG footprint	CO_2 CH_4, N_2O, and refrigerants	MTeCO_2	Leach et al. 2017 Heller and Keoilen 2014
Nitrogen footprint	NO_x, N_2O, NH_3, NH_4, organic N	Metric tons of N	Leach et al. 2017 Leach et al. in prep
Phosphorus footprint	P	Metric tons of P	Metson et al. 2020

The categories these calculations will evaluate are: food purchased, pet food, pet waste, fertilizer, wastewater, transportation, electricity, natural gas, agriculture crops, and animals. Food purchased was split into 18 different sub-categories, such as beans, fruits, beef, and nuts (Leach et al., 2016; Metson et al., 2020).

The same inventory data were used in all three footprint calculations, with different categories affecting different footprints. Inventory categories have different impacts on each of the three footprints. Many of the C, N and P footprints have similar major contributors at a community scale which include energy use, transportation, and food purchased (Table 3.2)

Table 3.2: *Categories of inventory data collected and sources of their emissions. This table indicates whether each category (left column) has an impact on the respective footprints (C, N, and P) with a Y for yes and an N/A for not applicable. Within the table, there are several references to where factors exist for each footprint.*

Categories	Greenhouse Gas (GHG)	Nitrogen (N)	Phosphorous (P)
Food purchased	Y (Keller & Heoleian 2014)	Y (Leach et al., 2017)	Y (Metson et al., 2020)

Pet Food	Y (Keller & Heoleian 2014)	Y (Leach et al., 2017)	Y (Metson et al., 2020)
Pet Waste	Y	Y (Okin et al., 2017)	Y (Okin et al., 2017)
Fertilizer	Y	Y	Y
Wastewater	Y	Y (Dukes et al., 2020)	Y (Metson et al., 2020)
Transportation	Y (Bureau of Transportation Statistics)	Y (Bureau of Transportation Statistics)	N/A
Electricity	Y (US EPA)	Y (US EPA)	N/A
Natural Gas	Y (US EPA)	Y (US EPA)	N/A
Agriculture-Crops	Y (ICLIE, 2013)	Y (see eq. 1)	Y (Metson et al., 2020)
Agriculture-Animals	Y (ICLIE, 2013)	Y (see eq. 2-4)	Y (Metson et al., 2020)

i. Nitrogen

For nitrogen, the methods from Dukes et al. (2020) were used to calculate emissions with the additional sectors and methodology outlined in Chapter 2.

ii. GHGs

For the GHG footprint, methods from Leach et al., (2017) were used. The majority of these calculations involved multiplying an emission factor by the inventory data. This was done for each of the three GHGs (CO_2., CH_4, and N_2O) and reported in units of $MTeCO_2$ or metric tons of CO_2 equivalent. The global warming potential of each of the three GHG's from the IPCC's 2018 report were used (Second Nature, 2021). An example calculation for transportation is below for Light Duty Trucks. (Eq. 1).

Equation 1:

$$MT\ CO_2 vehicle\ distance\ traveled(km) * CO_2\ emission\ factor\ for\ light\ duty\ trucks\ (kg\frac{CO_2}{km}) * GWP\ CO_2)$$

The total of all surface transportation categories (motorcycles, passenger cars, light duty trucks, heavy duty trucks, and busses) was summed for all GHG's to get the total GHG footprint for each locality based on the estimated number of kilometers traveled by residents within the BG. This was similarly done for each category impacted by the GHG footprint. The total reported units were in MTeCO_2 by BG. The only category not captured in the integrated community footprint tool but listed in UVA's GHG footprint was refrigerants and chemicals. This was excluded as there were no spatial data on where these refrigerants and chemicals were being used nor data on substances like this used in settings outside the university and around the community. Refrigerants and chemicals have a relatively small impact on the overall UVA GHG footprint of (0.75%) in 2017.

iii. Phosphorus

For P, there are no significant associated atmospheric emissions from energy use or transportation. For other sectors (wastewater, food purchased, agriculture (crops and animals), and pets), the inventory values were multiplied by emission factors from Metson et al. (2020) and reported in kilograms of P (Eq.2).

Equation 2:

$$Food\ Production\ (kg\ P) = kg\ food\ by\ category * virtual\ P\ factor\ (VPF)$$

For crop agriculture, the average amount of P applied and average uptake by plants was considered (Virginia Nutrient Management Standards and Criteria, 2014). For this work, the calculations did not include legacy P losses due to erosion. Legacy P refers to P existing in soils from past applications or natural sources. Since legacy P relies heavily on how land has been managed and fertilized in the past, it is nearly impossible to include the potential losses with only reviewing one year of data as was done in this study (Schlesinger, 2021).

iv. Data processing and Visual Analysis

The integrated tool was built in Microsoft-Excel, which is where the raw data were processed and the outcomes by census block group were tabulated. The tool then used ArcGIS Pro to visualize the three footprints across the three entities. The three footprints by sector were joined in ArcGIS Pro to the CEX (2017) census block groups to get a spatially explicit view of the total and per capita footprints of Charlottesville, Albemarle, and UVA. The spatially explicit view allows for users to evaluate the GHG, N, and P footprints on a more granular basis than a whole county level so differences in total and per capita footprints can easily be visible.

To determine the relationship between the three footprints, a linear regression and residuals analysis was performed. This was done for each unique combination of the three total footprints by BG. The R^2 value was calculated to determine the significance of the relationship between each of the footprints.

B. Evaluating synergies between the N, GHG, and P footprints reduction scenarios

The next step in answering the research questions is to evaluate the synergies or trade-offs among reduction strategies on the three footprints. Doing so presents a practical use of the proposed tool. First, the current climate action strategies and goals set by Charlottesville, Albemarle, and UVA were evaluated. Each jurisdiction has committed to certain reduction goals for GHGs but are at different stages of evaluating their baseline years and writing action plans to reach these goals. Charlottesville set a reduction target of 45% by 2030 based on 2008 emissions and has a goal of carbon neutrality by 2050 (Climate Action Plan, 2022). Charlottesville has calculated its GHG footprint for 2017, 2018, and 2019 and is in the process of calculating 2021. In September 2022, Charlottesville completed its revised climate action plan (Climate Action Plan, 2022). In this work, the strategies listed in Stanganelli (2020) are used to evaluate potential footprint reduction strategies for Charlottesville.

Albemarle has recently set a GHG footprint reduction goal of 45% by 2030 based on 2008 levels and carbon neutrality by 2050 and has several strategies with metrics listed in Phase 1 of their Climate Action Plan (Climate Action Plan, 2020).

UVA is objectively the farthest along in their Climate Action Planning. UVA set its first goal of reducing GHG emissions by 25% by 2025 from 2010 levels. In 2019 the university set an additional goal of carbon neutrality by 2030 and net zero emissions by 2050. UVA has a detailed action plan to go along with the 2025 goal and is in the process of creating a plan to reach the 2030 goals (UVA Greenhouse Gas Action Plan, 2018).

The only entity that has set a nitrogen footprint reduction goal is UVA (UVA, Nitrogen Action Plan 2019). No jurisdiction has set a P footprint reduction goal. However, UVA has calculated their baseline P footprint for 2016 using the Integrated Environmental Footprint Tool (IEFT) (Dukes et al., in review). UVA also has several other sustainability-focused goals which could impact the C, N, and P footprints. These include goals listed in the 2030 Sustainability Plan Goals such as reducing waste by 30%, increasing sustainable food by 30%, and reducing water use by 30% (Plans and Progress, 2021). Through this chapter, the published plans and additional pertinent strategies were evaluated within the integrated community footprint tool.

Secondly, additional strategies were created as part of this study that extended beyond the strategies listed in published action plans by the three entities. These strategies aimed to be ambitious, mutually beneficial strategies to reduce all three footprints across all entities at once. For example, replacing 30% of meat-based restaurant meals with vegetarian meals across the three jurisdictions.

i. Climate Action Plans and Goals

The integrated tool was used to determine the impact of some of the planned sustainability-focused strategies on the three footprints (C, N, P). Several strategies to reduce GHG and N footprints have been proposed within all three entities. Currently, all the entities have sustainability goals and action plans in place. These goals are:

- UVA:
    - Carbon neutral by 2030
    - Fossil fuel free by 2050
    - Reduce nitrogen (N) footprint by 30% by 2030 (based on 2010 baseline)
    - Reduce water use by 30% by 2030 (based on 2010 baseline)
    - Reduce waste footprint by 30% by 2030 (based on 2010 baseline)
    - Increase sustainable food purchases by 30% by 2030 relative to 2010 levels
- Charlottesville
    - Reduce GHG emissions by 45% by 2030 based on 2011 emissions
    - Carbon neutrality by 2050

- Albemarle
    - Reduce GHG emissions by 45% based on 2008 levels by 2030
    - Carbon neutrality by 2050

This research evaluates the impact of the planned changes made to operations at the city, county, and university levels. These strategies are either in the published action plans (UVA Greenhouse Gas Action Plan, 2019; UVA Nitrogen Action Plan, 2019; Albemarle Climate Action Plan, 2020) or, in the case of Charlottesville, have been suggested in recent work (Stanganelli, 2020). The goal of this work is to inform the city, county, and university of how an evaluation of numerous strategies could be on their and other jurisdictions' respective footprints and what the impact (Table 1).

ii. Additional proposed scenarios to reduce the C, N, and P footprint

In addition to the entity-generated strategies listed above, this work analyzes other potential reduction scenarios not included within these action plans. These scenarios will be applied to all three entities rather than the specific entities listed above. The suggested strategies focus more on scope 3 reductions which are highly dependent on consumer choices rather than strategies often regulated by governments or boards. These include reductions in meat consumption and changes in agricultural practices. These are listed alongside the reduction strategies proposed for each jurisdiction (Table 3.3).

Table 3.3: *Strategies for footprint reduction. The strategies listed are sourced from either UVA Greenhouse Gas or Nitrogen Action Plans, Albemarle Climate Action Plans, or Stanganelli (2020), or are strategies specifically for this research on reductions driven by consumer choice. These strategies will be run on certain entities depending on applicability.*

Number	Strategy	Source	Jurisdiction(s)
1	UVA Moves to 100% Solar	UVA greenhouse gas action plan (in progress)	UVA
2	Replace 80% on-ground heat plant with natural gas	UVA greenhouse gas and nitrogen action plans	UVA
3	10% of Charlottesville and Albemarle powered by solar	Stanganelli, 2020, Albemarle Climate Action Plan.	Albemarle and Charlottesville
4	50% of Charlottesville and Albemarle powered by Solar	Stanganelli, 2020.	Albemarle and Charlottesville
5	Replace 10% of natural gas with renewables	Stanganelli, 2020	Charlottesville, Albemarle
6	Improved energy efficiency in 10% of low-income housing	Albemarle Climate Action Plan	Albemarle
7	Replace 10% passenger cars and buses with electric	Stanganelli, 2020 and Albemarle Climate Action Plan	Charlottesville, Albemarle
8	Reuse 50% of cow and chicken manure in replacement of fertilizer	Original Scenario	Albemarle
9	Improve 100% of septic systems to advanced septic treatment	Original Scenario	Albemarle
10	15% increase in vegetarian meals served	Variation of UVA's Nitrogen Action Plan	UVA, Albemarle, Charlottesville
11	50% Beef Replaced with Vegetarian at UVA	Variation of UVA's Nitrogen Action Plan	UVA
12	30% reduction in food waste	Original Scenario	UVA, Albemarle, Charlottesville

13	30% Vegetarian Meals served at restaurants	Original Scenario	Albemarle, Charlottesville
14	Recommended weekly amount of beef consumed (0.35 two times a week)	Original Scenario	Albemarle, Charlottesville, UVA
15	Combined scenarios 1, 2, 4, 5,6,7,8,9,11,12,13,14	Original Scenario	Albemarle, Charlottesville, UVA

More information on how each of these strategies were calculated can be found in the Appendix Chapter 3, section 1. There was a potential that some of the strategies applied in the broader Charlottesville and Albemarle communities will have a spill-over effect and enhance the sustainability of UVA or vice versa. There are some potential implications to these spill-over effects. For example, if UVA purchases off-site solar to offset their footprints, there electricity grid will be improved for not only UVA but for the entire energy grid.

3. Results

A. GHG Footprint

The total GHG footprint for Albemarle was 2.47 million MTeCO$_2$, Charlottesville was 1.33 million and UVA was 0.288 million MTeCO$_2$. The per capita GHG footprint for Albemarle was 25.8 MTeCO$_2$, Charlottesville was 25.9 MTeCO$_2$, and UVA was 11.8 MTeCO$_2$. The term "full-time equivalent" refers to the calculated number of students, faculty, and staff that translates to number of individuals working (40 hours per week) or studying (15 credit hours per semester). Using this metric rather than per capita for an institution make all university users (students, faculty, staff) comparable although each may work or study different hours. In the next sections, per capita for UVA equates to per FTE. The footprints of the BGs ranged from 460,000 MTeCO$_2$ to 3,800 MTeCO$_2$ with the largest drivers being natural gas and electricity (Figure 3.1). Per area figures can be found in Appendix A3.4.

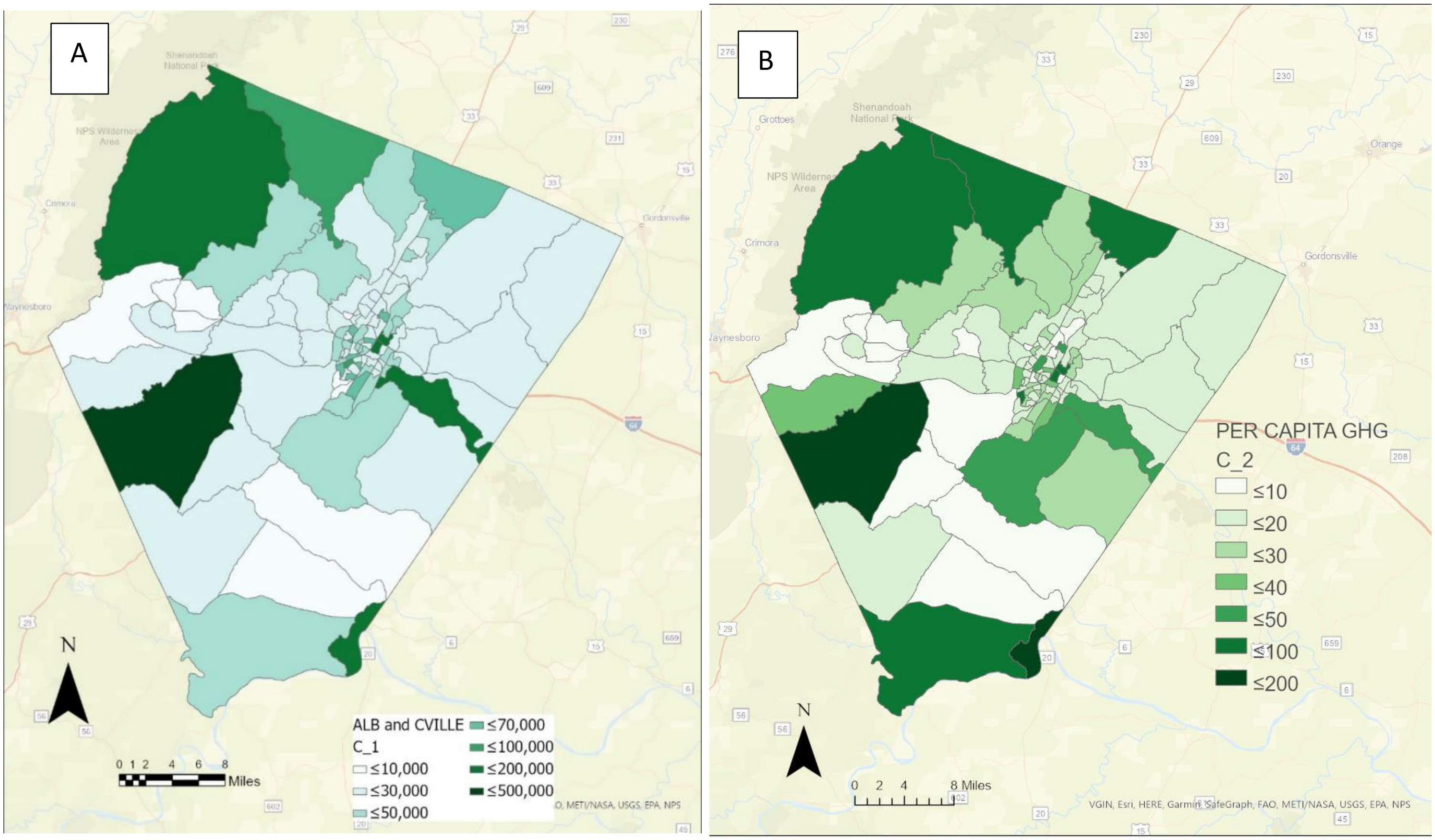


Figure 3.1: *The total GHG footprint of BGs within Charlottesville and Albemarle (A) and the per capita GHG footprint of BGs within Charlottesville and Albemarle (B). Darker green indicates higher footprints. The range begins at 10,000 MTeCO*$_2$ *and increases in increments of 20,000 until 70,000 where it increases to 100,000 (2 cases), 200,000 (4 cases), and 500,000 (1 case) in order to capture all BGs within the city and county for the total GHG footprint (A).*

B. Phosphorus Footprint

The total P footprint for Albemarle was 1,990 MT P, Charlottesville was 354 MT P, and UVA was 29 MT P. The per capita P footprint for Albemarle was 18.4 kg P Charlottesville was 7.6 kg P, and UVA was 1.1 kg P. The BGs ranged from 87 MT P to 4 MT P with the largest driver being food purchased (Figure 3.2). Per area Figures can be found in Figure A3.5.

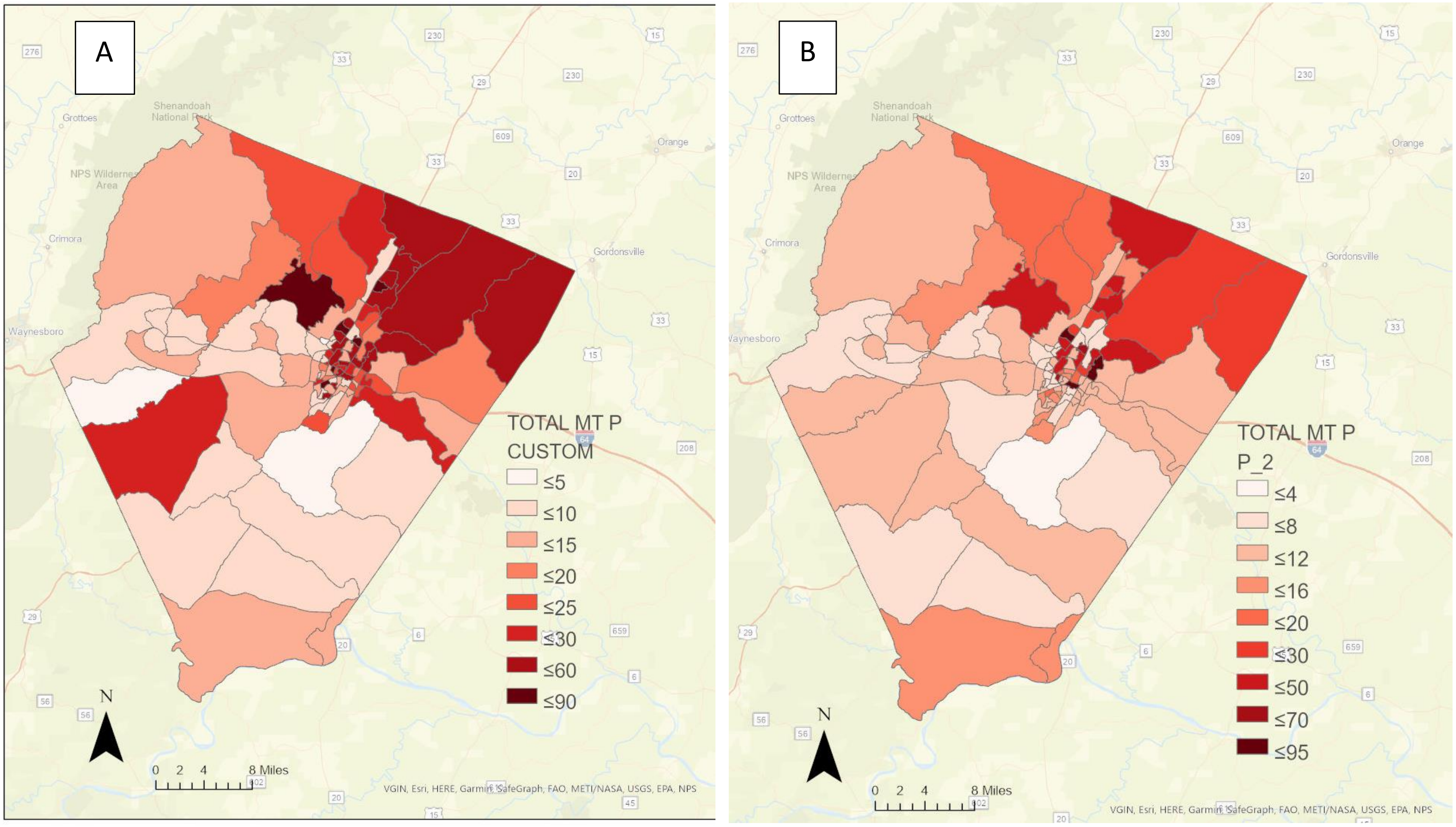


Figure 3.2: *The total (MT P) (A) and per capita (kg P) (B) phosphorus footprints of BGs in Albemarle and Charlottesville. The total footprint of BGs ranges from 5 to 30 MT P, counting in increments of 5 MT P. The figure then counts in increments of 30 until 90 to capture the remaining BGs far above average footprints (A). The per capita footprint ranges from 4 to 20 kg P, counting by increments of 4 kg P. The figure then counts in increments of 20 kg P to capture the remaining, high per capita P footprints (B).*

C. Nitrogen Footprint

To revisit from Chapter 2, in 2017, the total N footprint for Albemarle was 8,340 MT N, Charlottesville was 1,580 and UVA was 212 MT N. The per capita N footprint for Albemarle was 77 kg N, Charlottesville was 34 kg N, and UVA was 7.0 kg N. The BGs ranged from 362 MT N to 15 MT N with the largest driver being food purchased (Chapter 2, Figure 2.4)

D. Synergies in the three footprints

A linear regression analysis was completed to determine the relationship between the three footprints. All three footprints produced a significant correlation with each other with N and P having the strongest correlation and GHG and P having the smallest correlation. The N and P footprints had a significant correlation with a P-value 8.12e-21 and an R-squared value of 0.98 for both Charlottesville and Albemarle Footprints (Figure 3.3). Residual analysis presented in Figure A3.1.

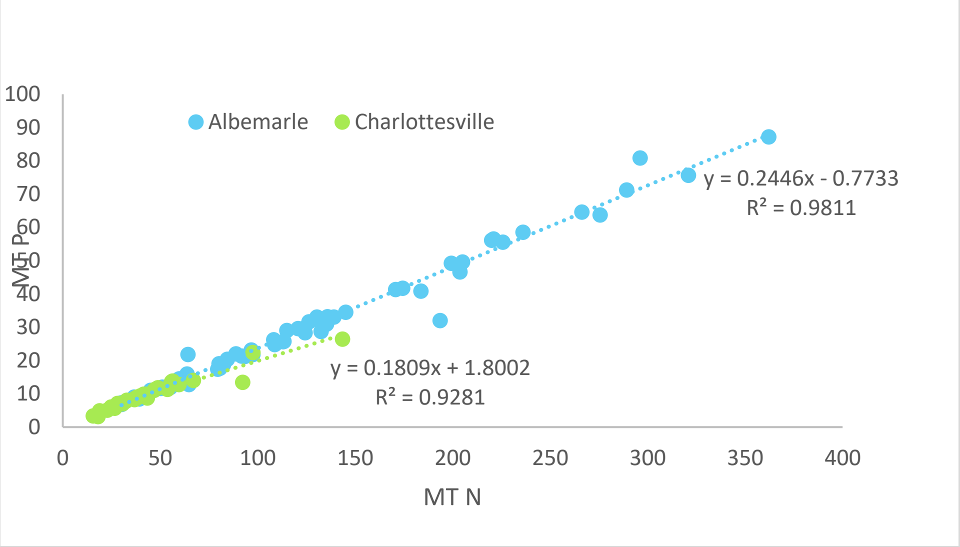


Figure 3.3: *The relationship between nitrogen (N) and phosphorus (P) footprints by census block group. Each point represents a census block group. Green points represent Charlottesville BGs and blue represent Albemarle BGs. The R-squared value is 0.98 for both the Charlottesville and Albemarle regressions. UVA is included within the Albemarle and Charlottesville BGs and is not included separately.*

The N and GHG footprints did have a significant correlation when Charlottesville and Albemarle were evaluated together (4.92e-12). However, when evaluated separately, the GHG and N footprint for Charlottesville seemed to show a better fit with the linear regression model with an R-squared value of 0.62. One item to note is how the linear regression was driven by two outliers with high GHG footprints. These two high outliers represented 1) where high energy use UVA buildings were present and 2) where a large number of businesses were present.

When these two BGs were removed, the R-squared value for Charlottesville dropped to 0.07 (Figure 3.4). Residual analysis presented in Figure A3.2.

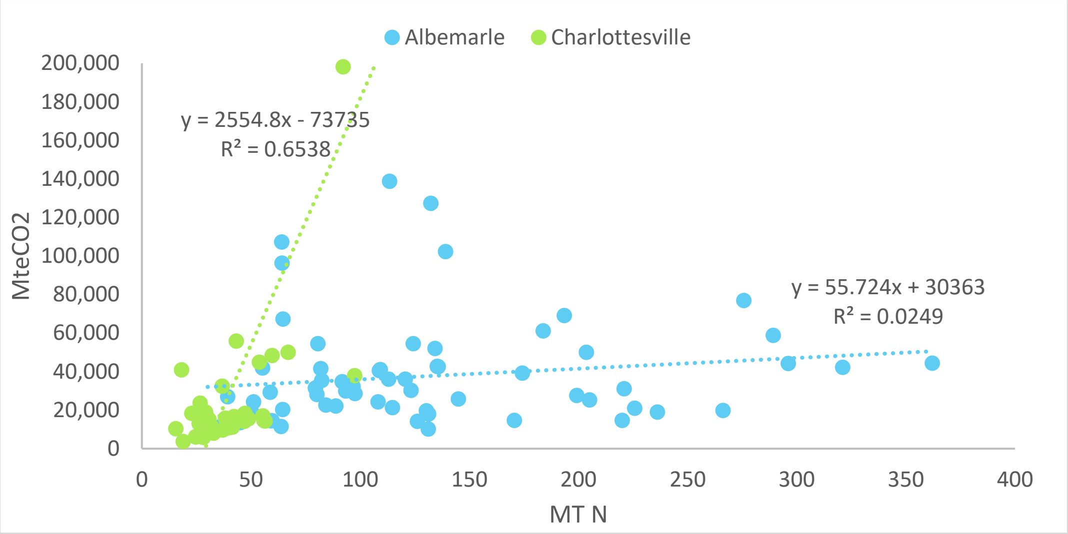


Figure 3.4: *The relationship between greenhouse gas (GHG) and nitrogen (N) footprints by census block group. Each point represents a census block group. Green points represent Charlottesville BGs and blue represent Albemarle BGs. The R-squared value for Charlottesville was 0.62. The R-squared value for Albemarle was 0.03. UVA is included within the Albemarle and Charlottesville BGs and is not included separately.*

The P and GHG footprints did have a significant correlation when Charlottesville and Albemarle were evaluated together (P-value of 4.5e-12). However, when evaluated separately, the GHG and P footprint for Charlottesville seemed to show a better fit with the linear regression model with an R-squared value of 0.44. One item to note is how the linear regression was driven by two outliers with high GHG footprints. When these two BGs were removed, the R-squared value for Charlottesville dropped to 0.05 (Figure 3.5). Residual analysis presented in Figure A3.3.

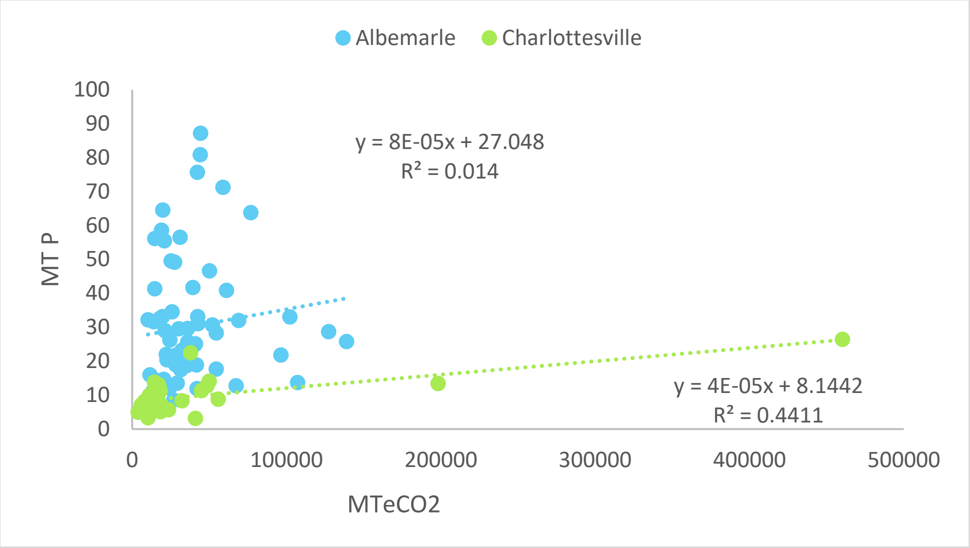


Figure 3.5: *The relationship between greenhouse gas (GHG) and phosphorus (P) footprints by census block group. Each point represents a census block group. Green points represent Charlottesville BGs and blue represent Albemarle BGs. The R-squared value is 0.0427. UVA is included within the Albemarle and Charlottesville BGs and is not included separately.*

N and P footprint tracked relatively well as both main drivers were food purchased and agriculture. The N and GHG footprints had a higher correlation than GHG and P as there was some overlap in the energy sectors in both footprints. The relationship between P and GHG footprints was not significant as the large sectors in each footprint do not overlap (Figure 3.6).

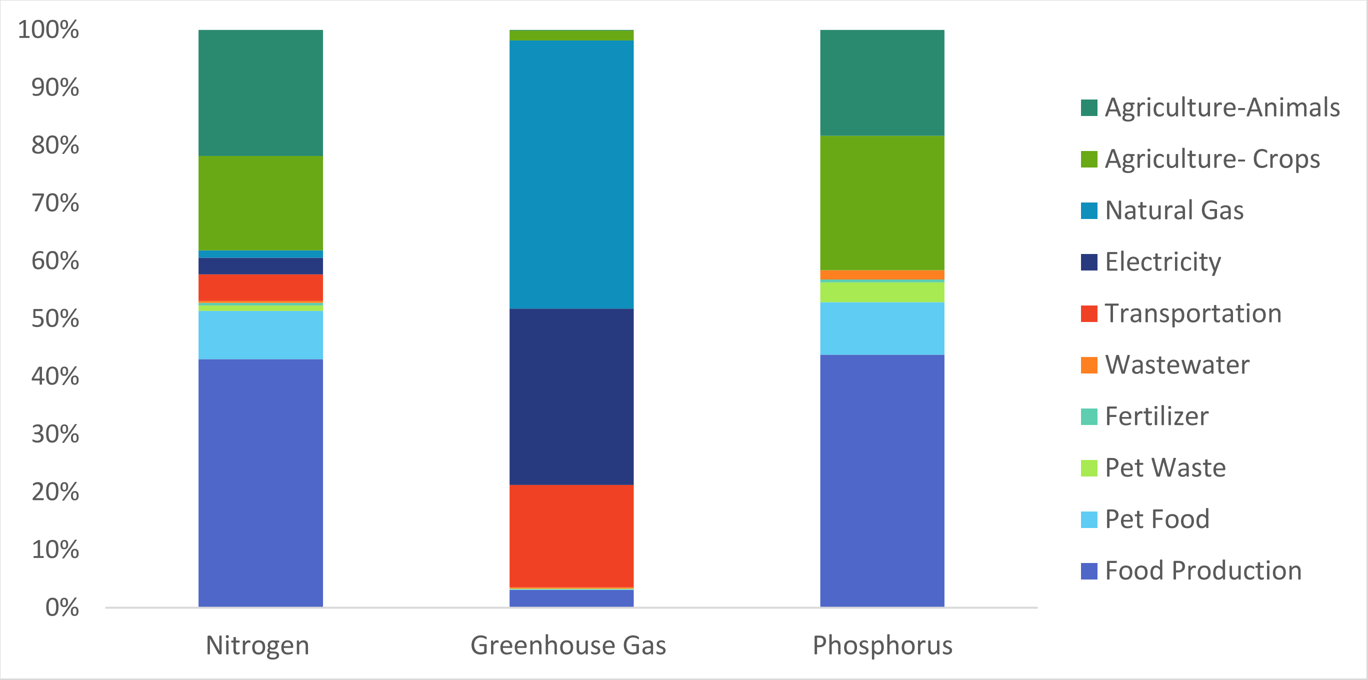
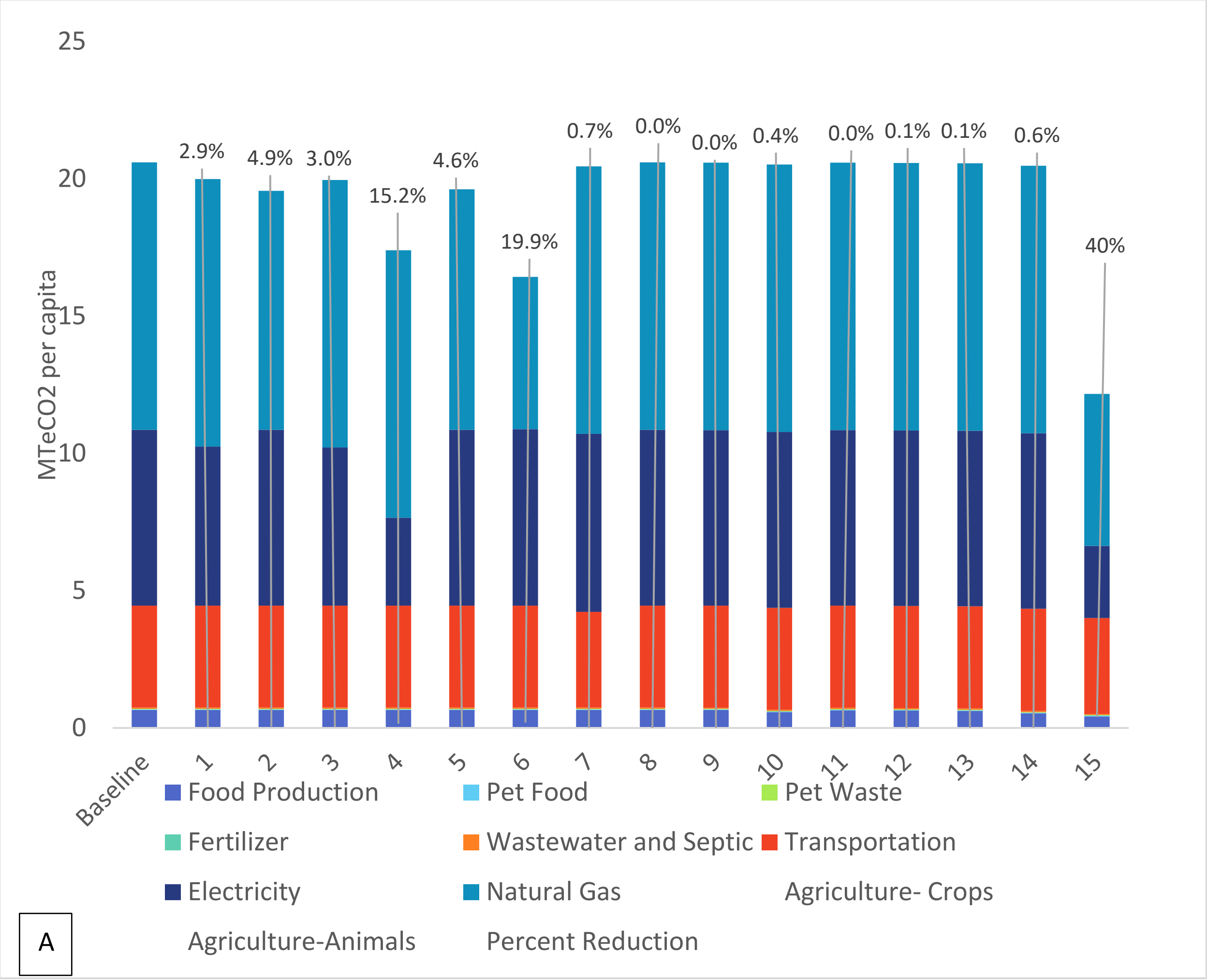


Figure 3.6: *The percent composition of each of the three footprints (N, GHG, and P) by category. The percent composition shows the drivers which influence the footprint. N and P are largely driven by food purchased and agriculture while GHGs are largely driven by electricity and on-site natural gas use.*

E. Scenario Analysis

Each of the scenarios listed in table 3.1 were analyzed and the footprint reduction from each of the three footprints were calculated from the baseline year of 2017. The largest N footprint reduction came from scenario 8, reuse 50% of manure as fertilizer (table 3.1) with a 6.5% reduction, for GHGs scenario 6, improve energy efficiency of low-income houses (table 3.1), with a 19.8% reduction, and for P scenario 8, reuse 50% of manure as fertilizer (table 3.1) with a 5.3% reduction (Figure 3.7a-c). Each scenario implemented either decreased or did not change the other footprints. Scenarios 1-7 had no impact on the phosphorus footprint as energy production has a limited P footprint.


25
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MTeCO2 per capita
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0.0%
0.4%
0.0%
0.1%
0.1%
0.6%
40%
Baseline
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3
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5
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Food Production
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Wastewater and Septic
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Electricity
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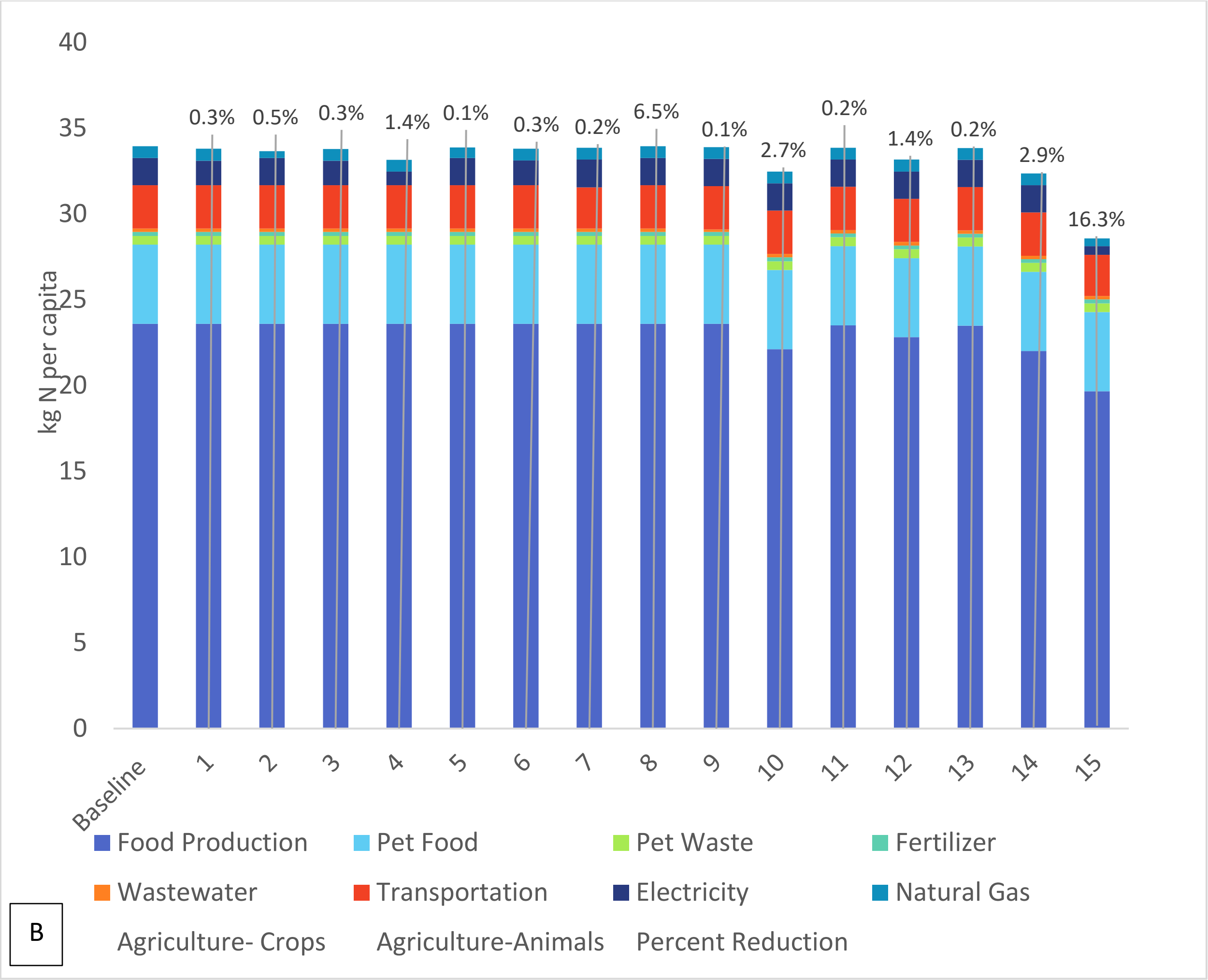
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Baseline
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Food Production
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Pet Waste
Fertilizer
Wastewater
Transportation
Electricity
Natural Gas
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Agriculture-Animals
Percent Reduction
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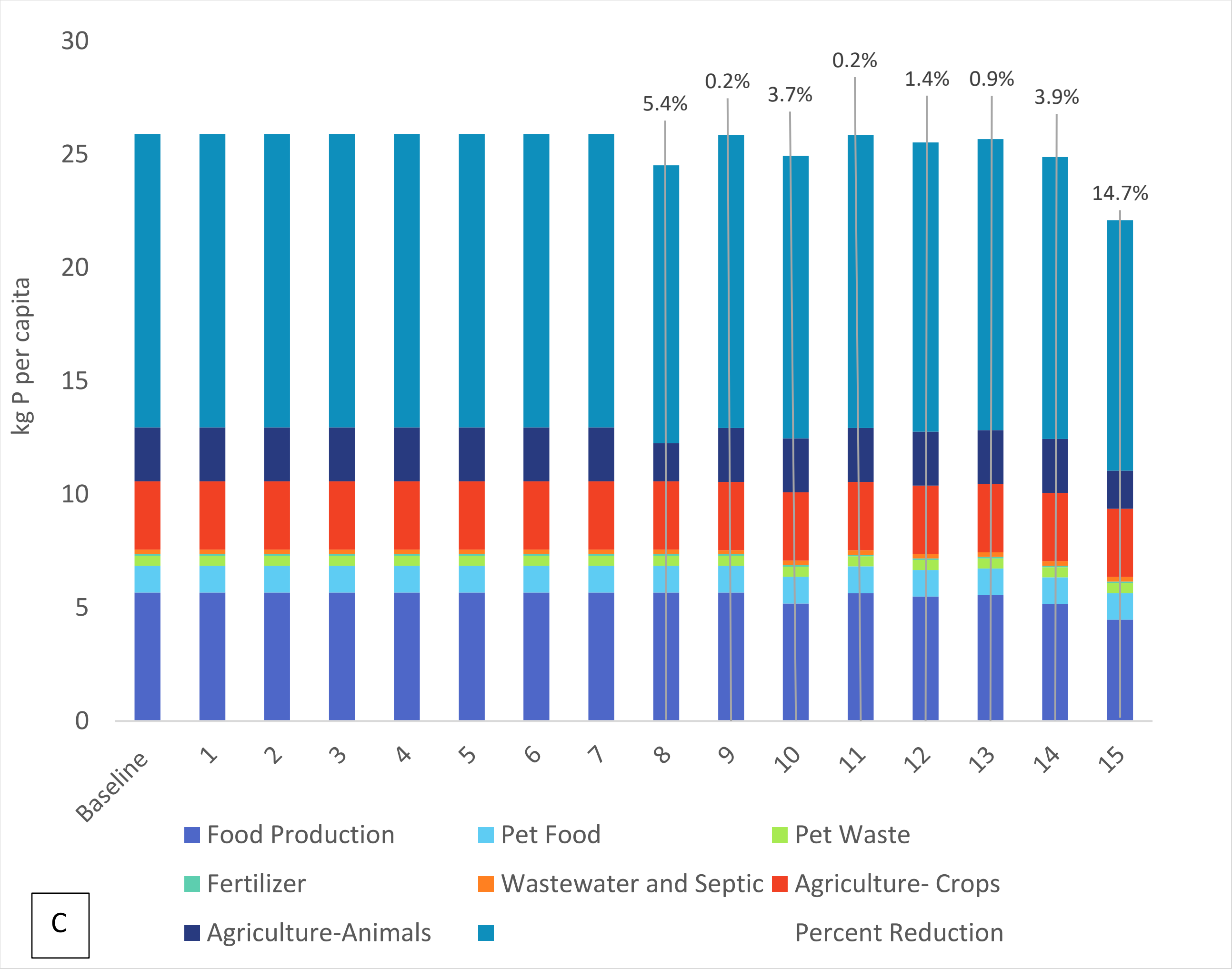

Figure 3.7a-c: *The impact of scenarios listed in table 1 on the three footprints; GHG (A), N (B), and P (C). The stacked bar graphs show the impact of each scenario by sector. The percent listed above the bars indicate the percent reduction in the total footprint of all three entities on the 2017 GHG, N, and P footprints. Scenario #15 combines all possible scenarios to determine how low each footprint could go with these potential scenarios implemented.*

4. Discussion

A. Comparing the GHG, N, and P footprints

This study provides the first spatially explicit analysis of the N, P, and GHG footprints of Albemarle, Charlottesville, and UVA. The spatially explicit aspect of these footprints shows locations and drivers of where total and per capita footprints are high. These types of data are important as stakeholders work to determine the locations where certain strategies would be most effective. For example, areas with a high transportation footprint it would be most effective to add public transportation routes. These types of analysis can also help view where public education is most needed. Areas with high per capita beef consumption may benefit from non-profit health or environmental groups public information sessions.

There were several reduction relationships seen among the three footprints. The strongest relationships were between N and P because both are highly tied to food purchased and agriculture and are two of the main nutrients applied to crops and feed. Since these nutrients are so closely tied, oftentimes BGs with high N footprints also had high P footprints, mainly due to food purchased and agriculture. BGs where animal and crop agriculture were present had significantly higher per capita footprints than those that did not. GHG and N footprints had some relationship and when the GHG footprint was high, the N footprint was also high in that category. For example, BG with many passenger car kilometers traveled had a high GHG footprint and a higher-than-average transportation N footprint. However, this was often not high enough to be the main component of the N footprint. The GHG and P footprints are unrelated except by some small overlap in purchased and agriculture. Still, food purchased only makes up ~5-15% of a GHG footprint while it makes up more than 50% of a BGs P footprint. This is likely why the relationship between the GHG, and P footprints was less strong than between N and GHG.

B. Importance of integrating the tools and potential outcomes

This work is timely in nature, as each jurisdiction is working on either revising or beginning to implement these climate strategies. In December of 2019, UVA set several new ambitious goals to meet by 2030 and 2050 and is in the process of writing action plans to meet these goals. Charlottesville has a proposed goal of a 45% GHG reduction by 2045 and is in the writing phase of a new action plan. Albemarle has a reduction goal of 45% GHG reduction but is not on track to meet it (Wrabel, 2021).

UVA is a large institution and employer spread throughout the county and city. However, the impact of the institution’s footprint itself is relatively small compared to both the city and county (7% of GHG, 2% of N, and 1% of P). However, the university brings student, faculty, and staff residents to the city and county. The footprints of these residents are included within the city and county footprints and are not captured in UVA's footprint. Being cognizant of this, the university can have a broader impact than on their grounds by educating students, staff, and faculty how their consumptive patterns could influence their community.

As each entity is working towards their environmental sustainability goals, it is important to know the impact their planned strategies and potential scenarios will have on intersecting jurisdictions' footprints. The three entities are already working together to combat climate change (Climate Action Together 2019). Currently, there are no plans outlined to create or evaluate strategies together. With this work, there is now a tool available and a framework of how strategies could be evaluated for interested groups to use to better collaborate to meet climate goals. Additional strategies and possible next steps are discussed in section E of this discussion.

C. Exploring the Scenarios Listed

The scenarios run here are a sample of the types of analysis the city, county, and UVA could use this integrated tool for. All scenarios showed either a co-benefit or neutral impact on the other footprint. However, there were some scenarios that had larger impacts on some footprints than others.

For energy scenarios, there were several which had the highest co-benefits between GHGs and N. As mentioned earlier, energy reductions do not have an impact on the P footprint so there was no change in the P footprint with the implementation of any energy or transportation related scenario. For GHGs and N, scenario 4 (transitioning to 50% additional solar sourcing in the city and county's electricity grid) reduced the N footprint by 1.4% and the GHG footprint by 15.9% (table 3.1). However, improving low-income housing energy efficiency reduced the GHG footprint the most (19.8%) by only reduced the N footprint by 0.3% (Scenario 7). This is something city sustainability or planning offices could consider when determining which energy scenarios to choose. There are equity issues also associated with this scenario. Improving low-income housing energy efficiency would reduce financial burdens of individuals in need of assistance by up to 25% (Office of Energy Efficiency and Renewable Energy).

In the food sector, all three footprints (GHG, N, and P) are impacted. GHG footprints are the least impacted by these scenarios but foods that are often high in N and P are also high in

GHGs. All foods scenarios run reduced the three footprints simultaneously. The food scenario that produced the highest impact for all three footprints was residents eating at the recommended daily value of beef consumption of 0.35 ounces twice a week. This reduced the GHG footprint by 0.6%, the N footprint by 2.9%, and the P footprint by 3.4%. This scenario both reduced the beef consumption to recommended daily value levels in over-consuming BGs and increased the beef consumption of individuals in under-consuming BGs. The goal of this was to ensure the nutritional needs of each BG were being meet. Even with the increase in some BGs beef consumption, this was still the scenario which had the largest N footprint reduction.

It is important to note the differences between energy footprints and food footprints. With energy production, emissions can fall to zero. This is due to the technologies that make renewable energy sources possible. Institutions, cities, and counties have set “net zero” carbon or GHG goals. These goals often neglect the food piece of the equation. Food GHG, N, and P footprints are present whenever food is grown. N and P are needed for animal and plant life and N is a part of protein composition. There is a current body of research working to determine the most nitrogen and phosphorus efficient agricultural practices (Lassaletta et al., 2014; Chen et al., 2020; Chowdhury et al., 2021). There is also research working to determine the potential for sequestering GHGs in crop production. Some of these practices claim to have a net-zero carbon footprint and in some cases a negative carbon footprint (Rhodes et al., 2017). However, there has been some pushback suggesting the feasibility and environmental benefits may not be as impressive as once thought (Gosnell et al., 2019).

Agriculture was also a sector which had a high N and P footprints. The highest N and P footprint reduction scenarios was scenario 8 (reusing 50% of chicken and cow manure in the county on fields) (Table 3.1). This scenario reduced the N footprint by 6.5% and the P footprint by 5.4% and the GHG footprint by only 0.03%. This scenario is only applicable in Albemarle as there is only agriculture within the county. Other scenarios such as improving septic treatment would also only apply to the county. However, the spillover effects of less N and P pollution in streams could be seen in the city. These types of considerations are beyond the reach of the current tool but could be a future addition to help with scenario analysis.

D. Feasibility of these scenarios

Some of the scenarios listed are derived directly from the city, county and university action plans (e.g., scenarios 1, 2, 3, 6, and 7) (table 3.1). Of these scenarios, the biggest reduction for N and GHGs are seen when low-income housing energy efficiency is improved. There are some items to consider when reviewing this scenario. The method of calculation used assumes a distribution of energy use to be equal among the BG based on dollars spent in the BG on electricity. The low-income energy efficiency is based off the percent of individuals within the BG that are living below the poverty level which is between 2%-35% of people within each BG. This may cause there to be an overestimate of the total amount of energy used in the BGs. Since the electricity use is based on the average BG resident's use, an 800 square foot home and a 3,000 square foot home are assumed to both use the same "average" energy use for their BG. If lower income families are living in some of these smaller homes, there baseline energy use could be incorrectly inflated.

These scenarios directly listed within the action plans are assumed to be feasible as each entity has shared these goals directly. Some scenarios are variations or additions to the current published action plans which include scenarios 4, 5, 10, and 11. These scenarios are either original scenarios or from Stanganelli (2020) which is based off discussion on what to include in the Charlottesville Climate Action Plan. Some of these scenarios (table 3.1 scenarios 1-6) are a top-down approach such as switching utility energy sourcing such as moving to 100% solar electricity grid. Others are bottom-up scenarios, relying on consumer choices (table 3.1 scenarios 7-14). These bottom-up scenarios are much more difficult to implement, especially in a city or county setting. Mandating increased purchases of vegetarian options and decreasing meat options is more than likely impossible. This change would require education and buy-in from the public to succeed. At a university, menus on-grounds could be changed without consult of the students. However, this could dissuade students from eating at this location on-grounds and to choose a higher N footprint meal at another location.

Scenarios 8, 9, 12, 13 and 14 that are original to this work and were for the purposes of examining how low each footprint could go. These included scenarios focused on consumer habit changes such as eating the recommended daily values of beef and increasing restaurant meal choices by 30%. This would require education and consumer-acceptance. This could be more feasible if it was attached to health data. Providing information at health clinics or in university courses about the health and environmental benefits of eating less beef has been shown to be beneficial for both causes (Maibach et al., 2008). Other scenarios require a change in both consumer and producer choices. Scenario 8 involves reusing manure from local farms on crops. This would require a large shift in the current infrastructure of farming in the county. Currently, only about 5% of manure nationally is used as fertilizer (Manure Use for Fertilization and Energy Use, 2009). This is in part due to the difficulty it is to collect the manure, ensure it has the correct ratio of nutrients that plants need, and ensure it is safe for application. There have been systems proposed to make this idea of a circular agricultural system work, but it has yet to be successful, likely in part due to the ease of continuing within the framework of existing systems (Macura et al., 2019). Scenario 9 on improving to the highest level of septic treatment could be done with a combination of both consumer and manufacture choices. The latter could improve upon their current septic tank systems and phase out less efficient tanks and consumers could invest in higher technology tanks and regularly check to ensure their existing tanks are fully functional.

E. Next Steps for this Analysis

One essential piece of work needed to make the tool useful is involvement of stakeholders. Over the course of the work, several stakeholders from the planning departments in Charlottesville and Albemarle were involved. These stakeholders found the project interesting and shared data readily. Sharing this tool with stakeholders is vital to determining its applicability and potential for future use. Certain groups of stakeholders can use the tool for different purposes. City planners or sustainability offices can use the tool to evaluate the co-benefits of certain plans on sustainability metrics. Consumers can use the tool to identify what general categories are highest in their BGs and which they can reduce. Producers like farmers and business owners can use the tool to determine how best to enhance the sustainability of their community to produce a sustainable product. The tool can be shared with collaborative efforts such as the Climate Action Together initiative to enhance efforts to improve environmental sustainability.

Additional analysis for future work could be to add more footprint indicators like the water footprint (Natyzak et al., 2017). Adding damage costs for N and GHGs would also give an idea as to what damages are occurring due to the city, county, and universities resource use and which sectors these fall in to (Sobota et al., 2014; Compton et al., 2017). Evaluating the relationship between income and poverty level would determine if cities and counties with universities are consistent with other studies and across N and P footprints (Dukes et al., 2020). This piece could enhance the equity discussions already present in our community. Using this data alongside other spatially explicit environmental emissions data such as NO_x emission data would further enhance studies to determine whether consumers with high footprints are feeling the effects of their choices (Demetillo et al., 2020). The tool could also add metrics to assess costs to the city and therefore constituents of implementing each program alongside the metrics to measure which makes the most sense.

5. Conclusion

This study presents a combined greenhouse gas (GHG), nitrogen (N), and phosphorus (P) footprint calculator for three entities: Albemarle, Charlottesville, and UVA. The tool is intended to help jurisdictions evaluate the co-benefits and tradeoffs of strategies to reduce environmental impact. The study gives examples of 14 unique scenarios derived from either city, county, or university Climate Action Plans or original scenarios to evaluate the co-benefits of these scenarios. All scenarios evaluated here showed either a neutral impact or co-benefits with all three footprints. Some scenarios showed higher co-benefits than others depending on the footprint. In general, the N and P footprints were significantly correlated while N and GHG and GHG and P were not. This was not unexpected as the two main drivers of the N and P footprints is food purchased and agriculture while natural gas and electricity are dominant in the GHG footprint. Ultimately this tool can be used by stakeholders in cities and counties to evaluate strategies and make informed decisions about community sustainability.

Chapter 4

Assessing the applicability, limitations, and future additions to the combined C, N, and P footprint tool for communities

1. Overview and Summary of Findings

The intent of this work was to answer the research questions:

1. What is the spatially defined N footprint of the integrated UVA, Charlottesville, and Albemarle community?
2. What are the integrated C, N, and P footprints and what actions can be taken to decrease footprints in the three jurisdictions?
    a. What is the impact of existing sustainability goals on the combined footprints of each jurisdiction?
    b. What additional strategies can be explored to reduce all three footprints simultaneously?

Chapter 1 introduced the research questions and explored some recent published work as well as work done specifically at UVA to give a basis of what research would be used to begin to answer these questions.

Chapter 2 addressed the first question. The chapter walked through how previously collected data for UVA (UVA Nitrogen Action Plan, 2019) and Charlottesville (Stanganelli, 2020) were integrated with newly collected data from Albemarle. The chapter also outlined the additional sectors added to Dukes et al. (2020) to include important N losses from a county with septic systems, airports, a university, and crop and animal agriculture. This chapter showed the importance of including these aspects to a rural community N footprint, especially agriculture. In Albemarle, the average per capita N footprint of residents in the county jumped from 40 kg N per year to 77 kg N per capita per year. This was driven by agriculture as crop (9%) and animal agriculture (11%) made up 20% of the total footprint of the county. The average per capita Charlottesville residents increased from 32 kg N per capita to 34 kg N per capita due largely to the inclusion of UVA to the footprint. This chapter set the basis for the analysis of additional footprints and scenarios in chapter 3.

Chapter 3 answered the second question. Using inventory data established in chapter 2, Chapter 3 took the analysis beyond N and calculated both the GHG and P footprints of the city, county, and university. The per capita GHG footprint for Albemarle was 25.8 MTeCO_2, Charlottesville was 25.9 MTeCO_2, UVA was 11.8 MTeCO_2. The per capita P footprint for Albemarle was 18.4 kg P, for Charlottesville was 7.6 kg P, and UVA was 1.1kg P. The N and P footprints were found to be statistically significantly related while GHG and N, and GHG and P were not. This was expected as the N and P footprints are driven by agriculture and food product while the GHG footprint is driven by energy use. Scenarios from the Albemarle Climate Action Plan (2021), UVA Greenhouse Gas Action Plan (2018) and Nitrogen Action Plan (2019), and Stanganelli (2020) were used to base scenarios for potential footprint reduction. All reduction scenarios showed co-benefits with other footprints except for energy scenarios which did not have an impact on the P footprint. The highest reductions for each footprint were reusing 50% of cow and chicken manure as fertilizer for N and P and improving low-income housing energy efficiency for GHGs. There were strategies which had greater co-benefits for all footprints than others. These included improving low-income energy efficiency for GHG and N and individuals consuming the recommended daily value of beef for GHG, N, and P. If all scenarios were run for all three footprints, reductions of 16% for N, 21% for GHGs, and 15% for P could be seen. Running these scenarios in conjunction and advise a community of the co-benefits and trade-offs if there are any of running certain scenarios over others.

2. How this tool can be used

As mentioned in previous chapters, this work comes at a timely moment. In 2019 Charlottesville, Albemarle, and UVA recently resolved to work together to achieve climate solutions in their Climate Action Together initiative. The stated goals of this group are to “work in parallel on specific goals and collaboratively work build up each other’s work” (Climate Action Together, 2019). In order to adequately fulfill this goal, the interactions between the three entities footprints should be explored. This work shows not only how the three entities’ GHG footprints interact, but also how strategies proposed could have an impact on other goals.

For example, strategies that involve reducing energy use will have an impact on the N footprint of each entity. This is especially important for UVA as there are numerous sustainability goals including an N footprint reduction and a nutrient load reduction target which would encapsulate P, for 2030 set in place (Great and Good University, 2019). Using the tool proposed here to run strategies planned for Charlottesville, Albemarle, and UVA would be beneficial to stakeholders as they are able to see the intent and unintended tradeoffs and synergies. These analyses could help by directing what types of scenarios would be most beneficial with limited resources. For example, improving the energy efficiency of low-income homes would be highly beneficial in both reducing the GHG footprint of the city and county as well as likely improving the financial well-being of residents. However, there is financial cost to the governing agencies which could be incorporated. For example, UVA choosing to upgrade building energy efficiency would have an upfront cost but could eventually save the university money as less energy use is needed. An example of this was in Clark Hall at UVA. The university invested in energy efficiency technologies such as LED lights, upgrades to energy recovery systems, and new heating and cooling systems reduced operating costs by two-thirds (Kelly, 2018). Other scenarios such as those focused on reducing the amount higher footprint food purchased could be targeted to certain high-meat consuming BGs with the spatial component of this tool. It would be ineffective to advise on eating less meat in BGs not able to eat to nutritional needs.

Ideally, this tool could be shared with city, county, and university stakeholders to receive feedback and be modified to make appropriate changes. These stakeholders should at least include sustainability director at UVA and the city and county climate protection program managers. For this project, the individuals in these positions were: UVA sustainability director Andrea Trimble, county planners Gabe Dayle and Andrew Lowe (Climate Protection Program Manager), and city planner Susan Elliott (Climate Protection Program Manager). Over the course of this work, data were gathered from these stakeholders and their teams. Aligning these footprints with additional metrics that are of concern by stakeholders such as total maximum daily load requirements (TMDLs) or air quality metrics could further advance the usefulness of this tool.

3. Review of limitations of datasets

In an ideal world, all the data needed to produce an accurate footprint for each entity and each sector would have been available however, this was often not the case. In this section, I will review the datasets used and methods of splitting up data and what ideal datasets would look like. I will do this for: Agriculture; Food purchased; Energy (Electricity and Natural Gas); Septic Systems. While this tool is useful in many ways, there were other data which were unavailable due to incomplete datasets or lack of granularity on the BG level.

A. Agriculture

To evaluate the agriculture crop and animal footprint data, information from the USDA Albemarle Agriculture Census Fact Sheet (2017) were used as a start. These data provided aggregate numbers of total animals and crops produced in the county. Then, the Cropscape database (USDA, 2018) was used to determine the total acreage of crops by type in each BG. The average fertilizer use was assumed by crop type. There was no indication of tilling techniques or type of fertilizer used in each BG. This meant assumptions were made on the 'average' for these types of analysis. No-till and organic fertilization could have a relatively large impact on the county crop footprint. If no-till practices were used around 20% of the GHG footprint from agriculture would be reduced (Ogla et al., 2019). However, no-till practices are not feasible for all types of crops. I assumed a 7% no-till and reduced-till practices were used evenly across BGs (UDSA Albemarle Fact Sheet, 2017). Other practices that may increase carbon sequestration or nitrogen and phosphorus retention were not evaluated in this study but would have an impact on the footprints.

For animal agriculture, the total acreage of pastureland (both forested and unforested) were used to determine the total number of animals per BG. To my knowledge, there were no more granular databases to determine the exact number of animals in each BG. Therefore, all animals were divided evenly according to the total acres of pastureland within the BG. Additionally, animal feed was assumed to come entirely from inside of Albemarle. Animal feed likely does come from other counties. However, Albemarle does produce enough hay to feed all horse and cattle within its bounds, so this assumption was made with some confidence (see chapter 2).

B. Food purchased

The food purchasing data were retrieved from the Community Expenditure Report (CEX, 2017). The CEX reports dollars of food purchased for both at home and in restaurant use by product type from a list of ~175 products. These ~175 products were then assigned a dollars per pound value from the Bureau of Labor Statistics 140 products tracked (2017). The dollars per pound value is based on the national average costs which would not account for discrepancies in product cost from store to store. For example, if ground beef ground beef on sale at a discount superstore would have the same cost per pound as grass-fed beef from a specialty market with the methodology used. This could cause an overestimation of weight of beef purchased from expensive stores and an underestimation of beef purchased from discount shops. Over the entire city or county, these discrepancies would likely cancel each other out but could have implications for specific BGs.

There are also some challenges is gathering data from UVA students living on-grounds. These data would not be captured by the CEX report. About 26% of students live on grounds at UVA and 60% of these students are 1st-years who are required to have meal plans (PC: Caroline Baloga, UVA Dining). Assuming 1st-year students are eating all meals on Grounds, this means ~2,500 students are potentially eating meals somewhere other than on Grounds. Assuming these students are eating at the US average N footprint (Leach et al., submitted.) level annually, this would add a total of 65 MT N to the total N footprint of the city and county. Adding this to the combined Charlottesville and Albemarle footprints would increase these by 0.6%. However, this could have impacts on the footprints of certain BGs. Without additional data from off-grounds students eating habits, this is impossible to determine.

C. Energy

The energy portion of the footprints (both natural gas and electricity) for Charlottesville and Albemarle were calculated by determining a rate for businesses and a rate for residents. Using the dollars spent on electricity by residents from the CEX report, the energy data was split between BGs. For businesses, there was no granular data on energy purchased by each business. The total number of businesses in the BG were used to split up the energy use and each business was assumed to have the same energy use. Ideally, having the type of business or size of the business would help to better split quantify electricity use by businesses in the BG.

D. Septic Systems

The data used to determine where septic systems existed were based on where city/county water and sewer hook-ups were not available. Each household within BGs not connected to the wastewater treatment plant was assumed to be on septic systems. This could be an overestimate of the total number of people on septic systems as some households could be living under one home or several households could have a community septic system. It was also assumed that each BG was on a traditional, unadvanced septic treatment. This could have also been an overestimate of nutrients lost as newer systems sometimes provide as high as 60% N removal (EPA, 2020). The potential reduction from advanced N septic reduced the footprint by 0.5% which shows that there would be a relatively small change in overall footprint due to the move to advanced septic.

4. Future Additions

There are several interesting analyses and additions that could be made to the N-C-P tool. Examples of the additional footprint analyses are the virtual water footprint (Natyzak et al., 2017) and the ecological footprint (Wakernagel et al., 2006). The virtual water footprint provides additional insights into upstream water use for items such as energy use, food purchased, sewage treatment, and direct water use. This indicator could be a very important part of a footprint analysis in a water-stressed community. The ecological footprint analyzes the impact that an entity has on the biological community and the “carrying capacity” of the local environment which could provide a unique analysis of the community’s impact.

Other indicators such as damage costs per footprints could be added to the tool to provide a financial view of the impacts GHG emissions (Prest et al., 2022) and N losses (Birch et al., 2011; Compton et al., 2017) are having on the environment. These quantify the environmental damage costs such as loss of income from recreation in polluted waters or costs of rebuilding after more frequent extreme environmental events. Damage costs also quantify human health effects such as increased respiratory illnesses due to NO_x emission exposure (e.g., Birch et al., 2011). Including these values to a tool like this provide community stakeholders the ability to compare the cost of implementing environmentally friendly infrastructures with the expected costs of damages from these pollutants after the fact.

Additional work that could be done to determine the social impact of this data is to determine whether there is a correlation with the footprint metrics. This could include correlating N, GHG, and P footprints with poverty, education, proximity to grocery stores or public transit, or income (figure 4.1).

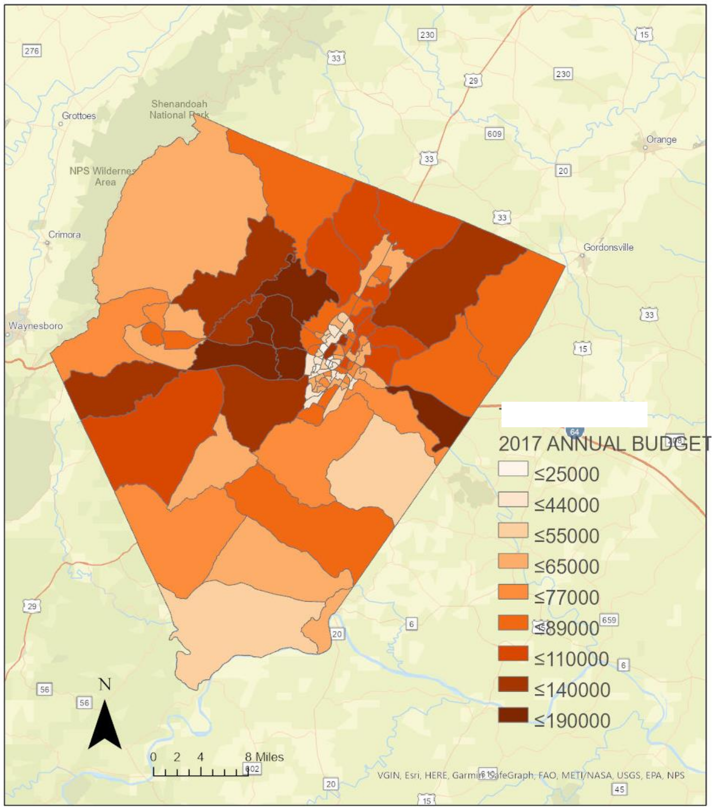

Figure 4.1: *Average per capita annual budgeted expenditures in Albemarle and Charlottesville based on data from the Community Expenditure Report (2017). The darker orange means a higher expected budgeted expenditures and lighter orange is lower. The figure was made in ArcGIS Pro using natural breaks to split each category.*

This additional analysis could give insights on where to expect footprints to be high in other communities as well as determining drivers of footprints within the Charlottesville and Albemarle footprints. For this community in particular, it could be interesting to determine where student, staff, and faculty off-grounds housing is located to see if the educational materials provided by UVA are influencing the footprints of BGs where these groups often live.

The GHG, N, and P footprint models are based on resource consumption and do not necessarily correlate with where the emissions are occurring. Tying these data points to spatially explicit emissions or loss data would be an interesting comparison. This would likely give some context to the deeply agricultural areas of Albemarle. While Albemarle is a highly agricultural area which is a driver of the high per capita footprint, the food is likely not being consumed within the area. A map of exports from the county could also be an interesting analysis to see where the food purchased footprint of the agriculture in this area is associated with.

5. Final thoughts

The work done here gives a new perspective on evaluating sustainability at the community level. The work takes a dynamic community which includes rural and agriculture areas, a relatively small city, and a large university and health system and integrates environmental footprints at the aim of evaluating how reduction strategies interact. Building the basis for this tool and evaluating scenarios gives insight in to how the three entities interact and what can be done to enhance environmental sustainability. There are certainly additional metrics, more granular data, and revised scenarios that can be run in the tool which would make the analysis better. However, having the basis for calculations and inventory data needed to add these things is a crucial development in the knowledge needed to bridge these gaps. The methodology shown here uses mostly publicly available data meaning the methodology used here can be expanded to other rural and urban communities across the United States and potentially other countries to advise environmental sustainability strategies and guidelines.

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Appendix

Appendix Chapter 1

Table A1.1: *Defines acronyms used throughout thesis.*

Acronym	**Description**
GHG	Greenhouse Gases
N	Nitrogen
P	Phosphorus
UVA	University of Virginia
IEFT	Integrated Environmental Footprint Tool
C-NFT	Community Nitrogen Footprint Tool
NFT	Nitrogen Footprint Tool
CEX	Consumer Expenditure Report
BG	Census Block Groups

Appendix Chapter 2

Table A2.1: *Crop calculation values used. Detailed values used for nitrogen taken up by crop (1-NUE) and nitrogen applied per acre (N applied) for each crop type used present in Albemarle, Va. Note "Dbl" means double cropping N application rates*.

Crop Type	**1-NUE (%)**	**N applied (kg/acre)**
Corn	0.01	109
Sorghum	0.27	36
Soybeans	0.08	0
Barley	0.27	36
Winter Wheat	0.27	41
Dbl Crop WinWht/Soybeans	0.14	0
Rye	0.27	23
Alfalfa	0.45	0
Other Hay/Non Alfalfa	0.45	68
Sod/Grass Seed	0.45	60
Peaches	0.66	14

Apples	0.55	11
Grass/Pasture	0.45	70
Dbl Crop WinWht/Corn	0.15	82
Pumpkins	0.43	45
Dbl Crop WinWht/Sorghum	0.27	82
Dbl Crop Barley/Corn	0.15	82
Dbl Crop Soybeans/Oats	0.08	36
Dbl Crop Barley/Soybeans	0.18	36

Table A2.2: *Animal calculation values used. Detailed values used for nitrogen produced in manure by animal type. Total manure, N content of manure, and average weight of the animal were used to determine the nitrogen per year from manure produced by animal type. Then, the WMS (waste management factor) or ground uptake factor was applied to the total.*

	total manure (kgs/455kgs)	N content (%)	Average Weight (kgs)	N/kg/year	Ground Removal factor or WMS
Broilers	36.4	0.9	2.8	0.75	0.75
Beef Cattle	26.9	0.6	636.4	181.2	0.55
Dairy Cattle	36.4	0.7	454.5	92.91	0.55
Horses	26.9	0.6	300.0	181.2	0.55
Hogs and Pigs	28.7	1.5	125.0	43.18	0.6
Layers	27.5	0.9	2.7	0.54	0.75
Pullets	19.8	0.9	1.9	2.67	0.75
Sheep and lambs	26.9	0.6	100.0	181.2	0.55
Turkeys	19.8	0.9	5.5	2.67	0.72

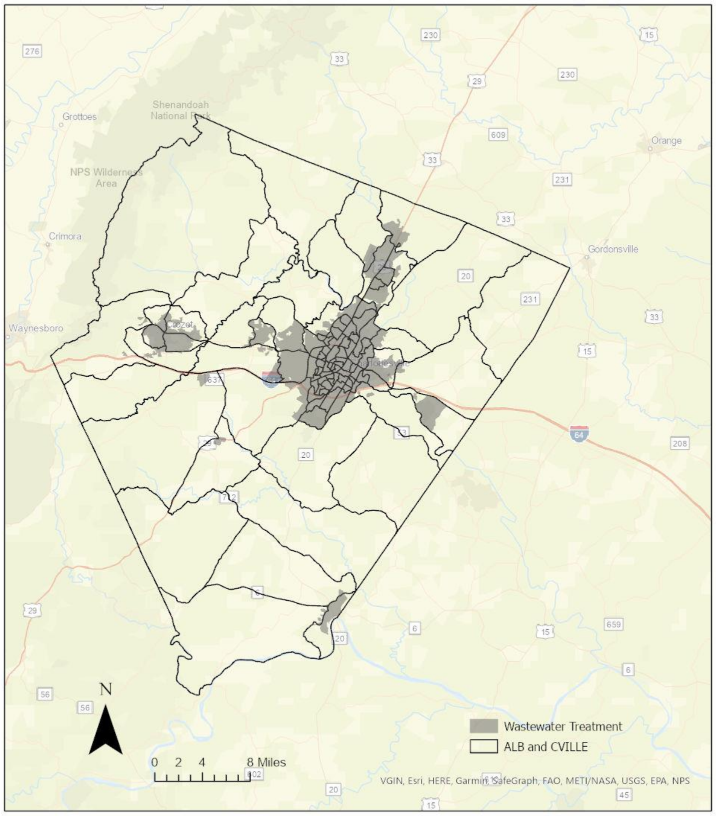

Figure A2.1: *Wastewater treatment areas in Charlottesville and Albemarle. Grey shaded areas indicate areas where homes are connected to the Rivanna Water and Sewer wastewater treatment plant. Black outlines indicate census block groups within Charlottesville and Albemarle. Census block groups partially or completed shaded gray were connected to the municipal treatment plant. Census block groups with less than 50% of its area shaded gray were assumed to be on septic systems. Map provided by Robert Woodside, Rivanna Water and Sewer (PC: 2021).*

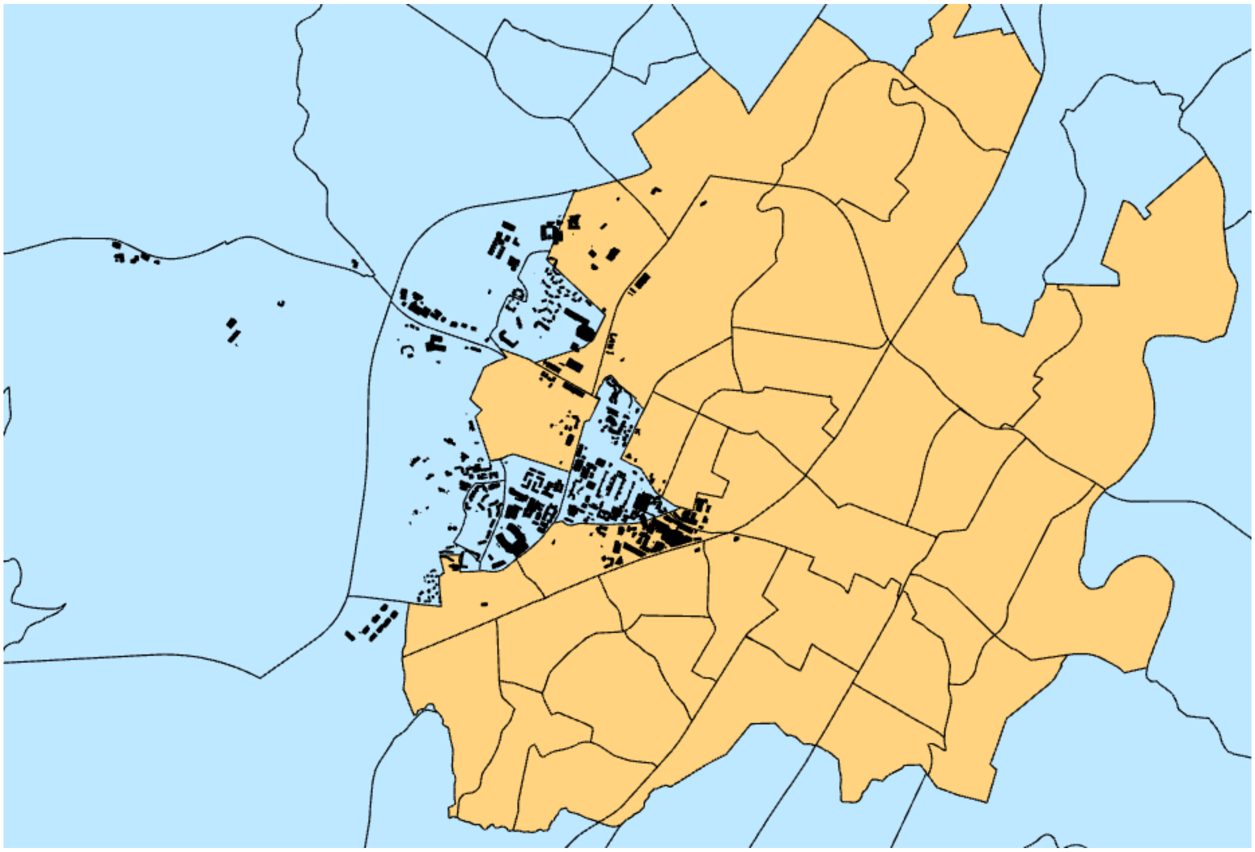

Figure A2.2*: Location of UVA buildings. Black buildings indicate locations of UVA Buildings within Charlottesville and Albemarle census block groups. Orange BGs are those in Charlottesville City and blue are Albemarle County. UVA buildings fell in 13 census block groups total; 9 in Albemarle and 8 in Charlottesville. A total of 552 buildings were included in the calculation. The black outlines indicate the parameters of the census block groups. Energy use and food consumption data from each of these BGs was added to the N footprint of Charlottesville and Albemarle. Data for UVA buildings provided by Ethan Heil, UVA Office for Sustainability.*

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Consumer Expenditure Report Details

The consumer expenditure report (CEX) is a data set collected by the US Census Bureau which consists of spend data from consumers for a large collection of products and services. These data are split up by census block groups (BG) across the US. Census block groups are subsections of census tracts with typically with 100-500 residents per BG. The CEX report collects 3 months or more of spend data per questionnaire sent. These questionnaires are sent to a random sample of individuals from different demographic groups and these chosen individuals are required to respond. The Census Bureau then attributes these spending habits to BGs in the entire US based on demographic make-up and income.

For this work spend-data on food by product type, gasoline, electricity, and natural gas were used. Food-spend data are the most heavily relied on source for the work here as it is used to determine the total weight of food purchased by individuals in BGs in both the city and county. Electricity and natural gas spend by BG was used to determine a rate for businesses and residents (dollars per kilowatt hour and dollars per therm). These rated were then used to split the county and city totals in to BGs. Dollars spent on gasoline was used to attribute total kilometers for personal car travel by BG.

More details on the consumer expenditure report can be found here: https://www.bls.gov/opub/hom/cex/home.htm.

Appendix Chapter 3

Residual Analysis

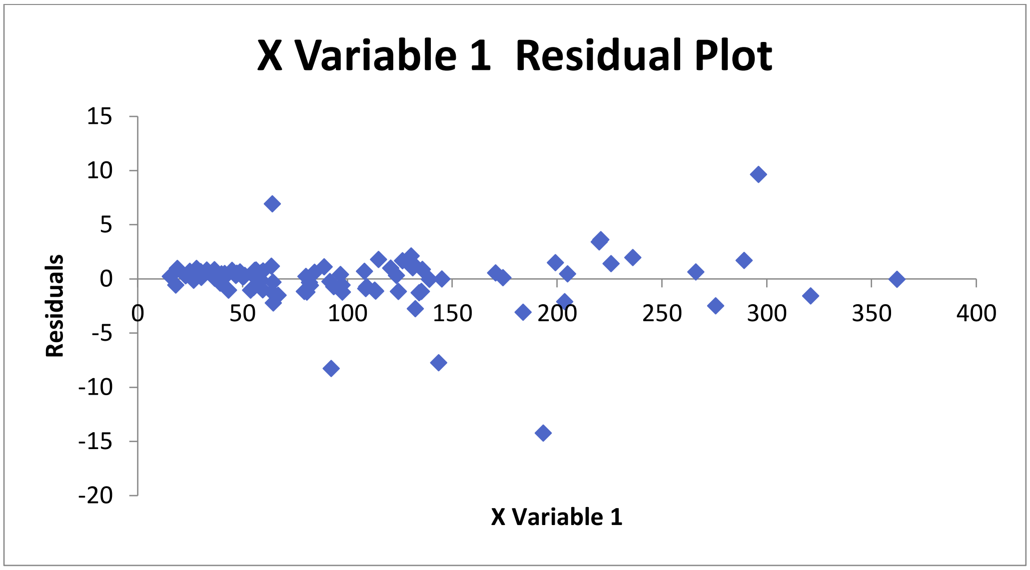

Figure A3.1 : *Residual analysis for nitrogen and phosphorus. The X variable is nitrogen.*

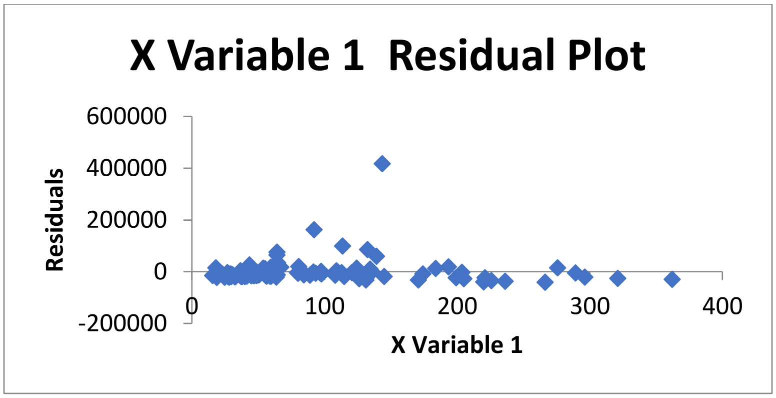

Figure A3.2 : *Residual analysis for nitrogen and greenhouse gases. The X variable is nitrogen.*

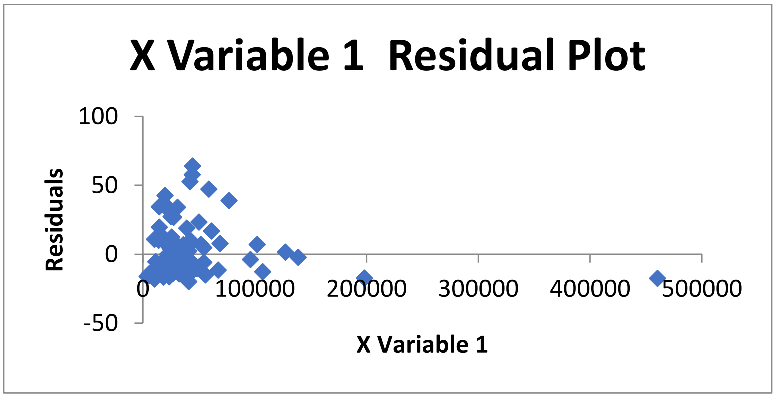

Figure A3.2 : *Residual analysis for phosphorus and greenhouse gases. The X variable is greenhouse gases.*

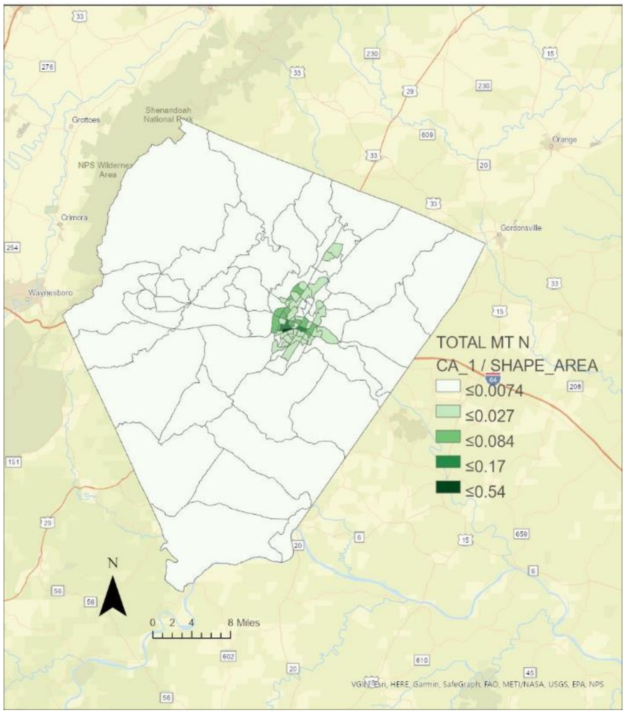

Figure A3.4: *GHG footprint per area. The total GHG footprint normalized by unit area (meters squared) in ArcGIS pro for UVA, Charlottesville, and Albemarle.*

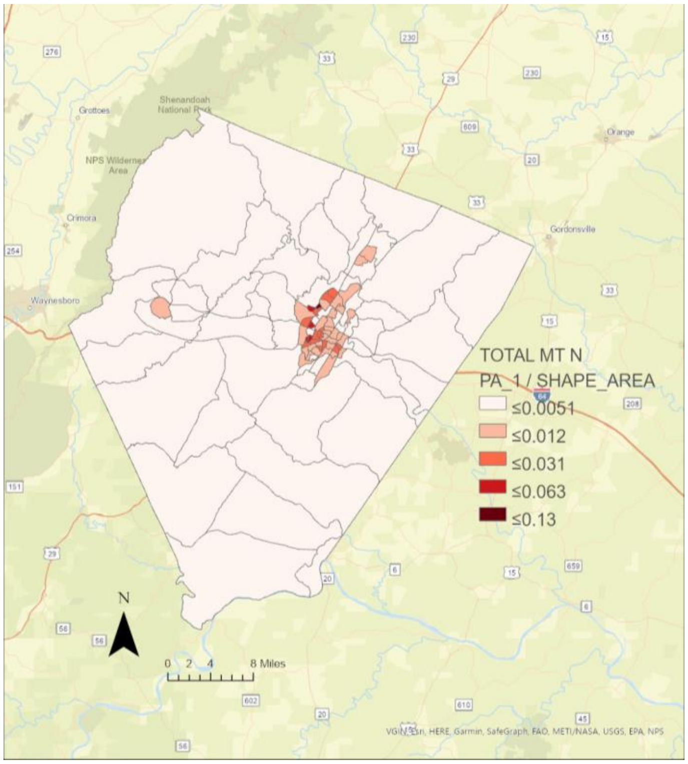

Figure A3.5 *P footprint per area. The total P footprint normalized by unit area (meters squared) in ArcGIS pro for UVA, Charlottesville, and Albemarle.*

Scenarios Descriptions

Scenario 1: UVA moves to 100% solar electricity powered.

To run this scenario, 100% of the electricity used by UVA was replaced with solar panels. The GHG, N, and P footprints of this electricity is zero. The total kilowatt hours replaced was 344 million across 13 BGs.

Scenario 2: 80% of UVA's on-site utilities moved to natural gas

80% of the total on-site heat plant fuel was transitioned to natural gas. This included a switch from a mix of coal, propane, oil, and natural gas. The current split in 2017 was 63% natural gas. The natural gas used at UVA's on-site heat plant was 1,060,000 MMBtus. The additional 20% of the MMBtus was split according to the 2017 composition of fuels (80% natural gas, 7% coal, 11% oil, and 2% propane).

Scenario 3: 10% of Charlottesville, Albemarle, and UVA's electricity comes from solar

An additional 10% of the electricity used at business and by residents would transition to solar from the 2017 eGRID mix. This was calculated by subtracting 10% of the electricity footprint from each BG as solar has no GHG, N, or P footprint.

Scenario 4: 50% of Charlottesville, Albemarle, and UVA's electricity comes from solar

An additional 50% of the electricity used at business and by residents would transition to solar from the 2017 eGRID mix. This was calculated by subtracting 50% of the electricity footprint from each BG as solar has no GHG, N, or P footprint.

Scenario 5: 10% of all at-home natural gas use is transitioned to electric, powered by solar.

This scenario involves removing 10% of the natural gas footprint from city and county homes and replacing it with a subsequent amount of solar electricity. Since solar has no footprint, there was no additional GHG, N, or P footprint added.

Scenario 6: Improve low-income housing energy efficiency

Households in BGs earning less than the poverty level in Charlottesville and Albemarle decreased their energy use in both electricity and natural gas by 25%. This is the average energy reduction due to home improvements. However, this may be an overestimate as the energy use is split evenly across residents within a BG. It is likely that low-income homes are not using the same amount of energy in the first place as higher-income homes.

Scenario 7: 10% increase in electric vehicles and cars

This scenario assumes a decrease in 10% of the total kilometers traveled by gasoline vehicles and gasoline and diesel busses. The equivalent amount of electricity 0.35 kwh per car travel and 2.45 kwh per mile of bus travel was added to the electricity footprint.

Scenario 8: 50% of cow and chicken manure is reused as fertilizer instead of synthetic fertilizer

50% of the N and P in cow and chicken manure was reduced and assumed to be applied to fertilizer. The total N and P applied to crops was not altered as there would be no change in fertilizer applied, just the source of the element.

Scenario 9: Best septic treatment for N and P for all septic tanks in Albemarle

All septic systems in Albemarle were assumed to improve to remove 60% of nitrogen and 30% of phosphorus was removed from wastewater and septic tanks. This was up from the average of 38% N removal and 20% of P.

Scenario 10: 15% increase in plant-based proteins consumed with a 15% decrease in animal-based proteins

The total weight of beef, chicken, and pork were decreased by 15% and subsequent total weight was replaced with beans and vegetables in the “Food at Home” purchased category. This models the impact of consumers choosing to purchase more plant-forward food items each year to replace the animal-based proteins.

Scenario 11: 50% of beef replaced with vegetarian options at UVA locations

50% of beef served at all UVA Dine, Health System, Catering, Darden School of Business, and Retail locations removed beef by 50% and subsequent weight was replaced with 25% chicken, 25% fish, 25% beans, and 25% vegetables. These totals were subtracted from UVA specific BGs and added back to these same BGs.

Scenario 12: 30% of food waste across Charlottesville, Albemarle, and UVA reduced

This scenario assumed post-consumer waste was reduced by 30%. Post-consumer waste refers to the waste that occurs after the consumer purchases food from the store to prepare and is uneaten for any reason. This makes up about 17% of food purchased (United Nations: Global Food Waste, 2019). Each category of food was multiplied by 17% to get the total amount of food waste. Of this 17%, 30% was subtracted from the food purchased by residents in the city and county to get the total reduction based off of food waste. This is one of two scenarios where the total weight of food purchased decreased.

Scenario 13: 30% increase in the number of vegetarian meals served at restaurants

30% of the total meat (beef, chicken, and pork) by weight was reduced in the "Food Away From Home" sector of the community expenditure report. This weight was subsequently replaced with an equal split of eggs, beans, cheese, and vegetables. The total weight of food from restaurants remained the same but the footprint decreased due to changes in what is served.

Scenario 14: Recommended daily value of beef consumed in all BGs in the city and county.

This scenario either increased or decreased the total beef consumption in each BG to 7 ounces of beef each week. This is based on the recommendation from the American Heart Associate (2018) that individuals consume no more than 3.5 ounces of beef two to three times a week. This scenario assumes each person is consuming 3.5 oz of beef twice a week. Some BGs increased the amount of beef consumed but most decreased. The BGs which increased their beef consumption were often lower-income BGs where individuals may not be getting enough nutrients.