PROJECT SUMMARY

Overview:
Food deserts have become a serious issue in rural and urban communities. The proposed research will study the relationships and interactions between human systems and natural systems contributing to food deserts in three geographically diverse regions of North Carolina. This project proposes to create a transformative platform to integrate the human systems with natural systems to understand the issues influencing food desert in the rural and urban communities. Specifically, the objectives are to (1) create a geo-coded spatial-temporal database for both human factors and natural factors; (2) build an integrated modeling framework that includes natural system models (biophysical model, GIS land use model), human system models (production model, consumption model), and integrated procedures (multi-agent simulation) to link human systems to natural systems; (3) validate the reliability and the robustness of the database and the integrated modeling framework in selected study areas; and (4) conduct training workshops and educational sessions for stakeholders such as local and state planning agencies, extension agents, producers, food retailers, and undergraduate/graduate students.

Intellectual Merit:
The intellectual merit of the project is its transformational and multidisciplinary approach, which integrates modeling of both natural and human systems to simulate issues of the food deserts. Our team members include researchers from engineering, economics, agriculture, geomatics, geography, computational science, and public policy. To the best of our knowledge, no one has attempted to tackle the dynamics of food desert from both human and natural systems. The proposed research method is innovative because we truly identify common factors influencing producers' decisions, consumers' decisions and biophysical processes. The project will link human systems and natural systems using a set of models, agent-based simulations, and GIS methods to investigate policy scenarios impacting food deserts in both rural and urban areas. The geo-coded spatial-temporal database we propose to create is unique in a way that it incorporates social, economic and environmental aspects.

Broader Impacts:
We are establishing pioneering effort to create a transformative platform coupling human systems and natural systems in understanding food desert issues particularly for low-income and underrepresented neighborhoods in three geographically diverse areas. This multidisciplinary research project involves researchers and students from two HBCUs in North Carolina. The project impacts well beyond improved understandings of the fundamental science in food desert issues in two critical areas: (1) the delivery of direct policy-relevant information for one of the most increasing complex problems in the United States, (2) the training of underrepresented students at both undergraduate and graduate levels (direct educational benefit), and education of stakeholders. Increased participation by underrepresented groups will be realized through the collaborative partnership with NC Cooperative Extension, National eXtension System, and the Center for Environmental Farming Systems (CEFS) (co-PI Liang is the director of CEFS). Results will be presented at national and international conferences and published in peer-reviewed journals. Elements of project activities and outcomes will be incorporated into existing undergraduate courses. Project activities will result several masters' theses and doctoral dissertations. Outreach materials will be developed to conduct training workshops through NC Cooperative Extension, National eXtension System, and CEFS. The project will also create an e-library for project-related data, models, publications, etc., at the eXtension Community of Practice website. Project outcome will be shared with USDA Food Desert Locator team to enhance and support their ongoing efforts in this area.
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**Cover Sheet for Proposal to the National Science Foundation**

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**Appendix Items:**

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.*
CNH-S: Dynamics of Rural and Urban Food Deserts Driven by the Interactions Between Community Socio-Economic Characteristics and Land/Water Quality

1.0 Background

Responding to the growing interests and urgent need to alleviate food insecurity, our project is designed to provide a transformative platform for communities to (1) understand the interactions and factors of influences between human systems, natural systems, and food deserts; (2) identify existing policies that either support or hinder the progress to alleviate food deserts; and (3) simulate policy scenarios including the interactions between human systems and natural systems to avoid the formation of food deserts in community planning processes.

Food access is a critical component in community planning and the issues are significantly different in rural and urban areas (Pothukuchi 2009). A recent USDA report discussed the changing structure of food retail industry and potential influences of such change on food deserts (USDA 2017). Mergers and acquisitions in this industry climbed since the late 1990s, resulting in a higher concentration of sales among fewer chain stores (Harris et al. 2002; DePillis 2013; Duff and Phelps 2016). Most large chain stores such as supercenters and supermarkets locate in high population density areas, while independent grocery stores and small-scale neighborhood grocery stores are more likely established in low-income neighborhoods and rural areas (Chung and Myers 1999; Block and Kouba 2006; Powell et al. 2007). The shifting concentration of large-format chain stores has created rising challenges to the existence of other types of food stores, which links to problematic food access in over half of the US counties (USDA 2017). Scholars have pointed out the urgency to conduct more studies on several aspects such as: (1) examining the potential impacts of food retail industry on food access particularly in remote rural areas and low-income neighborhood (Burns and Ingils 2007; Block et al. 2008; Larson et al. 2009; Dunn et al. 2012; Govindasamy et al. 2012); and (2) evaluating consumers’ decisions in food purchasing and education of choices corresponding to food prices, product availability, and healthy foods.

Most existing literature tackles the food desert issue from a health or consumption perspective, but no one to our knowledge has attempted to simulate the potential of shifting existing food production at the local level to accommodate small-scale food retail stores in rural or urban areas. This led to a research question that has yet to be explored: what is the potential to promote and support local farmers to increase the supply and variety of fresh produce to community-based food stores? Furthermore, to the best of our knowledge, we are not aware of any study that evaluates the environmental impacts such as changes in soil and water quality for re-purposing existing farmland to diversify local food supplies.

Our project aims to fulfill this knowledge gap by coupling human systems and natural systems, and link input and output from production, consumption and biophysical models to assess food accessibility, availability and affordability in three selected regions of North Carolina. We are particularly focused on supply and demand of fresh vegetables because (1) North Carolina has the capacity to produce large variety of vegetables, and (2) most households have challenges to access fresh vegetables living in a food desert.

Below we provided some innovative elements of our proposal:

a. The transformative framework we propose to create will link human systems and natural systems using a set of models, agent-based modeling simulations, and GIS methods to simulate policy outcomes concerning food deserts in both rural and urban areas.

b. To the best of our knowledge, this is the first time both human and natural systems are coupled to study food desert issues.

c. A multi-disciplinary team is formed including engineering, economics, agriculture, geomatics, geography, computational science, and public policy.
d. The geo-coded spatial-temporal database we propose to create is unique in a way that it incorporates social, economic and environmental aspects.

e. The project is well-conceived and well-positioned to integrate research, teaching and outreach capacity of NC A&T, and the resources through the Center for Environmental Farming Systems (CEFS; 25 years of partnership between NC Department of Agriculture, NC State University and NCA&T State University), Cooperative Extension, and National eXtension System.

f. We have tremendous support from the local stakeholders/organizations as can be seen from the support letters from many organizations that are interested in this idea.

2.0 Motivation and Study Area

The term “food desert” is used to describe neighborhoods and communities with limited access to affordable and nutritious food (Berg 2009; National Research Council 2009). The online Food Desert Locator, developed by the U.S. Department of Agriculture's (USDA) Economic Research Service (ERS), is a tool that can be used to assist efforts to expand the availability of nutritious food in food deserts, or low-income and underrepresented communities that lack of ready access to healthy food. This project focuses on county-level analyses in three diverse geographic regions of North Carolina including both rural and urban communities (Figure 1): Eastern coastal region represented by Robeson county, Central flat region (Piedmont) represented by Guilford county, and Western mountain region represented by Caldwell county. These regions are selected as testbeds to (a) verify our method of analysis for three distinct geographic, biophysical and socio-economic characteristics such as income, employment, household composition, education, and race and ethnicity, (b) test and validate the integrated modeling system we will develop during this project, and (c) compare and contrast food desert characteristics and sensitivity in different geographic areas. Additionally, these areas show significant growth in the number of underrepresented populations (new immigrants, ethnic minorities, veterans, and retirement communities) (US Census Bureau 2017).

Figure 1 shows the comparison of food desert locations in North Carolina between 2010 (red shade) and 2015 (green shade). It shows clearly that food desert areas have expanded in our study regions. At the same time, the number of farms and acreages of farmland in our study regions have declined between 2010 and 2015 (USDA NASS 2017). The number of total food retail stores in our study regions also declined (US Census Bureau 2017). These observations motivated our project to explore the following questions: (1) Can society increase the supply of fresh and healthy food by connecting local farmers to local food retailers? (2) If we propose to shift a percentage of the existing farmland to produce more
vegetables, what will the ideal prices be for farmers, local retailers, and consumers; and what will be the environmental impacts on water and soil? (3) If the community decides to sell a percentage of existing farmland for commercial development to attract more businesses, residents, and larger grocery stores, what are the potential consequences on social-economic characteristics and soil/water quality?

Previous studies have addressed food desert issues and their relationship to community health, consumers’ dietary risks, households’ mobility, transportation mode, travel time, and private/public coordination through a creative planning strategy (Diez Roux et al. 2001; Odoms-Young et al. 2009; Cummins and Macintyre 1999; Cummins et al. 2005; Cummins and Macintyre 2002; Opfer 2010; Bader et al. 2010; Giang et al. 2008; He et al. 2004; Higdon et al. 2007; Lopez 2007; Michimi and Wimberly, 2010; Moore et al. 2008; Morland and Evenson, 2009; Powell et al. 2007; Shaw 2006; Sorensen et al. 2004; Vainio and Weiderpass 2006; Widener et al. 2013). GIS is one of the most commonly adapted techniques to measure food retail stores’ spatial accessibility from the households (Giang et al. 2008; Michimi and Wimberly 2010; Xu 2014; Zenk et al. 2005; Donkin et al. 1999; Lee and Lim 2009; Mulrooney et al. 2017). While there are substantial studies capturing human and physical dimensions of food deserts, limited literature exists connecting food deserts with both human systems and natural systems. Complexities arising from community interest to adopt local food systems, and individual preferences for nutritious food (human decision), and interactions with the environment, promote the need for further research in both rural and urban areas.

3.0 Goals and Objectives

Our hypothesis is that if food desert phenomena are analyzed in a wholistic way that couples human systems and natural systems, then we can significantly improve the understanding of food accessibility, availability and affordability while maximizing the production and minimizing the negative environmental impacts. The overall goal of this project is to build a transformative platform to include multi-disciplinary datasets, and analytical and simulation tools for each community to respond to food desert issues during the community planning process. The specific objectives are to:

1. create a geo-coded spatial-temporal database for both human factors and natural factors such as socio-economic characteristics, cultural distinction, policy orientations, land use capacity, land characteristics, farming activities, distribution and characteristics of food retailers, and community infrastructure such as transportation modes and internet access;

2. build an integrated modeling framework that includes natural system models (biophysical model, GIS land use model), human system models (production model, consumption model), and integrated procedures (multi-agent simulation) to link human systems to natural systems to better understand and respond to food desert issues;

3. validate the reliability and the robustness of the database and the integrated modeling framework in three selected North Carolina regions; and

4. conduct training workshops and educational sessions for community planning members, local food policy council members, local land use and zoning committee members, conservation specialists, extension agents, farmers, food retailers, undergraduate/graduate students, and other stakeholders.

The proposed platform will be designed, developed, calibrated and tested in three different geographic regions of North Carolina (East coastal region, Central region, and West mountain region). The PIs and Co-PIs have strong skills, knowledge and experiences in research, teaching and outreach to address the key questions of the proposed study. The team will link existing resources and information through a multi-disciplinary approach to generate an integrated system providing advanced understanding of the food insecurity and food desert issues, and their impacts on natural systems.
4.0 CNH Components of the Project

This study proposes to create a transformative platform to include: (1) a geo-coded spatial temporal database which contains variables influencing food purchasing decisions (human systems), potential diversified land use in local food production or commercialization (human systems and natural systems) and environmental impacts on soil and water quality (natural systems); and (2) an integrated modeling framework including the coordinated database to evaluate coupling effects between human systems and natural systems using a multi-agent simulation.

The dynamics within human systems: Given the condition of a shifting food retail industry and community profile in each of our study regions, we will simulate farmers’ production decisions to set-aside a certain percentage of land to produce a vegetable mix. Local food retailers produce a reasonable inventory level for purchase by local households. Each household makes decisions on where to buy and what to buy given the produce prices and food retailers’ locations (food availability, affordability, accessibility). Household decisions on food purchases provides feedback to farmers and food retailers who then adjust their production and inventory levels.

The dynamics within natural systems: Given the condition of land characteristics and food retail locations, the natural system will be modeled using a biophysical model, which takes into account of farmers’ decisions to change use of farmland (vegetable production or commercialization) and other input parameters such as soil characteristics, crop choices, and climate. The model will capture impacts of farmers’ land use decisions on hydrology and the environment, crop/vegetable yield potential, and land and water quality (soil loss, soil water content, nutrients, runoff) with various spatiotemporal scales.

The processes through which the human systems affect the natural systems: Local farmers will only shift land use to produce vegetables when there is sufficient demand from local food retailers and households, or farmers may sell land for commercial development. Once land structures are changed, irreversible effects to soil and water quality are created.

The processes through which the natural systems affect the human systems: When land use is shifted for either food production or commercial development, land characteristics change. Such change may affect long-term soil fertility by switching the crop patterns, or may generate more food desert areas due to poor planning.

Integration of all 4 components: The transformative platform designed and developed to couple the human systems (using multi-agent simulation) with the natural systems will demonstrate the effects of re-purposing farmland on the community food system, the environment/farm preservation and commercialization of the land. The outcomes of the platform will inform new policies to improve community access to healthy and nutritious food, particularly for low-income households.
5.0 Research Methodology: Development of the Framework and Modeling Systems

Figure 2 provides the overall view of the integrated modeling framework, which consists of natural system model (biophysical model, land use model), human system model (production model, consumption model), and their interactions and linkages (coupling).

This project will first design and develop a spatial-temporal database of multiple datasets needed for both human system modeling and natural system modeling. This step will require extensive data search locally and through online portals. Our project team has extensive experience in collecting and managing such data for modeling. Table 1 (in section 5.1 below) elaborates on all various categories of data need with relevant sources of data collection. All data will be geo-coded and verified using GIS for data consistency and integrity.

Vegetable yield from the production model will be used by the consumption model and biophysical model. The biophysical model will simulate farm-level hydrology, water quality and vegetable yield for given sets of input from natural land use and socio-economic conditions (baseline). Calibration of the biophysical model will incorporate observed data as well as yield data of the production model. Relevant environmental indicator of interest will be soil erosion, soil water content, soil nutrients, and water quality parameters. The consumption model will consider yield production data (from the production model) and income constraints along with other geo-coded socio-economic factors and other variables to simulate and optimize consumer decisions on grocery shopping locations and produce mix (what, where and how much to purchase). These outputs will provide feedback for the production model to simulate equilibrium prices for locally grown vegetables.

A land use model will be developed and implemented that will utilize outputs from the biophysical model and the interactions of production and consumption models along with other variables such as flood-prone areas, or zoning data to delineate a new food desert zones. The land use model will be
integrated with the GIS proximity analyses to simulate the costs of delivery of the vegetable mix to grocery stores under alternative locations of retail stores, and subsequently, the impact of the equilibrium vegetable mix production on food desert sizes.

The dynamics of interaction and linkages (coupling) between the biophysical model, production model, and consumption model as well as land use prediction and proximity analyses will be modeled by a multi-agent simulation method. This integrated set of models and input/output variables forms the foundation of the transformative platform. The framework will be tested for various endogenous and exogenous scenarios including adaptive management programs, public policy, re-purposing of land use, and food accessibility, affordability, and availability. The initial conditions (e.g. prices, crop and vegetable yields) will be replaced by obtained results from the simulation, and will be used as the initial conditions for the next iteration. Simulation results at the consumption stage will be analyzed to evaluate food security.

5.1 Developing a Geo-Database
We will develop a spatial-temporal database to capture the human systems, natural systems, and their interactions:

<table>
<thead>
<tr>
<th>Model</th>
<th>Input data</th>
<th>Agency</th>
<th>Spatial and temporal resolution and frequency</th>
<th>Model output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biophysical model</td>
<td>Topography (DEM)</td>
<td>USGS</td>
<td>10-m resolution; GIS; static database; county level</td>
<td>Crop yield</td>
</tr>
<tr>
<td></td>
<td>Stream network</td>
<td>USGS</td>
<td>Vector GIS layer; static database; watershed level; provided at 1:24,000 scale</td>
<td>Runoff</td>
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<tr>
<td></td>
<td>Land use</td>
<td>USDA</td>
<td>Annual, GIS layer; county level</td>
<td>Recharge</td>
</tr>
<tr>
<td></td>
<td>Soil types,</td>
<td>USDA</td>
<td>GIS layer; static database</td>
<td>Soil water content</td>
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<tr>
<td></td>
<td>Precipitation</td>
<td>CRONOS</td>
<td>Time-series daily data</td>
<td>Soil erosion</td>
</tr>
<tr>
<td></td>
<td>Temperature (max, min)</td>
<td>CRONOS</td>
<td>Time-series daily data</td>
<td>N and P transport</td>
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<tr>
<td></td>
<td>Streamflow</td>
<td>USGS</td>
<td>Daily data; dense network</td>
<td></td>
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<tr>
<td></td>
<td>Water quality variables</td>
<td>EPA</td>
<td>Sampling data; static database</td>
<td></td>
</tr>
<tr>
<td>Production model</td>
<td>Farm production and finances data (Census of Agriculture)</td>
<td>USDA Forest Service</td>
<td>Farm level; once every 5 years; 1992, 1997, 2002, 2007, 2012</td>
<td>Crop production choices; Crop production practices; Land use choices</td>
</tr>
<tr>
<td></td>
<td>Forest Inventory and Analysis (FIA)</td>
<td>USDA Forest Service</td>
<td>Plot level, every 5 years; any sub-state level aggregated data</td>
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<td></td>
<td>Crop Data Layer (CDL)</td>
<td>USDA</td>
<td>Annual, GIS layer</td>
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<tr>
<td></td>
<td>Crop prices</td>
<td>USDA</td>
<td>Annual</td>
<td></td>
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<tr>
<td></td>
<td>Agricultural production input prices</td>
<td>USDA</td>
<td>Annual</td>
<td></td>
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<tr>
<td></td>
<td>Community profile, household demographics, income and expenditure</td>
<td>Consumer Expenditure Survey (CES)</td>
<td>Updated annually through ESRI; provided at various scales ranging from block group through county</td>
<td></td>
</tr>
<tr>
<td>Consumption model</td>
<td>Individual and household level income, employment, expenditure by categories for food and non-food items</td>
<td>Bureau of Labor Statistics (BLS); American Community Survey (ACS)</td>
<td>Annual; provided at various scales ranging from block group through county</td>
<td>Max consumption utility, bundle between food and non-food items given income, and expend. constraints</td>
</tr>
<tr>
<td></td>
<td>Groceries and food retail stores</td>
<td>American Community Survey (ACS)</td>
<td>Annual at various scales (block group, tract, zip code, county)</td>
<td></td>
</tr>
<tr>
<td>GIS Proximity</td>
<td>Road network and locations of groceries and food retail stores</td>
<td>InfoUSA NCDOT</td>
<td>Annual; Vector Layer, horizontal accuracy varies by county (2 – 6 meters)</td>
<td>Proximity to retail stores</td>
</tr>
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</table>
5.2 Human System Models

Consumption Model

The consumer model in this project focuses on household behavior and decision making when it comes to expenditures of food items (fresh produce, meat, and value added) and nonfood items (housing, transportation, utility, and other necessities). Households make decisions in purchasing motivated by priority and demand to maintain a reasonable quality of life (Thilmany et al. 2008; Bond et al. 2008). The following equation describes the concepts of consumer’s behavior subject to transportation mode, travel time, and household characteristics:

\[
max \text{ consumption possibility } \quad B_{ij} = I_{ij} - \sum_{n=1}^{k} (P_n Q_n)_{ij}
\]

where, \(B_{ij}\) = net disposable income (a proportion of total income minus tax and savings) for household \(i\) at neighborhood \(j\); \(P\) = retail price of food and nonfood items; \(Q\) = quantity of food and nonfood items.

For food items, households are motivated by availability (seasons of produce), affordability (prices), and accessibility (transportation mode, time to travel). Each household maximizes the possible options of food consumption given net disposable income as well as availability, affordability, and accessibility. Households also consider social characteristics of foods (ethnicity, religion, culture) when purchasing foods. Some of these variables are endogenous to each household such as income, residency, and food choices. Other variables are exogenous (i.e., beyond the households’ control), such as market locations and prices of foods.

The decision to “buy local food” by households can be conceptually modeled using the framework of Lancaster (1966) to incorporating the concept of public goods, recognizing that households’ objectives may be more complex than simple self-interested behavior (Zaichkowsky 1985). In our study, individual producers consider the optimal agricultural production bundle to maximize profits as well as satisfaction for farm family. Where farms and consumers interact are at the market location and shared perception of local identity. Farmers create product awareness through direct contact with the households at farmers’ markets, co-ops, or Community Supported Agriculture programs. Households evaluate the information shared by farmers and other food handlers to make decisions: (1) whether to buy local foods, (2) where to buy local foods, (3) whether they are willing and able to afford local foods, and (4) whether they will continue to buy local foods more frequently.

Production Model

The production model takes inputs from the GIS proximity analyses (distance to retail food stores), productivity of soils for crops and vegetable production, and allocation of any parcel of land to one of three uses: commercial row crops, vegetable mix production, or shifting land out of agricultural production.

To our knowledge, no study has attempted to predict the change in agricultural land use between large-scale row crops and small-scale vegetable mix. Few studies have attempted to study transitions of land between agricultural, forest, urban, and other land use in North Carolina at a fine spatial resolution. Lark et al. (2015) and Wright et al. (2017) analyses of 2008-2012 CDL data identified both a significant gross expansion in central region of North Carolina, and gross abandonment of existing cropland or removal from production in other ways in the eastern coastal region of North Carolina.

Sayemuzzaman and Jha’s (2014) analysis of 1992-2006 NLCD data concluded that if the past trends in the transition of land between alternative uses continue, urban and industrial use could increase by 20% by 2030, mostly at the expense of forest and agricultural land, when compared with 1992. The proposed research will extend the study in two crucial directions: by the analysis of the latest available, 2011 NLCD data (and that for 2016, expected to be available during the project’s lifetime), and by developing an economic model that accounts for not only natural resource but also economic drivers of land conversion.
The formal model follows the general outline of Lubowski et al. (2006; 2008). The model postulates that with \(K\) potential land uses \((j, k = 1\ldots, K)\), the owner of a unit of land in use \(j\) will choose the use \(k\) at time \(t\) that satisfies:

\[
\text{arg max}_k \left( R_{jt} - r C_{jkt} \right) \geq R_{jt},
\]

Where \(R_{jt}\) and \(R_{kjt}\) represent the instantaneous expected net benefits (profits) at time \(t\) of a unit of land in use \(j\) and \(k\), respectively; \(C_{jkt}\) is the expected marginal cost of converting one unit of land from use \(j\) to use \(k\) at time \(t\) \((C_{jkt} = 0)\); and \(r\) is the discount rate. Following Lubowski et al. (2006; 2008), we specify the probability \(P_{ijkt}\) of allocating land parcel \(i\) in use \(j\), to use \(k\) at time \(t\) as nested logistic function of land owner’s utility from making this decision. This shifting use decisions is a function of observed data on landscape properties (land slope and proximity to water bodies), soil characteristics (clay content), climatic variables (average temperature during crop growing season), and soil productivity.

The construction of the necessary data for the analysis will follow the steps outlined in Lubowski et al. (2008) and, as adapted for the GIS-based, CDL and NLCD data, in Brandes et al. (2016). Specifically, field-scale land use come from the NLCD, which provides spatially explicit, national land cover description every five years, with the latest data available for 2011 (NLCD 2017). The last three NLCD collections (2001, 2006, and 2011) will be used because they have maintained a consistent land cover classification scheme, covering water, developed land, barren, forest, shrubland, herbaceous, planted/cultivated land, and wetlands. To minimize the impact of potential misclassification of land use, we will follow the suggestions of Lark et al. (2017) when cleaning, organizing, and reconciling the NLCD data with other sources of the aggregate data (Table 1).

The land use data will be matched with the same digital soils data that are used in modeling the natural systems side – the SSURGO. The SSURGO soils data constitute the base for the National Commodity Crop Productivity Index (NCCPI) model (Dobos et al., 2012), from which we will extract the soil productivity measures for each field-scale unit of analysis.

The expected profits for alternative land uses will be constructed from publicly available data as in Lubowski et al. (2008). The estimation of the profits for row crop will follow Brandes et al. (2016) and will use the yields predicted by the biophysical model, published crop prices (FAPRI 2017), cash rental rates, and crop production costs based as estimated by the NC State Extension. For the profits for vegetable mix, it will additionally account for the major expense of importance to small-scale, local producers: the costs of transporting the produce to local grocery stores (Sevoian and Connor 2012). The distance to grocery stores estimates will come from the proximity analyses described below. We will follow Grigsby et al. (2015) in estimating transportation costs for locally produced food. Calibration and validation of the production model will follow Kurkalova and Carter (2017).

5.3 Natural System Model

Biophysical Model

Recent advance in biophysical models enables the evaluation of the effects of land use decisions and land management practice at various spatial and temporal scale with greater level of confidence and accuracy (Ahmad et al. 2014; Hodson and White 2010; Rauff and Bello 2015; Panagopoulos et al. 2015; Schilling et al. 2014; Jha et al. 2007, 2010a, 2010b). In this project, simulation of alternative land use and management scenarios for the selected study regions will be performed with the Agricultural Policy Environmental eXtender (APEX) model (Gassman et al. 2010; Wang et al. 2011; Zhang et al. 2016). APEX is capable of simulating detailed field conditions at scale of individual farms, whole farms and small watersheds (Clarke et al. 2017; Tuppap et al. 2010).

APEX is a dynamic and continuous simulation biophysical model that can evaluate the effects of wide ranges of soil and water management practices on hydrology, crop growth and other environmental variables (Wang et al. 2014). APEX simulates watershed processes based on weather data, soil types,
topography, vegetation and management practices. Multiple options are available in the APEX model to estimate evapotranspiration, surface runoff, peak runoff rate, and available soil water capacity to derive hydrology of the system (Figure 4). APEX model inputs include GIS data layers (digital elevation model, soil characteristics and land use), climatic data, and management practices. Its hydrology modeling component uses precipitation and irrigation as main inputs to perform water balance at daily time steps for surface runoff, subsurface flow, soil water, percolation, and evapotranspiration. The mass balance components are as follows:

\[
SW_t = SW + \sum_{i=1}^{t} \left( R_i - Q_i - ET_i - P_i - QR_i \right)
\]  

Where \( SW, SW_t, R_i, Q_i, ET_i, P_i, QR_i, t \) are initial soil water content, final soil water content, precipitation, runoff, evapotranspiration, percolation, return flow on a day \( i \) respectively (all units are in mm) and \( t \) is time in day. The routing phase of hydrology is based on important landscape processes across hydrologically connected units called subareas. Subareas are the smallest unit in APEX with homogenous watershed characteristics with a unique combination of soil type, land/crop cover, slope, and land managements.

APEX is capable of simulating plant growth. It has database of over hundred varieties of crops and vegetables. In APEX, crop yield is estimated using the harvest index concept:

\[
YLD = HI \times STL
\]  

Where \( YLD \) is the amount of crop removed from the field in t/ha, \( HI \) is the harvest index, \( STL \) is the above-ground biomass. For a non-stressed condition, the harvest index increases non-linearly from zero at planting to \( HI \) at maturity.

Calibration and validation of the model for hydrology, crop growth, and water quality will be performed at different spatial and temporal scales within the study regions and will build upon previous modeling efforts in North Carolina watersheds (Chattopadhyay and Jha 2016). Substantial knowledge has been obtained from these previous modeling efforts regarding the most sensitive parameters that will require calibration for the proposed application. This eliminates much of the need for extensive sensitivity analyses of different parameters that need to be investigated for both the hydrologic and pollutant calibration phases. The calibration and validation efforts will be a multi-step process and will include annual and monthly flow calibration followed by calibration for sediment and nutrients. Model simulated values will be compared with the observation data with multiple statistical performance criteria including Nash - Sutcliffe efficiency (NSE), Percent bias (PBIAS), Root Mean Squared Error - observation standard deviation ratio (RSR) and Coefficient of determination (\( R^2 \)).
5.4 GIS Models

Land Use Model

A GIS-based land use model will be developed and implemented that will utilize outputs from biophysical model and production model along with other variables such as flood-prone area, zoning data to delineate a new set of food desert locations. A set of rules will be established that will aid in developing the land use map.

For example, if the biophysical model output shows that the land quality of an area is not suitable (over a defined threshold) for farming, the human decision would be to shift use of that land from agriculture to commercialization. Degradation of land and water quality will affect the land use decisions made by the producers. A well-calibrated biophysical model of unique response units (unique sets of land use, soil characteristics and land management practices) will simulate the continuous long-term effect of cropping systems under control baseline condition and suggested changes such as monocropping, production mix, and other socio-economic considerations. We will define threshold levels for yield production, soil nutrient, moisture content, and other indicators to accept or reject the changes in the land use choice. From the simulation results of each unique set of response unit, clear guidelines will be developed to allocate three specific choices: continue the existing row crop production, change to specific vegetable production, or no production (re-purpose for commercial use). In addition, marginal lands for crop/vegetable productions (such as area with high erosion index, high slope and low moisture content, and/or currently fallowed) will be set aside or given priority for re-purposing of that land.

Similarly, the predictions from the production model (which crops to grow) and consumption model (whether and/or where to buy local foods) will be used to determine equilibrium prices on local vegetable mix at specific proposed grocery store locations. If equilibrium cannot be achieved because of, e.g., estimated unprofitability of supply of vegetables to the location, then the proposed grocery store location will be determined to be unsustainable; and an alternative location will be suggested, resulting in a new configuration for the proximity analyses.

GIS Proximity Analyses

The proximity analysis method will use a spatial method based on a proximity approach to determine accessibility, because proximity to a retail outlet usually correlates with consumer patronage. Proximity is defined as the measurement of distance or travel time between a person’s home and a food source. Density is typically regarded as the concentration of food sources within a defined geography area or enumeration unit. Food variety is the degree to which different types of food outlets exist within a specified area. Travel times are estimated using the road network information and analyzing the distance and speed of travel to different outlets. The spatial approach will measure accessibility considering transport usage characteristics of people in different areas:

- Accessibility criterion in rural areas: The zone of influence (or service area) of a retail outlet will be delineated as the area within 10 miles’ travel.
- Accessibility criterion in urban areas: The zone of influence of a retail outlet will be delineated as the area within one-mile’s travel.

More advanced metrics considering travel time between a location and resource using the raster data model will be developed. Furthermore, surfaces created from the raster modeling can be computed against each other to derive unit-less relative travel-time surfaces. Figure 5 shows the proposed proximity analyses to estimate travel times.

To estimate the demographic characteristics of each zone of influence or identify the population associated with each retail store, ArcGIS Geoprocessing Tools will be used to create a geographic intersection of the census tract polygon boundaries with each service area map. Then, population densities will be calculated for each census tract by dividing the total population within a census tract by the total
land area of the census tract. The population of each zone of influence polygon will be calculated by multiplying the surface area of the polygon by the population density for the census tract in which the zone of influence polygon is located. When a zone of influence intersects several census tracts, the population will be calculated by considering the densities, or prorated based on the smallest enumeration unit of available data, of each intersected census tract.

5.5 Multi-Agent Simulation

Multi-agent simulation (MAS) methods have been recognized as a powerful tool to represent the complex relationships between environment change, human actions and policy inventions as well as investigating land use and land cover change (LUCC) (Groeneveld et al. 2017). MAS is a bottom-up approach replicating the complexity of a human-environment system with relatively simple rules of actions and interactions, i.e., a set of interacting agents or entities (Abar et al. 2017; Groeneveld et al. 2017). MAS is used in our study to simulate the decisions, actions, and consequences among producers, consumers, and natural systems for which individual variability among the agents cannot be neglected.

The proposed project will develop the MAS method following to Let et al. (2008) to build a dynamic land use simulation representing the heterogeneity in socioeconomic (human systems), and biophysical conditions (natural systems), and their interactions. The dynamic of each model (production, consumption, and biophysical models) will be represented with agents, which allows for direct observation and interpretation of simulation results. The MAS will specifically simulate three components including:

1) The human systems: The human systems will be considered at the farm level and at the consumer household level. The variables include household profile $H_{profile}$ such as size, income, labor, accessibility to agriculture service/subsidy and the landscape as perceived by the agent. Production and Consumption models representing human decision making in food production and food consumption through the relationship of input and output.

2) The natural systems: Spatial layers of the natural systems will represent each land parcel with multiple attributes such as slope and soil characteristics. The spatial variables for this project include biophysical variables such as water quality, land condition, topography, and land cover; economic spatial variables include proximity to roads, and grocery stores; and other spatial variables include zoning classes, and land ownership. The status of land and soil characteristics will change over time even without any human intervention. Therefore, biophysical model in our project will have ability to predict the level of changes with or without human interventions.

Figure 5 Process for estimating the travel-time
3) **The interaction of human and natural systems:** The MAS will provide the binding mechanism to capture the dynamics and the interaction between human systems and natural systems as well as land use transition in response to both human decisions and natural constrains. The proposed project will investigate all possible decisions and activities related to farming and vegetable purchase (e.g., growing crops, selling, consuming, etc.) and how much each decision/activity contributes to the decision makers’ objectives (e.g., the household’s net income). Then a set of rules will be developed to link the decision variables and constrain them to only feasible solutions.

### 5.6 System Evaluation for Endogenous and Exogenous Changes and Modeling Uncertainties

We propose to use the integrated modeling system for a comprehensive set of social-economic-environmental scenarios (public policy and feedback/recommendations from stakeholders) to quantitatively assess the key relationships driving the dynamics of food desert. The results will recommend actions to prepare, plan and respond to the stress of food desert.

The overall plan for evaluation of the modeling system to be developed follows the standard scientific modeling process (Kruger et al. 2012; Groenveld et al. 2017): We will 1) develop and validate individual components of the CNH modeling system using sets of input and observed historical data; (2) integrate the components and validate the integrated system to benchmark against the USDA’s Food Desert Locator, and then 4) use the modeling system to assess the impacts of specific exogenous changes for a set of social-economic-environmental scenarios.

Sensitivity analysis will be used to access both epistemic and political dimensions of modeling uncertainties of the integrated CNH system assessments (Rotmans and van Asselt 2001; Nicolson et al. 2002; Beck and Kruger, 2016). We will use conventional means of comparing the observed and model-predicted data to document the epistemic dimension of uncertainty, which concerns “the relationship between the ‘world in the model’ and the real world as experienced by other means, including measured data” (Beck and Kruger 2016). The political uncertainty, which refers to the fact that “modeling decisions may be subject to political influence and, in turn, influence politics” (Beck and Kruger 2016) will be assessed by the evaluation of the alternative scenarios/exogenous changes. These scenarios include but are not limited to considering the alternative goal functions in the human system models, such as pure profit maximization, minimization of the loss of labor income, and/or minimizing the spatial income inequality in the study region.

### 6.0 Education Plan

The educational component of this project fulfills the goals and mission of NSF to enrich learning and training experiences as an outcome in STEM and interdisciplinary studies, particularly for underrepresented population (HBCU). The plan is composed of (1) development of the experiential learning curriculum to be used for undergraduate and graduate education, and interdisciplinary training of graduate students at partner HBCU institutions (NC A&T and North Carolina Central), and (2) outreach activities to train and educate local stakeholders through collaborative partnership with NC Cooperative Extension, National eXtension System, and the Center for Environmental Farming Systems (CEFS).

**Experiential Learning for Undergraduate Education**

The research proposed here is highly interdisciplinary and integrative. It addresses a pressing national growing concern. The potential solutions are complex and involve a wide range of possible social, economic and environmental tradeoffs. The research thus provides an ideal focal point for engaging undergraduate students and exposing them to research methods and findings from engineering, agriculture, economics, water quality, geography, geomatics, computational science and many interfaces between these fields. To capitalize on these educational opportunities, the PIs will incorporate research process and outputs/outcome to existing curriculum that will enhance learning experience for students to the combined use of natural system models (biophysical, land use, GIS models) and human system
models (economic, production, consumption). The existing courses include upper-level undergraduate courses at NC A&T (CIEN 364 Engineering Hydrology, ABM 250 Dollar Enterprise, GEOM Advanced Geospatial Method, ECON 492 Economics Seminar), and at North Carolina Central University (GEOG 4010 Applied GIS).

Graduate Student Training
This project will support three graduate assistantships, which will offer training for underrepresented group including women in engineering, agriculture, economics, natural system and human system modeling, and integration across the disciplines. Exposure to team efforts at the graduate level are likely to play sizable dividends in these students’ career; they will be well positioned to lead and participate in interdisciplinary research projects. The graduate students will be involved in data collection, geospatial database building, model setup, simulation and calibration of models, results analyses and visualization, and information dissemination via poster and oral presentations in conferences and publications in peer-reviewed journals.

Outreach Activities and Products
In addition to presentations at national and international conferences, we plan to engage stakeholders in outreach activities through NC Cooperative Extension, National eXtension System, and the Community Food Strategies Program supported by the Center for Environmental Farming Systems (CEFS 2017). As a co-director of the CEFS and a national leader of eXtension, PI Liang is well positioned to lead these outreach efforts. Potential topics of workshops and seminars include strategies using our transformative platform to (1) design and develop an effective strategic plan for community planning with respect to disaster preparation and food security; and (2) identify factors that contribute to food desert issues and potential solutions, trade-offs, opportunities to solve the problem.

To broadly disseminate the project outcome, we will link our project website to eXtension (eXtension 2017), as web-based portal designed to provide comprehensive information for extension professionals and public. In addition, this project will also create an e-library for project related data, model, publications, etc. on the eXtension Community of Practice (community, local and regional food systems program).

7.0 Evaluation Plan
Evaluation of the Project Activities
The research activities and outcomes of the project will be evaluated by an external advisory committee (Table 2) twice during the tenure of the project (support letters are attached).

<table>
<thead>
<tr>
<th>Name and Affiliation of the EAC</th>
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<tbody>
<tr>
<td>1. Susan Shumaker, President, Cone Health Foundation, Greensboro, NC</td>
</tr>
<tr>
<td>2. Kiera Mulvey Bulan, Coordinator, Food Policy Council, Asheville, NC</td>
</tr>
<tr>
<td>3. Esther Manheimer, Mayor, City of Asheville, NC</td>
</tr>
<tr>
<td>4. Maureen Berner, Professor, The UNC Chapel Hill</td>
</tr>
<tr>
<td>5. Christopher McGinn; Associate Professor; NC Central University</td>
</tr>
<tr>
<td>6. Janet R. Mayer, Department of Health &amp; Human Services, Guilford County, NC</td>
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<tr>
<td>7. Morgan Wittman Gramann, Director, NC Alliance for Health</td>
</tr>
<tr>
<td>8. Kevin Lundy, Community Foundation of Greater Greensboro</td>
</tr>
<tr>
<td>9. Susan Cox, One Step Further, Inc., Triad, NC</td>
</tr>
<tr>
<td>10. Don Miholin, President, Out of the Garden Project, Nonprofit Organization</td>
</tr>
<tr>
<td>11. Jackie Lucas, Executive Director, The Salvation Army Greensboro Center of Hope</td>
</tr>
</tbody>
</table>

The committee will guide and advise project development, help identify and finalize indicators at each stage of the project, and help with the design and deliver training information for stakeholders.
Evaluation includes qualitative and quantitative indicators, including task completion milestones, obstacles encountered and addressed, number of conferences, posters, presentations, and peer-reviewed journals. The committee will also be tasked to provide feedback and recommendations for developing plausible exogenous scenarios affecting food desert for evaluating potential impacts of the suggested changes.

**Evaluation of the Outreach Activities**

The project team will routinely collect feedback from outreach activities to improve upon modeling integration strategies and policy recommendations. This will be done by preparing written evaluations that will be given to each participant during the workshop. The written evaluation will include information about the usefulness of the provided training and educational materials and the likelihood of considering project outcomes in their planning and decisions. The results of the feedback and impacts will be summarized and documented in project reports as well as publications that result from this project.

Some specific details are (graduate and undergraduate students will assist):

- A web-site will be created for this project and will be linked to eXtension web portal.
- An e-library will be created at the eXtension website for project related data and products.
- Five workshops will be conducted as a part of this project within three years. We will invite key stakeholder groups such as North Carolina Food Policy Strategy Councils and Retail Food Council to participate in these workshops.
- Educational and training materials will be delivered to the workshop participants.
- We will also make these materials available on the project web-site.

**8.0 Management Plan**

Close integration among project personnel will be needed at all stages to successfully complete the project. The PIs will regularly meet (once a month) for in-person work sessions. In addition, regular conference calls will be held to ensure that each working group is kept abreast of progress elsewhere. Based on our previous experience, working with our team members, we are confident that our communications will be regular and productive. Table 3, below, shows the qualifications and responsibilities of the PIs:

<table>
<thead>
<tr>
<th>Name</th>
<th>Expertise</th>
<th>Roles and Responsibilities</th>
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</thead>
<tbody>
<tr>
<td>Manoj Jha (PI)</td>
<td>Associate Professor; water resources, field to watershed scale of hydrology and biophysical modeling</td>
<td>Coordinate and implement overall project activities; Lead natural system modeling using APEX including modeling setup, calibration, validation and application; Support (1) data collection activities, and (2) provide biophysical outputs for MAS simulation and Production model</td>
</tr>
<tr>
<td>Chyi Lyi Liang (Co-PI)</td>
<td>Professor; Agriculture research and extension; Director of CFES</td>
<td>Lead the Consumption model components; Support the model integration; Lead the extension outreach activities in collaboration with the CFES, eXtension, and stakeholder org.</td>
</tr>
<tr>
<td>Leila Hashemi Beni (Co-PI)</td>
<td>Assistant Professor; GIS, agent-based modeling, remote sensing, geo-referencing</td>
<td>Lead MAS, develop Land use model and GIS related work including design and development the geodatabase, proximity GIS model and food desert mapping; Will support data collection and Geocoding</td>
</tr>
<tr>
<td>Lyubov Kurkalova (Co-PI)</td>
<td>Professor; Agricultural and natural resources economics, Modeling</td>
<td>Lead the production model components and support the CNH components integration and MAS modeling</td>
</tr>
<tr>
<td>Greg Monty (Co-PI)</td>
<td>Director of the Energy Center at NCA&amp;T</td>
<td>Facilitate advisory board activities and engage stakeholder discussion; Support outreach and education activities</td>
</tr>
<tr>
<td>Timothy Mulrooney (Co-PI)</td>
<td>Associate Professor at NCCU; Geographic analyses and GIS</td>
<td>Lead GIS related work including data collection, geocoding and development of database; Support for proximity model and food desert mapping</td>
</tr>
</tbody>
</table>
This project will contribute new, fundamental modeling linkages and capabilities in the modeling and assessment of food deserts. Activities are briefly summarized in the following tasks with timeline:

Task 1: Create a geo-database to store, analyze and manage heterogeneous spatiotemporal data of natural systems, human systems and agent-based coupling systems (Year 1)

Task 2: Develop biophysical and socio-economic models at local scales (Years 1-2)

Task 3: Integrate/couple the modeling systems using multi-agent simulation (MAS) approach. Test the system and establish a baseline for exogenous and endogenous policy design scenarios and education activities (Years 1-3)

Task 4: Design and develop educational materials and conduct training sessions (Year 3)

9.0 Broader Impacts

We are establishing pioneering effort to create a transformative platform coupling human systems and natural systems in understanding food desert issues particularly for low-income and underrepresented neighborhoods in three geographically diverse areas. This multidisciplinary research project involves researchers and students from two HBCUs in North Carolina. The project impacts well beyond improved understandings of the fundamental science in food desert issues in two critical areas: (1) the delivery of direct policy-relevant information for one of the most increasing complex problems in the United States, (2) the training of underrepresented students at both undergraduate and graduate levels (direct educational benefit), and education of stakeholders. Increased participation by underrepresented groups will be realized through the collaborative partnership with NC Cooperative Extension, National eXtension System, and the Center for Environmental Farming Systems (CEFS) (co-PI Liang is the director of CEFS). Results will be presented at national and international conferences and published in peer-reviewed journals. Elements of project activities and outcomes will be incorporated into existing undergraduate courses. Project activities will result several masters’ theses and doctoral dissertations. Outreach materials will be developed to conduct training workshops through NC Cooperative Extension, National eXtension System, and CEFS. The project will also create an e-library for project-related data, models, publications, etc., at the eXtension Community of Practice website. Project outcome will be shared with USDA Food Desert Locator team to enhance and support their ongoing efforts in this area.

10.0 Results from Prior NSF Support

- **PI Manoj Jha; GP-EXTRA: Pathways to atmospheric science through immersion in geoscience research** (Co-PI, EAR-1600415, $477,594, 2016-19). **Intellectual merit:** The proposed program provides year-long academic-year geosciences research experience for cohorts of eight undergraduate students competitively selected annually (24 total students). **Broader impact:** NCA&T as an HBCU with over 85% minority student enrollment provides the pool of minority students for training in the geosciences who can then address the issues of severe weather impacts in disadvantaged communities. The program has hosted 15 students so far in the program.

- **Co-PI Greg Monty; NSF INCLUDES DDLP: EMERGE in STEM (Education for Minorities to Effectively Raise Graduation and Employment in STEM)** (PI, INCLUDES – 1744477, $300,000, 2018-19). **Intellectual Merit:** Innovative and transformative collective-impact model for STEM education, grades 4-12. Focused on how career knowledge and exposure can broaden participation of underrepresented minorities (URMs) in the STEM pipeline to the workforce. **Broader Impacts:** Broaden participation: engages URM/women (~12,000+ students). Societal benefits/outcomes will include: educating Deaf students; helping grade 4-12 teachers and administrators incorporate additional STEM tools; bringing parents/community directly into education process; and increasing collaboration between public, private, and university organizations.
References cited


