ABSTRACT

Title of Dissertation: A DECISION SUPPORT SYSTEM FOR THE SPATIAL CONTROL OF INVASIVE BIOAGENTS

Luc Hebou, Doctor of Philosophy, 2010

Directed By: Dr. Hubert J. Montas
Fishell Department of Bioengineering

A Decision Support System (DSS) is developed and applied to the spatial control of invasive bioagents, exemplified in this study by the resident Canada goose species (*Branta Canadensis*) in the Anacostia River system of the District of Columbia. The DSS incorporates a model of goose movement that responds to resource distribution; a two-compartment Expert System (ES) that identifies the causes of goose congregation in hotspots (Diagnosis ES) and prescribes strategies for goose population control (Prescription ES); and a Geographic Information System (GIS) that stores, analyzes, and displays geographic data.

The DSS runs on an HP xw8600 64-bit Workstation running Window XP Operating System. The mathematical model developed in this study simulates goose-resource dynamics using partial differential equations – solved numerically using the Finite Element Method (FEM). MATLAB software (v.7.1) performed all simulations.

ArcGIS software (v. 9.3) produced by Environmental Systems Research Institute (ESRI) was used to store and manipulate georeferenced data for mapping, image processing, data management, and hotspot analysis.

The rule-based Expert Systems (ES) were implemented within the GIS via ModelBuilder, a modular and intuitive Graphical User Interface (GUI) of ArcGIS software. The Diagnosis ES was developed in three steps. The first step was to acquire knowledge about goose biology through a literature search and discussions with human experts. The second step was to formalize the knowledge acquired in step 1 in the form of logical sentences (IF-THEN statements) representing the goose invasion diagnosis rules. Finally, in the third step, the rules were translated into decision trees. The Prescription ES was developed by following the same steps as in the development of the Diagnosis ES, the major difference being that, in this case, knowledge was acquired relative to goose control strategies rather than overpopulation causes; and additionally, knowledge was formalized based on the Diagnosis and on other local factors.

Results of the DSS application indicate that high accessibility to food and water resources is the most likely cause of the congregation of geese in the critical areas identified by the model. Other causes include high accessibility to breeding and nesting habitats, and supplementary, artificial food provided by people in urban areas. The DSS prescribed the application of chemical repellents at feeding sites as a goose control strategy (GCS) to reduce the quality of the food resources consumed by resident Canada geese, and therefore the densities of geese in the infested locations. Two other prescribed GCSs are egg destruction and harvest of breeding adult geese, both of which have direct impacts on the goose populations by reducing their densities at hotspots or slowing down their increase. Enclosing small wetlands with fencing and banning the feeding of geese in urban areas are other GCSs recommended by the ES. Model simulations predicted that these strategies would reduce goose densities at hotspots by over 90%. It is suggested that further research is needed to investigate the use of similar systems for the management of other invasive bioagents in ecologically similar environments.

Keywords: DSS, resident Canada goose, Spatial control, Model, Expert System, GIS.

A DECISION SUPPORT SYSTEM FOR THE SPATIAL CONTROL OF INVASIVE BIOAGENTS

By
Luc Hebou

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2010

Advisory Committee:
Dr. Hubert J. Montas, Chair/Advisor
Dr. James Dietz
Dr. Paul Leisnham
Dr. Adel Shirmohammadi
Dr. David Tilley

DEDICATION

To my mother and late father, who could not read or write, but who farmed hard – sacrificing all they had so I could go to school.

To my very dear wife, Dr. Annick Hebou, and my beloved children Addy, Brian, and Joyce, whom I so much missed during times spent both at work and on campus.

May this achievement comfort you all!

ACKNOWLEDGEMENTS

My heartfelt appreciation goes to my Advisor, Dr. Hubert J. Montas, whose guidance, patience and lessons mentored and strengthened me during the years spent on this research. Dr. Montas' advice and availability during and after office hours are just a few of the numerous qualities I admire and respect deeply.

I owe so much to Dr. Adel Shirmohammadi, for being such a good listener and humble professor. His advice and sense of humor encouraged me and raised my self-esteem every time we met.

I would also like to express my profound gratitude to my other committee members: Dr. James Dietz, Dr. David Tilley, and Dr. Paul Leisnham for their kind advice and positive recommendations made to improve this research.

I am very thankful to USDA APHIS, and particularly to Dr. Ken Seeley, my work supervisor, for the good working environment and training opportunities he offered to me.

I am grateful to my sister, Yvonne, who has responded promptly whenever I needed her to help with the children. Similarly my gratitude goes to the families and friends whose support and prayers are unforgettable: the Tangun family; the Nyassi family; the Sileu family; theYonta family, and Gaelle Yonta in particular; the Nguewou family, and my mother-in-law in particular; the Chikando family; my Metropolitan AME Church family; and Dr. J.R. Kouatchou, Sheila Coleman Castells, Lea Clarisse, and Tomy Tchatchou.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1:
INTRODUCTION

The spread of invasive species in natural and agricultural systems, and the proliferation of infectious diseases along with their vectors in human environments are some of today's most pressing concerns for ecologists and public health specialists in the United States and other nations.

Ecologists are concerned about biological invasions by exotic agents, and their threats to native species and ecosystems (Mack *et al.*, 2000). According to Pimentel *et al.* (2000), an estimated 50,000 exotic species have been introduced into the United States, thousands of which have escaped into the natural environment. These plants and animals are either intentionally or accidentally transported from one geographic region to another (Greer and Terlizzi, 1999), where they can establish, naturalize, and spread rapidly (Rejmanek, 1989) – outcompeting native species – and causing economic or environmental harm, or harm to human health (Clinton, 1999). In the United States, the invasion of exotic species is responsible for 42% of native species designated as threatened or endangered, and it costs the United States approximately $137 billion annually to manage invasive species. (Pimentel *et al.*, 2000; 2001).

Similarly, public health specialists are concerned about the spread of outbreak diseases and their causal agents. HIV/AIDS is a classical example and its spread and transmission have been modeled in a variety of settings (Lui, 1989; Salomon *et al.*, 2001).

Additional examples of pandemics include the severe acute respiratory syndrome (SARS) outbreak that killed hundreds in China; the highly pathogenic strain of avian flu (H5N1) that threatened millions in Europe and Asia (WHO, 2003); and the emergent strain of swine flu (H1N1) that infected hundreds in the United States and thousands worldwide (CDC, 2009; WHO, 2009).

Like ecologists and public health experts, military tacticians worry about weapons of mass destruction (such as anthrax, smallpox, and plague) that can seriously harm people, animals, and crops if released into the environment by terrorist organizations (Takafuji *et al.*, 1997). Such bioagents, in the form of spores and toxins, can disperse rapidly through air, water, or other mediums causing significant damages if not controlled spatially.

Developing and understanding the dynamics of invasion of new territories by biological agents and how an invasion varies spatially in relation to resource distribution is critically important prior to implementing control strategies (Salomon *et al.*, 2001). Making sound decisions about what strategies to implement and, more importantly, where and when to apply the strategies, requires the use of adequate decision-making tools. The control of resident Canada goose (RCG) in the Anacostia system is an example related to wildlife management. In this case, decisions related to goose chasing, habitat modification and other indirect control methods (Starfield and Bleloch, 1991) have been made over the years to address overpopulation issues but without success.

In the Anacostia River system, located in the District of Columbia, RCG management has included some of these practices.

These practices have not been (fully) successful because they have attempted to address the problems caused by resident geese without necessarily identifying and eradicating the causes of goose abundance in the first place. Such causes may vary spatially and temporally, and their identification is an important precursor to the development of an effective management plan where control strategies are varied spatially in accordance with the spatial variation in goose abundance causes (Montas, 2004).

The overall goal of this study was to design and build a Decision Support System (DSS) suitable for developing spatial control plan for invasive bioagents in areas where they have the potential to spread. Such tools could assist landowners and resource managers in their decision-making about the types of treatments or management strategies they should apply to control invasions such as the RCG problem in the Anacostia River system. The DSS developed in this study compiles information from raw data, documents, human knowledge, and predictive models used to identify and solve biological invasion problems. It provides support for hotspot identification, selection of appropriate spatial control strategies and verification of the resulting control plan. To do this, the system combines GIS, detailed models and Expert Systems.

This dissertation has seven chapters and employs the following structure:

Chapter 1: Introduction. An overview of the invasion problem and the need to control the spread of biological agents. This chapter also briefly describes the content and structure of the dissertation.

Chapter 2: Literature Review. A survey of published research relevant to this study.

Chapter 3: Objectives. The general goals and detailed objectives of this study.

Chapter 4: Presentation of the Study Area. A description of the human environment, land use, and physical environment of the study area, including the abiotic and biotic characteristics. This chapter also describes the approaches used to survey resident Canada geese and develops the image data discretized and analyzed in the goose model (Chapter 5).

Chapter 5: Modeling Canada Geese Dynamics. A literature review of previous scientific work on the simulation of ecological processes. This chapter also describes how the goose model was developed, pre-processed, evaluated, solved, and analyzed.

Chapter 6: Combining the Model, Expert System, and GIS Technology to Manage Resident Geese. A review of the biology of the Canada goose species, the types of conflict and damage caused by resident Canada geese in the human environment, the current regulatory framework, and some management options. This chapter also describes the tools and procedures used to develop, run and test the decision support framework, with a focus on hardware and software, data acquisition, and data implementation and representation. Finally, the chapter includes a discussion of the Goose Control Strategies recommended by the DSS, and the testing, verification, and validation of the DSS results.

Chapter 7: Summary and Conclusion. A summary of the research as a whole. This chapter discusses some of the limitations of this research, and provides recommendations that could be used to improve similar studies in the future.

CHAPTER 2:
LITERATURE REVIEW

There are five sections in this literature review. The first section examines the issues of biological invasions in natural systems. It discusses both the beneficial and the problematic aspects of invasive species through a few examples. The second section describes the dynamic processes by which bioagents move in space, and discusses the different types of formulas used to model these processes and the numerical techniques employed to solve such models. The third section provides an overview of Expert Systems, and particularly their usefulness in the diagnosis of problems and the prescription of appropriate solutions. The fourth and last section discusses the Geographical Information System and how this technology and other decision-making tools are used to perform spatio-temporal analyses.

2.1 The Problem of Biological Invasions in Natural Systems

Clinton (1999) defines invasive species as those “alien species whose introduction does or is likely to cause economic or environmental harm to human health.” According to Ray (2005), any species removed from its native range has the potential to become invasive.

Within a species’ normal range, predation, disease, parasites, competition, and other natural controls act to keep population levels in check. Once released from these controls, a species develops the potential to reach levels that interfere with or displace local fauna and flora (Torchin *et al.* 2003; Wolfe, 2002).

Invasive species have been both beneficial and problematic. Beneficial aspects include (Bjergo *et al.,* 1995): enhancing recreational opportunities such as sport fishing or hunting, which contributed an estimated $24 billion in expenditures to the U.S. economy in 1991; providing reliable and high quality food via mariculture or rearing; and aesthetically improving the environment via the aquarium industry. For instance, non-native zebra mussels have filtered intense algae blooms from large quantities of water (Cohen, 1992).

Another example of the beneficial side effects of invasive species is the weed control carried out by the golden apple snail *Pomacea canaliculata*, which is viewed by some as one of the world's 100 worst invasive alien species (Joshi *et al.*, 2005a, b). In Hawaii, this freshwater mollusk spread widely in the 1990s causing significant damage to taro (Cowie, 2002). However, this snail has also shown promise as an agent for paddy weeding in the transplanted rice systems of Japan, where two to three snails per km^2 area have successfully controlled rice weeds (Okuma *et al.*, 1994a). This "biological weeder" is now popular in Asia among rice and organic crops growers (Wada *et al.*, 2002).

Many invasive species are exotic (non-indigenous), and are capable of threatening the ecosystems where they have been accidentally or intentionally introduced (Ray, 2005). Like non-point source pollutants, invasive species can be diffuse (spatially distributed) or intermittent (sporadic, non-continuous) with respect to time (Montas, 2004). Therefore, the spread of such agents could be a serious threat to native ecosystems (Wilcove *et al.*, 1998).

Some of the best-known examples of invasive species in the United States are:

Africanized Honeybee (*Apis mellifera scutellata*); Asian Citrus Psyllid (*Diaphorina citri*); Asian Long-Horned Beetle (*Anoplophora glabripennis*); Asian Tiger Mosquito (*Aedes albopictus*); Cactus Moth (*Cactoblastis cactorum*); Chillip Thrips (*Scirtothrips dorsalis*); Citrus Longhorned Beetle (*Anoplophora chinensis*); Common Pine Shoot Beetle (*Tomicus piniperda*); Emerald Ash Borer (*Agrilus planipennis*); European Gypsy Moth (*Lymantria dispar*); European Spruce Bark Beetle (*Ips typographus*); Formosan Subterranean Termite (*Coptotermes formosanus*); Giant African Snail (*Achatina fulica*); Glassy-Winged Sharpshooter (*Homalodisca *coagulata*); Hemlock Woolly Adelgid (*Adelges tsugae*); Light Brown Apple Moth (*Epiphyas postvittana*); Mediterranean Fruit Fly (*Ceratitis capitata*); Mexican Fruit Fly (*Anastrepha ludens*); Pink Hibiscus Mealybug (*Maconellicoccus hirsutus*); Red Imported Fire Ant (*Solenopsis invict*a); Russian Wheat Aphid (*Diuraphis noxia*); Silverleaf Whitefly (*Bemisia argentifolii*); Sirex Woodwasp (*Sirex noctilio*); Soybean Cyst Nematode (*Heterodera glycines);* Brown Tree Snake (*Boiga irregularis*); Cane Toad (*Bufo marinu*s); European Starling (*Sturnus vulgaris*); and Wild Boar (*Sus scrofa*) (USDA APHIS, 2010; and Greer and Terlizzi, 1999).

Invasive species are detrimental to the U.S. economy and environment (Clinton, 1999 and Pimentel *et al.*, 2001). For instance, economists estimate the financial loss caused by the effect of invasive exotic species on U.S. natural resources at nearly $137 billion annually (Pimentel *et al.*, 2000). The situation has resulted in the passage of the Non-indigenous Acquatic Nuisance Prevention and Control Act of 1990 (amended in 2005).

The act mandates the development and implementation of a comprehensive national program to prevent the introduction, and to monitor and control the dispersal, of nuisance invasive species in U.S. natural systems (HR, 2005).

Gene flow from cultivated, to wild, relatives is another major aspect of biological invasion that concerns ecologists. Transgenes, escaped from farms, can cause negative impacts in wild ecosystems by affecting ecological processes and biological diversity when they become particularly dominant in number (Difasio *et al.*, 2004).

A review of studies focused on the invasiveness of certain bioagents provides a useful conceptual framework with which to formulate the biological invasion equations in a population dynamic modeling context. It also allows the GIS implementation of the diagnosis tool (for identifying the causes of biological invasions) and the prescription tool (for recommending appropriate control and management strategies).

2.2 The Nuisance Resident Canada Geese

Canada geese (*Branta canadensis)* are wild birds natural to Arctic and temperate regions of North America, but not natural along the Anacostia River **(**McKindley-Ward, 2006). Harris (2002) indicates that the Canada goose represents the most widespread and abundant goose species in North America, with many different subspecies or races. The giant Canada goose (*Branta canadensis maxima*), for instance, is a sub-species that was introduced from the Midwest **(**McKindley-Ward, 2006). There are two population types based upon mobility – one is migratory and the other is non-migratory (called "resident" geese).

The migratory geese, unlike the resident ones, usually leave the Mid-Atlantic region in March, heading north, toward their breeding grounds around Hudson Bay (Canada), where they nest and raise their young over the summer. At mid-Fall, as the weather turns cold in northern Quebec (Canada), these birds return south to spend the winter in ice-free latitudes. Unfortunately, many of these geese do not return to their original northern locations, for many reasons summarized by USFWS (2009) as follows:

1. they live in temperate climates with relatively stable breeding-habitat conditions and low numbers of predators;

2. they tolerate human and other disturbances;

3. they have a relative abundance of preferred habitat (especially those located in urban/suburban areas with current landscaping techniques);

4. they fly relatively short distances to winter compared with other Canada goose populations; and

5. the virtual absence of waterfowl hunting in urban areas provides additional protection to those urban portions of the resident Canada goose population.

Resident Canada geese originated from wild stocks released on the East Coast decades ago for hunting programs (Harris, 2002), which may have contributed to the loss of some wild habits (such as the ability to travel long distances, and their generalist diet).

Once hunted – in addition to the factors listed above (USFWS, 2005) – many geese moved to the continental United States (naturally by migration, or by human introduction) and ended up staying year-round in their new locations, where their populations have grown exponentially in recent years (Ankney, 1996). This situation creates regular conflicts with humans and challenging management efforts. These conflicts involve property damage, concerns about human health and safety, and negative impacts on agriculture and natural resources. Common problem areas include public parks, airports, public beaches and swimming facilities, water-treatment reservoirs, corporate business areas, golf courses, schools, college campuses, private lawns, athletic fields, amusement parks, cemeteries, hospitals, residential subdivisions, and along or between highways. Property damage usually involves landscaping and walkways, most commonly on golf courses, parks, and waterfront property. In parks and other open areas near water, large goose flocks create local problems with their droppings and feather litter (Conover and Chasko, 1985; Manny *et al.*, 1994; USFWS, 2009; DOI FWS, 2006; and USDA APHIS, 2009).

In the District of Columbia and Maryland, the Canada goose species is one of the top 10 nuisance pests (USDA APHIS, 2009), and is viewed by many as an *invasive species* (Bergman *et* *al.*, 2000; MISC, 2003; MISC, 2005; Hutchinson, 2010). Invasive species are “alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health” (Clinton, 1999). Bergman *et al.* (2000) indicate that 29 U.S. states and territories have requested federal assistance in controlling these invasive pests.

One specific illustration of the economic impact of geese on the environment is the Kingman Marsh restoration project in the District of Columbia, where resident Canada geese had eaten “about $400,000 worth of newly-installed plants, reducing the vegetated cover to one-third of its intended size (that is, from 40 acres to less than 15 acres)” **(**McKindley-Ward, 2006). In addition to devouring swathes of wetland plants, these “resident geese hang out on mowed lawns near water to eat nutrient rich turfgrass, defecating frequently, and fouling such places as the historic Langston Golf Course and recreational fields along the Anacostia (McKindley-Ward, 2006).

2.3 Modeling the Population Dynamics of Invasive Bioagents

Some managers have long drawn conclusions from raw data, usually without prior quantitative analysis based on appropriate modeling tools that predict the dynamics of such data in the future (Murty, 2005). Such “manual method of making decisions” is subjective, and it could even lead to errors and bad decisions, thus the importance of models.

The web-based Business Glossary defines *model* as an abstraction of a real-life system used to facilitate understanding. The field of Population Biology uses mathematical formulas and equations to simulate – or model – ecological processes for decision-making.

Mathematical models serve many purposes including:

1. to find an optimal solution to a planning or decision problem;

2. to answer a variety of *what-if* questions;

3. to establish understandings of the relationships among the input data items within a model; and

4. to attempt to extrapolate past data to derive meanings.

Models can serve as single decision-making tools, but they can also be associated with other systems in order to maximize benefits. For instance, mathematical models could be associated with GIS or Expert Systems (or with both GIS and Expert Systems) in order to predict the dynamics of entities being modeled, identify causes of any particular problems, and prescribe solutions for such problems (Montas, 2004).

Techniques used in modeling include linear programming, computer simulations, regression analyses, and partial differential equations. Several approaches, either individual- or population-based techniques, model the spatio-temporal dynamics of bioagents. This study focuses on a population-based technique that uses biomass density-dependent variables, because of its analogy to transport modeling approaches.

2.3.1 Movement of Bioagents

Montas (2004) defines "transport" as a process by which biological agents move, or are moved, from one place to another within a bioenvironment. There are three major categories of transport processes, including:

Diffusion – Bioagent entities (*e.g.,* molecules, algae, animals) move randomly by Brownian motion, *i.e.*, they "bounce off" one another and end up farther and farther from their initial position, causing gradual spreading of the bioagent plume (*e.g.,* pollutant cloud, herd) out from its center of gravity;

Advection – Bioagents are either carried by a moving medium (air or water) in which they are dissolved, suspended or ingested, or they move under their own will in a specific direction (*e.g.,* direction of increasing food supply). In either case, this displacement causes a movement of the center of gravity of the bioagent "plume;"

Dispersion – Bioagents are advected in a heterogeneous field (*e.g.,* heterogeneous flow field, or heterogeneous resource field, causing heterogeneous movement) with high or low velocities. They simultaneously diffuse into and out of zones of varying velocities, speeding the spread of the bioagent plume about its center of gravity faster than occurs by diffusion alone (the center of gravity moves at the rate determined by the advective process).

In the transport processes, difference equations are used to model bio-pollutants as a group rather than as an individual agent. Similar approaches are used in population-based models, which deal with groups of organisms.

2.3.2 Individual-based Models

Individual-based models (IBMs), also known as entity- or agent-based models, describe how energy, assimilated from feed by individual members of a population, is distributed between growth, maintenance, development and reproduction (Kooijman, 2000, and Alver *et al.*, 2006). These individuals might represent plants and animals in ecosystems.

IBMs typically consist of an environment or framework in which the interactions occur, and some number of individuals defined in terms of their behaviors (procedural rules) and characteristic parameters (Reynolds, 1999).

In an individual-based model, the characteristics of each individual are tracked through time, whereas in population-based models, the characteristics of the entire population are averaged together and the model attempts to simulate changes in these averaged characteristics for that whole population (Reynolds, 1999).

IBMs allow ecologists to explore – using computer simulations – how properties of populations and ecosystems might evolve from the characteristics and behaviors of individual organisms. In other words, individuals are viewed as the building blocks of ecological systems, whose properties and behaviors determine the properties of the system they compose (Grimm and Railsback, 2005). Individual-based systems allow each agent to have its own set of internal state variables, affected by its own history, and therefore allow for spatial locality in the dynamics (Hiebeler, 1994).

In their study of the population dynamics of the endangered red-cockaded woodpecker (*Picoides borealis*), Letcher *et al.* (1998) developed an individual-based, spatially explicit simulation model. This model combined demographic data from a long-term study, with a description of the spatial location of the species' territories. From this study, sensitivity analysis of demographic parameters revealed that population stability was most sensitive to changes in female breeder mortality, mortality of female dispersers and the number of fledglings produced per brood. Population behavior was insensitive to initial stage distribution, and reducing the initial number of birds by one-half had a negligible effect.

Most importantly, the authors found that the spatial distribution of territories had an effect on response to demographic stochasticity, and that populations were stable when territories were highly aggregated. When territories were highly dispersed, more than 169 territories were required to achieve stability. While such an approach is worthy of further development, the results indicate the importance of considering the spatial distribution of territories in management plans.

Kreft *et al.* (1998) developed BacSim, a generic, quantitative, spatially explicit, individual-based model that simulates growth and behaviour of bacteria. This object-oriented program is an extension of Gecko, an ecosystem dynamics model that uses the Swarm toolkit for multi-agent simulations. The authors studied the growth of a single *E. coli* cell into a colony. The potential of this approach was in relating the properties of cells (microscopic individual entities) to the properties of biofilms (macroscopic and complex systems). This model described bacterial properties including substrate uptake, metabolism, maintenance, cell division, and death at the individual cell level. With the aim of making the model easily applicable to various bacteria under different conditions, the model used as few as eight readily obtainable parameters, which researchers could randomly vary. For substrate diffusion, they used a 2-D diffusion lattice; for a conceptual model of cell division, they used growth-rate-dependent cell size variation. For maintenance, reseachers used the Herbert model (constant specific rate of biomass consumption), and for substrate uptake, they used the Michaelis-Menten or the Best equations.

The simulator output faithfully reproduced all input parameters. When maintenance and uptake rates were proportional to either cell mass or surface area, the authors were able to compare growth characteristics. They proposed a new generic measure of growth synchrony to quantify the loss of synchrony due to random variation of cell parameters or spatial heterogeneity. Variation of the maximal uptake rate completely desynchronized the simulated culture, but variation of the volume-at-division did not. Thus, a new measure for spatial heterogeneity (the standard deviation of substrate concentrations as experienced by the cells) was introduced. Spatial heterogeneity desynchronized population growth by subdividing the population into parts, synchronously growing at different rates. At a high enough spatial heterogeneity, the population appeared to grow completely asynchronously.

Pettifor *et al.* (2000) have developed a spatially explicit, individual-based behavioral model that predicts the response of two migratory goose populations to both natural and humaninduced environmental changes. The two arctic-breeding goose populations, Barnacle goose (*Branta leucopsis)* and Brent goose (*Branta bernicla)*, have been the subject of increasing conflict with agricultural interests. The authors developed this model by addressing two issues in the application of such models: the need to adopt a large-scale spatially explicit approach, and the need to consider the year-round dynamics of animal populations.

This study showed a good agreement between empirically derived and model-generated density-dependent functions; of seasonal patterns of the distribution and movement of populations within and between sites; and of energy reserve levels within a population. However, sensitivity analyses highlighted the importance of accurate parameter estimation with respect to the predictions of such models, and the potential flaws in the predictions of existing models that had not adopted a spatially explicit approach when dealing with wide-ranging migratory populations. These simulations predicted a decline of both Barnacle goose and Brent goose populations following habitat loss in their winter or spring-staging sites. These simulations also suggested that Barnacle geese might be less vulnerable to winter habitat loss than Brent geese, reflecting, therefore, the relative strengths of the density-dependence of productivity and winter mortality in the two models and providing a clear illustration of the need for a year-round approach to animal population dynamics.

Goss-Custard *et al.* (2006) developed a behavior- and individual-based model that tests the response of shorebird mortality to habitat loss. The model aimed at predicting the change in winter mortality of shorebirds following the removal of intertidal feeding habitat. After an adjustment of calibration parameters to the level required for replicating the observed mortality rate before habitat loss, the authors were able to obtain a mortality prediction increase of 3.65%, which compared with the observed increase of 3.17%. The findings confirmed the implication that mortality was density-dependent by predicting mortality over a range of bird densities.

Further simulations showed that the density dependence was due to an increase in both interference and depletion competition as bird density increased. Others suggested that an additional area of mudflat (equivalent to 10% of the area that had been lost) would be needed along the migration route to return mortality to its original level.

The results of these simulations suggest that (1) the chosen calibration procedure was effective; (2) where no new fieldwork is required, despite being parameter rich, a behavior-based IBM could be parameterized quickly and cheaply; and (3) that behavior-based IBMs could be used to explore system behavior (such as the role of depletion competition and interference competition in density-dependent mortality).

Hellweger (2008) has studied the spatially explicit individual-based modeling of planktonic microorganisms (bacterioplankton and phytoplankton) using a "fixed super-individual density." In general, using a fixed representative number (the number of individuals represented by a super-individual) results in a lower computational resolution (number of super-individuals) at times and in areas of low individual densities, which is undesirable when (a) large spatio-temporal gradients exist and (b) variability in state variables or behavior at low densities is high. In order to solve such problems the author used a local method that maintained an approximately constant super-individual density in time and space.

In this study, each spatial model segment had a local super-individual population that was resampled when the number decreased or grew outside user-specified bounds, or when the variance of the representative numbers exceeded a user-specified threshold. The local method was evaluated quantitatively against the analytical solution, and qualitatively in a biogeochemical phytoplankton model applied to a point source nutrient discharge into a river. The author used a system called iAlgae – an individual-based phytoplankton framework – to evaluate the model. The applications demonstrate that the local method resulted in a spatially uniform, or density-independent, relative error, and it was computationally more efficient at controlling relative error at low densities. However, for the same total number of super-individuals, it was computationally more demanding and therefore less efficient at controlling absolute error.

IBMs have been used more and more in ecology, thanks to growing technology in recent years; but these models have faced criticisms due to the weakness of conclusions based on simulation as compared to analytical results of other models (Hiebeler, 1994). Other gaps and weaknesses of this modeling approach are described in Grimm and Railsback (2005) as follows:

1. The complexity of IBMs, which "imposes a heavy cost compared with the other model types" in understanding, testability, data requirements, and generality.

2. The requirements of IBMs, which some have criticized as too demanding in terms of data, particularly adequate or sufficiently precise parameter values, which are unfortunately difficult to obtain in ecology.

3. The uncertainty and eror propagation of data available to parameterize IBMs – especially if the number of these parameters is high, which could lead to a potential risk of error propagation, and thus the uselessness of IBMs.

A lack of standards, given that most IBMs have been built from scratch using ad hoc assumptions not guided by general concepts. IBMs have been controversial, which makes them difficult to compare and could be preventing a more coherent development of this approach.

Comparatively, in the population-based approach, for instance, equations describe the local dynamics, where assumptions are in general familiar and noncontroversial.

2.3.3 Population-based Models of Interacting Bioagents

Many authors (*e.g.,* Deijfen, 2003) define the population-based model as a continuum growth model that describes the spread of an entity referred to as an invasion. Continuum-based population models for invasive species are usually nonlinear reaction-diffusions such as Fisher-Kolmogorov equations (Baeumer *et al.,* 2008).

These models, based on partial differential equations (PDE), have been used to describe quadratic growth coupled to Brownian motion (Okubo, 1980; Hastings, 1996; Shigesada and Kawasaki, 1997; Keitt *et al.,* 2001; Arditi *et al.*, 2001; and Neubert and Parker, 2004).

Fisher's PDE type models also have been widely used to describe the spread of genes in a population (Fort and Mendez, 2002), the spread of an epidemic (Murray, 1989), and combustion waves (Ratanov, 2004).

The idea is to describe a function indirectly, by a relation between itself and its partial derivatives, rather than writing down a function explicitly. The model can be written as a single equation (single species population models) or as a system of equations describing the dynamics of two or more entities (interacting population models).

Population models for a single species

Single species population models are described as the dynamics of a species within the population of concern. For instance if N (t) represents the population of a certain species at time *t*, then the rate of change

$$\frac{\partial N}{\partial t} = births - deaths + migrations \tag{2.1}$$

is the conservation equation for that population, where migrations include both immigration (*i.e.*, the introduction of new individuals into the population) and emigration (*i.e.*, the departure of individuals from the population).

The simplest form of this model would have no migration, and the birth and death terms would be proportional to N, that is (Malthus, 1798):

$$\frac{\partial N}{\partial t} = bN - dN \qquad \Rightarrow \qquad N(t) = N_0 e^{(b-d)t} \tag{2.2}$$

where b, d, are positive constants and the initial population $N(0) = N_0$. Thus if $b > d$, the population grows exponentially while if $b < d$ it dies out.

This approach is unrealistic because a population cannot grow or die infinitely. Actually, there must be some adjustments to such exponential growth.

Verhust (1838, 1845) proposed that a self-limiting factor process should operate when a population becomes too large. He suggested a logistic growth described as follows:

$$\frac{\partial N}{\partial t} = rN\left(1 - \frac{N}{K}\right), \tag{2.3}$$

where r and K are positive constants.

In this model, the per capita birth rate is $r\left(1 - \frac{N}{K}\right)$ that is, it is dependent on N. The constant K is the carrying capacity of the environment, which is usually determined by the available sustaining resources.

There are two steady states for the logistic model, namely $N = 0$ and $N = K$, that is, where $dN/dt = 0$. $N = 0$ is unstable since linearization about it (that is, N^2 is neglected compared with N) gives $dN/dt = rN$, and so N grows exponentially from any small initial value. The other equilibrium $N=K$ is stable: linearization about it (that is, $(N-K)^2$ is neglected compared with

$|N-K|$) gives $d(N-K)/dt = -r(N-K)$ and so $N \to K$ as $t \to \infty$. The carrying capacity determines the size of the stable steady state population while r is a measure of the rate at which it is reached; that is, a measure of the dynamics. If we incorporated it in the time by transforming *t* to *rt*, then *1/r* would be a representative timescale of the response of the model to any change in the population.

If $N(0) = N_0$, then the solution of the equation above is

$$N(t) = \frac{N_0 K e^{rt}}{[K + N_0(e^{rt} - 1)]} \to K$$

as $t \to \infty$, and is illustrated in Figure 2.1.

If $N_0 < K$, $N(t)$ simply increases monotonically to K while if $N_0 > K$ it decreases monotonically to K. In the former case there is a qualitative difference depending on whether $N_0 > K/2$ or $N_0 < K/2$; with $N_0 < K/2$ the form has a typical sigmoid character, which is commonly observed.

In the case of $N_0 > K$ this would imply that the per capita birth rate is negative meaning the births plus immigration are less than the deaths plus emigration (in the first equation).

The point about the second equation is that it is more like a metaphor for a class of population models with density-dependent regulatory mechanisms – a kind of compensating effect of overcrowding – and must not be taken too literally as the equation governing the population dynamics.

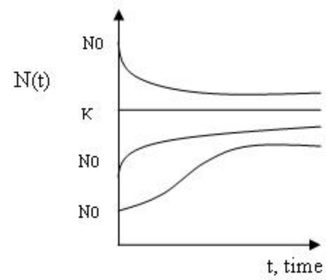

Figure 2.1 Logistic Population Growth Model for Two Case Scenarios
N_0 < K/2 and K > N_0 > K/2

In general if we consider a population to be governed by

$$\frac{dN}{dt} = f(N) \tag{2.4}$$

where *f (N)* is a nonlinear function of N then the equilibrium solutions *N** are solutions of *f(N) = 0* and are linearly stable to small perturbations if *f'(N*) < 0*, and unstable if *f'(N*) > 0.*

This is clear from the linearization about *N** by writing $n(t) \approx N(t) - N^*$,$|n(t)| << 1$ and the equation above becomes:

$$\frac{dn}{dt} = \frac{dN}{dt} = f(N) = f(N^*+n) \approx f(N^*) + n(t)f'(N^*) + \frac{1}{2}n(t)^2 f''(N^*) + \ldots, \tag{2.5}$$

which to the first order in n(t) gives, after neglecting higher order (and thus smaller) terms:

$$\frac{dn}{dt} \approx nf'(N^*) \tag{2.6}$$

The solution to this linear system is simply

$$n(t) = n(t=0)\exp\left[t\frac{df}{dN}(N^*)\right] \tag{2.7}$$

So N grows or decays accordingly as *f' (N*) > 0 or f'(N*) < 0.* The timescale of the response of the population to a disturbance is of the order of $1/|f'(N^*)|$.

For illustration let consider a system defined as:

$$\frac{dN}{dt} = f(N) = N(N-1)(N-2)(3-N) \tag{2.8}$$

Figure 2.2 can be used to deduce the stability of stationary points or steady state populations N*, which are solutions of *f (N) = 0.* Graphically plotting *f (N)* against *N* immediately gives the equilibriums as the points that intersect the N-axis.

The gradient *f'(N*)* at each steady state then determines its linear stability. However, such steady states may be unstable to finite disturbances. The gradients *f'(N*)* at *N = 0, N = 2,* are positive so these equilibriums are unstable while those at *N = 1, N = 3,* are stable to small perturbations.

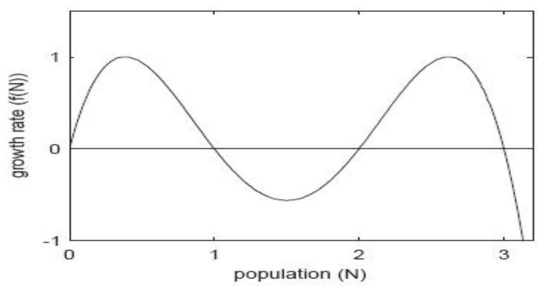

Figure 2.2 Population Dynamics Model with Four Steady States. The gradient f'(N) at the steady state, that is, where f (N) = 0, determines the linear stability.

The model is defined by

$$\frac{dN}{dt} = f(N) = N(N-1)(N-2)(3-N) \qquad (2.9)$$

Population models for interacting species

The mass action approach to modeling trophic interactions is known as Lotka-Volterra (or predator-prey) model, which describes the relationships between two species, one of which feeds upon the other one (Wangersky, 1978).

When two or more species interact, the population dynamics of each species is affected.

There are three main types of interaction (Vandermeer and Boucher, 1978):

1. *predator-prey* situations in which the growth rate of one population is decreased while the other one is increased;

2. *competition* in which the growth rate of each population is decreased; and

3. *symbiosis or mutualism*, in which each population's growth rate is enhanced.

Many scientists use a population-based approach, be it for a single or interacting species, to simulate ecological processes. Often, nonlinear partial differential equations (PDEs) have been used to predict the dynamic of such processes. For instance, considering the spread of an invasive species over time and space, Hooten and Wikle (2008) demonstrated that many insights could be gained via a spatiotemporal model that incorporates both reaction and diffusion components to predict the spread of the invasive dove in Southeastern United States. The study yielded a series of maps that approximated the extent of the dove invasion over time and space in the study area. From the analyses, the authors concluded that there was remaining variability of about 1/10 of the United States size associated with the invasion rate of species that was due to human population. This study opened doors to research targeting other factors that could potentially contribute to the spread of this pest species.

Fisher's model is a classic approach that has been successfully used by mathematical biologists to describe and predict the spread of invasive species in natural systems (Murray, 2002). In the Fisher's models and many authors (Hastings, 1996; Keitt *et al.*, 2001; and Neubert and Parker, 2004) the direct movement of the predator density is due to the advective velocity, which is assumed to be proportional to the gradient of the prey density. However, such an assumption has not always been reflected in field observations, especially in the situations where the shape of the resource gradients was sharp or coarse.

This gap makes Fisher's model less suitable for GIS-based analyses, where the densities of the resources are usually derived from land cover classes.

Therefore a slightly different approach (Fisher modified) was used in this study, which accounts for GIS features regardless the shape of the resource gradient (Arditi *et al.* 2001; Sapoukhina *et al.*, 2003; Chakraborti, 2006; and Chakraborti *et al.*, 2007).

This approach assumes that the directed movement of the predator density is determined by the velocity variation (that is, acceleration), which is proportional to the prey gradient or, in general, to the gradient of some stimulus (Arditi *et al.,* 2001).

Hastings (1996) has reviewed and made a synthesis of models that describe the dynamics of the spatial spread of invading organisms, emphasizing two apparently robust results. First, the author found that there appears to be a linear rate of spread with time. Additionally, he found that this rate is proportional to the per capita growth rate of the population when the invading species is rare.

According to the author, both results hold for a variety of single and two-species models, and the constant linear rate of spread may only hold after an initial period of slower spread. This last observation may also have important implications for understanding the rate of spread of those species – which are likely to disrupt the communities they invade.

In their study of "allee effects, invasion pinning, and species borders," Keitt *et al.* (2001) have analyzed the properties of invasion models when a species cannot persist below a certain population density known as an "Allee threshold."

The authors show that in patchy landscapes (with dynamics described by the spatially discrete model), range limits caused by propagation failure (pinning) are stable over a wide range of parameters, whereas, in an uninterrupted habitat (with dynamics described by a spatially continuous model), the zero velocity solution is structurally unstable and thus unlikely to persist in nature. This led the authors to suggest that under a wide range of plausible ecological conditions, species' ranges may be limited by an Allee effect – for example, priority effects in interspecific competition, or a scenario involving a generalist predator that might only be able to contain a prey species when the prey is rare.

Arditi *et al.* (2001) used this approach in their study of the directed movement of predators and the emergence of density-dependence in predator-prey models. Considering a bitrophic spatially distributed community consisting of prey and actively moving predators, and assuming predator reproduction and mortality to be negligible in comparison with the time scale of migration, the model developed by Arditi *et al.* demonstrated heterogeneous oscillating distributions of both species, which occured because of the active movements of predators.

Sapoukhina *et al. (*2003) have studied a reaction-diffusion-advection model for the dynamics of populations under biological control, where the control agent (predator) has the ability to perceive the heterogeneity of pest distribution.

The researchers used the advection term as the predator density movement, according to the basic prey taxis assumptions that the acceleration of predators is proportional to the prey density gradient, and that the spatially explicit approach subdivides the predation process into random movement represented by diffusion (directed movement described by prey taxis, local prey encounters, and consumption modeled by the trophic function). They were then able to show conditions under which prey taxis generates spatial patterns, and how this affected the predator's ability to maintain the pest population below some economic threshold.

Neubert and Parker (2004) studied the projecting rates of spread for *Cytisus scoparius*, a large shrub in the legume family, considered a noxious invasive species in eastern and western North America, Chile, Australia, and New Zealand. They used an integro-difference equation

(IDE), a model formulated in the 1970s to describe the spatial spread of advantageous alleles that has now been co-opted by population biologists to describe the spread of populations.

The authors reviewed how IDE models are formulated, how they are parameterized, and how they can be analyzed to project spread rates and the sensitivity of those rates to changes in model parameters.

They found that solutions to the IDE are often qualitatively similar to Fisher's model solutions, and that the IDE approach is advantageous in that the population growth and spread can be expressed on an infinite domain – unlike in the Fisher's approach, where they are restricted to a finite portion of space.

In addition, the rates of spread generated can be made quantitatively equivalent by using a normal distribution for the probability density, and a compensatory growth function for the local population density. The study allowed the authors to address some of the shortcomings of Fisher's model.

Chakraborty (2006) and Chakraborty *et al. (*2007) investigated the effect of prey-taxis on predator–prey models with *Paramecium aurelia* as the prey and *Didinium nasutum* as its predator. The logistic Lotka–Volterra predator–prey models with prey-taxis were solved numerically with four different response functions, two initial conditions and one data set. The authors showed that both response functions and initial conditions played important roles in the cyclic pattern formation, especially when diffusion in predator velocity was incorporated into the system.

The literature reviewed above shows that each modeling approach (individual-based and population-based) has its own strengths and weaknesses despite the discrepancies between the two approaches. A study of predator-prey model by Wilson (1998) describes how these discrepancies can be resolved. Wilson used various combinations of long-range dispersal for both the offspring and adult stages of both prey and predator species, providing a broad range of spatial and temporal dynamics to compare and contrast the two model frameworks. Taking the individual-based modeling results as given, two examinations of the reaction-dispersal model were made: linear stability analysis of the deterministic equations and direct numerical solution of the model equations.

The author modified the numerical solution in two ways to account for the stochastic nature of individual-based processes, which included independent, local perturbations in population density and a minimum population density within integration cells, below which the population was set to zero. These modifications introduced new parameters into the population-level model, which the author adjusted to reproduce the individual-based model results. The individual-based model was then modified to minimize the effects of stochasticity, producing a match of the predictions from the numerical integration of the population-level model without stochasticity. The study shows that whatever approach a modeler chooses, individual-based and population-based can be complementary to gain a better, and more, understanding of a population within a system.

Grimm (1999) described this assertion as follows:

> The individual-based approach is a bottom-up approach which starts with the 'parts' (*i.e.*, individuals) of a system (*i.e.*, population) and then tries to understand how the system's properties emerge from the interaction among these parts.
>
> However, bottom-up approaches alone will never lead to theories at the systems level. State variable or top-down approaches are needed to provide an appropriate integrated view, *i.e.*, the relevant questions at the population level.

From the literature reviewed above, it can be suggested that individual-based simulation models represent an idealized predator-prey system formulated at the scale of discrete individuals explicitly incorporating their mutual interactions, whereas the population-based model is a generalized version of reaction-diffusion systems that incorporate population densities coupled to one another by interaction rates (Wilson, 1998).

2.3.4 Solution Techniques for Population-based Models

The need for numerical techniques to solve population models stems from the difficulty of solving these equations analytically, except in some of the simplest cases. Problems with irregular domain geometry, space-time dependent coefficients and nonlinear parameters often require numerical techniques in order to be solved. The goal of such techniques is to obtain an approximate solution of a PDE over a domain of interest under pre-specified boundary condition (BC) and/or initial condition (IC). The solution consists of a series of numerical values, which approximate the true solution at a pre-specified and often finite set of spatial locations and times.

This is in direct contrast to analytical solutions, which consist of mathematical expression (rather than numerical values) valid over all space and time (rather than a finite set of space-time coordinates or patches), and that exactly solve a PDE problem rather than approximating it.

Finite Difference Method (FDM) and Finite Element Method (FEM) are two of the most common numerical techniques used to solve PDEs. FDM employs Taylor series expression to derive discrete approximations of spatial and temporal derivatives, which are then substituted into the model equations.

This substitution transforms the original continuous model into a system of algebraic equations that can be solved using linear algebra techniques such as Gaussian elimination or Jacobi iteration (Gardner *et al.,* 1989; Montas, 2004).

As does FDM, FEM approximates solutions of PDEs and integral equations based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations (ODEs), which are then numerically integrated using standard techniques such as Euler's method or Runge-Kutta. While in many cases FEM reduces to FDM, the most noticeable difference between these two methods is that FDM domains and equations are discretized over points, whereas in FEM, patches (contiguous regions) are used. Furthermore, FDM may be viewed as rooted in Taylor series approximations, while FEM emanates from localized polynomial expansions and error minimization principles.

Some examples of studies where the FDM approach has been used to solve PDEs are reviewed below.

Meselhe *et al.* (2005) developed a numerical model for a portion of the Lower Mississipi River using a combination of both methological approaches (finite difference and finite element) in order to provide detailed information on the spatial and temporal patterns of the River's hydrodynamics, salinity, sediment and water quality parameters.

Garvie (2007) has also used finite-difference algorithms for studying the dynamics of spatially extended predator–prey interactions with the Holling type II functional response and logistic growth of the prey.

The algorithms used were stable and convergent, provided the time-step was below a (non-restrictive) critical value. According to the author, this approach was advantageous because the dynamics of approximations of differential equations can differ significantly from that of the underlying differential equations themselves. This is particularly important for the spatially extended systems presented in this study, as they display a wide spectrum of ecologically relevant behavior, including chaos.

In the study, the author presents two high-quality finite-difference schemes that allow him to confirm a wide variety of spatiotemporal dynamics reported in the literature for spatially extended predator–prey interactions. He provides complete implementational details, so that applied mathematicians and biologists can quickly apply and adapt the numerical methods to investigate the dynamics of predator–prey interactions.

Although the finite-difference methods (Schemes 1 and 2) were subject to the same conditions that guaranteed stability and convergence, they differed somewhat in their convergence properties. Thus, using both methods together provided a useful additional test of convergence.

The U.S. Army has developed a Three-Dimensional Time-Variable Integrated-Compartment Eutrophication Model (CE-QUAL-ICM) to simulate time-varying concentrations of water quality constituents by coupling hydrodynamic and water quality components. This model incorporated detailed algorithms for water quality kinetics; interactions among state variables were described in 80 partial-differential equations that employed over 140 parameters (Cerco and Cole, 1993).

An improved finite-difference method was used to solve the mass conservation equation for each cell in the computational grid and for each state variable. The model predicted time-varying concentrations of water quality constituents. It incorporated advective and dispersive transport and considered sediment diagenesis benthic exchange (Limno-Tech, 2002).

Environmental Fluid Dynamics Computer Code (EFDC) has been developed to provide 3-D simulations of hydrodynamics and water quality components of a system (Limno-Tech, 2002). This model uses a finite-difference scheme with three time levels and an internal-external mode splitting procedure to achieve separation of the internal shear, or baroclinic mode, from the external free-surface gravity wave, or barotropic mode.

An implicit external mode solution was used with simultaneous computation of a two-dimensional surface elevation field by a multicolor successive over relaxation procedure. The external solution was completed by calculation of the depth-integrated barotropic velocities using the new surface elevation field.

MODFLOW is a computer program that numerically solves the three-dimensional ground-water flow equation for a porous medium by using a finite-difference method (Harbaugh *et al.*, 2000). The model was developed to simulate systems for water supply, containment remediation and mine dewatering. In MODFLOW, the flow region was subdivided into blocks in which the medium properties were assumed to be uniform. In plan view, the blocks were made from a grid of mutually perpendicular lines that might be variably spaced. A flow equation was written for each block, called a cell.

Several solvers were provided for solving the resulting matrix problem. Flow-rate and cumulative-volume balances from each type of inflow and outflow were computed for each time step. Groundwater flow within the aquifer was simulated in MODFLOWusing a block-centered finite-difference approach.

Kaur *et al.* (2004) have developed an integrated multi-class phytoplankton-zebra mussel ecosystem model (SAGEM) to understand the interactions between the trophic state and contaminant concentrations of a system that is perturbed by zebra mussels (*Dreissena polymorpha)*. SAGEM is a dynamic mass balance model that represents nutrients, contaminants (such as PCBs), five phytoplankton and one benthic algal functional group, zooplankton and three cohort groups of zebra mussels.

The fundamental governing principle for the model is conservation of mass in space and time. Each state variable is described by the two-dimensional advective-diffusion equation. The solution method used in the model consists of a finite-difference approximation to the derivatives of advective-diffusion equation.

The authors present two application examples of SAGEM, one that evaluates the effect of zebra mussels on total primary productivity of the system (Example 1), and another one that evaluates the effect of zebra mussels on total PCB fate and transport (Example 2). Model results of application Example 1 showed that the primary productivity of the system did not change, but the distribution of primary production shifted from a pelagic-dominated (in the pre-zebra mussel period) to a benthic-pelagic coupled system with the introduction of zebra mussels.

The authors believe that these model results are consistent with reported field studies. Model results of application Example 2 showed that the particulate matter filtration by zebra mussels has caused an increased flux of suspended particulate matter to the sediments, which has manifested itself as an increase in sediment PCB concentrations. The authors conclude that these application examples demonstrate the feasibility and utility of a multi-stressor ecosystem model such as SAGEM for aquatic ecosystem management.

Examples of studies where FEM has been used to solve PDEs are numerous. Some of these studies are reviewed below.

Gómez-Revuelto *et al.* (2007) used a two-dimensional self-adaptive FEM for the analysis of open region problems in electromagnetics. The adaptive strategy was fully automatic, and was based on minimizing the interpolation error (by using the projection of the error from a fine grid) delivering exponential convergence rates for the energy error – even in the presence of singularities.

The authors solved a low number of closed domain problems with the same matrix; the particularities due to the open nature of the problem were hidden, and self-adaptive strategies developed for conventional closed domains were used without modifications. The FEM discretization was made in terms of quadrangles/triangles of variable order of approximation supporting anisotropy and *hanging nodes*.

Gudla *et al*. (2001) described a simple algorithm for triangulating the solution domain represented in images. The goal was to generate a quadtree-based triangular mesh for finite element analysis of heterogeneous spatial data. According to these authors, the quadtree mesh generator starts by enclosing an entire domain inside an axis-aligned square (2n x 2n dimension). A *provably good mesh generation algorithm* recursively divides each node until each leaf node contains, at most, one connected component of the domain's boundary with, at most, one vertex. The algorithm then splits squares near the vertices of the domain two more times, so that each vertex lies within the buffer zone of equal size squares. Quadtree squares are then wrapped and cut to conform the boundary. Finally, the cells of the wrapped quadtree are triangulated so that all angles are bounded away from zero degree.

The proposed algorithm (imageMesher) generated quality triangular meshes with provably good angle bounds. The authors were able to illustrate real-time applications of the proposed approach, which demonstrated its ability to use the solution domain described in images to fit directly into the finite element analysis.

In their effort to simulate biochemical and environmental processes (such as plant growth and related biochemical reactions), Krol *et al.* (2009) proposed the coupling of the finite element method approach with Fuzzy models, which are used to estimate model parameters for modelling spatial distributed phenomena. This concept of fuzzy-based parameter estimation assumes that spatially distributed models represented by PDEs (such as Navier-Stokes equations) can be numerically solved by finite element method. The coupling of the Fuzzy models and FEM was demonstrated in this study by the modelling and simulation of algae growth and related eutrophication in flat water bodies (Orbetello Lake) in Italy. Results showed that expert knowledge was successfully transferred to the FEM simulation of the hydrodynamic model.

Sadegh Zadeh *et al.* (2007) developed and implemented a Galerkin-based finite element model to solve a system of two coupled partial differential equations governing biomolecule transport and reaction in live cells.

The simulator was coupled, in the framework of an inverse modeling strategy, with an optimization algorithm and an experimental time series (obtained by the Fluorescence Recovery after Photobleaching (FRAP) technique) to estimate biomolecule mass transport and reaction rate parameters. In the inverse algorithm, an adaptive method was implemented to calculate a sensitivity matrix. The researchers developed a multi-criteria termination rule to stop the inverse code at the solution. The applicability of the model was illustrated by simulating the mobility and binding of GFP-tagged glucocorticoid receptor in the nucleoplasm of mouse adenocarcinoma. The numerical simulator showed excellent agreement with the analytic solutions and experimental FRAP data. Detailed residual analysis indicated that residuals were normally distributed and uncorrelated. Therefore, the necessary and sufficient criteria for least square parameter optimization, which was used in this study, were met. The authors conclude that the developed strategy was an efficient approach to extract as much physiochemical information from the FRAP protocol as possible.

From the model solution techniques reviewed above, it could be asserted that both FDM and FEM are suitable for approximating PDEs solutions. While FDM solution is defined only at punctual locations, FEM solution is defined over the entire problem domain. Whatever method is chosen to solve PDE problems, Montas (2004) summarizes the overall process of obtaining numerical solutions to such equations in five steps:

1. define the PDE(s), solution domain, ICs, and BCs

2. discretize the domain

3. discretize the equation

4. solve the resulting matrix equation, and

5. analyze the solution (plot, interpolate, back-recalculate, etc.)

The literature reviewed in this section shows that models are important decision-making tools, which have long been used to simulate ecological processes. Models can provide useful and accurate information if they are properly chosen, well designed, and appropriately solved. However, models are not perfect, because there can be some drawbacks associated with them.

For instance, many traditional Lotka-Volterra systems (predator-prey models) are time-dependent only, and even those having spatial components built in may be designed in 1-Dimension only, or developed for homogeneous systems – which in most cases is not realistic. To close any gaps, mathematical models have been associated with other decision-making tools in order to maximize the understanding of processes before making decisions.

Examples of such decision tools that could be associated with mathematical models are expert systems and geographical information systems, which are described in the next sections.

2.4 Expert Systems

Definition

Expert Systems (ES) are computer software programs that capture the knowledge of experts in a particular field (Graham, 2003), and are capable of carrying out reasoning and analysis functions in narrowly defined subject areas at proficiency levels approaching that of a human expert (Montas and Madramootoo, 1989).

The experts are usually referred to as “domain experts” while the computer professionals who capture this knowledge in a database are referred to as “knowledge engineers”.

Structure and functions

Every expert system (Figure 2.3) consists of several parts, of which two of the most important are the knowledge base and the inference engine.

The *knowledge base* contains factual and heuristic knowledge.

Factual knowledge is the widely shared knowledge typically acquired from the literature, and that which experts in some particular field commonly agree upon. Heuristic knowledge is more experiential, judgmental, and individualistic. It is the knowledge of good practice, good judgment, and plausible reasoning in the field.

The *inference engine* is a program module into which problem-solving methods are built. These problem-solving methods, or paradigms, organize and control the steps taken to solve the problem; the inference engine manipulates and uses the knowledge in the knowledge base to form a line of reasoning. The formalization of the knowledge is based on IF-THEN rules; that is, IF a set of conditions are satisfied THEN its related problem-solving action can be taken. In other words, the Expert System would scour the database and eliminate every possibility but one, which is the most likely solution to a given problem.

The structure of IF-THEN rules is called chaining. When the chaining of the rules starts from a set of conditions and moves toward some conclusion, the method is called “forward chaining.” If the conclusion or goal to be achieved is known in advance but the path to that conclusion is not known, then backwards reasoning, and the method is termed “backward chaining.”

Although the knowledge base and inference engine constitute the principal parts of an Expert System, other features also need to be mentioned:

1. *Knowledge Acquisition* component, which helps the expert collect the data in order to engineer the knowledge bases;

2. *Explanation* component, which explains the actions to be taken, and which can range from how the final or intermediate solutions are arrived upon, to justifying the need for additional data; and

3. *Graphical User Interface*, which is the mean of communication with the end user.

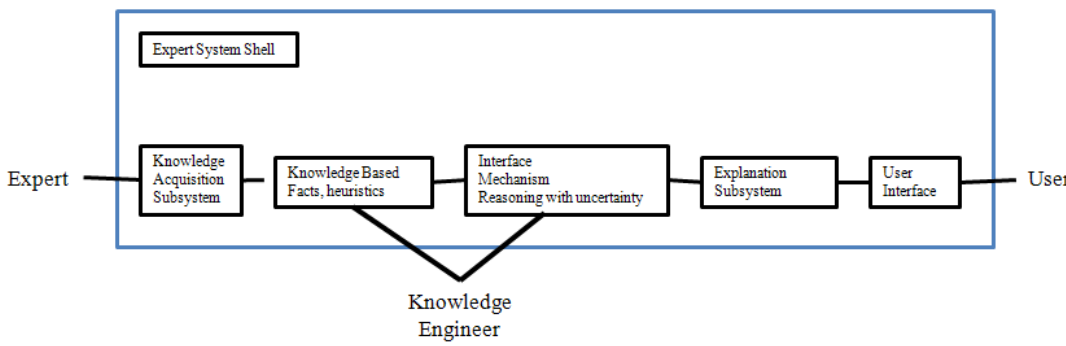

Figure 2.3 Basic structure of an Expert System (Engelmore and Feigenbaum, 1993)

Knowledge engineering

Knowledge engineering is the art of designing and building expert systems. There are two ways to build an expert system. They can be built from scratch, or built using a piece of development software known as a “tool” or “shell.”

Though different styles and methods of knowledge engineering exist, the basic approach is the same: a knowledge engineer collects knowledge from experts; he then translates the knowledge into a computer-usable language and designs an inference engine, that is, a reasoning structure that uses the knowledge appropriately. He also determines how to integrate the use of uncertain knowledge in the reasoning process, and the kinds of explanations that could be useful to the end user.

This basic approach is described in detail in Pomykalski *et al.* (1999). According to those authors, there are six key activities to be performed within the development life cycle of an expert system:

1. Problem Selection
2. Knowledge Acquisition
3. Knowledge Representation
4. Implementation
5. Testing, Evaluation, Verification and Validation; and
6. Maintenance

Applications

Expert Systems (ES) have long been applied in the engineering and manufacture of robot control (where they inter-relate with vision systems), in emergency response systems (*e.g.*, marine oil spill response operations), troubleshooting (*e.g.*, auto mechanics), and in the medical field – particularly with respect to interpreting laboratory results, or for prospecting medical diagnosis (Graham, 2003).

ES has numerous applications in agriculture, notably for controlling diseases, selecting chemicals to spray, machinery management practices, animal herd management, and weather damage recovery. Examples of studies illustrating these applications are reviewed below:

Warren (1999) has developed an Integrated Pest Management (IPM) expert system to determine potential risks of an outbreak of wheat crop pests common to Virginia. These potential outbreak risks are presented as low, medium, and high levels of risk and are presented for each of 15 wheat pests in Virginia. The system was evaluated using thirty random cropping system scenarios. By comparing expert system output with that obtained from human experts, it was shown that the expert system agreed with human expert opinions in 84% of the decisions made.

Mansingh *et al.* (2007) developed CPEST, an expert system suitable for coffee pests and disease management in developing countries. Their knowledge base contained information relevant to farmers such as climate, topography, soil type of the farm, agronomic practices, crop phonology, biology and damage potential of pests, and options available for suppressing pest populations below the economic injury levels.

The development of expert systems (ES) for dairy herd management is now possible thanks to recent advances in computer technology. According to Spahr *et al.* (1988), these dairy herd management ES are mainly used for:

1. Advising dairy farmers on management problems in a well defined, and narrowly scoped subject domain (Advisory ES);

2. assisting dairy farmers in making strategic management decisions for predicting the likely consequences of a given situation, such as that of cow or herd performance or market (Strategic Planning ES); and

3. diagnosing equipment malfunctions or determining subnormal animal or herd performance (Diagnostic ES).

Vakeva and Saarenmaa (1992) have built a consultative expert system to aid in the diagnosis of biotic damage to Scots pine *(Pinus sylvestris).* The diagnostic knowledge collected from experts and books was transferred to about 250 production rules concerning 48 damaging agents.

Uncertainties were taken into consideration by certainty factors. The diagnosis was based on site factors, tree characteristics, date, observations of symptoms and damage, and, in some cases, insect descriptions. Diagnosis was reasonably correct in 81% of 63 test cases tried by experts. Of the 25 test users, 84% considered the system at least fairly successful with typical cases, and 77% of them found the system at least quite useful in their own work. Narrowness of expertise, slowness and lack of pictures were considered as the system's shortcomings.

Mulatu (2006) has developed a Bayesian expert system (ES) that combines airborne hyperspectral imagery with terrain data and ecological knowledge of the distribution of vegetation types for the diagnosis of land covers change between 1999 and 2005 in the Islands of Schiermonnikoog, in northern Netherlands.

A Spectral Angle Mapper was used to classify the hyperspectral imagery. The expert system maps were compared with a post classification comparison method to identify the changes between the two years. An overall accuracy of 47.5% was achieved.

The application of the Bayesian ES increased the overall accuracy of the vegetation mapping compared to the Spectral Angle Mapper classification of the hypersctral imagery alone.

The change-detection results showed changes in all of the land cover types, confirming that the Bayesian ES can be used for detailed vegetation mapping and monitoring purposes. The authors suggested however, a need for a proper data calibration to verify the change results prior to implementing the method for planning and decision-making purposes.

A Learning Base System (LBS) was developed by Stockwell (1993) to enable the development of testable expert systems. Stockwell used a Bayesian classifier system as the knowledge representation, and adapted it to allow for the incremental acquisition of knowledge from both data and experts, as well as prediction and validation procedures.

The advantages and limitations of the system are described for three applications: The first application is the diagnosis of diseases in crops, illustrating knowledge acquisition by an expert in a data-poor domain; the second illustrates how LBS can be used in a geographic information system; the third is the development and testing of models for predicting wildlife density solely from data. The Bayesian classifier was shown to be a flexible formalism for implementing a wide variety of knowledge-based tasks.

The literature reviewed above demonstrates that expert systems not only diagnose problems (Diagnosis ES), but also troubleshoot and prescribe solutions to the identified problems (Prescription ES).

Both components of ES (Diagnosis and Prescription) can be developed within Geographical Information System. As a standalone system, however, ES lack the ability to predict phenomena as can models. In addition, they rely on GIS to store and display geographic data for visualization.

2.5 GIS-based Decision Support Systems

2.5.1 Geographic Information Systems (GIS)

Definition and structure

A geographic information system (GIS) integrates hardware, software, personnel, and data for capturing, storing, managing, analyzing, and displaying all forms of geographically referenced information (Montas, 2004).

This information, along with related properties, is stored in a database (geodatabase) in the form of attribute tables set with a regular structure in some machine-readable format accessed by a computer (ESRI, 2004).

There are a wide variety of geodatabases, from simple tables stored in a single file to very large databases with many millions of records, stored in rooms full of disk drives.

For example, a habitat suitability model would have several layers – such as political boundaries – on top of which are set layers of land use, land cover, hydrology, elevation, and road systems stored as shape files (ESRI, 2004).

Commonly used GIS software includes: Desktop GIS, which usually serves all GIS tasks and is sometimes classified into three functionality categories (GIS Viewer, GIS Editor, and GIS Analyst); Spatial Database Management Systems (DBMS), which are mainly used to store, analyze, and manipulate the data; and Web Servers, used to distribute maps, display data and query functionality from Server GIS over the internet or intranet.

Data acquisition and processing

Spatially distributed data can be derived from field work, maps, and satellite images obtained from government agencies and private data suppliers. The U.S. Census Bureau provides socioeconomic and demographic data, and census tract boundary files for the entire nation.

The U.S. Geological Survey (USGS) produces topographical maps for the nation, as well as land use and land cover maps that include information about ownership, political boundaries, transportation, and hydrographic data. USGS map generators include: the Global Visualization Viewer, Earth Explorer, and the Seamless Data Distribution System. NASA provides remotely sensed data from all over the world, while The National Atlas produces basic cartographic and environmental data for the American continent.

ESRI (2004) summarizes the data acquisition and processing as follows:

datasets need to be created (1) and – in case something has changed – edited (2), and then stored (3). If data are obtained from other sources they need to be viewed (4) and eventually integrated (conflation) with existing data (5).

To answer particular questions, *e.g.*, who is living in street X and is affected by the planned renewal of a power line, the data are queried (6) and analyzed (7). However, some specific analysis tasks may require a data transformation and manipulation (8) before any analysis can take place. The query and analysis results can finally be displayed on a map (9).

Data analysis

Contemporary GIS software contains many tools for spatial data analysis. The most common technique for using spatial analysis tools is through a Graphical Unit Interface (GUI). A GUI allows users to perform basic analyses pre-programmed by GIS developers. GIS scripting language permits users to extend the capabilities of the system by writing their own sets of spatial data analysis routines or models.

Montas (2004) distinguishes four steps in GIS data analysis:

1. Define the sub-region (if any) on which the analysis is to be performed (this can be an irregular area of interest - AOI, or simply the intersection or the union of data layers);

2. input the necessary data layers, attribute tables, and constants;

3. perform the analysis (computations); and

4. output the result which may be new or modified data layers, attribute tables and constants.

A GIS typically performs several types of analyses through GUI: topographic, proximity, and overlaying. Topographic analysis includes slope and aspect calculations from ground elevations stored as Digital Elevation Model (DEM). Proximity analysis permits the user to determine the distance between a feature of interest and other features within a data layer. This can be used to determine how much land would be affected by implementing buffer zones of various sizes around streams to prevent invasion for example. Overlay analysis combines data from several layers to determine the suitability, or unsuitability, of areas within a region to various activities.

For example, an overlay may consider slopes (from the topographic analysis), grass fields (from land cover analysis), and distance to streams (from the proximity analysis) to identify favorable habitats for Canada geese.

GIS Applications

GIS can be applied to many fields and used for many purposes including scientific investigations, resource management, asset management, archaeology, environmental impact assessment, urban planning, cartography, criminology, geographic history, marketing, logistics, prospective mapping, etc.

Other specific applications are described in ESRI (2004) as follows:

- Meteorologists use GIS to map weather conditions and issue warnings for counties in the path of severe storms.

- Hydrologists monitor water quality to protect public health using GIS.

- Police departments uses GIS technology to map crime areas necessary for the deployment of its personnel, and to monitor of the effectiveness of neighborhood watch programs.

- Land managers use GIS to produce planning maps for monitoring earthquakes, road and bridges conditions, natural disasters, etc.

- Electrical companies use GIS to map suitable locations for their utility circuits, in order to minimize power loss and plan the placement of new devices.

- GIS allow biologists to map the impact of construction plans on watersheds and natural critical habitats of endangered animal and plant species. It also helps build habitat suitability models for plant and animal species.

2.5.2 Decision Support Systems (DSS)

Concept and definitions

The concept of DSS is extremely broad, and its definitions vary depending on the author's point of view. Finlay (1994) defines DSS broadly as "a computer-based system that aids the process of decision-making." In a more precise way, Turban (1995) defines DSS as "an interactive, flexible, and adaptable computer-based information system, especially developed for supporting the solution of a non-structured management problem for improved decision-making. It utilizes data, provides an easy-to-use interface, and allows for the decision maker's own insights."

Other definitions fill the gap between these two extremes. For instance Druzdzel and Flynn (1999) define DSS as interactive computer-based systems that aid users in judgment and choice activities. The definition of DSS is sometimes reduced to that of knowledge-based systems referring to their ability to formalize domain knowledge so that it is amenable to mechanized reasoning. This is perhaps due to some similarities in the architecture of both systems.

Architecture and integration

While there is no universally agreed definition about what a DSS architecture should look like, Marakas (1999) and Power (2007) believe the three fundamental components of such systems are the:

1. *database*, where the information is stored;

2. *model*, which can be a mathematical equation, a graphical representation, or any other concept; and the

3. *user interface*, that is, the means by which people interact with the system (*e.g.*, data entering and data visualization).

Combining mathematical models and GIS-based expert systems in order to create a single flow architecture can be a challenging process. In their book "*Decision Support Systems: A Knowledge-Based Approach,*" Holsapple and Whinstel (1996) describe the building tools of DSS, and explain how these tools can be integrated with one another.

In a single tool system for example, *synergistic integration* makes it possible for DSS to intetrate tools, while in a multiple components system, the integration of the tools can be performed via a direct *format conversion, clipboard, or confederation*. Some examples of DSS applications are reviewed below.

DSS Applications

Decision Support Systems have been developed and applied in many areas, for instance:

Tronstad *et al.* (1993) implemented a DSS to determine optimal culling decisions in their Tucson cow ranch located in the State of Arizona. They acquired both biological data (cow fertility rate, weight, and age) and market knowledge (*e.g.*, prices) to build the system. They based their assumptions on the fact that biological factors determine a cow's ability to produce marketable products – specifically calves, and salvage value as slaughter cows. They estimated the biological factors (fertility, calf weights and slaughter cow weights) from the herd's individual cow records for the years, 1982 to 1989. They assumed that as a cow grows older, its conditions and associated fertility are likely to deteriorate; in other words, that the chance it will die within the next year or become physically unable to produce another calf increases with age. In addition, assuming that an existing cow in the herd has value for either slaughter or replacement stock, the authors were able to develop a predictive model of price movements, which was then exploited for deriving optimal culling strategies or decisions. The resulting DSS was able to prescribe whether a cow of a given age and pregnancy status should be kept or culled given the cattle prices on the market.

In wildlife management, Turner *et al.* (1994) developed a DSS (made of spatially explicit individual-based simulation model coupled with GIS) to explore the effect of fire scale and pattern on the winter foraging dynamics and survival of free-ranging elk (*Cervus elaphus*) and bison (*Bison bison*) in Yellowstone National Park.

Their Northern Yellowstone Park (NOYELP) model simulated the search, movement, and foraging activities of individual or small groups of elk and bison on a 77 020-hectare landscape, represented as a gridded irregular polygon with a spatial resolution of 1 hectare.

Simulations were conducted with a 1-day time step, for a 180-day maximum time (approximatively from the beginning of November through the end of April). Turner *et al.* (1994) found that when winter conditions were extremely mild, even fires that affected 60% of the landscape had no effect on ungulate survival during the initial and the post-fire winter. They also found that the effects of fire on ungulate survival became important when winter conditions ranged from average to severe, and that the effects were apparent in both the initial and later post-fire winters. The spatial patterning of fire influenced ungulate survival if the fires covered small to moderate proportions of the landscape (*e.g.*, 15% or 30%), and if winter snow conditions were moderate to severe. Finally, the authors discovered that ungulate survival was higher with a clumped, as compared to a fragmented, fire pattern – suggesting that a single, large fire was not equivalent to a group of smaller disconnected fires. The interaction between fire scale and spatial patterns shown in this study suggest that the knowledge of fire size alone is not always sufficient to predict ungulate survival. Winter severity played a dominant role in ungulate survival. The information obtained from this study, according to the authors, was relevant for planning and managing the Yellowstone's fires and natural resources.

Clevenger *et al.* (2002) also developed three GIS-based models for the identification of black bear (*Ursus americanus*) habitat linkages and the planification of mitigation passages across a major transportation corridor. One model was based on empirical habitat data, and the other two (opinion-based and literature-based) were based on expert information developed in a multicriteria decision-making process.

The models were validated with an independent dataset. Four classes of highway linkage zones were generated.

Class 3 linkages were found to be the most accurate for mapping cross-highway movement. Tests showed that the model, based on expert literature, most closely approximated the empirical data, both in the results of statistical tests and the description of Class 3 linkages. In addition, the expert literature-based model was consistently more similar to the empirical model than to either of two seasonal, expert opinion-based models. Among the expert models, the literature-based model had the strongest correlation with the empirical model. Expert opinion-based models were less in agreement with empirical model. The authors believe both empirical and expert models represent useful tools for resource and transportation planners charged with determining the location of mitigation passage for wildlife when baseline information is lacking and when time constraints do not allow for data collection before construction.

In the area of animal production, Jorgensen and Kristensen (1995) developed a stochastic simulation model with emphasis on management and information aspects and with a direct incorporation of the DSS as elements in the model.

Their simulation system was comprised of the herd – consisting of the animal and its biological states – the housing system or confinement, and the rest of the production system, including the managers, the workers, and all the decisions and corresponding actions that are carried out. Their simulation model was run under Windows 3.1 using Borland Pascal 7.0, a software program. This Bayesian framework enabled the combination of information from different sources in a coherent and reproducible manner (Belief Management Systems or BMS) that helps to handle registrations in animal herds.

Montas *et al.* (1999a) developed a DSS for precise BMP selection in Maryland. The implemented DSS incorporated a raster-based IMAGINE GIS (a rule-based Expert System), and a distributed parameter hydrologic model incorporated within the IMAGINE system. This hydrologic model simulated the water movement and transport of associated sediment pollutants across the landscape by treating each raster cell in associated GIS layers as an individual control volume. Control volume properties pertinent to sediment transport (such as soil properties, crop attributes, chemical application rates) were obtained from raster attribute tables. The results of the DSS implementation show that the system was efficient in providing sound prescriptions of BMPs at the field level in several watersheds in the study area.

A DSS tool similar to the one described above was developed by Djodjic *et al.* (2000) to address phosphorus management issues in a Swedish watershed. The DSS consisted of Maryland phosphorus index calculated by a GIS, a rule-based Expert System, and a non-point source pollution model.

Model simulations conducted for a selected field for a 24-year period showed that the recommended GCSs reduced phosphorus losses by 55% and sediment losses by 71% if applied from the first year.

Similar results were obtained three years later by Nejadhashemi *et al.* (2003), whose DSS was developed for phosphorus management throughout a watershed on the Eastern Shore of Maryland. The authors used four basic steps to achieve their goal:

1. identifying critical source areas using the hydrologic model;

2. determining the most probable causes for excessive "export" from each critical area using a Diagnosis Expert System;

3. using a second Expert System to prescribe appropriate GCSs for each critical area based on the corresponding diagnosis; and finally

4. running the hydrologic model with GCSs in place to verify the prescriptions.

As a result, the predicted reduction in phosphorus loading of watershed streams was 79%, which exceeded the 50% reduction goal of the analysis (Nejadhashemi et al., 2003),

Morgan *et al.* (2000) built an object oriented DSS for the management of black-tailed deer on Vancouver Island, British Columbia. They used GIS and expert systems to investigate the relationships between the deer's food quality and cover. Maps of each of the scored habitat categories were combined in the GIS to generate a composite map.

The resulting data were exported to a database, where a model equation was applied to the habitat category data in each habitat polygon for severe and mild winter scenarios. Although slow, the system allowed for the identification of a potential grazing habitat for deer spatial control.

The Agricultural Non-point Source Pollution Model (AGNPS) is an example of a model that has been coupled with GIS by many researchers. For instance, He *et al.* (2001) developed ArcView Non-Point Source Pollution Modeling (AVNPSM), an interface between ArcView GIS and AGNPS, in support of agricultural watershed analysis and non-point source pollution management. These authors used a Windows, PC-based interface consisting of seven modules (AGNPS utility, parameter generator, input file processor, model executor, output visualizer, statistical analyzer, and land use simulator). Basic input data to the interface included soil, digital elevation model, land use/cover, water features, climate, and information on management practices. Applying AVNPSM to a sample watershed showed that this DSS was user-friendly, flexible, and robust; it significantly improved the efficiency of the non-point source pollution modeling process.

Xiao (2003) also developed an integrated GIS-AnnAGNPS (Annualized AGNPS) modeling interface for non-point source pollution assessment. His goal was to facilitate organizing and preparing the input data, running the model, and visualizing modeling and management results. The interface was based on ArcGIS 8.2 and AnnAGNPS 3.2 using Microsoft Visual Basic 6.0 and ArcObjects.

Although the development of this DSS was still ongoing, the author demonstrated that major components of the system were functional, and that the completed system would be user-friendly – requiring minimal user interaction while providing full flexibility for changing input parameters. According to the author, this system should be able to reduce the tedious task of data collection and organization.

Baran and Jantunen (2004) developed a DSS to propose generic guidelines for stakeholder consultation in the management of tropical floodplain fisheries. They focused on the technical aspects of the stakeholders’ consultation, describing in detail the steps of the consultation and analyzing the methodology (selection of stakeholders, collective building of a model structure, probabilities elicitations, etc.). Then they reviewed the possible pitfalls and problems encountered in the process. Ultimately, the system proposed generic guidelines for a stakeholders’ consultation in view of building Bayesian models for environmental management. The authors believe that the framework provided an effective dialogue between stakeholders, as well as feedbacks for understanding the consequences of management decisions.

The Soil and Water Assessment Tool (SWAT) is a continuous, basin-scale hydrologic model that has been coupled with a GIS. Hanna (2006) has combined SWAT and GIS for determining irrigation application and projected agricultural water demand in the Pocomoke River basin, located in the Coastal Plain of Maryland’s Eastern Shore.

This model processed SWAT output data along with user supplied economic data as a basis for identifying hotspots (agricultural fields likely to produce greatest economic return for irrigation installations) and for prescribing best recommendations (the most profitable irrigation system from an array of possible systems, based on user supplied economic and performance data).

GIS features used as the data input basis for the SWAT model included land-use, topography, and soil properties. Hotspot data was analyzed in the GIS environment in order to produce areas of recommended irrigation, areas that favor drip irrigation, and areas of greatest net benefit.

From a literature standpoint, GIS can serve as a promising decision-making tool. It allows the acquisition, storage, manipulation, analysis, and display of geo-referenced data for better decision-making purposes. However, this data analysis is more spatial than temporal – in other words, GIS lacks the ability to predict future events. Although efforts have been made in recent years to close this gap by incorporating simple mathematical tools in the GIS' Spatial Analyst Toolbox, there remains a need for complex equations and predictive models built and embedded within GIS.

2.6 Conclusion

The spread of infectious diseases and the invasion of agricultural and natural systems by biological pollutants constitute some of the most serious threats concerning public health specialists and ecologists today.

Making decisions about what types of treatment or control strategies to implement – and especially about where and when to apply those treatments – is not always easy. Therefore, land and resource managers need decision-making tools that not only describe and predict natural phenomena, but which also prescribe solutions for such problems. These tools can be used separately (individually) or in combination one with another (Integrated Decision Support System) to provide better results.

The literature reviewed here shows that while each one of the traditional Decision Support Systems (Model, Expert Systems, and Geographical Information Systems) has some advantages, they also present limitations, such as:

1. *Model limitations*: Mathematical models are useful tools for predicting events and making management decisions, but they are not always suitable in analyzing GIS-based data (*e.g.,* land cover images), which are often time-heterogeneous systems. Moreover, many mathematical models reviewed in the literature, such as Lotka-Volterra systems, usually do not account for movement (advection/diffusion) of the populations. They are often time-limited to local dynamics, that is, population reactions (growth and death) only. Even more spatio-temporal models that account for both reaction and movement components have at times been limited to 1-Dimension or homogeneous systems. However many natural systems are heterogeneous, which makes it difficult to apply 1-D models for homogeneous systems to the real world.

2. *Expert Systems limitations*: Expert Systems are useful tools for identifying and troubleshooting problems. Unfortunately, unlike models, these systems lack the ability to predict future events. They also rely on GIS' Spatial Analyst for the development of the diagnosis and prescription decision trees, and for the display and visualization of maps.

   Moreover spatial data manipulated in Expert Systems are stored in the GIS' database. For these reasons, it could be asserted that Expert Systems alone would not be sufficient as decision-making systems. They need to be supplemented with other systems in order to produce more accurate results and maximize benefits.

3. *Geographical Information Systems limitations*: GIS are used for the acquisition, storage, manipulation, analysis, and representation of geo-referenced data. As

such, they are critical for decision-making. However, like Expert Systems, GIS are not designed for the prediction of events. The GIS' Spatial Analyst Toolbox cannot be used to project spatial data in the future. Such projections and representations are useful to land managers and other decision makers for many reasons including preparedness, readiness, and emergency management situations.

For the reasons described above, it is obvious that Decision Support Systems that have been built as stand-alone systems have limitations in terms of either predicting events (*e.g.,* ES and GIS) or accurately mapping georeferenced data (*e.g.,* Lotka-Volterra models). Therefore, combining all three systems (Model, ES, and GIS) – the overall objective of this study – could be very productive and more efficient in terms of producing more accurate results and maximizing the benefits presented by individual systems.

While many DSS have been developed for the control of non-point source pollutants, few have dealt with self-moving entities (such as invasive animals) that have the ability to move on their own (unlike amorphous pollutants, which are moved by media such as air, water, wind, etc.). The DSS developed within the framework of this study is designed for both categories of pollutants (amorphous and self-moving).

Therefore, this system could be applied for entities ranging from small bioagents (such as bacteria, viruses, prions, fungi, toxins, etc.) to larger nuisance animals known as invasive or potentially invasive, such as theAsian Longhorned Beetle, the Light Brown Apple Moth, the cane toad, the brown tree snake, the sea lamprey, the European starling, nutria, and resident Canada geese.

The uniqueness of the current research is that it combines three decision-making systems (mathematical model, geographical information system, and expert systems) in a single flow system that describes and predicts spatio-temporal events (*e.g.*, resident geese spread) while prescribing solutions for such events (*e.g.*, goose management and control strategies). It could be applicable to both amorphous and self-moving agents.

The DSS developed in this study will benefit society in many ways including:

1. serving as an available and usable net decision checklist;

2. serving as a stable tool, despite eventual changes in staff;

3. helping to protect biodiversity by limiting invasive species' pressures on native species, and controlling the spread of pandemic diseases including their causal agents (bacteria, viruses, prions, fungi, and toxins);

4. helping to reduce economical impacts attributed to invasive animals (such as cane toad, brown tree snake, sea lamprey, European starling, nutria, etc.) on human activities (*e.g.*, farming);

5. serving as a transparent, easy-to-use mapping instrument available to end users; and,

6. serving as a transparent and effective communication device for explaining decision-making to the public.

CHAPTER 3:
OBJECTIVES

The overall goal of this research is to develop a Decision Support System (DSS) that will aid in controlling invasive bioagents. The resident Canada goose species (*Branta Canadensis*) is used in this study as an example of an "invasive" bioagent whose population has grown dramatically in the past few years, posing challenging management problems in the Anacostia River system, District of Columbia. More specifically this study aims to:

1. Develop a mathematical model that simulates the spatio-temporal dynamics of resident Canada geese (called hereafter, *goose model*). In the target system, the nuisance goose species interacts with Anacostia resources, whose density is affected.

2. Formalize the knowledge that can be applied to diagnose the causes of geese congregation in critical source areas (hotspots) and to the selection (prescription) of Goose Control Strategies (GCSs) to implement in those hotspots.

3. Combine the Model, Geographic Information System, and Expert Systems within a single flow system that can seamlessly store, predict, manipulate, and display spatial data while prescribing appropriate strategies for controlling and managing invasive agents (exemplified in this study by the resident Canada goose species).

The goose model was developed to simulate at least two basic ecological processes: growth and movement of goose populations relative to resource densities, and distribution within the Anacostia system.

The goose model is a system of partial differential equations composed of reaction (growth component), advection (directed movement), and diffusion (random movement) that describes and predicts goose and resource dynamics. In this study, a goose hotspot was defined as a localized area where resident Canada geese congregate at high density (that is, approximately 200 geese, or one ton of goose biomass, per km^2) for at least three months. The goose model was evaluated and validated against survey data and used to identify goose hotspots in the study area.

The expert systems developed in this study separate the GCS selection process into two steps: diagnosis and prescription. The diagnosis expert system (DES) is aimed at determining the most likely causes of goose congregation at hotspots, and is performed based on data stored in the attribute tables of geographic features found in the study area. Examples of such features are land use and land cover resources (such as grass, water bodies, roads, topography, and wetlands). The other component of the expert system, the prescription expert system (PES), is focused on identifying the best control strategies for reducing goose infestation of critical areas. The prescription is performed based on the diagnosis and attribute data stored in the knowledge base.

Geographic Information System software offer facilities to store and manipulate spatial data as well as tools that are used in this study to implement the diagnosis and prescription expert systems. When the goose model and expert systems are combined with Geographic Information System, the resulting DSS is expected to overcome some of the current limitations in resident Canada goose management planning by providing the opportunity to diagnose the most likely causes of goose congregation in critical areas, and prescribing appropriate control strategies, on spatial basis, in those areas.

CHAPTER 4:
PRESENTATION OF THE STUDY AREA

4.1 Introduction

The Anacostia River watershed is part of the Chesapeake Bay watershed, 85% of which is within Maryland and 15% within the District of Columbia (EPA, 2008). The area where this research was conducted is a portion of the lower tidal Anacostia watershed located in the District of Columbia (Figure 4.1). The geographic coordinates are Lat. 38º53 - 38º55 N and Long. 76º56 - 76º58 W. This is part of the Anacostia National Park system is one of the District's largest and most important recreational areas, with over 1,200 acres (4.9 km^2) at multiple sites. Included in Anacostia National Park are the Langston Golf Course, the Kingman and Heritage Island marshes, Kenilworth Aquatic Gardens and Kenilworth Marsh, and Anacostia sport and recreation areas with hundreds of acres available for ballfields, picnicking, basketball, tennis, and the Park Pavilion (a 307 m^2 of space used for roller skating and special events). These fields and marsh areas are where resident geese have been surveyed while conducting this research. The following sections describe the Anacostia natural environments (abiotic, biotic and goose specific, the resident Canada goose survey performed in the study area, and the land cover reclassification of the study area using a Geographical Information System.

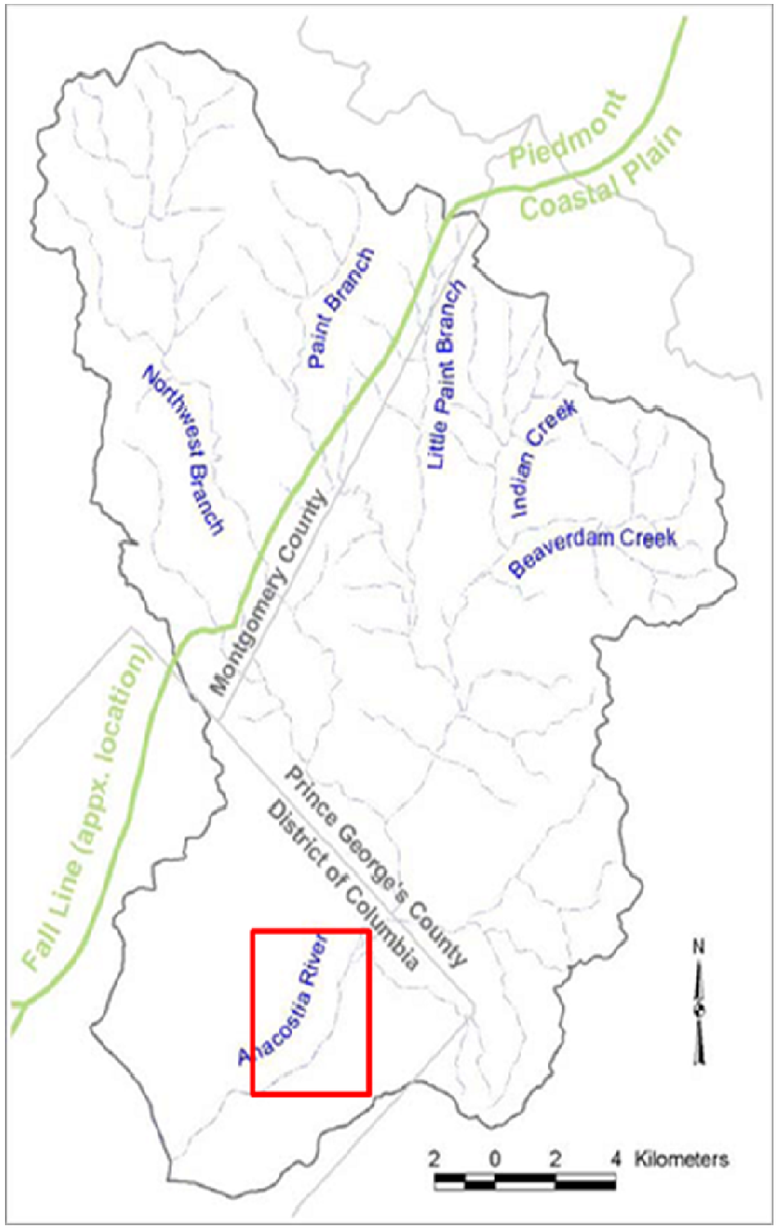

Figure 4.1 Location of the Study Areas in the Anacostia watershed system. The research area is the lower portion of the watershed located in the District of Columbia, in the middle section of the river (Lat. 38º53 - 38º55 N and Long. 76º56 - 76º58 W).

Source: Teague *et al*. (2006).

4.2 Human Environment and Land Use

Overall land use in the lower tidal Anacostia watershed is described in NOAA (2007). This area is located in the Northeastern quadrant of Washington, D.C., that is, north of East

Capitol Street and east of North Capitol Street. The political boundary of Northeast D.C. includes most of Ward 5; much of Wards 6 and 7, and parts of Ward 4. The neighborhoods within the study area also include a few schools and institutions such as Brown Junior HS, Phelps HS, Young ES, and Spingarn HS all located on the east side of the River; and Thomas ES and River Terrace ES on the right side of the River.

There are two large public gardens in this study area: the National Arboretum and Kenilworth Aquatic Gardens. Parks and open space comprise about one-tenth of the land use. Much of the open space is concentrated along the banks of the river and includes areas such as golf courses, cemeteries, and developed parks. Other important sites and landmarks in the study area include RFK Memorial Stadium, Langston Golf Course, Kenilworth-Parkside Recreation Center, and Kingman Lake. The most significant open space is Anacostia Park along the south bank of the Anacostia River (DDOT, 2007).

About two centuries ago, agriculture was a predominant land use in the Lower Anacostia River watershed, but today, signs of agriculture are virtually non-existent, and over 80 percent of the area is already heavily populated and developed (DDOT, 2007). Much of the land within or surrounding the study area is densely developed, with residential, commercial, government, and light industrial uses (Figure 4.2).

Commercial and industrial activities occur in close proximity to the river, particularly along the lower river, the Lower Beaverdam Creek area, and the headwaters of Hickey Run. In general, the population of Northeast Washington, D.C is predominantly African-American, particularly east of the Anacostia River.

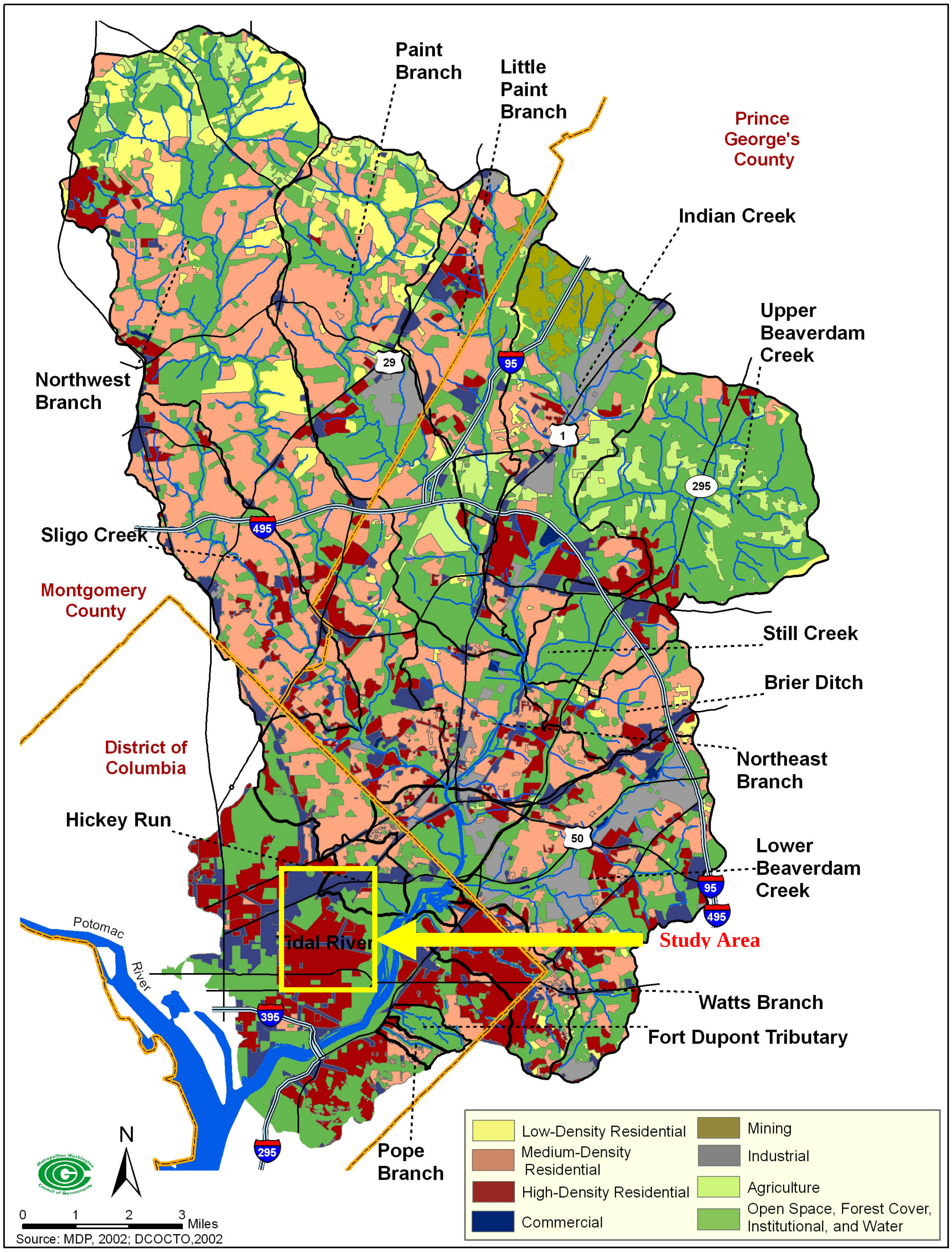

Figure 4.2 The Anacostia Watershed Land Use

(**Source:** MWCG (2009))

4.3 Natural Environment

4.3.1 Abiotic Environment

The study area is limited in the North by New York Avenue (US 50), in the South by East Capitol Street NE, in the West by Baltimore-Washington Parkway 295, and in the East by Bladensburg Road NE, Florida Avenue, and 17th Street SE (Figure 4.2). The abiotic factors of this study area, including the climate, soil, and hydrology are briefly described below.

Climate

The climate of the lower Anacostia watershed in the District of Columbia is located in the humid temperate climate zone (Koppen climate classification), that is, in plant hardiness zone 8a (ADF, 2006). In general, winters are cool, with a January average of 34.9 °F (1.6 °C) – lows averaging 27 °F (−2.8 °C) and reaching the freezing mark in the upper teens °F (-9 to -7 °F), but very rarely below 10 °F (−12 °C) in town (NOAA, 2004). Highs in January average 42 °F (5.6 °C), though they fail to rise above freezing for about nine days each year. The coolness is often interrupted, as highs rise above 50 °F (10 °C) on 31.6 days from December to February (NOAA, 2004). Snowfall occurs mostly in small accumulations, totalling an average 14.7 inches (37.3 cm) per season, mostly in January and February, with some accumulation in December and March, but rarely November or April (NOAA, 2004).

The strongest winter storms are usually "nor'easters,", which typically feature high winds and heavy rains, occasionally in the form of a "blizzard" (Watson, 2005).

Winter normally transitions to spring in late February/early March while summers are hot and humid, with a July mean of 79.2 °F (26.2 °C) (NOAA, 2004). Autumn is mild to warm with crisp mornings, though summer-like warmth often lasts until mid-October. The first freeze usually falls in the first half of November. Annual precipitation averages 39.4 inches (1,000 mm). February and April are the driest months, while May and September are the wettest. The area receives adequate amounts of sunshine year-round, with an annual total of more than 2520 hours, or 57.6% of the possible amount (Watson, 2005)

Geology

The study area is physiographically located in the coastal plain province, which is underlain by vast deposits of sediments including gravel, sand, silt, and clay of the Lower Cretaceous Potomac Group (Patuxent Formation) thickening to more than 8,000 feet at the Atlantic coast line (MGS, 2001). These deposits overlie crystalline bedrock and are highly variable throughout the formation, ranging from small to massive, heterogeneous lenses to interbedded layers (Teague *et al.,* 2006). The thickness of the unit varies from thin layers in places along the fall line to several thousand feet off the eastern shore, with an average thickness of 500 feet (Teague *et al.,* 2006).

Hydrology

The main water body in the study area is the tidal Anacostia River. The river is about 10 km (8.4 mile) long and fairly shallow, averaging at low tide between three and six feet deep from Bladensburg Marina (Anacostia River Waterfront Park) downstream to the 12th Street Bridge, and approximately 10 to 25 feet deep downstream from this bridge to the Potomac River confluence.

The surface area of the tidal river is about 850 acres, and the average volume of tidal river is approximately 2,640 millions gallons (MWCG, 2009). The river's watershed drains a predominately urban area that covers about 129 square miles in Maryland (Northwest and Northeast Branches) and 47 square miles in the District of Columbia (DDOT, 2007). In July 2000, the net flow at the river mouth was 4.9 cubic meters per second, while inflow was 3.1 cubic meters per second at the Northeast and Northwest Branches (DDOT, 2007).

With regard to the water quality, many parts of the Anacostia and its tributaries have poor water quality making it unsafe to consume fish from or swim in most of the river (NOAA, 2007). The water system is polluted with contaminants, stormwater and sewage runoff that carry trash and chemical waste from land to the river. Additionally, many of these factors contribute to chronically low dissolved oxygen levels that threaten aquatic life (NOAA, 2007). Due to intense urban development there is a high percentage of impervious surface, large amounts of stormwater runoff, stream channelization, and loss of riparian buffering and streamside forest canopy. During significant rainfall events, the Anacostia receives sewage and other pollutants from combined sewer and stormwater overflows that discharge directly into the river (NOAA, 2007).

With regard to wetlands, there are approximately 3,208 acres of wetlands in the Anacostia watershed (Figure 4.3), the majority of which are located in the Coastal Plain portion. Of the total wetland acreage, palustrine wetlands constitute approximately over 76% while riverine http://www.anacostia.net/history/wetlands_large.pdf(20%) and lacustrine (4%) are just a small fraction (MWCG, 2009).

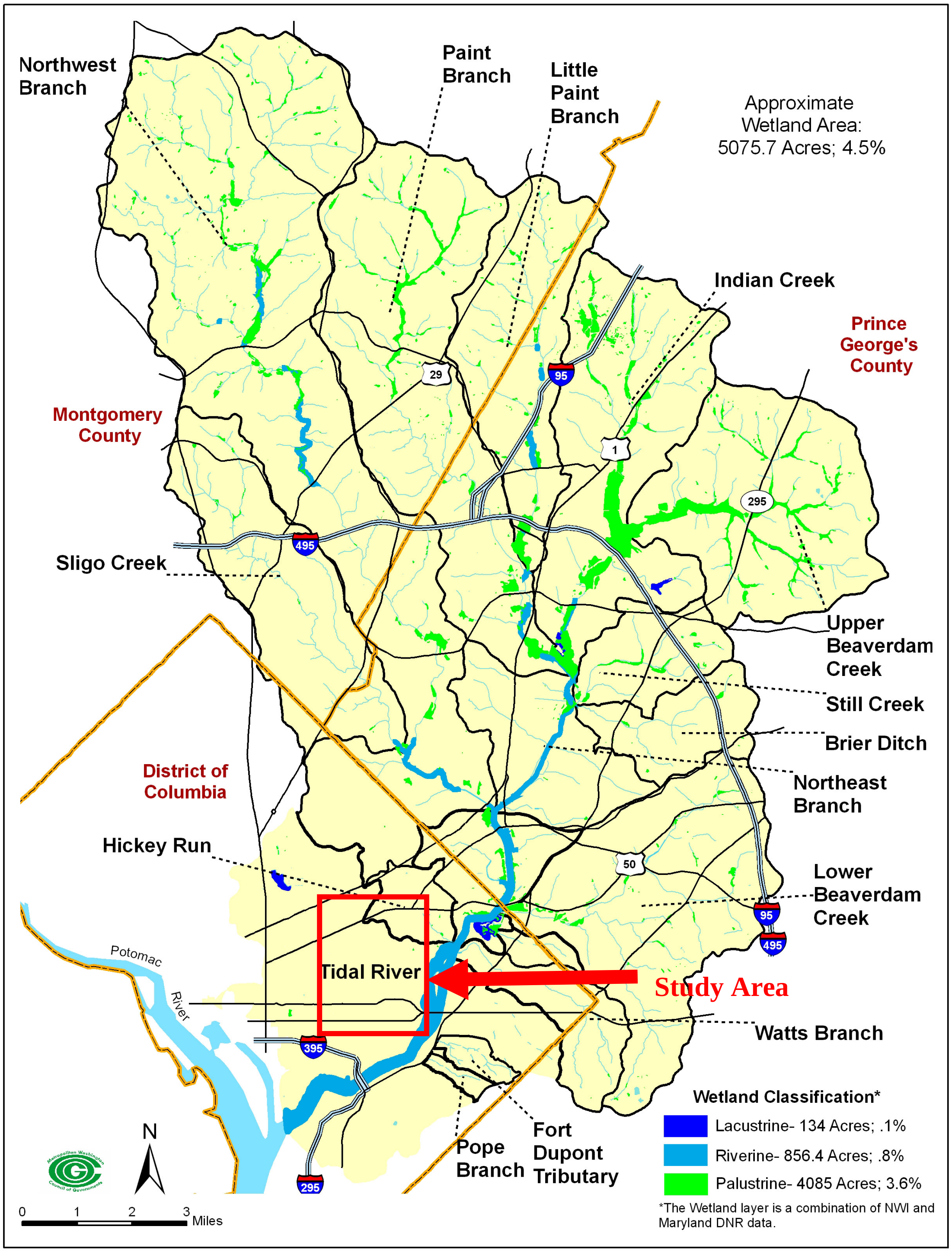

Figure 4.3 The Anacostia Watershed Wetlands

Source: MWCG (2009).

Anacostia tidal and nontidal wetlands have been disappearing during the last few decades due to urban development and suburban sprawl and agricultural activities. For instance over 4,000 acres of nontidal wetlands have been lost in the recent years while, according the Army Corps of Engineers; about 2,500 acres of tidal emergent wetlands have been destroyed solely in the section between Bladensburg and the Anacostia's confluence with the Potomac River (MWCG, 2009).

4.3.2 Biotic Environment

Vegetation

The dominate vegetation tree blooming along the Anacostia River system is cherry, viewed as the signature of spring in Washington. Other plant species found in the study area include northern wild rice, cattail, milkweed, Joe Pye, button bush, berries, and the ancient species *Nuphar*, which fills the Anacostia marshes along the river (NPS, 2010).

Much of Anacostia wetland plant species, particularly those in Kingman and Kenilworth marshes are described in Hammershlag *et al.* (2002). There are *Pontederia cordata* (pickerelweed), *Schoenoplectus tabernaemontani* (softstem bulrush), *Peltandra virginica* (green arrow arum) and *Sagittaria latifolia* (broadleaf arrowhead), which have been planted (Hammershlag *et al.*, 2002). Among the pioneer volunteer species noticed by the authors, there are: *Ludwigia palustris* (marsh seedbox), *Eleocharis obtusa* (blunt spikerush), *Cyperus erythrorhizos* (redroot flatsedge), *Salix nigra* (black willow), *Lythrum salicaria* (purple loosestrife), *Panicum dichotomiflorum* (fall panicgrass), *Juncus effusus* (common rush), *Typha* spp (including T. *latifolia, angustifolia* and *glauca*), *Leersia oryzoides* (rice cutgrass), *Phalaris arundinacea* (reed canarygrass), *Mikania scandens* (climbing hempweed), *Impatiens capensis* (jewelweed), and *Schoenoplectus fluviatilis* (river bulrush), *Impatiens capensis, Polygonum sagittaria* and *P. arifolium* (arrowleaf and halberdleaf tearthumbs), *M. scandens, P. arundinacea*, *P. punctatum (*dotted smartweed*), Sparganium eurocarpum* (broadfruit bur-reed) and *Typha* species. *Zizania aquatica* (annual wild rice) and *Acorus calamus* (calamus), which historically were keystone species in the Anacostia before the marsh restoration are still lacking in this study area (Hammershlag *et al.*, 2000).

Animals

Given the riparian-type vegetation in the Anacostia system, which combines small marshes, open fields, and wooded river edge, the animal species found in the study area are diverse including fish, aquatic mammals, and birds.

Fish and amphibians

The Anacostia has three main types of fish (NOAA, 2007):

1. resident inhabitants of the freshwater tributaries and main channel;

2. anadromous fish (such as shad or striped bass), which live in marine or estuarine waters but return to freshwater to spawn; and

3. catadromous fish (such as the eel), which live in freshwater but migrate to the sea to spawn.

Frogs and turtles are also found in the Anacostia watershed system. A list of fish species observed in this system is shown in Appendix B.

Aquatic mammals

The National Park Service has listed 17 species of mammals that reside in the entire Anacostia watershed, of which beaver, river otter, muskrat, mink, raccoon and fox are the most common (NOAA, 2007).

Birds

The National Park Service has listed 188 species of terrestrial, riparian, and aquatic birds in the lower Anacostia watershed, of which over 50 are associated with the aquatic environment (NOAA, 2007). Aquatic birds using the river include year-round residents, local breeding populations, and highly migratory species that either overwinter in the area or pass through to northern or southern destinations. Most breeding areas are limited to Kenilworth Marsh, Kenilworth Park, and Kingman Lake. The largest groups of aquatic birds on the river are ducks and geese, loons, grebes, coots, and rails.

Nearly 30 species represent these families in the study area, most of which are associated with Kenilworth Marsh, Kingman Lake, and the main stem of the Anacostia River in the upper river zone.

The ducks, geese, coots, and rails are largely grazers and eat plants and insects (omnivorous). Canvasback duck, ringnecked duck, ruddy duck, widgeon, wood duck, Canada goose, and snow goose are primarily grazers of aquatic and terrestrial plants. Several other species, such as mallards, goldeneye, bufflehead, oldsquaw, and common gallinule are omnivorous, feeding on vegetation, insects, and small aquatic invertebrates. The mergansers, loons, and grebes are strong divers and swimmers and feed on fish and aquatic invertebrates. The ducks and geese primarily use the river for overwintering, although a few species such as wood duck, mallard, and rails may breed during the spring and summer in the upper river. Osprey, bald eagles, song birds, and other bird species (Appendix C) are also founds in the study area.

4.3.3 The Anacostia Resident Canada Goose Situation

The biology of the Canada goose (*Branta Canadensis*) is reviewed in Chapter 6. The genus *Branta* is native to Arctic and temperate regions of North America, but not “natural” along the Anacostia River **(**McKindley-Ward, 2006). Canada geese are migratory birds, whose annual migratory pattern has been to leave the Mid-Atlantic region in March and wing north to their breeding grounds around Hudson Bay (Canada), where they nest and raise their young over the summer.

At mid-Fall, as the weather turns cold in northern Quebec (Canada), these birds return south to spend the winter in ice-free latitudes. Unfortunately, most of the geese no longer return to their northern original locations because of a combination of factors including climate, protection by the regulations, and habitat conditions (lots of breeding and nesting sites, feeding both in the nature and by humans, etc.). As their populations grow, “resident” geese cause ecological damage by overgrazing environmentally-sensitive wetland areas during the warm months of the growing season, when young, vulnerable plant shoots are emerging from the mud in Anacostia tidal wetlands **(**McKindley-Ward, 2006). Such grazing impacts have been very costly to the District and U.S. Army Corps of Engineers, who have spent over $5 million creating the 40-acre Kingman Marsh. It is estimated that resident Canada geese not only ate about $400,000 worth of newly-installed plants, but reduced the vegetated cover to one-third of its intended size (from 40 acres to less than 15 acres).

When not devouring swathes of wetland plants, resident geese eat nutrient rich turfgrass on mowed lawns near water bodies, defecating frequently and fouling such places as the historic Langston Golf Course and recreational fields along the Anacostia. A decade ago, the population of resident geese in this study area was approximately 600 (Harris, 2002; McKindley-Ward, 2006) and this population has remained almost stable over time (~ 565, this last summer). A Canada Goose Management Committee (GMC) has been created for controlling and managing the resident goose populations in the Anacostia system.

4.4 Resident Canada Goose Survey

Canada goose survey data were acquired in order to verify and validate the model predictions. Surveys were conducted by the GMC, a multi-agency team composed of the D.C. government, U.S. Army Corps of Engineers (USACE), National Park Service (NPS), Anacostia Watershed Society (AWS), and U.S. Geological Society (USGS).

4.4.1 Materials and Methods

The resident Canada goose surveys were carried out at four locations including Kingman Golf Course, the Heritage roadside field, Kenilworth Aquatic Gardens, and the Anacostia picnic area (Figure 4.4). The method of surveying is called Direct Counting, a technique recommended by the USGS Patuxent Wildlife Research Center, which has been employed for years by scientists (*e.g.*, Newell and Hicks, 1982; and Gustavo *et al.*, 2006) to estimate the population size and record the distribution of wildlife species within small accessible natural systems.

The direct counting of resident Canada geese can be described as follows: two surveyors position themselves in a given survey site in such a way that they can see each other and are able to communicate.

Each surveyor is given a pencil and a pre-designed survey sheet containing data entries such as the observer's information, date, time, weather conditions, and number of geese counted.

At a given signal both surveyors simultaneously walk forward from a starting point along a lane or path (a transect) – one surveyor watching and counting geese on the left side of transect and the other watching and counting geese on the right. Transects are not marked or traced in the field, and their width expands as far as surveyors can see. Both surveyors communicate in order to avoid double-counts, especially in situations when a goose flies from one side to the other of the transect. At the end of each survey session, all sheets are collected and the data are recorded for further analyses.

The Anacostia goose surveys usually took place in the mornings (between 9:00 a.m. and 11:00 a.m.) when sightings were optimal and the geese were active enough to be easily seen. The surveys normally lasted 1-2 hours, depending upong the number of surveyors. They were performed on open grounds along the Anacostia River, in wetlands, in Anacostia Park, and in fields, which are the main habitats used by Canada geese in the Anacostia system. The survey data (from April 2004 to September 2007) were analyzed in MATLAB to evaluate trends of goose populations at all four survey locations (Kingman, Kenilworth, Heritage, and Anacostia). Goose densities were converted into goose biomass densities assuming an average adult resident goose weights approximately 12 pounds, that is, nearly 5.5 kg (MCE, 2003).

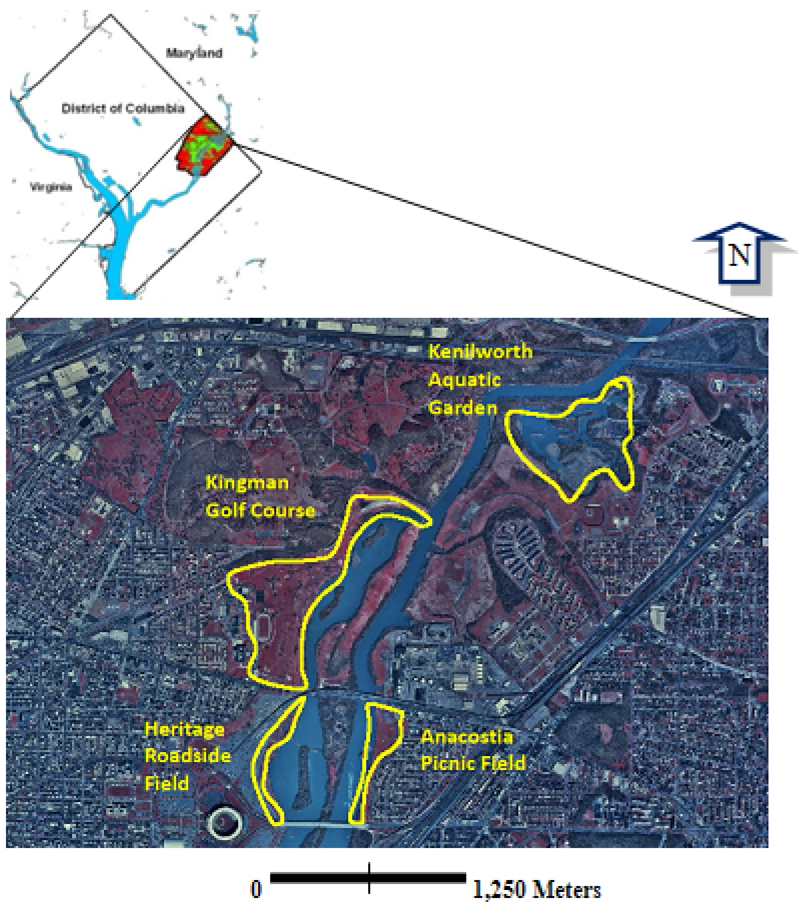

Figure 4.4 Orthoimagery of the Study Area Showing Resident Goose Survey Sites

4.4.2 Results and Analyses

Over 22 surveys were carried out between April 2004 and September 2009. The goose biomass densities obtained from those surveys were recorded in a datatable (Appendix A). An unpaired *t-test* shows that there is no statistically significant difference in average RCG densities between September (3.02±1.75 T/Km^2), July (2.84±2.76 T/Km^2) and April (2.42±0.98 T/Km^2). Population densities for each survey site are presented in Figure 4.5.

Canada geese seem to congregate the most at Kingman during spring (April) and summer (July), with an increase from spring to summer. Population densities also increased at East Anacostia from spring to summer while densities at Kenilworth and Heritage decreased. These trends were mostly reversed between summer (July) and fall (September), when the Kingman density decreased while densities at East Anacostia, Kenilworth and Heritage increased.

Survey data suggest that RCG may be undergoing a seasonal micro-migration within the sutudy area. The geese appear to move to Kingman in summer, where vegetation is probably more succulent, and back to other survey areas during the rest of the year. Moreover, the standard deviation of the goose population measurements were large at all locations during the study such that the presence of a micro-migration cannot be conclusively inferred with suitable statistical significance.

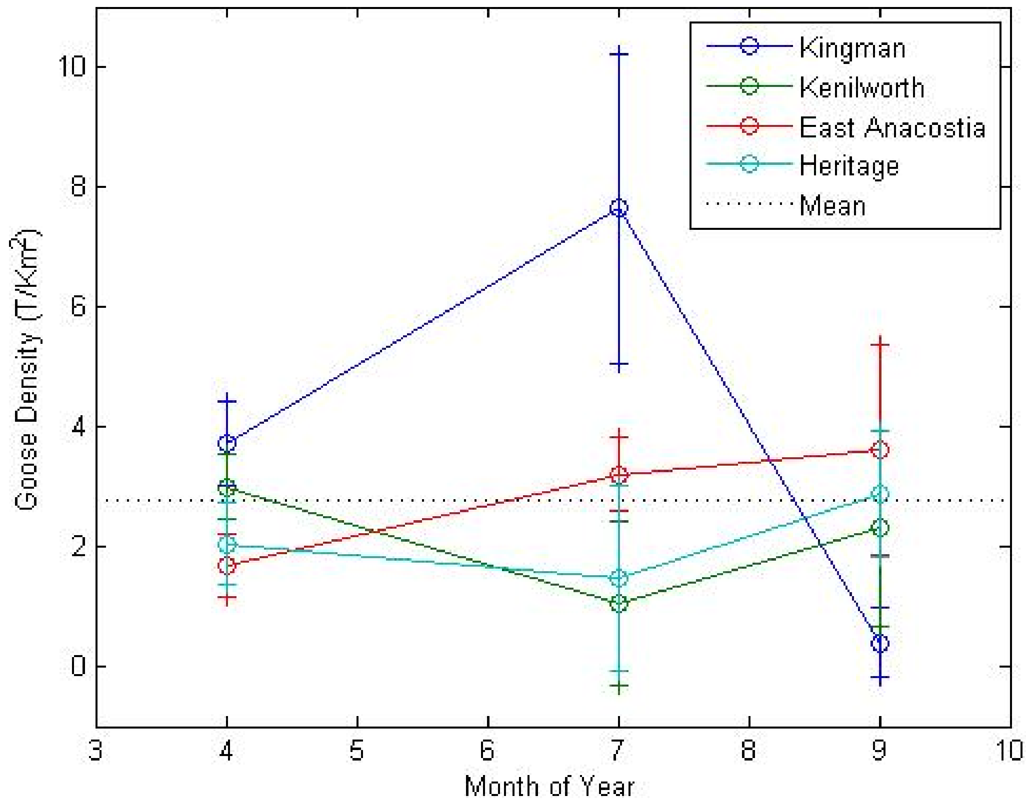

Figure 4.5 Observed Goose Population Densities at Four Survey Sites and Different Seasons: April (4), July (7), and September (9). Data are averages from 2004-2007. Error bars indicate one standard deviation (Appendix A).

4.4.3 Conclusion

The population densities of resident Canada geese in this study area vary with respect to seasons and survey sites. Although these densities change from season to season – and from one location to another – the populations are relatively stable overall. No systematic increase or decrease of the population, over time, was detected from survey data.

4.5 GIS and Land Cover Reclassification

4.5.1 Materials and Methods

Land cover data

Land cover data was acquired from the U.S. Geological Society's (USGS) National Map Seamless Server. This Seamless DOQ (Digital Orthophoto Quadrangles) of Washington, D.C.

was retrieved and downloaded from the website http://seamless.usgs.gov/index.php. The obtained imaged raster dataset consisted of ortho-rectified true color imagery with a pixel resolution of 0.5-meter (approximately 1.6-foot) covering the SW quadrant of Washington, D.C., SE. The design accuracy of the selected dataset is estimated not to exceed 3-meter diagonal RMSE (2.12m RMSE in X or Y). Each orthoimage of the dataset provides imagery for a 1500- by 1500- meter block on the ground, and is considered the "best available" data from the USGS. The projected coordinate system used is UTM 18 with a NAD83 datum. Geospatial data layers acquired from this source included: orthoimagery, transportation (roads in particular), hydrography, elevation, and vegetation cover. This vegetation data (Anderson Level 1 NLCD 2001) was reclassified in ArcGIS into three classes (woody perennials, grass, and developed areas) using Spatial Analyst's tool ("Extract by Attributes").

Study area boundary

The District of Columbia (D.C.) boundary shapefile was obtained from the 2009 Tiger/Line files in ESRI ArcGIS shapefile format, which works with most GIS programs including ArcExplorer and ArcGIS. The data was downloaded from the U.S. Census Bureau website at http://www2.census.gov.

ArcGIS' Analyst Tools were used to overlay both the boundary and the road layers, which helped delineate, digitize and edit these shapefiles. The resulting study area was stored as a feature in the GIS database.

Wetlands data

Seamless wetlands data for the District of Columbia was acquired from the U.S. Fish and Wildlife Service (USFWS), which is the principal federal agency that provides information to the public on the extent and status of the nation's wetlands. The wetlands data layer is available for download at http://www.fws.gov/wetlands/data/ESRI.html, and it comes as either a compressed file Geodatabase or a shapefile, in the Albers projection with a North American Datum (NAD) of 1983.

The above datasets were processed in ArcGIS' ModelBuilder using Spatial Analyst tools and the Query Script Language (QSL). All layers were resampled to raster format with a 24 m cell size. The GIS tools were used to query the land cover information from raster data Attribute Table, and to classify this land cover, within the boundaries of the study area, into five classes:

1. Grassfields (including mowed grass, pasture hays, and herbaceous wetlands);

2. Developed area (including residential, commercial, and services);

3. Waters (including the tidal Anacostia River and the ponds at Kenilworth aquatic garden);

4. Woods (including shrubs and woody wetlands);

5. Major roads.

4.5.2 Results

The result of land cover classification over the study area is presented in Figure 4.6. The study area is 11.30 km² (2.79 acres) in size. Grassfields and developed areas dominate the landscape. The five selected land covers, their spatial extent in the study area and their relevance to goose dynamics and control are detailed in the following sections.

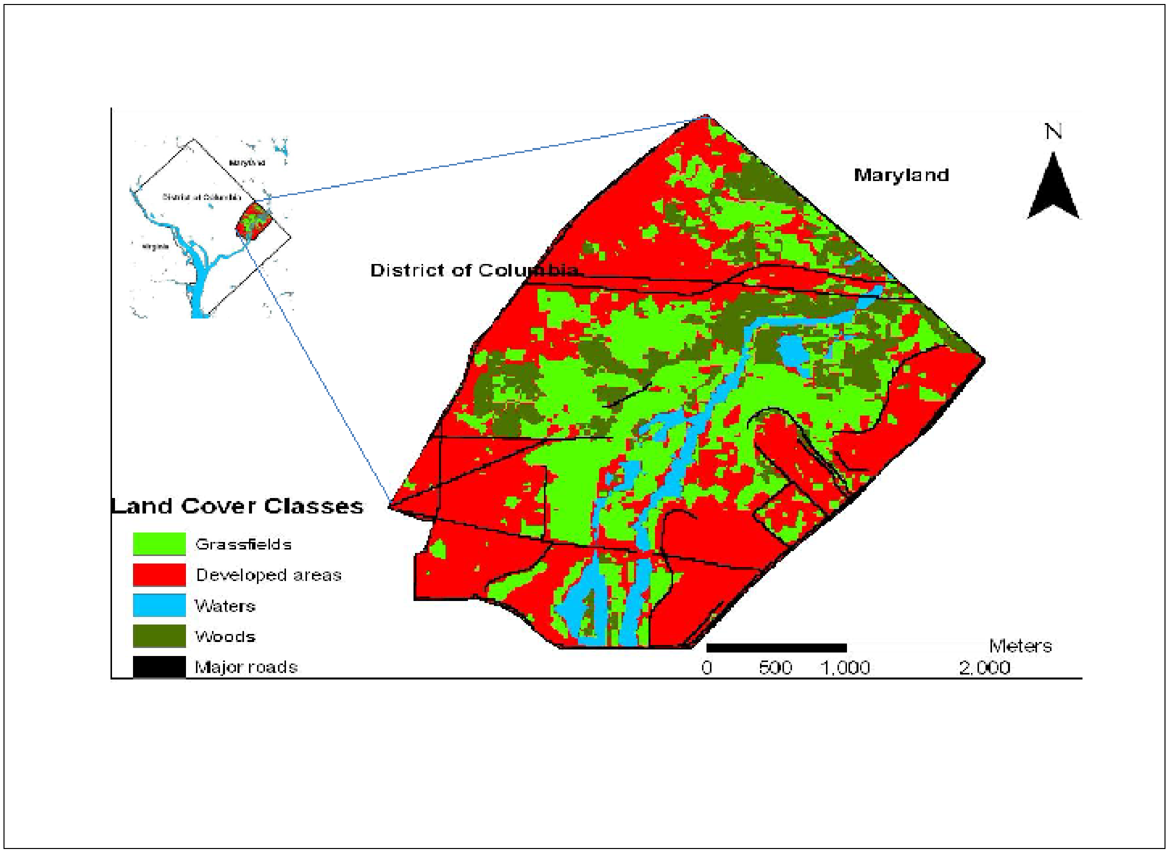

Figure 4.6 Digitized Image of the Study Area Showing Land Cover Classes

Grassfields

Grassfields, particularly those located near water bodies are the main land cover type used by Canada geese. In fact, these fields are regularly maintained and treated, which allows tender and succulent grasses to emerge. The treatments provided to grassfields (*e.g.,* watering, mowing, and fertilizers) probably improve the quality and quantity of grass, and therefore influence their use by resident Canada geese.

In fact, Riddington *et al.* (1997) found that fertilizing fields increased grass nitrogen content and made the fields much more attractive to geese.

The public also uses these grassfields for various purposes including picnicking, playgrounds, recreation, and sport activities (soccer, football, and golf). The grass species are mainly Kentucky bluegrass, water bentgrass, and rice cutgrass.

There are many grassfields in this study area, four of which were surveyed for goose counts: Kingman (golf course), Heritage (road-side field), Anacostia (Park, playground, picnic fields), and Kenilworth (aquatic garden, marsh system). These fields can be described in detail as follows:

Kingman golf course: ~ 0.334 Km^2; 18 holes; flat land overall, covered with treated and maintained grass; sighting is clear; few trees scattered; site is limited in the north by the National Arboretum with a lot of trees, in the south by Benin Road, on the west side by schools with sport fields (Young ES, Brown Junior HS, Phelps HS, and Spingarn HS), on the east side by the wetlands (Kingman marsh and Anacostia River).

Kenilworth Aquatic Gardens: ~ 0.47 Km^2; many ponds; mainly wild flowers, grass (violet, turtlehead, and rice cutgrass), and freshwater plants (nuphar, lotus, and water lilies); some shrubs and bushes; land is more or less flat, and visibility is unclear in shrubs and bushes; site is bordered on the west side by the tidal Anacostia River, to the north by New York Avenue, to the south by Fort Circle Park and the Kenilworth Park Recreation Center complex, and to the east by Anacostia Avenue NE and a housing development.

Heritage road-side field: ~ 0.053 Km^2; open, flat, and easily accessible from Kingman Marsh and Anacostia River on the east side; borders also include RFK football stadium and D.C. United soccer fields to the west, Benin Road to the north and South Capital Street East to the south.

Anacostia Park picnic area: ~ 0.053 Km^2; large playgrounds and picnic areas (with trash cans) along the Anacostia River; many soccer fields and sport trails; site is bordered by Benin Road to the north, South Capital Street East to the south, the tidal

Anacostia River to the west, and the Anacostia Community (housing development) to the east.

Developed areas

Urban areas are heavily populated and developed. The neighborhoods consist of government buildings; commercial, transportation, and industrial facilities (*e.g.*, Metro stations, PEPCO installations); residential communities; Anacostia Park (swimming pool, picnic areas, and boat ramps); the Washington Navy Yard; schools, churches, hospitals, restaurants; and many other landmarks. Urban plazas and small parks – some built near artificial ponds – are very attractive to waterfowl and resident Canada geese.

Waters

The main waters are the tidal Anacostia River and Kenilworth ponds. Some of the constituent elements observed at the surface of those water bodies are plant materials, waterfowl and insects, and other solid debris.

Most constituent elements in wetlands are marsh plants (such as *Ludwigias*, *Salix*, and *Lythrum*, *Juncus*, *Peltandra*, *Typha* and *Schoenoplectus tabermontanae*, rice cutgrass (*Leersia oryzoides*), *Phragmites australis* and associated *Lythrum salicaria* (purple loosestrife). Of six planted species (excluding *Nuphar*), three are palatable to geese (*Sagittaria*, *Pontederia* and *Schoenoplectus pungens*) and have been decimated, while the less palatable ones (*Peltandra*, *Schoenoplectus tabermontanae* and *Juncus effusus*) have recently increased – providing an important component of the remaining marsh structure (Hammerschlag *et al.*, 2002).

Woods

The wood system includes the shrubs along the Anacostia River and at Kenilworth Aquatic Garden as well as the Woody Landscape Germplasm Repository at The U.S. National Arboritum. There are also some trees scattered over the Anacostia system.

Major roads

Major roads and parking lots are built with bituminous materials. Roads are usually cleaned and maintained, but occasionally food debris is found on the street, or in the trashcans bordering the streets. Food debris and other leftovers could be attractive to Canada geese and other urban pests.

4.5.3 Conclusion

ArcGIS' ModelBuilder software and Spatial Analyst tools have been used to process the imagery data of the study area. This process led to the reclassifiaction of the land cover data acquired from USGS. Five major land covers that could potentially influence resident goose population dynamics were classified as grassfields, shrubs and woodlands, roads, developed areas, and water bodies (including wetlands).

This land cover classification was critical for further analyses such as resident goose Hotspot analysis (Chapter 5) and Expert System analysis including the diagnosis of the geese congregation in hotspots, and the prescription of goose management strategies (Chapter 6).

CHAPTER 5:
MODELING CANADA GOOSE DYNAMICS

5.1 Introduction

Modeling the population dynamics of Canada geese (*Branta canadensis*) requires an understanding of the ecology of these birds, and particularly their feeding and movement behaviors. Canada geese are migratory waterfowl, and as such, they usually follow the same paths (called *routes* or *flyways*) every year (McKindley-Ward, 2006). The flyways used by Canada goose are the Atlantic flyway (along the east coast of North America), the Mississippi flyway (named after the river), the Central flyway (along the Rocky Mountains) and the Pacific flyway (west of the Rockies) (DOI FWS, 2010). For many years, the annual migratory pattern of Canada geese has been to leave the Mid-Atlantic region in March and head north to their breeding grounds around Hudson Bay, where they nest and raise their young over the summer. At mid-Fall, as the weather turns cold in northern Quebec, or in the winter when snow falls and the lakes and rivers of the north freeze over, the geese become unable to swim or find food. Therefore, geese migrate to places where it is warmer and where food is available. The United States and other southern regions become the usual destinations for Canada geese wishing to spend their winters in ice-free latitudes. When they fail to migrate back to the north, and instead become year-round residents, these 12-14 pound grazers start creating problems, particularly in suburban and urban areas (McKindley-Ward, 2006).

Examples of such problems include: the overgrazing of grassfields (*e.g.,* golf courses, athletic fields, cemeteries, hospitals and residential lawns); environmental pollution (by the spread of droppings and possibly with associated disease risks); and safety hazards near roads and airports (Manny *et al.*, 1994; USFWS, 2009; DOI FWS, 2006; McKindley-Ward, 2006; USDA APHIS, 2009). In the District of Columbia and Maryland, the Canada goose species is one of the top 10 nuisance pests (USDA APHIS, 2009), and is viewed by many as an invasive species (MISC, 2003; 2005).

Harris (2002) underlines in his thesis that Canada geese are the most widespread and abundant goose species in North America, with many different subspecies or races. There are two ecologically distinct populations along the Atlantic Flyway, both of which make use of the Anacostia River system in the District of Columbia and Maryland. One population type is the migratory Canada goose, which historically uses the mid-Atlantic for breeding grounds; the other type is the resident Canada goose, which originates from stocks released on the East Coast decades ago for hunting programs (Harris, 2002). Unlike the migratory population, resident Canada geese stay year-round in the continental United States where their population has grown exponentially in recent years (Ankney, 1996).

Canada geese are primarily grazers (herbivores), althouth the species can become omnivorous (generalist consumer), eating a broad range of food items including insects, fish, and other things – particularly when the food is in short supply.

Moist fields and marsh systems located near water bodies are preferable feeding habitats, where geese may feed on forbs, green shoots, grass seeds, aquatic plants and small grains from urban and wild grasses (Granholm, 1990; Bos, 2002; Harris, 2002).

In this study, a system of Partial Differential Equations (PDEs) is formulated to describe the local population interactions between the resident Canada geese and the “resource” (*resource* in this study simply means *grass*), coupled with migration processes caused by the heterogeneity of the environment and of the populations themselves (Arditi *et al.*, 2001). This plant-herbivore model is simulated and analyzed based essentially on Lotka-Volterra principles known as predator-prey model to which a movement component is added. Scientists have long used such systems as management tools to predict population interactions (Van Oene *et al.,* 1999). Unfortunately, model simulations have often been limited to the time factor (local population interactions) or spatially homogeneous systems, while spatial attributes present in heterogeneous systems should also be considered (Arditi *et al.*, 2001).

The system of PDEs describing the goose-resource relationship (called hereafter, *goose model*) is of the reaction-advection-diffusion type, known in theoretical biology as Fisher model (Baeumer *et al*., 2008). It considers both random movement (diffusion) and directed movement (advection) for actively dispersing species.

This approach has been used by several mathematical biologists (Murray, 2002; Turchin, 1998; Okubo, 1980; Hastings, 1996; Shigesada and Kawasaki, 1997; Keitt *et al.* 2001; Neubert and Parker 2004) to exhibit solutions that are heterogeneous in time as well as in space (Arditi *et al.,* 2001). In the framework of Fisher's Equation, the advective velocity of the migrant organisms is a function of the weighted sum of the gradients of various environmental factors (*e.g.,* food, water, or other prey types).

However, in the current study, it is assumed that not the velocity of the migrant itself, but the derivative of the velocity (*i.e.*, acceleration) is influenced by the spatial distribution of environmental stimuli (Arditi *et al.,* 2001). This (Fisher-modified) approach was chosen because it allows the researcher to obtain stable spatially heterogeneous solutions and also mitigates other shortcomings of Fisher's Equation, such as the oscillation issues (spikes) that sometimes occur in numerical solutions – particularly when resource gradients are steep. Such steep gradients are critical for GIS-oriented analyses where the resource densities are usually derived from class-based land cover layers that are spatially discrete (rather than continuous or smooth) leading to discontinuities in model parameters at the interfaces between these land cover types.

The overall goal of this research was to model the dynamics of Canada geese in the Anacostia River system, a necessary step prior to the design of the decision-making tools for controlling goose population spread or invasion.

Specifically, this study focused on three objectives:

1. to develop a goose model that predicts goose dynamics over space and time;

2. to evaluate/validate the goose model against survey data; and

3. to identify goose hotspots based on the evaluation/validation results.

In this study, a goose hotspot is defined as an area where geese congregate in high densities for at least three months with a threshold selected as one ton of goose biomass per Km^2.

5.2 Materials and Methods

5.2.1 Model Development of Goose Dynamics in the Anacostia River System

Model Equation

The goose model developed for this study is based on a two-species system consisting of actively moving herbivores (the resident Canada goose population) and a passive resource population (grass biomass) acting as the stimulus of the movement of geese. Following Arditi *et al*. (2001) modification of the basic Fisher formulation, the model uses partial differential equations in which the gradients of the resource density influence the acceleration of geese movements within the natural system. The PDEs comprises three components: a reaction describing the local population growth, an advection describing a directed movement of the goose population, and a diffusion describing a random movement of geese.

Letting G and R be the population densities of the geese and the resources consumed, respectively, the PDE system describing the population dynamics of resident geese and the resource dynamics can be expressed as follows:

$$\frac{\partial G}{\partial t} = f(G,R) - \nabla.(\vec{J}_V) + \nabla.(\vec{J}_D) \tag{5.3}$$

$$\frac{\partial R}{\partial t} = g(G,R) \tag{5.4}$$

where t is time (in years) and in which $f(G,R)$ and $g(G,R)$ represent the reaction (birth and death or growth and decay) components of the PDEs. Their expressions chosen for this work are:

$$f(G,R) = ck_{dR1}RG - k_{dG}G \tag{5.5}$$

$$g(G,R) = -k_{dR1}GR + k_{gR}R - k_{dR_2}R^2 \tag{5.6}$$

where the constants c, k_{dR1}, k_{dR2}, k_{dG}, k_{gR} are biological parameters related to goose and resource populations (Table 5.1).

Table 5.1: Model Parameters and Biological Meanings

Parameters	Meaning	Unit
G	Goose density	*T/Km²*
R	Resource density	*T/Km²*
k_{dR1}	Resource consumption rate	*Km²/T.yr*
k_{dR2}	Resource death rate	*Km²/T.yr*
k_{gR}	Resource growth rate	*1/yr*
k_{dG}	Goose mortality rate	*1/yr*
C	Conversion efficiency	no unit
D	Goose diffusivity constant	*Km²/yr*
K_v	Goose spread factor	$Km^4/T.yr^2$
d_v	Goose velocity diffusivity constant	*Km²/yr*

Equations 5.5 and 5.6 represent a modified Lotka-Volterra system where there is an additional limit on resource growth due to environmental constraints. The corresponding

maximum resource level, attainable only in the absence of geese will be discussed in the next section.

The advection and diffusion components of the PDE system are expressed as follows:

$$\vec{J}_V = \qquad \vec{v} = (v_x, v \qquad (5.7)$$

,

$$\vec{J}_D = \qquad (5.8)$$

where v is the advective velocity, d is the coefficient of diffusion of the goose population and x and y are horizontal coordinates in the east-west and north-south directions, respectively. Depending on the modeling approach, the geese advective velocity or its derivative (acceleration) is integrated into the dynamics (eq. 5.3).

The expressions of this velocity and acceleration are as follows:

$$\vec{v} = k\nabla R \qquad \text{(used in the Fisher's approach)} \qquad (5.9)$$

$$\frac{d\vec{v}}{dt} = k_v \nabla R + \qquad \text{(used in the Arditi } et\ al. \text{ approach)} \qquad (5.10)$$

where k (or k_v) is a parameter related to the stimuli of the goose movement and d_v is the diffusion coefficient of the goose population. In this study, the primary stimulus of the goose movement is the resource (although other stimuli may exist such as the presence of predators, dogs, effigies, noises and other geese – that were ignored in the model).

Substituting the above terms into the goose model expressed in (eq. 5.3) and (eq. 5.4) produces:

$$\frac{\partial G}{\partial t} = ck_{dR1}RG - k_{dG}G - \left[v_x \frac{\partial G}{\partial x} + v_y \frac{\partial G}{\partial y} \right] - G\left[\frac{dv_x}{dx} + \frac{dv_y}{dy} \right] + d\left[\frac{\partial^2 G}{\partial x^2} + \frac{\partial^2 G}{\partial y^2} \right] \qquad (5.11)$$

$$\frac{\partial R}{\partial t} = -k_{dR1}GR + k_{gR}R - k_{dR2}R^2 \qquad (5.12)$$

The final form of the model is then obtained by inserting the velocity formulation 5.10 and is presented and discussed in the result section.

Model parameterization

Identifying valid biological parameters with which to run and evaluate the goose model was an important step in this research. These parameters (Table 5.1) were estimated based on the knowledge acquired from previous studies (literature review), and selected to meet biological principles as follows:

(1) The model should always produce non-negative outputs (goose and resource densities) from the parameters used.

(2) The resource density at equilibrium when there are geese in the system (R_{eqG}) should be lower than the resource density at equilibrium when there are no geese in the system (R_{eqNG}). This requirement is justified by the fact that when resources are accessible to geese, the geese consume the resources, and the density of the resource population drops from its initial value to a lesser amount.

(3) The equilibrium goose density (G_{eq2}) when the resource has a second-order death rate (resource growth with a carrying capacity) is lower than the equilibrium goose density (G_{eq1}) when the resource has a first-order death rate (R) - resource growth with no limit). This requirement was also justified by the fact that when there is a limiting factor for the resource (carrying capacity), either the resource density stabilizes under a threshold or it decreases. In either case, when there are limited resources (or when the resources are no longer available), the goose density decreases from its initial value to a lesser amount.

Unlike when there is no limiting factor on the resource population (first-order death rate), this resource population grows exponentially (which is unrealistic) causing the goose population density to grow also as a response to the infinite resource availability.

Requirement (2) and (3) are mathematically expressed as follows:

$$0 \le R_{eqG} \le R_{eqNG} \tag{5.13}$$

$$0 \le G_{eq2} \le G_{eq1} \tag{5.14}$$

Condition (3) is automatically satisfied whenever both conditions (1) and (2) are, as demonstrated below by solving for the three relevant equilibria:

(1) **Case 1**: Equilibrium condition when there are geese, and the resource dynamics has a second-order death rate (*i.e.*, resource growth with carrying capacity).

$$\frac{\partial G}{\partial t} = ck_{dR1}RG - k_{dG}G = 0 \tag{5.15}$$

$$\frac{\partial R}{\partial t} = -k_{dR1}GR + k_{gR}R - k_{dR2}R^2 = 0 \tag{5.16}$$

The solutions are:

$$R_{eqG} = \frac{k_{dG}}{ck_{dR1}} \text{ and } G_{eq2} = \frac{k_{gR} - k_{dR2}(\frac{k_{dG}}{ck_{dR1}})}{k_{dR1}} \tag{5.17}$$

(2) **Case 2:** Equilibrium when there are geese and the resource dynamics has first-order death rate (*i.e.*, resource exponential growth).

$$\frac{\partial G}{\partial t} = ck_{dR1}RG - k_{dG}G = 0 \tag{5.18}$$

$$\frac{\partial R}{\partial t} = -k_{dR1}GR + k_{gR}R = 0 \tag{5.19}$$

The solutions are:

$$R_{eqG} = \frac{k_{dG}}{ck_{dR1}} \text{ and } G_{eq1} = \frac{k_{gR}}{k_{dR1}} \tag{5.20}$$

(3) **Case 3**: Equilibrium when there are no geese and the resource dynamics has a second-order death rate (growth with carrying capacity).

$$\frac{\partial G}{\partial t} = ck_{dR1}RG - k_{dG}G = 0 \tag{5.21}$$

$$\frac{\partial R}{\partial t} = -k_{dR1}GR + k_{gR}R - k_{dR2}R^2 = 0 \tag{5.22}$$

The solutions are:

$$R_{eqNG} = \frac{k_{gR}}{k_{dR2}} \text{ and G = 0} \tag{5.23}$$

G_{eq2} (Case 1) can be expressed as a function of G_{eq1} and R_{eqG} (Case 2) and R_{eqNG} (Case 3) as follows:

$$G_{eq2} = G_{eq1}(1 - \frac{R_{eqG}}{R_{eqNG}}) \tag{5.24}$$

When geese consume the resources, the population of the resources decreases. The density of the resource becomes smaller. This situation is expressed mathematically as follows:

$$R_{eqG} \le R_{eqNG} \quad \Rightarrow \quad (1 - \frac{R_{eqG}}{R_{eqNG}}) \le 1 \quad \Rightarrow \quad G_{eq2} \le G_{eq1} \tag{5.25}$$

Since both the resource density (R) and the goose density (G) are positive, we conclude:

$$0 \le R_{eqG} \le R_{eqNG}$$

$$0 \le G_{eq2} \le G_{eq1}$$

More importantly, condition (2) implies a constraint on model parameters:

$0 \le \frac{k_{dG}}{ck_{dR1}} \le \frac{k_{gR}}{k_{dR2}}$ and violation of this constraint could lead to unphysical results, including the potential for negative goose population densities.

The estimation of the model parameters was completed through a literature review. While the review focused on goose population dynamic models, very few studies dealt with Canada geese (resident and migratory). Therefore, a review of non-goose related studies helped identify some parameters needed for simulating the goose model.

For example, studies carried out by Yodzis and Innes (1992) and McCann and Yodzis (1994) show how model parameters can be estimated by analyzing the body sizes and metabolic characteristics (such as endotherm, vertebrate ectotherm, or invertebrate ectotherm) of the animals whose population is being modeled.

5.2.2 Solution of the Model Equations

Galerkin Finite Element Method (FEM) was used to solve the goose model. The goal was to obtain an accurate solution of the model partial differential equations over the study area (domain) with predefined boundary condition (BC) and initial conditions (IC). FEM approximates solutions of nonlinear system of transport equations based either on a transformation of the partial differential equations (PDEs) into an approximating system of ordinary differential equations (ODEs), which are then numerically integrated using standard techniques such as Euler's method or Runge-Kutta (Montas, 2004). Five basic steps are used in this process:

- define the PDE(s), solution domain, ICs, and BCs;
- discretize the domain;
- discretize the equation (Crank-Nicolson in time, Galerkin in space);
- solve the resulting matrix equation; and
- analyze the solution.

Most of the solution process was performed using the flexible FEM software developed by Montas (2003) and the domain discretization was performed by the Image Mesher developed by Gudla (2005). The MATLAB functions developed in this study for each basic step of the numerical technique are presented in Appendix D.

These functions include the code that sets initial condition, boundary conditions, capacitance, source, reaction, advection, and diffusion parameters for the goose model. In particular, the Driver is the M-file where the model was run, that is, where the execution of FEM codes of all functions indicated above were set.

The information set in the *Driver* includes the domain's spatio-temporal extents, goose and resource parameters, time-stepping parameters, names of M-files that specify the initial conditions (IC) and boundary conditions (BC), maximum number of iterations and allowable error for the iterative solution of nonlinear equations, spatial discretization, and solution display.

The goose model (eq. 5 and eq. 6) was assessed over a spatial domain corresponding to the study area and a maximum time T_{max} = 6 years (~ 2190 days) with a time-step $\Delta t = 1$ day. The goose IC was assumed zero everywhere except on a 250 m^2cell, located between the Kingman and Anacostia sites (Figure 5.1). At this location, the goose initial biomass density was 0.25 T/km^2, that is, approximately 45geese/km^2 assuming an average adult resident goose weights 12 pounds or 5.5 kg (MCE, 2003). This was scripted in the IC file as follows:

goose_icnodes = find (x > 3.875 and x < 4.125 and y > 8.975 and y < 9.225) (5.35)

u (goose_icnodes) = 0.25 (5.36)

The resource IC was assumed to vary across the study region according to land cover classes (Table 5.2).

The model assumed that no geese were entering or exiting the system boundaries during the observation period (Neumann BC), which was validated against the goose survey data.

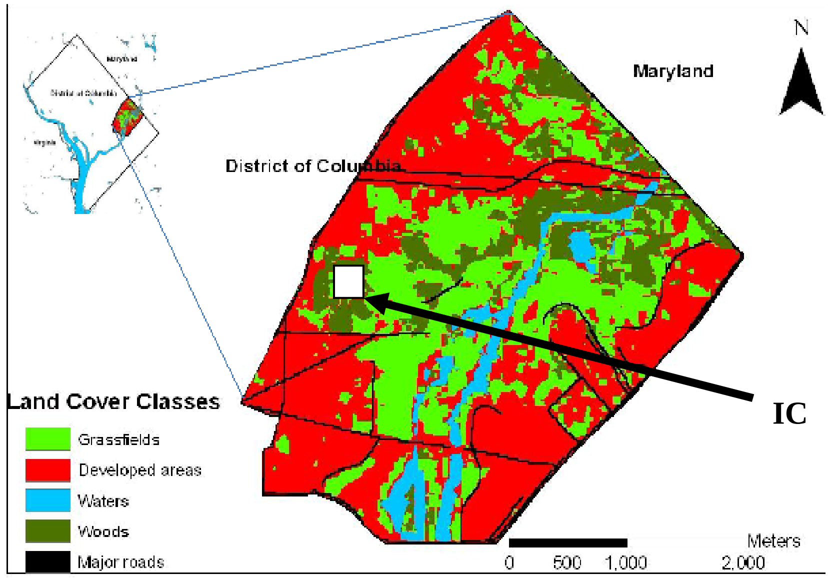

Figure 5.1 Study Area Showing the Goose Initial Conditions (IC) on a 250 by 250 m Cell

Table 5.2: Model Initial and Boundary Conditions

Land cover type	Resource IC_nodes
Grassfields	3.00 T/km^2
Developed area	0.79 T/km^2
Waters	0.79 T/km^2
Woods	0.79 T/km^2
Major roads	0.79 T/km^2

Neumann BC
$\nabla u \cdot \vec{n} = 0$ where $\vec{n}$ is a vector normal to the boundary of the domain

Domain discretization was performed by exporting the related coverages from ArcGIS in digital image form and applying the Java-based Image Mesher software developed by Gudla

(2005). This software produces unstructured triangular meshes based on a quadtree decomposition of an image (Figure 5.2). The mesh is adapted to the heterogeneous features of the image with smaller triangles used for fine features and larger ones in homogeneous areas. The generated meshes are quality-guaranteed and compatible with the MATLAB-based flexible FEM.

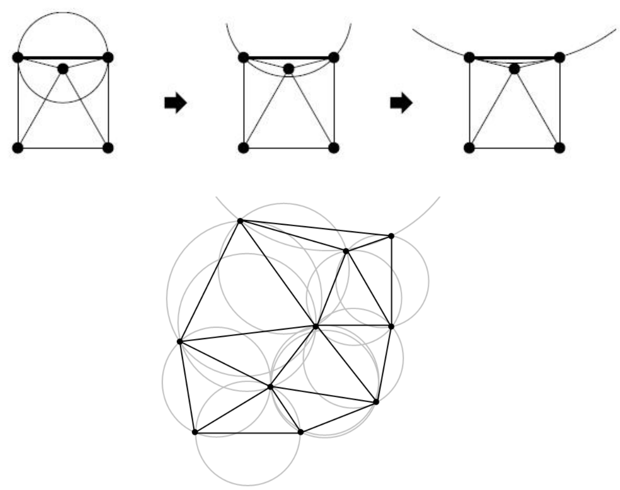

Figure 5.2 Unstructured Delaunay Triangulation. For a set of vertices in the plane, each triangle satisfies empty circumcircles (adapted from Gudla, 2005).

The model equations were then solved on the discretized domain using the flexible FEM code (Montas, 2003) and the results were displayed and analyzed using MATLAB scripts presented in Appendix D.

5.2.3 Model Evaluation

Model prediction

The goose model was evaluated using biological parameters estimated as described earlier (Section 5.2.1). The goose model was run in MATLAB (v. 7.1) in 2-D on the spatio-temporal domain described in the previous section. Spatial maps of Canada goose and resource population dynamics were produced from model output illustrating the goose population spread over space and time and the response of the resource.

Model validation

The goose model was validated by comparing its predictions of goose population densities with observations from goose surveys. The predictions were the goose population densities obtained at the end of the six-year simulation period such that the effect of initial conditions was minimized. The observations are the goose densities obtained from the goose field surveys conducted by the Anacostia National Park Service and other partner agencies. Over 20 goose surveys were performed between April 2004 and September 2009, and goose average densities (representing the observations) for April (spring), July (summer), and September (fall) had been computed (Chapter 4). Model predictions and observations were compared for all four survey locations described in the previous sections, that is, the Kingman site (golf course), Heritage site (roadside grassfields), Kenilworth site (aquatic gardens), and Anacostia (Park picnic fields) site.

Application to hotspot identification

Based on the validation results, resident Canada goose hotspots were identified by extracting from the simulation results all areas where goose density was above 1 T/km^2 for three months or more using a MATLAB script. This identification was essential for the selection of appropriate Goose Control Strategies relative to the land cover types (Chapter 6).

5.3 Results and Discussions

5.3.1 Model Development of Goose Dynamics in the Anacostia River System

Model Equation

The expanded goose-resource relationship (*goose model*) is shown below. In this system, the first equation describes the dynamics of the goose population, the second equation is the dynamics of the resource population, the third and fourth equations are the velocity dynamics in time and space (both *x* and *y* directions).

$$\frac{\partial G}{\partial t} = ck_{dR1}RG - k_{dG}G - \left[v_x \frac{\partial G}{\partial x} + v_y \frac{\partial G}{\partial y} \right] - G\left[\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} \right] + d\left[\frac{\partial^2 G}{\partial x^2} + \frac{\partial^2 G}{\partial y^2} \right] \quad (5.37)$$

$$\frac{\partial R}{\partial t} = -k_{dR1}GR + k_{gR}R - k_{dR2}R^2 \quad (5.38)$$

$$\frac{\partial v_x}{\partial t} = k_v\left[\frac{\partial R}{\partial x} \right] + d_v\left[\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} \right] \quad (5.39)$$

$$\frac{\partial v_y}{\partial t} = k_v\left[\frac{\partial R}{\partial y} \right] + d_v\left[\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} \right] \quad (5.40)$$

where the model parameters have been defined in the previous section. The modification of Fisher's model was made (1) by expressing the velocity dynamics separately (velocity as a state variable), in both *x* and *y* directions, and (2) by defining these accelerations (not the velocities themselves) as functions dependent on the resource gradient.

Unlike in the Fisher's model, where the velocity would have been incorporated into the goose dynamics, this system splits the derivative of the velocity in two (north-south and east-west directions), and is expressed separately from the goose dynamics. This leads to a system with four equations; one for the goose population (predator, consumer), one for the resource population (prey, producer), and two for the velocity (describing the movement in each direction). The velocity equations show that the dynamics are a combination of two types of movement (advection and diffusion). This approach was used for at least two reasons: first, it eased the system to be solved numerically with minimal oscillation issues; and second, it allowed a better GIS-oriented analysis given the heterogeneity of the natural system (Arditi *et al.*, 2001).

Model parameterization

Eight biological parameters were estimated and presented in Table 5.3. The calibration of these parameters was completed based on knowledge acquired from previous studies (literature review). The parameters obtained were to meet the biological conditions of section 5.2.1. The literature survey provided (or allowed estimating) the following biological parameters:

1. *Goose conversion efficiency (c = 0.6)*

This measure of ingestion rate represents the goose's *conversion efficiency* (*c*), that is, the amount of energy needed by the goose to produce offspring (Durant *et al.*, 2009). A value of 0.6 was selected for this study based on results of Molnar (1990) who analyzed the influence of high temperature on food intake, transformation, energy and protein demand of geese during the laying period.

This value is close to the value (0.65) used by Chakraborty *et al.* (2007) while investigating the effect of prey-taxis on predator-prey models with *Paramecium aurelia* as the prey and *Didinium nasutum* as its predator.

2. *Resource consumption rate* (k_{dR1})

This parameter was used to measure the quantity of the resource consumed by resident Canada geese in a given period. The formula:

$$k_{dR1} = \frac{area\_used\_by\_geese\_for\_foraging}{time} * \frac{1}{b} \tag{5.41}$$

was adapted from Durant *et al.* (2009), who computed the *resource consumption rate* as the mean instantaneous area searched during a foraging activity as square distance units per time unit (cm^2/min). The formula was adapted by factoring a parameter (*b*) into the equation to reflect the goose population-based biomass.

Assuming that an average adult resident goose weights approximately *12 pounds or 5.5 kg* (MCE, 2003), and considering the goose number ($n = 423$) obtained from the April 2007 survey for a 6½ month-period (t = 0.54 yr), a goose total biomass $b = 2326.5$ *kg* (or ~ *2.327 tons*) was used in the equation above along with the size of the study area (~ *11 km*²); thus

$$k_{dR1} = \frac{11}{0.54} * \frac{1}{2.327} = 8.75 \tag{5.42}$$

3. *Resource death rate* (k_{dR2})

Because the literature offered very limited information regarding the population dynamics of grasses, it was assumed in this study that both the resource death rate due to the geese consumption and the death rate due to impacts by natural stressors could be the same or close. A value of 9.00 km²/T.yr was then assumed for k_{dR2}.

4. *Resource growth rate (* k_{gR} *)*

This parameter governs the growth of the resource over time, and it was estimated by solving the equation of the resource dynamics at doubling time, t_2, (Stewart and Boyd, 1999) to obtain:

$$k_{gR} = \frac{\log(2)}{t_2} \tag{5.43}$$

Some studies (*e.g.*, Rogers *et al.*, 1993; Durako *et al.*, 1993) have found that the doubling time for grass species was between five and 30 days. Assuming that $t_2 = 5$ days (or 0.013 year), the calibrated value for the resource growth rate was $k_{gR} \approx 53.00$ /yr.

5. G*oose diffusion (* d *)* and *velocity diffusion (* d_v)

Goose diffusion was used in the model to describe the spread or invasiveness of resident Canada geese as a pest species through random motion – not motivated by the search for resource. This study used the diffusion coefficient, d = 0.1 km²/yr, determined by Chakraborty *et al.* (2007) to solve logistic Lotka-Volterra equations while investigating the effect of prey-taxis on predator–prey models with *Paramecium* as prey and *Didinium*as as predator. For simplicity, it was assumed that both *goose diffusion (d)* and *velocity diffusion (d_v)* had the same value, that is, $d = d_v$ = 0.1 km²/yr.

6. *Spread factor (k_v)*

The spread factor (or rate of invasion) was used to represent the expansion velocity of the goose-infested areas. The spread factor of 2.0 km/year estimated by Liebhold (2000) for gypsy moth (*Lymantria dispar*) considered as a predator of hardwood trees (prey) was used in the current research. Although the current study is focused on the goose species, the value of k_v above, was used to simulate the goose model.

7. *Goose mortality rate (k_{dG})*

The goose mortality rate (or death rate) was used in the goose dynamics equation to describe the number of deaths (or the reduction) in the goose population undergoing exponential decay at half-life, $t_{1/2}$, (Ayto, 1989):

$$t_{1/2} = \frac{\log(2)}{k_{dG}} \tag{5.44}$$

This study assumed that the goose half-life was approximately 48 days, that is, $t_{1/2} \approx 0.13$ year. Therefore, the *goose mortality rate (k_{dG})* was estimated at 5.25 km²/T.yr.

Table 5.3: Model Parameters, Meanings, and Values

parameters	Meaning	Value used	Other Values (sources)	Unit
kdR1	Resource consumption rate	8.75	2.1 (a)	$Km^2/T.yr$
kdR2	Resource death rate	9.00	0.10-0.50 (b)	$Km^2/T.yr$
kgR	Resource growth rate	53.00	75.6 (f)	$Km^2/T.yr$
kdG	Goose mortality rate	5.25	0.06 (b)	$Km^2/T.yr$
c	Conversion efficiency	0.60	0.60 (d)	no unit
d	Goose diffusivity constant	0.10	0.10 (c)	Km^2/yr
kv	Goose spread factor	2.00	2.00 (e)	$Km^4/T.yr^2$
d_v	Goose velocity diffusivity constant	0.10	0.10 (c)	yr^{-1}

(a) McCann and Yodzis (1994); (b) Van Langevelde *et al.* (2008); (c) Chakraborty *et al.* (2007); (d) Molnar (1990); (e) Liebhold (2000), and (f) Xu and Huang (2001).

Solution of the Model Equations

Model equations were solved using the process described earlier in section 5.2.1. The results are analyzed in detail in the next section and the generated meshes are described here.

Figure 5.3 shows the mesh derived from the land cover image, originally obtained from USGS and reclassified using ArcGIS' Spatial Analyst tools. There were five land cover classes in the study area (grassfield, water body, shrubs and woodland, urban area, and road), and they occupied various parts of the study area. The generated mesh is adapted to this heterogeneity.

By zooming in on the mesh, one can see that smaller triangles are used where land covers have substantial spatial variations while coarse triangles are used where the land cover is rather homogeneous. The smallest triangles have edges with size equal to the cell size of the source land cover image (24 m) but the adaptation of the mesh to larger triangles in homogeneous areas reduces the total number of nodes and triangles which in turn leads to a more efficient solution of the model equations over the mesh.

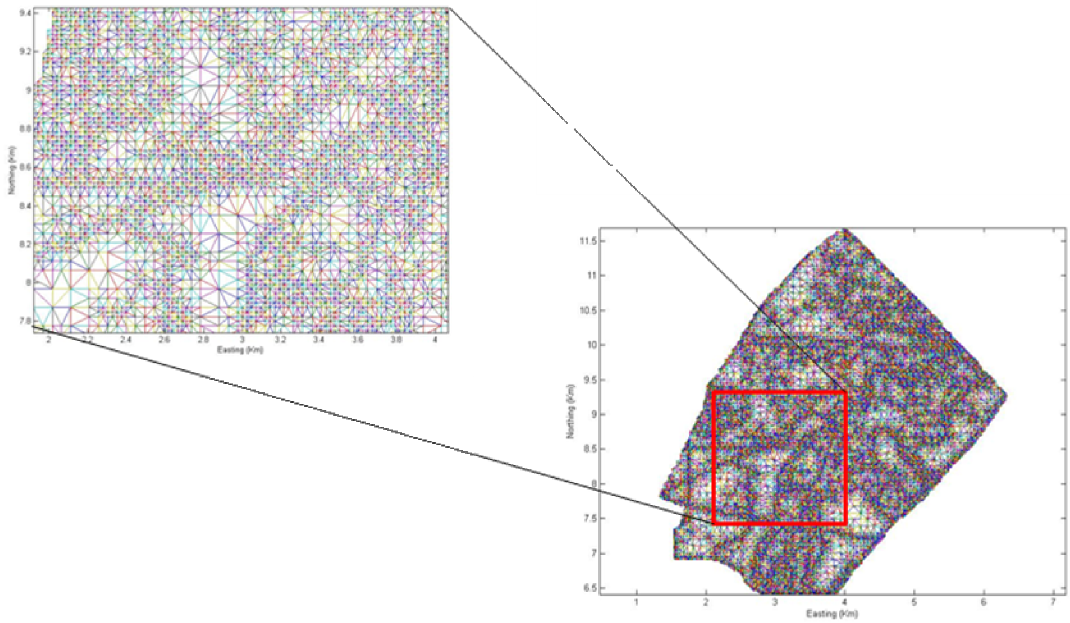

Figure 5.3 Unstructured Delaunay Triangulation

Figure 5.4 presents a zoom on the portion of the mesh representing the four goose survey sites. The zoom illustrates the adaptiveness of the mesh both in terms of triangle sizes and its ability to depict complex domain geometries. These four sub-meshes are used later to extract predicted goose resource populations, for each survey site individually, and calculate their means over the survey areas.

The graphs show that larger numbers of smaller meshes are found where the shapes tend to be coarse or at the edges.

Areas on images where elements are finer and dense illustrate a good data resolution, while larger elements with fewer numbers would provide an output with a lesser resolution. These factors (size and number of mesh elements) affect not only the resolution of the image data but also the computer memory space, and the time the model would run before displaying solutions.

In general, the more cells or pixels (smaller elements), the better the resolution, but the slower the model would run. Inversely, lesser cells or pixels (larger elements) would provide an image with poorer resolution, but the system would be faster in displaying solutions.

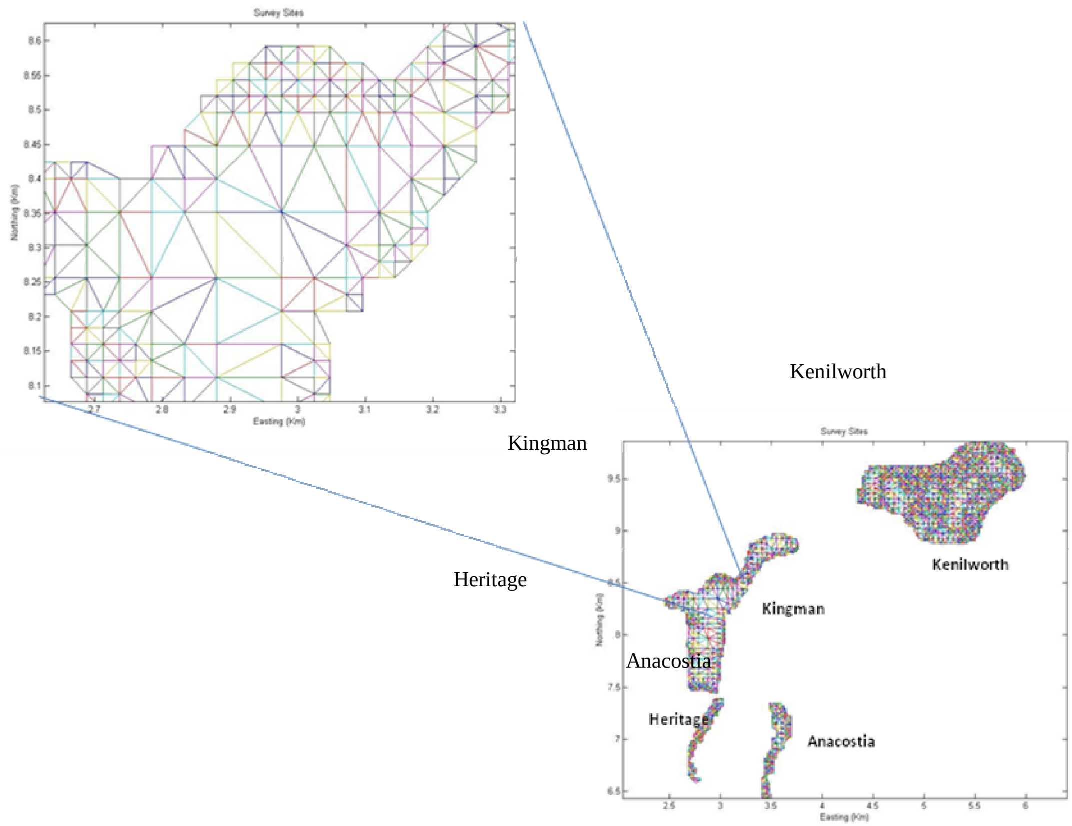

Figure 5.4 Meshing of Survey Site Image Using Delaunay Triangulation

5.3.2 Model Evaluation-Validation

Model Predictions

The results of the 2-D simulation of the goose dynamics in the study area (11.30 Km²) for a period of six years is shown in Figure 5.5. Results illustrate how geese spread out within the system targeting areas of greater resource gradients where they congregate the most (goose hotspots). The color bars in the Figures depict the goose biomass densities, the dark red color indicating resident goose hotspots.

This Figure shows that if a few geese (density = 0.25 T/km²) were initially set in the middle of the study area (initial conditions) with the assumption that food (grass) was the driving resource, the goose population would spread out in the environmental system toward greater resource gradients.

The initial location where geese were set in this particular example is northeast of Langston golf course and southeast of the National Arboretum. The simulation predicts that if nothing is done to control resident Canada geese (that is, no GCSs), then after two years resident geese would invade all areas covered with grass (especially hotspots). Goose biomass densities in all (or almost all) hotspots were $\geq$ 2.0 T/km², that is, eight times the initial density (0.5 T/km²). Simultaneously, the resource densities have substantially decreased in the invaded area (hotspots) because of the goose spread and overgrazing. The resource densities in the invaded locations decreased to around 1.0 T/km², that is, about 1/3 of its initial density. This simulation shows that after four years, resident geese have occupied all grassfields – almost the entire study area (11.30 km²).

The resource is almost completely depleted after the fourth year of the simulation due to the goose population spread and overgrazing.

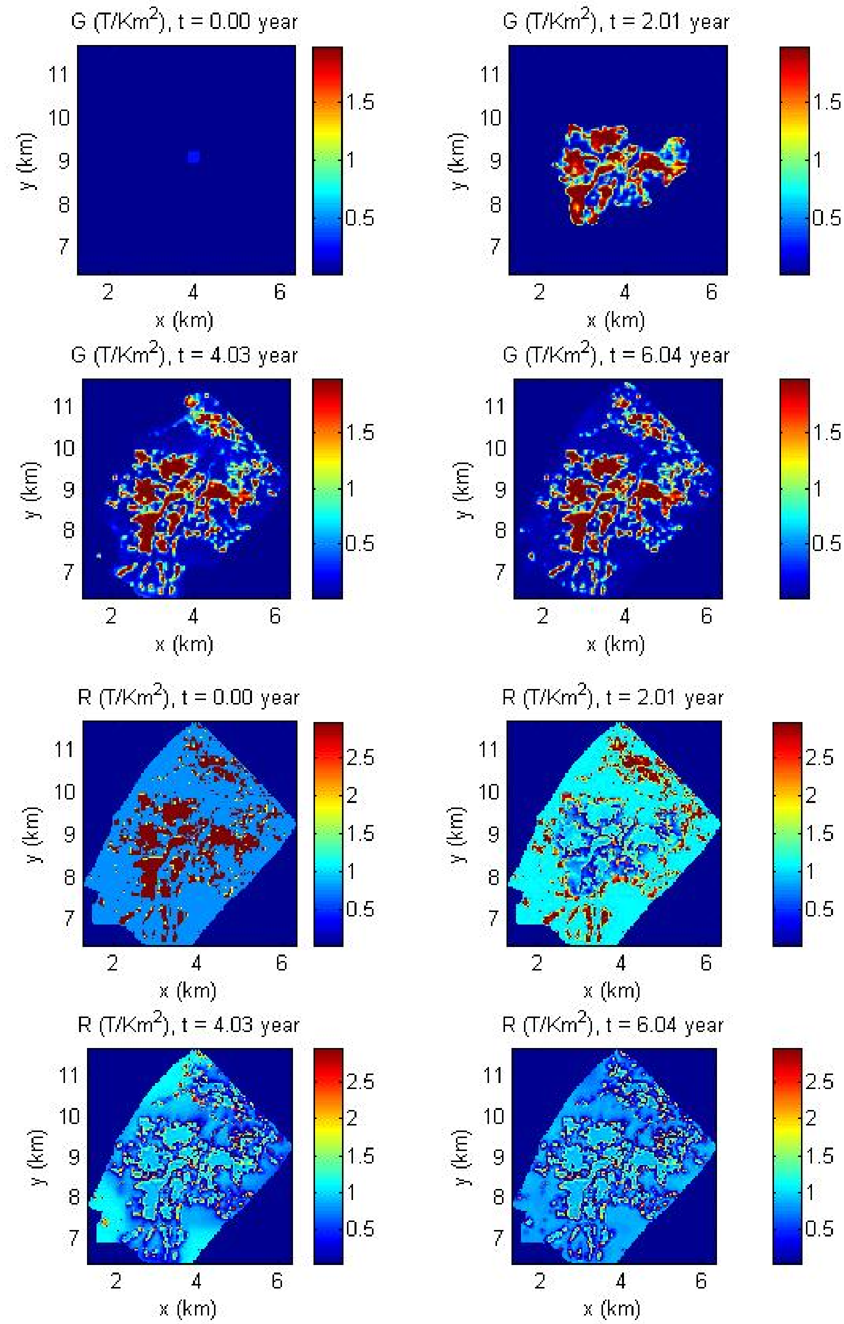

Figure 5.5 Spatio-Temporal Dynamics of Goose and Resource Populations in 2-Dimensions. The Simulation is for a six year Time Period. Parameters used are $k_{dR1} = 8.75; k_{gR} = 53.00; k_{dR2} = 9.00; k_{dG} = 5.25; c = 0.60$. Color bars indicate goose and resource densities in T/km².

Model Validation

Figure 5.6 presents the predicted Goose-Resource dynamics at survey sites (Kingman, Kenilworth, Anacostia, and Heritage) during the six-year simulation period. Goose population densities grow at all four locations while the resource population densities simultaneously decrease. The Figure shows that the biomass' growth curve at Kingman is leading those at Kenilworth, Anacostia, and Heritage; in other words, the goose population densities at Kingman (golf course) are by far higher, and seem to grow faster, than the goose population densities at Kenilworth (Aquatic Gardens), Anacostia (Park picnic field), and Heritage (roadside field). This is probably because the resource level at Kingman is higher and therefore more attractive to the goose populations.

The simulation also shows that it is after the first year ($t \sim 1.25$) that goose hotspots (densities ≥ 1.0 T/km^2) begin to form at the Kingman location. This location remains a goose-critical area for the rest of the simulation time, with a maximum stable population of 1.79 T/km^2 of goose biomass.

Hotspots are also shown in Anacostia, but they occur after the third year ($t \sim 3.25$) with a maximum population of about 1.25 T/km^2, but this biomass density quickly drops and stabilizes at 1.12 T/km^2. According to these results, both Kenilworth and Heritage are not resident Canada geese hotspots as goose densities at these locations remain under 1.0 T/km^2 during the entire period of simulation. The populations at Heritage and Kenilworth stabilize at 0.87 T/km^2 and 0.67 T/km^2, respectively.

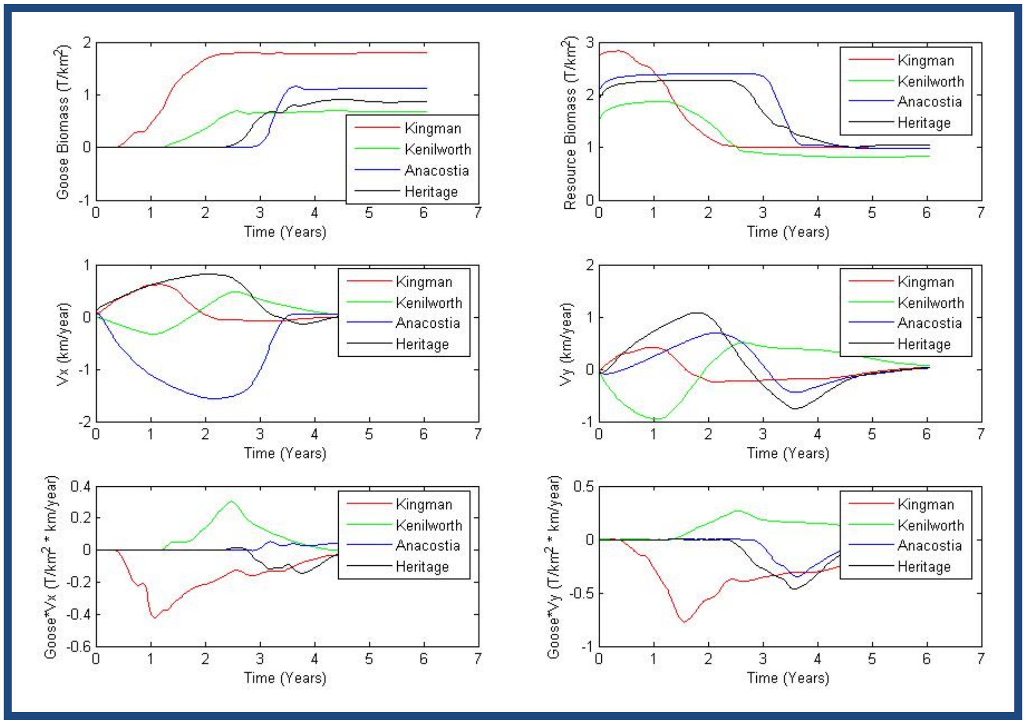

Figure 5.6 Goose-Resource Population Dynamics in the Anacostia River System: Densities at Four Survey Sites and Different Seasons. The goose (G) and the resource populations are simulated for six years. Parameters used are $k_{dR1} = 8.75; k_{gR} = 52.00; k_{dR2} = 9.00; k_{dG} = 5.25; c = 0.60$

The resource densities at all survey sites are affected by the goose population dynamics there. For instance, the resource density at Kingman (initially close to 3.0T/km²) dropped earlier and faster than anywhere else. This is probably because the higher goose population at this location (Kingman) caused a higher consumption of the available resource. Meanwhile the resource densities at the Anacostia and Heritage locations remained stable slightly above 2.0T/km² for two to three years before dropping. The decrease in Heritage is slower than the decrease in Anacostia.

The Kenilworth resource population seems to be the least affected, and this may be because of its lower goose population. The maximum resource density at Kenilworth was slightly below 2.0T/km² the first 18 months, but that number also decreased as geese continued to graze in this site. The resource population at Kenilworth dropped and stabilized a little under1.0T/km² while at other locations this number was about the same, that is, 1.0T/km². Resource biomass equilibria occurred approximately in the fourth year while goose biomass equilibria occurred at different times depending upon the locations (between the second and third year for Kingman and Kenilworth, and right before the fourth year for Anacostia and Heritage).

The goose velocity dynamics appeared to vary spatially and temporarily as well. For instance, when resident geese moved eastward (*x*-direction), their movements at Anacostia (picnic area) and Heritage (roadway field) were much faster (*Vmax* ~ 2 km/yr and ~1 km/yr, respectively, during the first three years) than in Kingman (golf course) and Kenilworth (aquatic garden), where the maximum velocity in each site was about ½ km/yr during the first two years).

The eastward velocities at all four survey sites stabilized to zero, approximately before the fourth year. After this period the resident geese were no longer moving eastward, but northward (*y*-direction) instead.

In the northward (*y*-direction), resident geese seemed to move faster in both Heritage field and Kenilworth Aquatic Gardens (*Vmax* in each site is 1 km/yr during the first two years), but the velocities at these two locations decreased to maximas that neared those at Anacostia picnic area and Kingman golf course (½ km/yr or so). Unlike the movement in the x-direction, the northward movement seemed to be cyclic, but the cycles or periods were short (< five years) and the movements stabilized to zero between the fifth and sixth year.

The mass flux varied depending on the *x*- and *y*-directions. Numerically speaking, these magnitudes could represent the numbers of geese counted along a transect line, a pathway, or the road per unit of distance walked. For instance in the eastward (*x)* direction), the goose mass flux at Kingman (maximum ~ 0.45 T/km.yr) and at Kenilworth (maximum ~ 0.30 T/km.yr) were greater than at Anacostia and Heritage, where maximas were much smaller (< 0.10 T/km.yr for

Anacostia and about 0.20 T/km.yr for Heritage). The goose mass flux in the northward (*y)* direction) is likely higher than in the eastward direction, with maximas that were above 0.50 T/km.yr except in Kenilworth (about 0.25 T/km.yr).

Overall, the model predicted that it would take two to four years to see the goose population densities at survey sites reach steady states, with both the Kingman and Anacostia populations leading the Kenilworth and Heritage populations. Qualitatively, the predictions of steady population levels is in agreement with the field observation data collected during the Canada goose survey and discussed in Chapter 4 .

Table 5.4 compares quantitative steady-state populations predicted by the model to observed values for the four survey sites. The model predicted that goose population densities at all survey sites would reach their steady state at densities between 1.0 T/km² and 2.0 T/km². These predictions are lower than the means of observations but well within the 95% confidence intervals, which indicates that they cannot be considered statistically different at this level of confidence (Neter et al., 1990).

Table 5.4: Steady-state goose (G) populations prediction versus observed data

Survey site	**Predicted steady state** ***(T/km^2)***	**Mean of observations** ***(T/km^2)***	**Standard deviation of observations** ***(T/km^2)***	**Number of observations**	**95% Confidence Interval** ***(T/km^2)***	
					Low	**High**
Kingman	1.79	3.50	2.68	15	-2.25	9.25
Kenilworth	0.67	2.45	1.62	15	-1.02	5.92
Anacostia	1.25	2.86	1.41	15	-0.16	5.88
Heritage	0.87	2.23	1.68	15	-1.37	5.83

It could be asserted that the model predictions and the observations agree both qualitatively and quantitatively, but the quantitative agreement is not perfect. There would be a need for more observed data (collected in 10 – 20 years, for example) in order to have a better appreciation of the goose dynamics (Hammershlag, *pers. Comm*.).

In fact, current observed data abnormally lack patterns over time, and this may be due to the variability of the tides and weather conditions that have unusually occurred in the study area during recent years causing eventual changes in goose population behavior and dynamics (Hammershlag, *pers. Comm*.). Therefore, collecting and training more observed data is expected to improve the quality of trend analysis by minimizing the outlier effects and therefore offering a much better comparison with the model predictions.

Application to hotspot identification:

From the model simulation results discussed in the previous section, resident Canada goose hotspots were identified and are presented in Figure 5.7 below. The dark spots in this Figure represent the areas of goose overpopulation, that is, the goose critical areas where goose density was above 1.0 T/km^2 for at least 3 months of the simulation. The total predicted area of hotspots is 5.0 k m^2 , which represents over 44% of the study area.The goose spread seems to follow the grassfield gradient. This is because in this model, “resource” was represented by “grass” (no other land cover class, except grassfields, was simulated). The hotspot map produced by the goose model was imported to ArcGIS and used in the selection of Goose Control Strategies for the goose management and control (Chapter 6).

Figure 5.7 Goose Hotspots in the Study Area

5.4 Conclusion

In this Chapter, a goose model was developed based on Fisher's Partial Differential Equations modified to account for GIS-oriented analyses (Arditi *et al.*, 2001). The model was evaluated using biological parameters estimated from the literature and constrained by basic biological principles (such as (1) the goose and resource densities should have positive values; and (2) the resource equilibrium density when there are geese in the system should be smaller than resource equilibrium density when there are no geese in the system). The simulation results showed that the majority of goose hotspots were located in areas where food resources (grassfields) were accessible. This is because the goose population dynamics were assumed in this study to be driven by the resource (grass) distribution.

The model predicted that the goose densities at all survey sites would increase in the first couple of years and then stabilize thereafter, with the population densities at Kingman and Anacostia leading the population densities elsewhere. These results were in agreement with observation data collected during field surveys, and they were somewhat expected given the constituent elements found in these particular sites (Kingman and Anacostia). Kingman is a golf course and Anacostia is a large grassfield within the Anacostia Park, used often time for picnics.

Compared to Kenilworth Aquatic Gardens, which is bushy from one place to another, and to Heritage, which is surrounded by shrubs, both Kingman and Anacostia sites are open flat habitats, where grasses are regularly treated and maintained providing both food – *i.e.*, tender grass, and safety – through their openness for a better watch for predators. Quantitatively, the model agreed with observations, although the average predicted density was slightly underestimated (approximately 1.0 - 2.0 T/km^2) compared to the average observed density (2.5 T/km^2). The differences were found to be non-significant statistically due to the high variance of observed data.

Future developments (Chapter 6) will focus on integrating the goose model within a Geographical Information System and developing related Expert Systems to produce a state-of-the-art DSS for resident Canada goose control and management.

CHAPTER 6:
COMBINING MODEL, EXPERT SYSTEM, AND GIS TECHNOLOGY TO MANAGE RESIDENT GEESE

6.1 Introduction

Canada geese (*Brenta Canadensis*) have increased in numbers in North America during the past few decades to levels that cause management issues and public health concerns (FR, 2006). While the current goose population in the Atlantic Flyway exceeds a million with an average increase rate of 1% per year (USFWS, 2005) the estimate in the sole vicinity of Kingman Marsh in the District of Columbia is between 500 and 2000 (Harris, 2002). In 2000 the District of Columbia and the U.S. Army Corps of Engineers spent over $5 million creating a 40-acre wetland (Kingman Marsh, located near RFK Stadium) that, unfortunately, resident Canada geese invaded and ate about $400,000 worth newly-installed plants (Harris, 2002); this represents a reduction of the vegetated cover estimated at one-third of its intended size (McKindley-Ward, 2006). Similar goose pressures on resources are observed on private and public properties in the District of Columbia metropolitan area. In order to address this problem, a Canada goose Management Committee (composed of National Park Service, Army Corps of Engineers, US Geological Society, District of Columbia Animal Control, and U.S. Department of Agriculture) is currently developing a resident Canada goose management plan for the District portion of the Anacostia area.

Developing Goose Control Strategies for resident goose control require a great understanding of the causes of the goose population increase in the infested areas. In other words, sound decisions about resident goose population management need science-based decision-making tools such as the goose DSS, developed in this study.

This Chapter starts with a brief review of goose biology, the problems caused by resident Canada geese and the goose control framework, including recommended strategies. It then proceed to describe the procedural development of the Expert Systems (Diagnosis and Prescription Expert Systems) and their combination with the goose Model and the Geographical Information System, a platform where hotspots and other geo-referenced data are stored, processed, analyzed, and displayed. Results of the diagnosis and prescription are discussed and evaluated by simulation of goose population dynamics.

The study area of interest is a portion of the Anacostia River System, which has been presented in the previous Chapters. The information obtained from this research could contribute to the overall Anacostia Resident Canada Goose Management Plan currently under development by the National Park Service and partner agencies.

6.2 Canada Goose Biology

Taxonomy

Canada goose (*Branta canadensis*) is a wild bird species belonging to the family of Anatidae, the subfamily Anserinae, and the tribe Anserini. The genus *Branta* is native to Arctic and temperate regions of North America, a black head and neck, white patches on the face, and a brownish-gray body. Often time, Canada goose is mistakenly called “Canadian goose”, but that name is not strictly correct. The correct name, found in most literatures, is Canada goose.. The family of Anatidae also includes swans, most of which are larger than true geese, and ducks, which are smaller. According to Harris (2002), Canada geese are the most widespread and abundant geese in North America, with many different subspecies or races, of which the three migratory ones in the Atlantic Flyway are *Branta canadensis canadensis* or Atlantic Canada goose, *Branta canadensis interior,* and *Branta canadensis hutchinsii* or Richardson's Canada goose.

There are two ecologically distinct populations along the Atlantic Flyway, both of which make use of the Anacostia River system in the District of Columbia and Maryland. One population type is the migratory Canada goose, which historically uses mid-Atlantic for breeding ground; and another population type is the resident Canada goose (RCG), which originates from stocks released on the East Coast decades ago for hunting programs. RCG stay year-round in the continental United States and in the southern regions (Harris, 2002).

Habitat characteristics and behavior

Like the related Brent geese (*Branta bernicla bernicla*), Canada geese forage on small grains such as rice cut grass (*Leersia oryzoides*) and millet (*Echinocloa* sp.) in wetlands and agricultural lands, where marsh plants and pastures, respectively, are the two major habitats used by geese in spring (Bos, 2002). The selection of these areas by geese is justified by the fact that high quality forage has high nitrogen content (Ydenberg and Prins, 1981; Prins and Ydenberg, 1985) and better digestibility (Boudewijn, 1984). Beside quality food, geese might be attracted by areas with large quantities food (Vickery *et al.* 1995; Rowcliffe *et al.* 2001); but circumstantial evidence suggests that geese would prefer feeding on marsh vegetation first, among other habitat choices (Bos, 2002). Granholm (1990) describes the general habitat characteristics and feeding behavior of this waterfowl species as follows:

- Regularly graze, glean, and seek grit in moist fields feeding on forbs, green shoots, seeds, wild grasses, and aquatic plants.

- In winter, geese prefer feeding in fields near safe roosts on open water of lakes and ponds. Nest sites highly variable, but usually on a firm, dry, slightly elevated site located near water and feeding areas, relatively isolated, with good visibility from nest. Island nests are preferred, but may use other birds' nests found in marshes.

- Yearlong activity pattern mainly include seasonal migrations (wild geese essentially) and feeding (mostly diurnal, early and late in day, but may feed nocturnally under hunting pressure).

- Year-round activities in the same areas (resident geese essentially) but could momentarily leave the area if water freezes; home range limited to nesting and grazing areas if suitable forage and water remains but could extend up to several miles from nests if water freezes.

- Male geese can become territorial for nesting and feeding especially during breeding.

6.3 Problems Caused by Resident Canada Geese: Types and Causes of Conflicts

Canada geese are a valuable natural resource that provides recreation and enjoyment to bird watchers, hunters, and the public. But in recent years, flocks of local-nesting (so called resident Canada geese) have become year-round inhabitants of urban areas – too often causing conflict and problems with humans.(Harris, 2002).

Figure 6.1 shows that resident Canada geese are among the top 10 nuisance urban pests in the District of Columbia metropolitan area. The problems these pests cause to the environment are numerous ranging from ecological to socio-economical (Conover and Chasko, 1985; Forbes, 1996; Cleary *et al.*, 1997; Harris, 2002; USFWS, 2009; McKindley-Ward, 2006), and include:

- overgrazing of parks and lawns (such as corporate business areas, golf courses, schools and college campuses, athletic fields, cemeteries, hospitals and residential);

- accumulations of droppings and feathers on play areas and walkways; nutrient loading to ponds, water-treatment reservoirs, beaches and drinking water supplies;

- health concerns, which are related to excessive goose droppings in the environment especially at public beaches, where diseases such as *Giardia*, *duck viral enteritis*, and other fecal coliforms are spread at high levels (Harris, 2002; USFWS, 2009). In heavy concentrations, goose droppings can over-fertilize lawns and degrade water quality resulting in eutrophication of lakes and excessive algae growth (Manny *et al.*, 1994); and

- safety hazards near roads and airports. Aircraft strikes resulting in dangerous landing and take-off conditions, costly repairs, and loss of human life (Forbes, 1996; Cleary *et al.*, 1997; Harris, 2002; USFWS, 2009). The strike to aircrafts is perhaps the most dramatic negative impact of Canada geese on humans in terms of lives and economic damages. Recent examples of aircraft strikes include:

    - January 2009 near New York City, where Canada geese collided with US Airways flight 1549 forcing the pilot to perform an emergency landing into the Hudson River after the geese damaged both of the plane's engines;

    - November 2007, a strike on the 27A CRJ-200 at Memphis International Airport, TN;

    - October 2007, a strike on the aircraft CRJ-700 at Denver International, CO;

    - August 2006, a strike at the General Aviation airport, IN;

- September 2003, a strike on CC-560 Fokker at LaGuardia Airport, NY;

- June 1995, a landing Air France Concorde, on a final approach to JFK International Airport, struck several geese which destroyed two engines and causing damages totaling about $6 millions; and

- September 1995, a Boeing 707 crashed after striking a flock of Canada geese on a takeoff at Elmendorf Air Force Base in Alaska killing 24 military personnel and causing over $189 millions of damages. This is perhaps the most damaging strike in recent years in terms of human loss.

One indicator of the extent of resident Canada goose problems in the District of Columbia metropolitan area, like in many other states, is the annual number of complaints received by resource management agencies. While the number of complaints was decreasing in DC-Maryland between 1998 and 2003, it is now rising again (Figure 6.1).

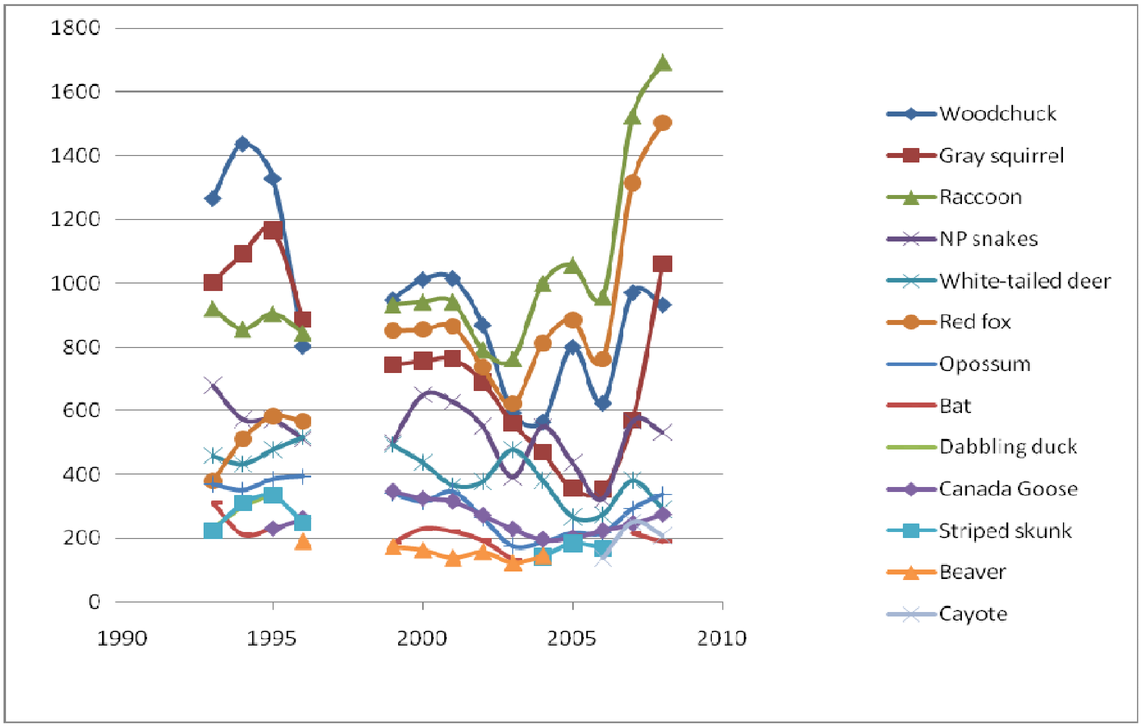

Figure 6.1 Complaint Calls About the Most Nuisance Animal Species in DC-Maryland. (USDA APHIS, 2009)

The population trends, along with the associated complaints, would likely continue to grow unless proper goose control strategies are implemented. Moreover, the investments made by the District and federal governments may be lost if geese are left uncontrolled.

The current goal of the Maryland Department of Natural Resources is to reduce its resident (non-migratory) Canada goose population from 83,000 to 30,000 (McKindley-Wards, 2006).

While the carrying capacity goal is still unclear with respect to District of Columbia population, resource managers aim at reducing the number of geese to the level where the Kingman marsh vegetation resembles the state it was before the degradation, few decades ago (Hammershlag, *pers. Comm.*). Therefore, the National Park Service and partner agencies are preparing an Environmental Impact Statement for resident Canada goose management in the District of Columbia. This plan is expected to come with recommended sets of decisions and actions, and the current study could contribute to this aim. In the past, control strategies had not produced satisfactory results, and one of the reasons could be because management actions focused more on solving the problems caused by Canada geese without necessarily eradicating the causes of those problems. Such causes could vary in space and time, and therefore their prediction by a model is an essential step prior to the design of effective control tools (such as Decision Support Systems), which is the overall goal of this research.

6.4 Regulatory Framework of Canada Goose Management

As a migratory bird, the Canada goose species is protected under four bilateral migratory birds Treaties the United States entered into with Great Britain (for Canada in 1916 as amended in 1999), the United Mexican States (1936 as amended in 1972 and 1999), Japan (1972 as amended in 1974), and the Soviet Union (1978).

Regulations allowing the take of migratory birds are authorized by the Migratory Bird Treaty Act (16 USC. 703-711), and the Fish and Wildlife Improvement Act of 1978 (16 USC. 712).

The Migratory Bird Treaty Act (Act), which implements these treaties, indicates that the Secretary of the Interior is authorized and directed to determine when, to what extent, and by what means it is compatible with the conventions to allow hunting, killing, and other forms of takes of migratory birds, their nests, and eggs. The Act requires the Secretary to implement a determination by adopting regulations permitting and governing those activities.

Regulations governing the issuance of permits to take, capture, kill, possess, and transport migratory birds are promulgated in title 50, Code of Federal Regulations (CFR), parts 13 and 21, and issued by U.S. Fish and Wildlife Service (USFWS).

The Service annually promulgates regulations governing the take, possession, and transportation of migratory birds under sport hunting seasons in 50 CFR Part 20.

Given the scope of the goose damages and management problems described above, the Department of Interior and agency partners, believes the development and evaluation of alternative strategies to reduce, manage, and control resident Canada geese in the continental United States are needed in order for local agencies to be more efficient in their management activities (USFWS, 2005; USDA APHIS, 2009).

Such management alternatives, regrouped into two categories as lethal and non-lethal, are listed in Table 6.1, and reviewed further below.

Table 6.1: Goose Management Techniques

Lethal control
• Hunting • Egg destruction (puncturing, oiling) • Chemical capture by euthanasia
Non-lethal control
• Surround trapping • Habitat modifications (*e.g.*, strategic planting, selected vegetation types, and steepening of ponds' banks) • Exclosure fencing • Harassment (dog chasing, mute swan chasing, explosives and rocket devices using air guns, screamer sirens, carbide cannons, etc., and other passive approaches using Mylar and inflatable eyespot-painted balloons, human effigies, and scarecrows) • Chemical repellents (*e.g.*, methyl anthranilate and anthraquinone)

6.4.1 Lethal Controls

Lethal controls involve the killing of resident Canada geese. Some of these management techniques are reviewed below.

Hunting

Hunting regulations are set at a federal level by the USFWS in accordance with the Migratory Bird Treaty of 1916. State regulations can be more restrictive than federal regulations, but they may not be more liberal. In many States, hunting seasons are opened when migratory populations have departed to their original northern regions.

Hunting helps slow down the fast growth of Canada goose populations. It has in some cases resulted in large numbers of resident geese being killed annually (Harris, 2002).

In the State of Maryland, the goal is to reduce the resident goose population to 30,000, which is about one-third of the current population (McKindley-Ward, 2006). The daily bag limits are eight (for the early season) and five (for the late season).

Resident Canada goose seasonal hunting schedules for FY 2010 – 2011 are as follows (MD DNR, 2010):

- Early season

September 1st-15th (Eastern Hunt Zone): Calvert, Caroline, Cecil, Dorchester, Harford, Kent, Queen Anne’s, St. Mary’s, Somerset, Talbot, Wicomico, Worcester Counties, part of Anne Arundel County located east of Interstate 895, Interstate 97, and Route 3; part of Prince George’s County located east of Route 3 and Route 301; and part of Charles County located east of Route 301 toward Virginia.

September 1st-25th (Western Hunt Zone): Allegany, Baltimore, Carroll, Frederick, Garrett, Howard, Montgomery, and Washington Counties; part of Anne Arundel County located west of

Interstate 895, Interstate 97, and Route 3; part of Prince George's County located west of Route 3 and Route 301; and part of Charles County located west of 301 to the Virginia line.

- Late season

November 16th-November 27th and *December 17th-March 6th* (Hunt Zone): Allegany, Frederick, Garrett, Montgomery, and Washington Counties; portion of Carroll County located west of Route 31 to the intersection of Route 97 and west of Route 97 to the Pennsylvania line; portion of Prince George's County located west of Route 3 and Route 301; and portion of Charles County located west of Route 301 to Virginia.

The State recommends that for special hunting methods for resident Canada geese during the September season, shotguns capable of holding more than three shells may be used to take resident geese and the shooting hours be from one-half hour before sunrise to one-half hour after sunset.

Destruction of eggs and nests

Managing Canada geese through destruction of nests and eggs, or through treatment of eggs anywhere applicable (*e.g.*, sidewalks, entryways, enclosed courtyards, picnic areas, playgrounds, and near paths and roadways) is intended to cause geese to abandon the nests and flee the problem areas (USDA APHIS WS, 2009). According to the Atlantic Flyway Council and the Maryland Department of Natural Resources, destroying 95% of resident Canada geese eggs annually as part of goose control strategies is believed to reduce goose population densities by 25% over 10 years (McKindley-Ward, 2006).

The USFWS recommends that destroyed nest materials and eggs (usually March 1-June 30) be buried on site, incinerated, placed in outgoing trash, or covered with objects (overturned garbage can, wood, branches, etc.), in accordance with local ordinances so that nesting geese may not recognize the initial nest locations (USDA APHIS WS, 2009). However, there are times when the pair does not leave and instead initiates a new nest nearby, and in this case, the destruction of the new nest is necessary, followed by integrated harassment activities (USDA APHIS WS, 2009).

Chemical capture

This technique consists of capturing nuisance geese by means of sedation using approved drugs and appropriate drug administering equipment by a certified governmental animal control agency. In 1992, the Federal Drug Administration (FDA) gave Wildlife Service the permission to use the anesthetic alpha-chlorase (AC) to capture waterfowl (Harris, 2002). This method has been successful in areas where hunting is impractical or prohibited such as urban areas (Belant *et al.*, 1999).

Surround trapping

Surround trapping is another commonly used technique to control nuisance birds captured during molting when they are flightless. This management method has been very successful in the Twin Cities, Minnesota, where State and local governments have created over the past 20 years the largest, most cost-efficient goose reduction program in a seven-county metro area. What happened here is that wildlife managers began to trap geese in the mid 1980’s during annual feather molt (a three- to four-week period when geese can’t fly in early summer) and ship them to other Midwestern States that wanted to increase their goose populations. Over 88,000 resident geese were trapped from 140 different sites in the seven-county metro area, sent live to poultry processing plants, and turned into USDA-approved meat that was given away at food pantries (Lien, 2000 and McKindley-Ward, 2006).

While lethal controls would reduce the goose population in the problematic areas there could be protests and oppositions from animal rights advocate groups, who believe these management methods are not humane.

6.4.2 Non-Lethal Control

Non-lethal controls consist of managing the nuisance Canada geese in a humane way, that is, without causing geese injury or death. Some of the non-lethal techniques are described below.

Habitat Modification

Habitat modification involves physically altering property to make it less attractive to Canada geese, and this is done by eliminating or reducing nesting sites and food sources, as well as the access between these items and the water bodies. Suitable habitats can be modified in many ways including (Dornbush *et al.*, 1996; Harris, 2002):

Strategic planting – Canada geese usually feed on grass, especially on young and succulent shoots, found on mowed, fertilized lawns. So eliminating mowing at least 20 feet from pond shorelines would encourage geese to shy away from these areas and look for safer spots with better food sources. Planting shrubs or tall, lush native prairie grass stands along shorelines could also provide the same benefits as eliminating mowing because geese would see over the grass while they walk through it.

Replacing the vegetation **–** Replacing plants that geese like to eat (*e.g.*, Kentucky bluegrass, Brome grass, Canary grass, Colonial bentgrass, Perennial ryegrass, Quackgrass, and Red fescue) with ones they do not typically bother (*e.g.,* mature tall fescue, Periwinkle, Myrtle, Pachysandra, English ivy, Hosta or plantain lily, Ground Juniper, and Switch grass) may discourage them from remaining in an area.

Steepening banks of ponds – Canada geese prefer a gentle, grassy slope coming out of the water that enables them to walk easily into and out of the water to feed or rest. If access to the water is poor, the adult geese may leave that area to raise their young elsewhere. Steepening the shoreline can be done by building a vertical seawall above the surface of the water.

Allowing water to freeze - Allowing a pond to freeze over could force the geese to seek alternative water sources and may force them to migrate. Concentrations of geese could maintain open water even in below freezing temperatures. Harassment may be necessary to force the birds to leave long enough for the ice to form.

Exclosure fencing

Exclusion methods are used to keep Canada geese from entering the problem areas. Exclosures can be erected over water bodies to prevent or discourage landing, or around the land system to prevent access to the resources. Examples of exclosures are overhead grids with tree branches and wire fences.

Harassment

This technique aims at scaring Canada geese in some ways so that they can leave the problem areas. Some of the methods used to harass resident Canada geese include:

Balloons – both Mylar and regular inflatable balloons (especially those with eyespots painted on them), flags, streamers, reflective tape, mute swan decoys, human effigies, and scarecrows can all be used to repel Canada geese (Harris, 2002), and can be used at a rate of at least 3-5 per acre. It is recommended that balloons be moved every few days to be effective (French and Parkhurst, 2001). Mylar flags seem to be very productive for farmers living near the Horicon National Wildlife Refuge (Harris 2002).

Dogs – Using dogs to harass geese from problem areas can be very productive. For example herding breeds such as highly trained border collies, have been used to scare geese off manicured areas like golf courses (Woodruff and Green, 1996; McKindley-Ward, 2006). To be more effective, dog harassment should continue and be repeated until the geese leave the area permanently. While dog chasing could provide excellent results, it is worth mentioning that dogs need to be monitored to avoid any physical injury to geese. In fact it is illegal to catch, injure or kill a Canada goose without a permit (MD DNR, 1999)

Pyrotechnics **–** Pyrotechnics are specially designed Class C fireworks that are used to frighten wildlife in general. They can be very effective in scaring resident geese out of problem areas as well. The types of pyrotechnics in this class include air guns, carbide cannons, screamer sirens, and bird bangers (large bottle rocket-type devices fired from a 15-mm starter's pistol that whistle loudly or explode) and shellcrackers fired from a 12-gauge shotgun (Harris, 2002).

Propane Cannons **–** Propane cannons are popular tools in use at hundreds of airports around the country, and many farmers also have used them with some success (Harris, 2002). Operating from the gas in a standard propane tank, a small amount of propane is ignited on a timed basis producing a loud report that can be heard more than a mile away (Harris, 2002). Comparing relative efficacy of several auditory harassment techniques for moving shorebirds off buildings, scientists found that only propane cannons were more effective, and that it took two cannons, carefully placed, to repel birds (Harris, 2002). Propane cannons may not be suitable for large communities because the devices are loud and may be more of a nuisance, than the geese, to the public and area residents (BNWR, 2000).

The major concern with the harassment techniques described above is that geese quickly get used to the techniques, which also become inefficient with time. McKindley-Ward (2006) believes that "harassment techniques to push geese away don't really solve the problem, but rather they just move the problem somewhere else while also impacting non-target wildlife species." Harassment techniques could be more useful in preventing goose damage (before it begins) rather than stopping it (once it has already started); in other words it would be difficult to disturb resident geese in areas with which they are familiar, given that this animal species is particularly placid (Harris, 2002). Harassment techniques would be more effective if used in combination and if repeated persistently (Dornbush *et al.*, 1996; Harris, 2002).

Chemical repellents

Some chemical additives can be sprayed on grass to make distasteful to geese. Such repellents have shown some efficacy at deterring goose herbivory (Harris, 2002).

Because not all chemicals are safe for the environment, or may cause mortality in non-target species (Harris, 2002) they must be registered, that is, shown to have little or no adverse environmental impact while demonstrating it can do what the manufacturer claims. There are two types of goose repellents registered with the U.S. Environmental Protection Agency, and these are *methyl anthranilate* (MA) and *anthraquinone* (AQ), both of which are naturally occurring chemicals that, upon degradation, leave no dangerous residues (Titchenell and Lynch Jr., 2010). The labels of these products provide the applicator with instructions on applying these compounds to the grass. While MA products make the grass unpalatable to geese, AQ products cause a slight stomach discomfort to the birds.

Geese avoid areas treated with MA or AQ products. Both MA and AQ products can remain after rain, but mowing would reduce the amount of product available. One problem with the repellent strategy is that the products tend to be expensive, especially since the entire grass area needs to be treated (Titchenell and Lynch Jr., 2010).

6.5 Objectives

The knowledge gained from the literature reviewed above along with the information acquired from the model (Chapter 5) and the human experts (*e.g.,* field managers) are used in this Chapter for the design of the Canada goose Decision Support System (DSS), which is the overall goal of this Chapter.

Two specific objectives are targeted:

(1) To diagnose the most likely causes of Canada goose population congregation at hotspots; and

(2) To prescribe the best goose control strategies at each of the identified hotspots.

Both the Diagnosis Expert System (DES) and Prescription Expert System (PES) are implemented within the GIS via ArcGIS' ModelBuilder. The engineered DSS is expected to assist resource managers and landowners in managing the nuisance geese in the natural system.

Specific direct benefits from this study could include:

1. providing an inexperienced staff with a safety net decision tool, and a more experienced staff with an intelligent checklist;

2. offering the opportunity to use the DSS continuously despite the changes in staff; and

3. providing a transparent easy-to-use map instrument to end users and an effective communication device either for explaining the reasoning behind a recommendation to decision-makers, or to present the same reasoning to the public.

6.6 Materials and Methods

6.6.1 Hardware and Software

The GIS-based DSS is developed on HP xw8600 64-bit Workstation running Windows XP Operating System. The GIS software used is ArcGIS (9.3 version) produced by Environmental Systems Research Institute (ESRI). This tool provides a platform for mapping, spatial analysis, data storage, and data management allowing users to manipulate geo-referenced data via a modular and intuitive Graphical User Interface (GUI). These are required to identify goose population hotspots, diagnose causes of goose invasion, and prescribe appropriate control strategies.

6.6.2 Data Acquisition

Two spatial datasets were needed to develop and apply the DSS: study area data and hotspot locations. The spatial data on land cover, study area boundaries and wetlands were acquired from public sources and processed into GIS format as described earlier in Chapter 4 (section 4.5). The hotspot data was obtained from simulations performed using the goose model as described in the previous Chapter (section 5.3.3). The hotspot output from the model is in the form of a digital image that was georeferenced and rectified prior to importing it into ArcGIS.

6.6.3 Coupling Goose Model with Expert System and GIS

The goose model was used in conjunction with GIS, using the loosely coupled approach (Kilgore, 1997) where the model and GIS maintain two separate databases and interact through some file exchange or conversion process between MATLAB and ArcGIS. Many researchers have used this approach to combine hydrologic models with GIS (He *et al.*, 2001; Xiao, 2003; Hanna, 2006).

ArcGIS ModelBuilder was used to import the goose model hotspots, implement the Expert Systems, and apply these systems within the DSS following the approach presented in previous studies (Georgoussis *et al.*, 2009; Montas, 1990; Montas and Madramootoo, 1992; Montas and Shirmohammadi, 1999; and Montas *et al.*, 1999b).

The process is completed in three basic steps summarized as follows (Montas, 2004):

1. First, the goose congregation hotspot layer is added into GIS.

2. Second, the diagnosis ES is applied to the study area and its results are filtered by hot spot.This step produces a map of the most likely causes of goose congregation in the potential hotspots identified by the model.

3. Third, the prescription ES is run and its results are filtered by hotspots.

This prescription ES considers the diagnosed causes of excessive goose congregation and local conditions to identify the most appropriate control strategies for each hotspot. The eventual result of its application is a map of recommended control strategies for the pre-identified goose overcrowding hotspots.

Diagnosis expert system

The diagnosis expert system (DES) was developed in three steps:

(1) The first step was the acquisition of knowledge about goose biology. This step entailed both a literature search and discussions with human experts. The objectives were to identify the potential causes of resident Canada geese excessive congregation in a given bio-environment and, based on these factors, to develop general rules, which can be used to diagnose the cause of a goose infestation problem.

(2) The second development step was to formalize the knowledge acquired in step 1 in the form of logical sentences (IF-THEN statements) representing the goose invasion diagnosis rules.

(3) In the third step, the ModelBuilder tool of ArcGIS software – along with other Spatial Analyst tools, were used to translate the DES from IF-THEN rules into decision trees.

Prescription expert system

The Prescription Expert System (PES) was developed by following the same steps as in the development of the Diagnosis Expert System. The major difference was that knowledge was acquired relative to appropriate goose control strategies rather than overpopulation causes. Additionally, knowledge was acquired and formalized based on control strategies that are applicable to goose congregation causes identified by the Diagnosis, and on other local factors (in addition to overcrowding causes) that needed to be considered in order to determine the Goose Control Strategies (GCSs) for a given cause/bio-environment pair. This knowledge was formalized, written into logical rules and converted to a decision tree.

6.6.4 Testing and Verification of Goose Control Strategies Allocation

The Goose Control Strategies (GCSs) recommended by the DSS were tested by assessing their impacts on the goose hotspots in the study area. The assessment was done by identifying, for each recommended GCS, the model parameters that could be affected by the related GCS. Once the parameters were changed in the model, the system was re-run with the new parameter set, and the goose hotspots re-assessed.

This testing allowed to verify the effectiveness of the system by measuring the percent of hotspot reduction that the prescribed GCS would provide.

6.7 Results and Discussions

6.7.1 Coupling Goose Model with Expert System and GIS

Resident goose hotspots were obtained from the goose model for a six-year simulation period (Chapter 5). *Hotspot* was defined in this study as a localized area where resident Canada geese congregate at high density (that is, over 200 geese or 1 Ton of goose biomass per km²) for at least three months. Goose hotspots are shown below in Figure 6.4, and they cover about 5.0 km² (that is about 45% of the total landcover). It can be seen from the graph below that all areas (or almost all) covered with grass were identified as being goose hotspots in this study area.

These are treated and maintained grassfields (such as golf course and other athletic fields) located near the tidal Anacostia River. Kentucky bluegrass and water bentgrass are the most common species in those fields. Other hotspots included in the graph below are wetland systems (Kingman marsh, Heritage marsh, and Kenilworth Aquatic Garden) where rice cutgrass, wild rice (*Zizania aquatica*), *Sagittaria* sp., *Pontederia* sp., and *Schoenoplectus pungens* are grass species among the most eaten by Canada geese in the Anacostia wetland systems (Hammerschlag *et al.*, 2002).

Figure 6.2 Goose Hotspots in the Study Area

Diagnosis expert system

Based on the literature review and discussion with experts, three causes of goose congregation in hotspots were selected for Expert System development: (1) high access to resources (food and water); (2) high access to breeding and nesting sites; and (3) provision of additional food from humans in urban areas.

A set of IF-THEN rules was then developed to diagnose goose hotspots into these three causes:

<u>High Accessibility to Resource Rules</u>**:**

IF	*goose-infested area is an open food source (e.g., hay-pasture, golf course, lawn, and other grassfields) and this food source is located within the study area*
THEN	*high accessibility to resources (grasses and waters) is the cause of goose congregation (**Diagnosis 1**)*
IF	*goose-infested area is located near water bodies and water bodies are located within the study area*
THEN	*high accessibility to resources (grasses and waters) is the cause of goose congregation (**Diagnosis 1**)*

<u>High Accessibility to breeding-nesting sites Rules</u>:

IF	*goose-infested area is an open wetland (e.g., Kingman, Heritage) and wetland is located within the study area*
THEN	*high accessibility to breeding-nesting sites is the cause of goose congregation (**Diagnosis 2**)*
IF	*goose-infested area is* a *courtyard/sidewalk/entryway field and this field is located within the study area*
THEN	*high accessibility to breeding-nesting sites is the cause of goose congregation (**Diagnosis 2**)*

<u>Urban Feeding Rule</u>:

IF *goose-infested area is a developed area (e.g., urban park, managed pond, touristic plaza), where birds are often time fed with artificial (extra) food in addition to food and water resources found in the natural environment, and the developed area is located within the study area*

THEN *urban feeding is the cause of goose congregation (**Diagnosis 3**)*

The general explanation for these rules is that Canada geese are attracted to areas that provide food, water, and protection, as found in urban areas with lakes and ponds (MDNRE, 2010). The food in particular is found in grasslands (pasture and hays, herbaceous wetlands, etc.) and wetlands (such as Kingman marsh, Heritage marsh, and Kenilworth Aquatic Gardens). Other food supplies are found in urban areas particularly in city plazas and public parks usually managed near manmade ponds.

Diagnosis 1: High access to resources (food and waters)

In this Chapter, *resource is* meant to denote food and water resource. Food resources are provisions found in grassfields such as small grains and seeds of Kentucky bluegrass, rice cutgrass (*Leersia oryzoides*), water bentgrass and other wetland plants such as *Sagittaria*, *Pontederia* and *Schoenoplectus pungens*, which are some of the most palatable grasses by geese in the Anacostia system (Hammershlag *et al.*, 2002). These grasses are essential to Canada geese for living.

Like grass, water resources are critical for Canada geese. They rely upon waters for drinking and social interactions, and they usually feed in open fields near water bodies (Granholm, 1990). Therefore, the decision logic for *high access to resources* was based on the proximity of food supplies (feeding sites) or water bodies to use by Canada geese.

Diagnosis 2: High access to breeding and nesting habitats

Other land features that were found to be important to the biology of the Canada geese in the study area were the marsh systems or other grounds found near sidewalks, entryways, courtyards, picnic areas, playgrounds, and roadways, which are potentially suitable for breeding, nesting, and rearing young.

Therefore, the decision logic for *high access to breeding and nesting habitats* was based on the proximity to the marshes or those habitats identified as potential suitable for breeding, nesting, and rearing young. In 2000, Kingman and Heritage wetlands were found to be permanent breeding and nesting sites for resident Canada geese after the District of Columbia Government and the U.S. Army Corps of Engineers replanted these marshes for restoration purposes (Hammershlag *et al.*, 2002 and McKinley-Ward, 2006).

Diagnosis 3: Provision of artificial food by humans in urban areas

While Canada geese are protected under the Migratory Bird Treaty, the urban resident populations seem to be covered even more through the protection (prohibition) from hunting.

This probably contributes to the urban population increase in the infested hotspots (USFWS, 2005). Moreover the provision of artificial food by the public in urban areas certainly aggravates the situation.

In fact, Canada geese have become very reluctant to leave these areas because food has been provided on a regular basis by people (Dunkley and Cattet, 2003; and Titchenell and Lynch, 2010).

The supplemental food fed upon by resident Canada geese in developed areas (streets, picnic grounds, parks, and plazas) was the decision logic considered for *provision of artificial food by humans in urban areas.*

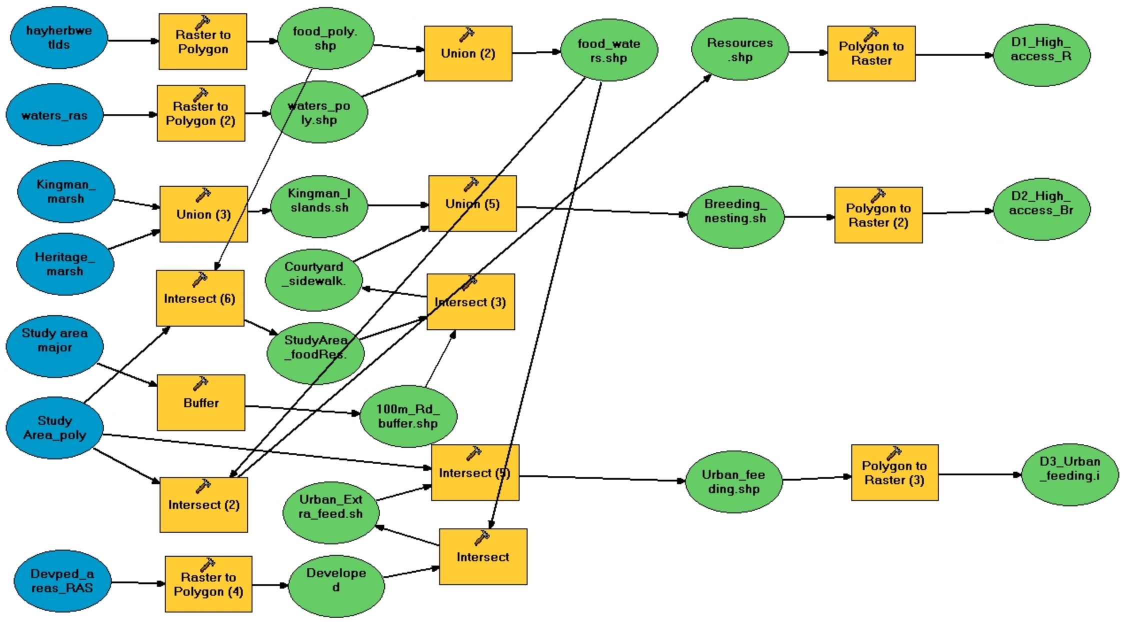

Figure 6.3 Diagnosis Expert System Knowledge Tree for Determining the Probable Causes for Resident Canada Goose Overpopulation

The ArcGIS ModelBuilder was used to translate the IF-THEN goose congregation diagnosis rules into a decision tree. Figure 6.3 presents the resulting model. In this model, the georeferenced input is on the left and the resulting georeference diagnosis is on the right-hand side. Model blocks in between the input and output nodes perform data format conversions and implement conditional statements representing the diagnosis rules.

The result of the ES classification of probable causes of resident Canada goose infestation problem is shown in Figure 6.4. The total area occupied by these causes is 3.93 km², that is, 35% of the study area (11.3 km²). This map was generated by applying the diagnosis ES shown in Figure 6.3 to the study area (Chapter 4) and hotspots (Chapter 5).

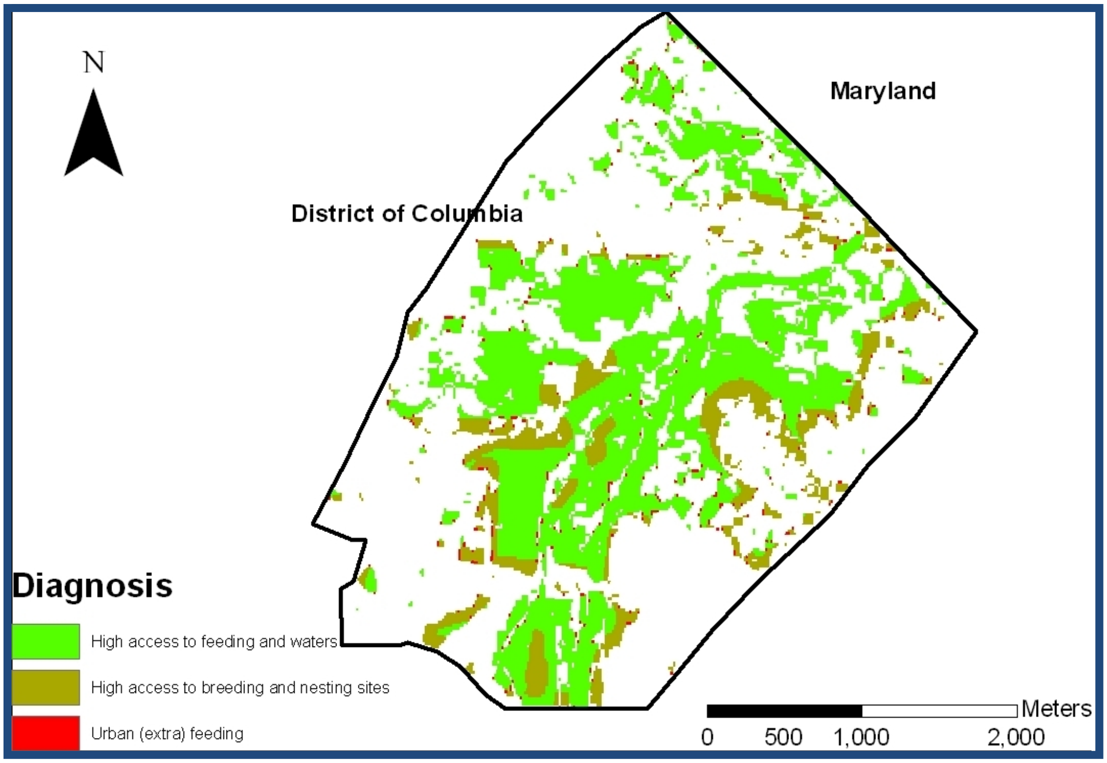

Figure 6.4 Diagnosis Expert System Results Showing Probable Causes of High Goose Congregation at Hotspots

High access to food and water resources spatially represented the most important portion of the overall diagnosis (3.6 km², 92%) indicating that the Canada goose species heavily depends on water and food for living. Canada geese are waterfowl, and as such, they are very attached to water systems (Granholm, 1990). Lakes, ponds, and similar open waters are of vital importance, and they are used for swimming, drinking, dabbling, resting, and performing many social activities (Stewart, 2009).

The presence and easy accessibility to the tidal Anacostia River, the Kenilworth aquatic garden as well as nearby Islands (Kingman and Heritage) which are also surrounded by large water bodies could explain the high level of goose congregation at these locations.

Likewise quality food plays an important role in resident Canada goose behavior. Canada geese are both grazers and seedeaters. They tend to forage mostly on tender new shoots and stems of grasses, clover, watercress, seeds of sedges, millets, bulrushes, and other wetland plants that can be found in the Anacostia River system. From the literature, evidence suggests that geese would feed on marsh vegetation first, among other habitat choices (Bos, 2002), and that large fields are preferred because predators can be seen at greater distances while small fields surrounded by dense cover or forested habitat are less preferred (MCE, 2003). This study area comprises a multitude of grassfields that supply food (such as Langston golf course, RFK sport field complex, Anacostia Park playgrounds and soccer fields, roadside managed lawns, and many local school and community center grassfields).

Kentucky bluegrass and water bentgrass are the grass species most seen in the fields (Hammershlag *et al.*, 2002), and these fields are regularly treated (mowed and watered) allowing the regrowth of soft succulent palatable grass.

Kenilworth aquatic garden is a unique system in the sense that it has many ponds. Plants grown in this system are wild flowers (such as violet, turtlehead, and wild rice) and other marsh species such as rice cutgrass (*Leersia oryzoides*), *Sagittaria*, *Pontederia* and *Schoenoplectus pungens,* these last three being the most palatable by Canada geese (Hammerschlag *et al*., 2002). The selection of marsh plants as food resources by Canada geese may be because they have high forage quality and nitrogen content (Ydenberg and Prins, 1981; and Prins and Ydenberg, 1985) and therefore a better digestibility (Boudewijn, 1984). Beside quality food, resident Canada geese are attracted by areas with high quantity of food (Vickery *et al*. 1995; Rowcliffe *et al*. 2001), and the Anacostia system provides all these suitable features.

High access to breeding and nesting sites represented the second most important diagnosis (0.32 km^2, 8%). Many waterfowl use wetlands found along the tidal Anacostia River as breeding and nesting habitats for rearing young. Most (if not all) of these wetlands are open, easily and directly accessible from the water bodies and nearby fields. They play critical functions in waterfowl life including feeding, sheltering, rearing and nursing goslings (Stewart, 2009).

Waterfowl prefer island habitats because they provide safe roosts on open waters (lakes and ponds), and nests are usually built on firm, dry, and slightly elevated sites that are relatively isolated (Granholm, 1990).

Other geographic features that probably cause resident Canada geese to congregate in hotspots in this study area are the accessibility to suitable grounds for breeding and nesting usually found near sidewalks, entryways, courtyards, picnic areas, playgrounds, and roadways (USDA APHIS, 2009).

Wetland are probably the most (or among the most) preferred habitat for waterfowl in general and for geese in particular (Stewart, 2009). In 2000, Kingman and Heritage wetlands were found to be permanent homes for resident Canada geese after the District of Columbia Government and the U.S. Army Corps of Engineers replanted these marshes for restoration purposes (Hammershlag *et al.*, 2002; McKinley-Ward, 2006).

Provision of artificial food by people in urban areas was the third identified diagnosis of the cause of goose infestation of hotspots (0.01 km^2, negligible percentage). While Canada geese are protected under the Migratory Bird Treaty, the urban resident populations seem to be covered to an even greater degree by regulations that prohibit hunting in the metropolitan area. This may have contributed to the increase in the urban goose population (USFWS, 2005). Moreover the supplemental food provided by tourists, campers, and other general public in developed areas (streets, Malls, plazas, playgrounds, picnic areas, public Parks, and lakes and ponds in downtowns) may justify the reasons why geese occupy such places.

Access to high quantity of artificial food supplements from people stimulates Canada geese to become very reluctant to leave human interfaces (Dunkley and Cattet, 2003; Titchenell and Lynch, 2010).

Prescription Expert System

Based on the literature and discussions with experts, five control strategies were selected as applicable to the study area: (1) chemical deterrent; (2) egg depredation; (3) harvest of breeding adults; (4) exclosure fencing; and (5) legislation to ban urban feeding.

Five rules were developed that led to goose control strategies. The rules shown in Figure 6.5 are also presented below as follows:

Chemical Deterrent Rule:

IF *"high resource accessibility" is identified as cause of goose congregation (**Diagnosis 1**) and infested area is a grassfield*

THEN *treat area with chemical deterrent (**Prescription 1**)*

Egg Depredation Rule:

IF *"high access to breeding and nesting sites" is identified as cause of goose congregation (**Diagnosis 2**) and infested area is a flatland*

THEN *proceed with egg depredation treatment (**Prescription 2**)*

Harvest Breeding Geese Rule:

IF *"high resource accessibility" is identified as cause of goose congregation (D**iagnosis 1**) and infested area is within 100 m buffer of waters*

THEN *harvest breeding adult geese from the infested waters (**Prescription 3**)*

Ban Feeding Rule:

IF *"artificial feeding of geese in urban areas" is identified as cause of goose congregation (D**iagnosis 3)** and infested area is not a grassfield*

THEN *introduce (re-enforce) legislations to ban goose feeding (**Prescription 3**)*

Exclosure-Fencing Rule:

IF	*"high access to breeding-nesting sites" is identified as cause of goose congregation (**Diagnosis 2**) and infested area is not a "dryland" (courtyard, sidewalk or entryway fields)*
THEN	*build fences around the infested wetlands (**Prescription 2**).*

Prescription 1: Chemical deterrent

This prescription was recommended to solve the issue related to "high access to resources," particularly food resources found in grassfields. EPA-approved chemicals (such as Methyl-Anthranilate-Rejex-It) applied to lawns, fields, and other grassy areas would deter the quality of food by changing the taste of the grass from palatable to non-palatable. Instead of tasting succulent or juicy, the grass would taste sour, bitter, scratching, or spicy, and therefore could cause geese to flee the occupied fields (Harris, 2002).

Methyl Anthranilate (MA) is a naturally occurring sweet flavored compound found in plants such as jasmine, concord grapes and orange blossoms. While MA tastes sweet to humans, it is distasteful to many bird species including Canada geese (Curtis and Jirka, 1994).

The decision logic considered for *chemical deterrents* was based on the fact that when geese attempt to feed from areas treated with MA they are met with an extremely foul, bitter taste keeping geese away from feeding and causing them to gradually leave the area due to a lack of edible food. The Environmental Protection Agency approval indicates the product is safe for humans, geese, and the environment.

This study recommends that MA repellents be applied on grasslands preferably (and not on water supplies) in order to avoid or minimize potential impacts on non-target systems.

Prescription 2: Egg depredation

This prescription was the second GCS in the decision tree, and is appropriate for marsh systems or other habitats used by Canada geese for breeding, nesting, and rearing goslings. Such habitats include sidewalks, entryways, enclosed courtyards, playgrounds, and picnic sites nearby paths and roadways (USDA APHIS WS, 2009). The logical explanation of *egg depredation* as a GCS in breeding and nesting habitats is that this prescription would slow down the reproduction and thus, the growth of the goose populations.

Prescription 3: Harvest of breeding adult geese

This prescription was recommended for areas where resources were highly accessible and for wetlands habitats in particular. Likewise egg depredation, the decision logic for recommending this prescription is that *roundup of breeding adults* reduces the goose population density and slow down the reproduction and population increase overall. Targeting breeding adults in particular is critical because they constitute the source of population increase. Because hunting is not allowed inside the metropolitan area, urban geese could be harvested using chemical capture or surround trapping techniques.

Chemical capture means trapping nuisance geese by means of sedation using approved drugs and appropriate drug administering equipment by a certified governmental animal control agency. Surround trapping means capturing nuisance geese during molting when they are flightless (three- to four-week period in early summer).

In 1992, the Federal Drug Administration (FDA) gave Wildlife Service the permission to use the anesthetic alpha-chlorase (AC) to capture waterfowl (Harris, 2002). This method has been successful in areas where hunting is impractical or prohibited such as urban areas (Belant *et al.*, 1999).

The Harvest strategy is essential and perhaps the best of the management practices compared to non-lethal ones, which simply usually consist of moving the goose problem from one place to another without necessarily solving it in the longer term (McKindley-Ward, 2006). The removed geese could be relocated elsewhere out of the District of Columbia metropolitan area, or simply shipped to poultry processing plants where they could be processed into USDA-approved meat to supply food pantries. Removal strategy, whether for relocation or consumption purposes, has successfully controlled urban geese in The Twin Cities, MN, for the past 20 years.

For instance in 1999, over 2000 resident Canada geese were culled and donated to charities for use as food (Lien, 2000 and McKindley-Ward, 2006).

Prescription 4: Exclosure fencing

This strategy was the fourth appropriate control strategy in the decision tree, and it was suggested for either one of the Island system (Kingman or Heritage marsh). The explanation of this GCS is that exclosures such as hedgerow-type settings or similar constructed physical barriers would keep geese away from accessing marsh resources and prevent them from moving comfortably in the protected wetlands.

Exclosure fencing would restrict goose landings on the surface of water bodies as well as the take-offs from the wetland systems (Dornbush *et al.*, 1996; McKindley-Ward, 2006).

Prescription 5: Ban of goose feeding

The legislation to *ban goose feeding* by the public was the recommended management strategy for the issue related to goose infestation of urban areas because of extra (artificial) feeding by people. Public places where urban birds are usually observed to be feeding includes streets, plazas, playgrounds, mall places, lakes and ponds in downtowns, and picnic sites within Parks. These areas should be cleaned and garbage-free regularly; trash cans should be secured all the time, and emptied as soon as possible.

This strategy is justified by the fact that feeding geese attracts even more geese (and other urban wildlife); it encourages geese to congregate and to remain in areas where people tend to feed them, therefore causing geese to become tamer than they should be for their own protection

(Dornbush *et al.*, 1996). Passing or enforcing legislations that prohibits feeding of urban wildlife is therefore critical.

The ArcGIS ModelBuilder was used to convert the IF-THEN prescription rules described above to a decision tree that could be applied automatically over the study area. The resulting prescription tool is presented in Figure 6.5 where spatial input data layers, including diagnoses, land covers and buffers are on the left, processing steps are in the middle and the resulting prescription data layers are on the right-hand side.

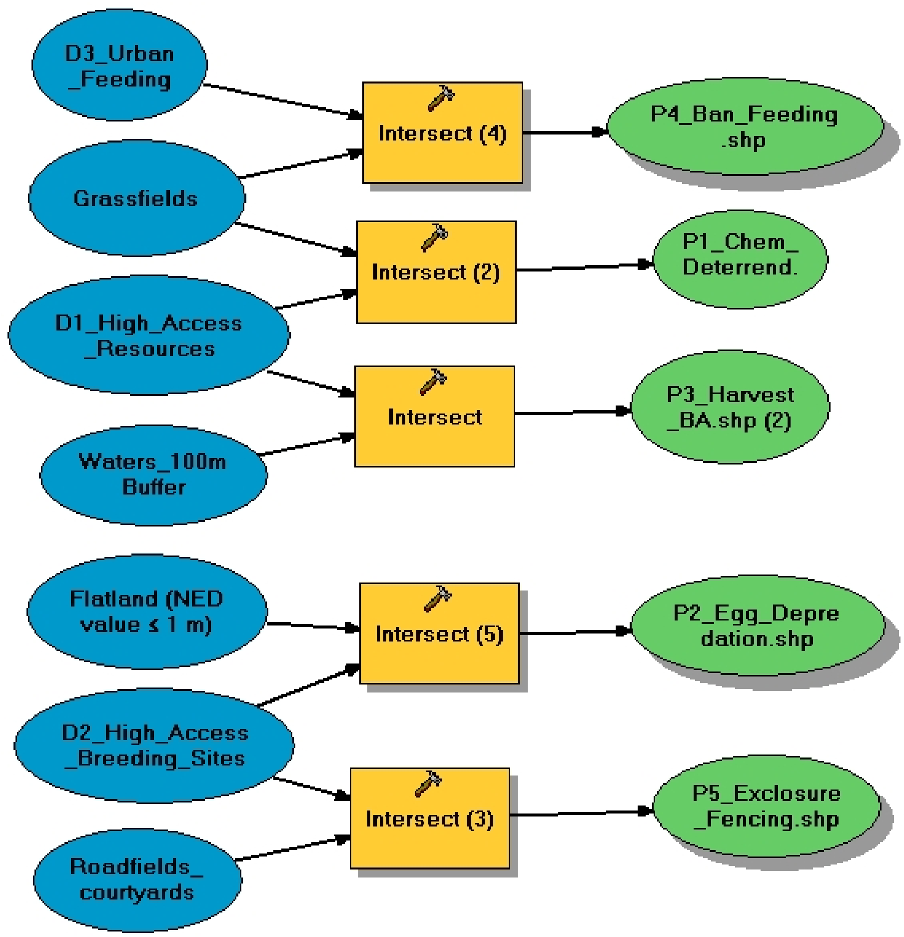

Figure 6.5 Prescription Expert System Knowledge Tree for Determining the Best Strategies for Resident Canada Goose Control

The Weighted Sum function of ArcGIS' Spatial Analyst Tools was used to analyze the most likely causes of geese congregation in hotspots. Each diagnosis was given the same weight (that is assigned equal percentage of influence) and the combined output was generated by using the Weighted Sum tool.

The ArcGIS' ModelBuilder was then run to generate the resulting maps of the Diagnosis-by-pixel, which are further analyzed below. The same process was done to weight each of the prescribed GCS, and to generate an overall Prescription-by-pixel map.

The result of the ES classification of Goose Control Strategies (GCSs) to reduce the goose population densities from their current hotspots are shown in Figure 6.6.

This result is based on pixel-by-pixel conditions, and probable causes as established by the diagnosis ES (Figure 6.4). The total area occupied by the CGS is 4.77 km^2, that is, 42% of the study area (11.3 km^2).

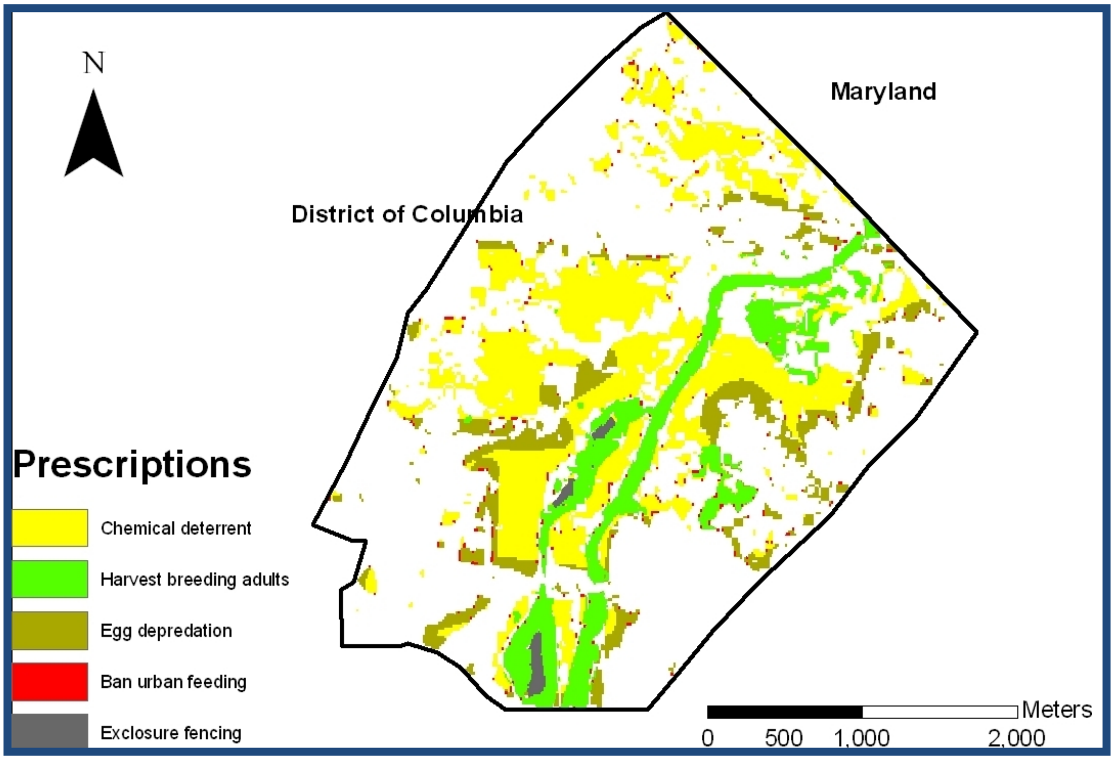

Figure 6.6 Prescription Expert System Results Showing Goose Control Strategies Allocation Plan

Chemical deterrent spatially represented the most important GCSs prescribed by the DSS in this study (2.20 km², 46%). This result (Figure 6.6) was expected given the larger size of the grass cover (in yellow) compared to other land cover types such as water, road, and shrubs. Moreover, the model was designed in such a way that the resource type interacting with the goose populations was grass only ("resource" meant grass).

Chemical repellents were recommended for grassfields especially areas not overlapping with water bodies (a 100 meter buffer around waters was used). Given this safety measure (buffering of water bodies) and given that the repellents are environmental friendly (EPA-approved), and that they do not harm geese in any way (Higgins and Guinn, 2009), this prescription could be popular, or at least acceptable as a good compromise between the "anti-goose" groups and the Humane Society communities and other animal right advocates. In fact, chemical repellents (such as methyl anthranilate and anthraquinone) can be sprayed on grass to make it distasteful to geese. Such repellents have shown some efficacy at deterring goose herbivory (Harris, 2002). Because not all chemicals are safe for the environment, or may cause mortality in non-target species, they must be registered, that is, they should prove to have no (or insignificant) effects on the environment or non-target species while demonstrating they can do what the manufacturers claim they are able to do (Harris, 2002). Therefore, the use of registered chemical repellents is suggested in this study to solve the goose problems caused by high access to food supplies (grassfields).

Examples of such approved repellents are described in Bradley *et al.* (1998), Harris (2002), and Higgins and Guinn (2009) as follows:

> *Dimethyl anthrnilate (DMA)* and *Methyl Anthranilate (MA)* **–** These products have been approved by FDA as food additives, and seem to be universally offensive to birds. There are three new products using the active ingredient MA including *ReJeX-It Migrate*, *GooseChase* and *Goose-B-Gone*. When applied to grass, MA makes the grass unpalatable by geese, and the product would not wash off after a rain if allowed to dry first, but must be reapplied after mowing. Geese may still frequent the treated area, but they would not feed there.
>
> *Anthraquinone* **-** Flight Control (FC), a relatively new product containing 50% of anthraquinone, is an effective foraging repellent for Canada geese.
>
> *Nicarbazin*, is also available as contraceptive bait for Canada geese, but users (mostly wildlife specialists or pest control operators) should be licensed as this restricted-use chemical is regulated by the EPA although it has no effect on the goose populations.

Treated grass appears unnatural and uninviting because the anthraquinone brings out the ultraviolet spectrum when applied to turf. If geese eat the grass treated with FC, they would experience a “gut reaction.” FC does not wash off after a rain, but needs to be re-applied after mowing.

The application of chemicals on grassfields would certainly deter geese food and pressure them to leave their hotspots. However, it is relevant to mention that the use of pesticides to repel Canada geese from critical source areas could have unintended effects on the environment especially if the chemical is not registered, or if it is inappropriately used. According to Miller (2004), most of sprayed chemicals reach a destination other than their target species, including non-target species, air, water, bottom sediments, and food. Therefore, chemical deterrent strategy should be applied carefully.

Harvest of breeding adults spatially represented the second most important GCS prescribed by the DSS (1.53 km^2, 32%). Roundup (or harvesting) strategy was recommended for areas where resources were highly accessible and for wetlands habitats in particular. While goose harvesting would allow an immediate reduction of the population densities in the infested habitats it would also slow down the reproduction growth by targeting breeding adults in particular. This management practice is done using surround trapping techniques, which consist in capturing mature geese during molting, that is, when geese are flightless (early summer). Captured geese could be processed to feed the hungry at food pantries, many of which are found in the District of Columbia metropolitan areas (such as The Capital Area Food Bank, Hunger in America, Feeding America, and Bread for the City). The harvest management option has been very successful elsewhere such as the Twin Cities, Minnesota, where State and local governments have created in the last two decades the largest, most cost-efficient goose reduction program in the seven-county metropolitan area (Lien, 2000; McKindley-Ward, 2006).

While the regulations on takes are set at a federal level by the USFWS in accordance with the Migratory Bird Treaty of 1916, the District of Columbia could allow the harvest of geese down to levels that minimize their impacts on resources (Hammershlag, *pers. Comm*.). One indicator of such levels could be the regeneration of wild rice (*Zizania aquatica*), *Sagittaria* sp., *Pontederia* sp., and *Schoenoplectus pungens*, which are grass species among the most eaten by Canada geese in the Anacostia wetland systems (Hammerschlag *et al.*, 2002).

It would be important to mention that each control strategy has its difficulties. One problem with the harvest strategy is that the target number of geese to be harvested can be hard to determine especially when the carrying capacity of the system is unknown, which is the case in the study area. Studies indicate that if the harvested amount is not large enough the management goal will not be reached (Harris, 2002). This was for instance the case in Massachusetts, where goose harvesting of between 22 and 25% each year for two consecutive years produced unsatisfactory results (Heusmann, 1999). Another downside of harvesting is that this control strategy may face protests from animal rights advocates (Harris, 2002).

Egg depredation spatially represented the third most important GCSs prescribed by the DSS in this study (0.76 km^2, 16%). Destroying Canada goose eggs would slow down the overall population growth by reducing the population of offspring. Egg depredation is proposed in this study to solve the problem caused by the availability of too much food or suitable nesting habitats.

The egg depredation treatment, whenever and wherever applicable, is intended to pressure geese to abandon nests and flee the occupied habitats (USDA APHIS WS, 2009).

The USFWS recommends that destroyed nest materials and eggs (usually during the period March 1-June 30) be buried on site, incinerated, placed in outgoing trash, or covered with objects (overturned garbage can, wood, branches, etc.) in accordance with local ordinances so that nesting geese may not recognize the initial nest locations (USDA APHIS WS, 2009). It is necessary to mention that there would be instances where geese would not leave the occupied habitats, but instead would initiate new nests nearby.

In such circumstances, the destruction of the new nests should be followed by other integrated management techniques (*e.g.*, dog chasing, harassing approaches), which are not recommended as best GCSs by the DSS but were reviewed in the previous sections.

Canada geese eggs can be treated, as recommended in the USFWS' Depredation Order according to three techniques (oiling, puncturing, and shaking) described in Harris (2002) and (USDA APHIS WS, 2009). These techniques are reviewed below:

Oiling - Egg treatment with castor oil, corn oil, safflower oil, soybean oil, and white mineral oil has been very effective at clogging the pores of eggs' shell preventing further development of their contents. Best results are obtained by coating the entire egg with a thin layer of oil and placing it back in the nests so that geese continue to incubate those.

Contents of eggs build up with gas and may burst if they are disturbed or knocked together. When eggs fail to hatch, the adult geese gradually cease incubation and leave the immediate area as the time to molt approaches.

Puncturing - Egg puncture is done by securely bracing it against the ground and inserting a long, thin metal probe (*e.g.*, awl and ice pick) into the pointed end of the egg. Best results are attained by placing slow steady pressure. Once the probe has passed through the shell, its tip is placed against the inside of the shell, and swirled with a circular motion.

Shaking/Addling - This activity consists of shaking eggs forcefully, one at a time, for 5-10 minutes, and placing them back in the nest. While this technique can be very time consuming and requiring a lot of physical effort it seems preferable by many resource managers especially when the number of nests or eggs to be treated is limited. However, it is difficult to determine with certainty when the egg is shaken enough, and the treatment can be problematic due to the time and effort required, and the uncertainty of its effectiveness.

Although nest and egg destruction are useful to curb population growth at a local scale, it should not be relied upon for immediate population reduction effect given that Canada geese are long-lived birds (10-25 years in the wild, and perhaps longer for urban resident geese, who are not exposed to hunting like the wild geese). Moreover, these geese have a single, defined nesting season (USDA APHIS WS, 2009).

Therefore, egg oiling could drastically reduce the number of geese in the Anacostia system in a near term, but would not necessary reduce or alleviate geese overgrazing problems in the long run given the relatively longer life span of urban resident geese (McKindley-Ward, 2006).

According to the Atlantic Flyway Council's Canada Goose Committee, if 95% of all eggs in a local population were found and destroyed each year, it would "result in only a 25% reduction over 10 years," and therefore egg oiling alone would not relieve the overgrazing pressure on the Anacostia resources (McKindley-Ward, 2006).

In fact, research indicates that elimination of nesting in a large-scale regional effort would have to be conducted over many years before population stabilization would even occur (USDA APHIS WS, 2009).

Exclosure fencing is the fourth appropriate GCSs recommended by the DSS (0.23 km^2, 5%). Exclosure fencing was suggested in this study to prevent Canada geese from accessing any of marsh in restoration (Kingman or Heritage). In general, a fence system (including conventional woven wire, chicken wire, snow, or chain link) could successfully barricade geese from accessing these wetlands. Exclosure fencing has shown to be efficient as a management practice. According to McKindley-Ward (2006) the "only reason why the stand of Wild rice (*Zizania aquatica*) at the edge of Langston Golf Course survived was because of a 4-foot high wire fencing arranged in small, contiguous cells to prevent geese from easily flying in and out..."

Unfortunately, in late June 2005, a floating log bashed into the four-foot fence at Kingman Marsh and knocked it over. Geese invaded the Marsh system and sheared off at knee-level thousands of immature wild rice plants (McKindley-Ward, 2006). Fencing these wetlands could significantly improve the restoration effort. Grid systems have shown to work efficiently on wetlands including bodies of water less than 150 feet across, and even larger ones that can reach up to 300 feet across (MCD, 2002).

It is worth indicating that, like most non-lethal control strategies, exclosure fencing is a temporary solution, at best, unless it is coupled with other management practices. Other concerns with fencing are that (1) it prevents other life forms (such as large body-size fish, muskrat, beaver, turtles, and grey fox) from circulating in the marsh; (2) it requires annual maintenance and (3) it has some aesthetic drawbacks in a natural system (McKindley-Ward, 2006).

The fifth GCS recommended by the DSS (0.05 km^2, 1%) was to introduce a legislation (or reenforce the ones in place) that forbid goose feeding in urban areas. Like many species of urban wildlife, Canada geese behave according to the way humans treat them. For instance they concentrate wherever people feed them and tend to stay there building up flock sizes the habitat can't support (MDFG, 2008). Additionally the lack of disturbance sources (*e.g.,* lack of natural predators and ban of hunting in urban areas) provides urban resident geese with more safety compared to their rural or wild relatives.

Therefore, the Expert System developed in this study prescribed the ban of goose feeding. This GCS could address the urban conflict situations between men and resident Canada geese. It has been shown that when people feed Canada geese, they lose their normal fear of humans, adapt to handouts, and become very reluctant to leave areas where food is provided on a regular basis (Dunkley and Cattet, 2003; and Titchenell and Lynch, 2010). The "No Feeding" policy recommended here would serve as a first step toward mitigating the geese infestation of urban areas. The second step, beside the legislation, would be the change of human behavior in providing artificial food to urban wildlife. Individual non-lethal management options reviewed in the previous sections have shown to be temporary solutions only, but combining some of these options with harvest and/or egg depredation could significantly alleviate the goose-overcrowding problem in our cities.

6.7.2 Testing and Verification of Goose Control Strategies Allocation

The model parameters affected by each GCS included in the Prescription Expert System were identified along with the level to which GCS were expected to modify them. The resulting parameters, along with an explanation of their impacts are presented in Table 6.2. These GCS-modified parameters are expected to affect both the rate at which goose and resource population change with time and their equilibrium levels as discussed in Chapter 5.

Table 6.2: Model Parametric Values After Goose Control Strategies Allocation Plan

GCSs prescribed	**Parameters affected**	**Explanations**	**values used before GCSs**	**values used after GCSs**
Chemical repellent	k_{dR2} $[km^2 / T \cdot yr]$	Resource death rate (apparent) increases due to the deterioration by the chemicals, that is, the resource becomes unavailable	9.00	90.00
Egg depredation	c	The depredation of eggs causes the reduction of the conversion efficiency (from food to offspring), that is, the decrease of the gosling population (young)	0.60	0.15
Harvest of breeding adult geese	k_{dG} $[1 / yr]$	Harvest of geese would cause the (apparent) mortality rate to increase (the population decreases)	5.25	72.20
Exclosure fencing of small wetland systems	k_v $[km^4 / T \cdot yr^2]$ d_v $[km^2 / yr]$	Fencing and other barricades slow down the geese movement, and even stop them from moving into the wetlands	$k_v = 2.00$ $d_v = 0.10$	$k_v = 0$ $d_v = 0$
Ban artificial goose feeding in developed areas	k_{gR} $[1 / yr]$	Ban goose feeding means reducing the (extra) amount of food supplied by developed areas.	52.00	26.00

Chemicals (such as Methyl-Anthranilate-Rejex-It) applied to lawns, fields, and other grassy areas deter the quality of grass by changing its taste from palatable (succulent or juicy) to non-palatable (sour, bitter, scratching, or spicy). The grass becomes (apparently) “unavailable” to geese, that is, it is no longer a (usable) resource. In this study, the related parameter, resource death rate, is increased by a factor of 10 to represent this process.

Egg is an animal reproductive body consisting of an embryo with nutritive envelopes. The destruction of goose eggs (or egg depredation) causes a decrease in the population of embryos or goslings (goose offspring). In this study, the related parameter, conversion efficiency (that is conversion from food to eggs), is reduced to ¼ of its previous value to represent egg depredation.

Harvest of breeding adult geese cause the (apparent) mortality rate to increase, that is, the goose population decreases due to terminal removal of animals. To represent this process, the related parameter, goose death rate, is set to 72.20/yr, which is over 13 times the rate without harvesting.

Fences and other barricades built around wetlands slow down the movement of geese and stop them from moving into these areas. In this study, both the speed factor (related to advection) and the diffusion coefficient (related to random movement) are set to zero to represent this process ($k_v = d_v = 0$).

The prescription to ban goose feeding reduces the amount of food supplied from developed areas. In this study, it is assumed that it results in a 50% reduction of the resource growth rate, k_{gR} (from 52 to 26/yr). Stated differently, the resource supply rate where goose feeding is banned is reduced by 50% relative to locations with no ban.

In order to verify the efficiency of the GCSs allocation, the model was re-run using the new parametric values in Table 6.1, and the goose dynamics were re-assessed.

This also also allowed comparing the spatial distribution of goose hotspots before and after GCSs allocation. The initial conditions for this simulation consisted of the goose and resource distributions obtained at the end of the six-year simulation used to identify goose hotspots without controls in Chapter 5. This simulation was performed for a duration of two years.

Figure 6.7 shows the 2-D simulation results of the goose model when prescribed GCSs are implemented. Results show that when control strategies are applied, the goose population decreases quickly and considerably. By the end of eight months, goose hotspots are almost non-existent. There are only very few areas that display high goose densities (1.0 – 2.0 T/km^2) and their size remains quite constant for the rest of the simulation time.

Two of these locations (dark red dots in the center south) are likely portions of the marsh system (Kingman Islands), where exclosure fencing was suggested as GCS while the other small remaining hotspots (light red dots) are likely portions of the grassfields, where chemical repellent application was recommended as GCS. A combination of actions (GCSs) could perhaps completely control resident geese in these spots.

Figure 6.7 also shows that as the densities of resident goose populations decrease over time due to the allocated GCSs, the resource densities conversely increase. Vegetation regrowth is most evident near water bodies where harvesting of breeding adults was prescribed.

In areas where a chemical repellent was prescribed, the vegetation is expected to have undergone similar regrowth but the simulation results only display that part of the vegetation that geese might use as a resource which excludes the part treated with repellent.

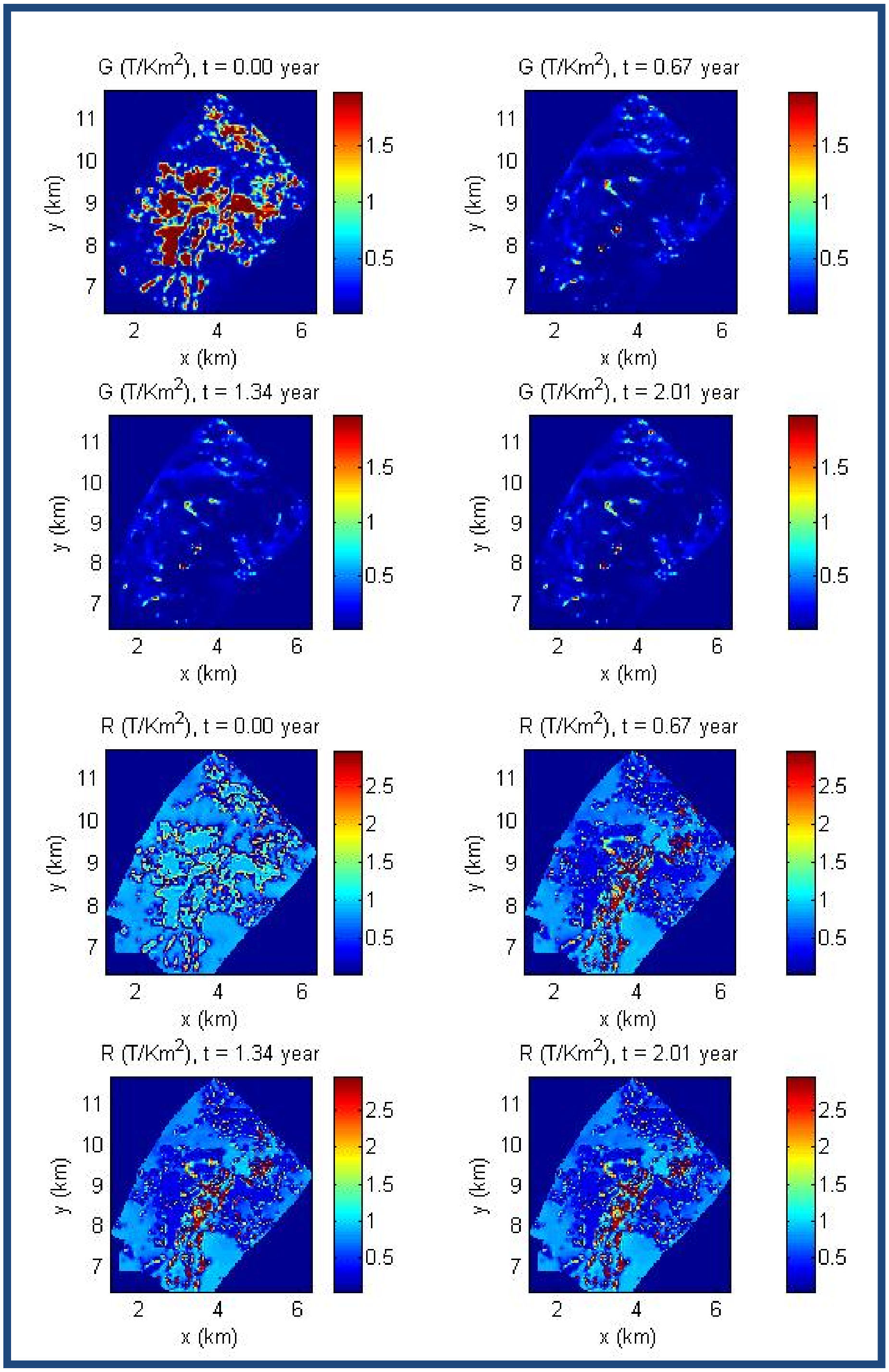

Figure 6.7 Spatio-Temporal Dynamics of Goose and Resource Populations in 2-Dimensions after Goose Control Strategies Allocation Plan. The Simulation is for a 2-year Time Period.

Figure 6.8 describes the predicted temporal dynamics of the goose population at the four survey sites when Goose Control Strategies (GCSs) are applied. The goose population densities when GCSs are applied are seen to decrease quickly in all four survey locations. After six months, the populations at all locations appear stable with comparable goose biomass averages nearing zero (0.06 T/km^2 for Heritage, 0.05 T/km^2 for Kingman, 0.03 T/km^2 for Kenilworth, and 0.03 T/km^2 for Anacostia). The biomass curve at Kingman decreases slower than the curves elsewhere and this is probably because at the time GCSs are applied the average goose density at Kingman is higher (bout 1.75 T/km^2) compared to the densities elsewhere (about 1.0 T/km^2 or less). As a result of the goose density decrease, the resource level increases at all four survey sites with the curves of resource biomass at Anacostia and Heritage leading those at Kenilworth and Kingman. These subpopulations (Anacostia/Heritage and Kenilworth/Kingman) stabilize after 6 months to 2.0 T/km^2 and a little under 1.0 T/km^2, respectively. None of the goose and resource populations are observed to display cyclic fluctuations (micro-migrations).

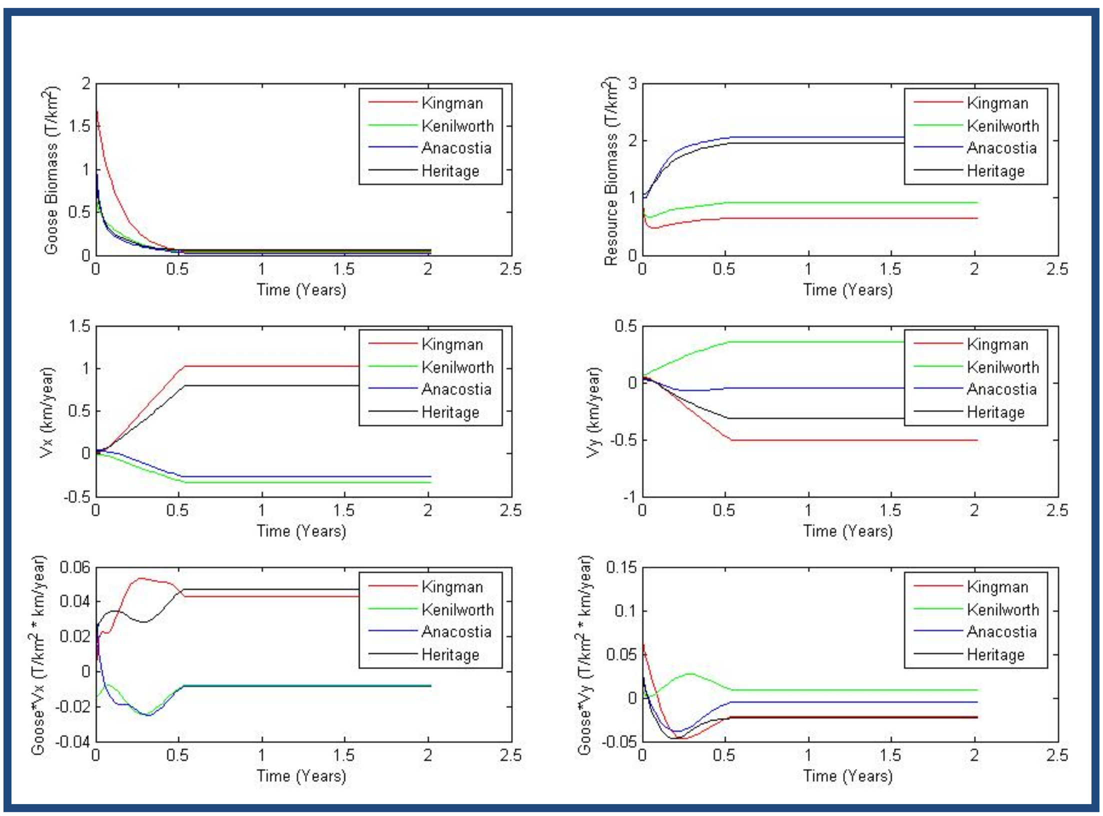

Figure 6.8 Goose-Resource Population Dynamics in the Anacostia River System after Goose Control Strategies Allocation Plan: Densities at Four Survey Sites and Different Seasons. The Goose (G) and the Resource

Populations are Simulated for a 6-year Time Period. Parameters used are $k_{dR1} = 8.75; k_{gR} = 26.00; k_{dR2} = 90.00; k_{dG} = 72.20; and C = 0.15$

The goose velocity dynamics appear also to vary spatially and temporarily, but unlike in the first case scenario (no GCSs applied) where the velocity dynamics were highly non-linear, the movements when GCSs are applied are relatively simple and linear.

For instance when resident geese move eastward (x-direction) their velocities continuously increase during the first 6 month, but compared to other locations geese seem to move faster in Kingman (golf course) where their densities are higher and the resource densities smaller.

After six months, both goose populations at all locations move with constant velocities, but the velocity at Kingman (1.0 km/yr) remains higher than the velocities at Heritage (~ 0.75 km/yr), Anacostia and Kenilworth (both < 0.50 km/yr). Similar types of movements are observed northward (y-direction), but the velocity equilibriums at any locations are 0.50 km/yr or less.

The goose mass fluxes also vary depending on the x and y-directions. For instance in the eastward (x) direction the goose mass fluxes are higher in Kingman and Heritage than in Kenilworth and Anacostia. Their maximum values are offset from one another in the first six months, but they stabilize after the first half year around 0.04 T/km.yr at Kingman (golf course) and Heritage (roadside field) and 0.01 T/km.yr at Kenilworth (aquatic garden) and Anacostia (picnic area). In the northward (y) direction, the goose mass fluxes follow the same trends as in the eastward direction, but they are much smaller with stable values very close to zero at all four locations. Overall, these mass fluxes are approximately one order of magnitude smaller than in the case without controls, owing to the much smaller goose population level resulting from the application of prescribed GCS.

Figure 6.9 illustrates the spatial extent of goose hotspots before and after the application of the management practices prescribed by the DSS. Those hotspots that remain after application of Goose Control Strategies occupy less than 0.5 km², which is one tenth of the area of hotspots before the the GCSs allocation (5.0 km²).

These results correspond to a reduction of 90%, and therefore it could be asserted that the Decision Support System developed in this study has been successful in prescribing effective control strategies on spatial basis. This very promising result must however be interpreted within the appropriate context that considers the various assumptions made during the development of the DSS and especially its modeling subsystem.

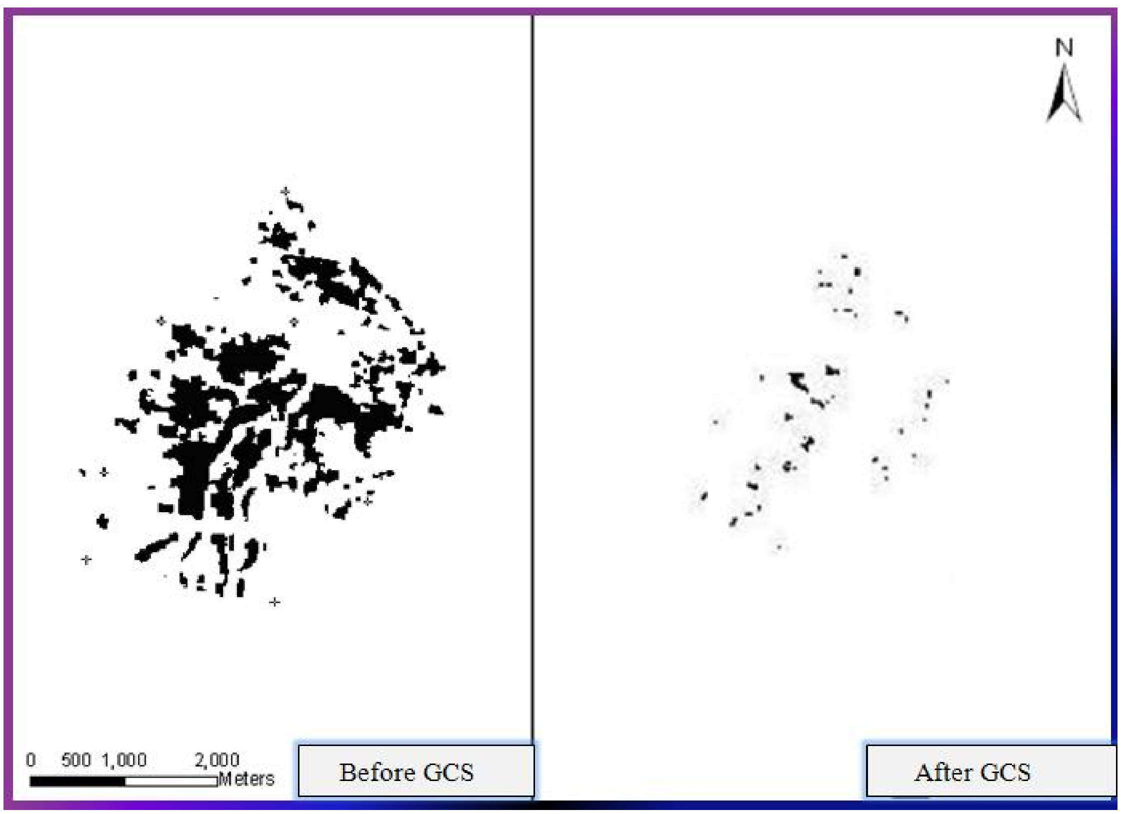

Figure 6.9 Effectiveness of the DSS: Goose Hotspots before and after Goose Control Strategies Allocation Plan

The goose hotspot remaining after the application of the management practices occupu less than 0.5 km² compared to the situation before the GCSs allocation (5.0 km²).

Given the model assumptions and initial conditions set in this study, the above described simulation results show that many locations in this research area are goose hotspots, that is, areas where goose densities are between 0.50 and 2.0 T/km^2 (this represents 90 – 300 $geese/km^2$ assuming a goose weights six to 12 pounds). The goose densities in the Anacostia system seemed to be higher than the densities in many other places in North America including Hudson Bay and Ungava Peninsula, in Northern Québec, where the highest goose densities were found to be between 4.6 and 19.8 $geese/km^2$ (Malecki and Trost, 1990), that is, 15 – 20 times lesser that at Anacostia.

This simulation also showed that resident Canada goose populations were primarily driven by food (grass). This is because the model was purposely designed this way. The assumption was that for a given range of resources (including food, water, cover, nesting site, etc.) resident Canada geese would preferably search for food first (the resource type that would enable them to live) although one could argue that water would be the preferred resource. While there are currently no such research on resident Canada goose species (*e.g.,* water versus food) this study assumed that resident Canada goose population would be more likely dependent upon grass for feeding and growing, and that preferable food sources are those found in herbaceous wetlands and managed fields located near water bodies (Granholm, 1990; Harris, 2002; and Bos, 2002).

Tender and short/cut grasses found in these land cover types seem to be rich in nitrogen content and much more digestible, thus their selection and preference by Canada geese (Ydenberg and Prins, 1981; Boudewijn, 1984; Prins and Ydenberg, 1985; and Riddington *et al.*, 1997). Grass types and parts of the plant most eaten by resident geese in marsh and moist fields may include, but are not limited to, forbs, green shoots, seeds, wild grasses, emergent wetlands plants, hay pasture and cultivated crops. Future studies may enhance the current model by considering both grass and water as principal resources, or water-only, and compare results to those presented here.

While grass was assumed to be the resource type driving the resident Canada goose dynamics, there was no specificity as to what particular grass species were preferably consumed by the Anacostia resident geese for a maximum profitability of such consumption (optimal foraging theory). In this study, “resource” meant grass (only), and for simplicity reasons, the model did not simulate any other resources consumed (or potentially used) by resident Canada geese. This study did not include specific considerations of topography. In the study area for instance, there is a topographic factor that might positively influence the selection of habitats by Canada geese (Mary Paul, *pers. Comm*.). In addition, habitats selected by Canada geese are often those that are regularly treated (fertilized, mowed, and watered) making it easy for geese to eat juicy and fresh cut grasses and also to spot-check potential predators (the visibility factor counts according to Dhananjaya Katju (*pers. comm*.).

It would be also worth mentioning that the tides and weather variability observed these past years in the region are other local conditions that could be used as input for simulating the goose model and for developing the Expert Systems because such conditions affect the goose distribution in the Anacostia natural system (Hammershlag, *pers. Comm*.). For instance at low tides, geese would tend to spread out in wetlands from the golf course and other grassfields where they normally congregate at high tides (Hammershlag, *pers. Comm*.).

Results obtained in this study are also dependent on the selected model parameters, especially those related to the application of control strategies (Table 6.2). These parameters were selected based on information from the literature and the expected effectiveness of control strategies. They represent a best estimate based on contemporary knowledge and could be updated in the future from results of actual GCS implementation in the study area. The DSS can accommodate such changes without structure modifications. Considering all these factors along with the model assumptions and initial conditions, this study has shown that the Decision Support System developed is efficient in controlling resident Canada goose populations in the Anacostia River system. It's believed that similar systems could also be used for controlling other bioagents of great concern such as disease-causing agents (*e.g.,* bacteria, viruses, prions, fungi, and toxins) and ecosystem pests (*e.g.,* Asian Longhorned Beetle, Light Brown Apple Moth, cane toad, brown tree snake, sea lamprey, European starling, nutria, etc.)

6.8 Conclusion

The Diagnosis Expert System identified high access to resources (water bodies and feeding sites) as the most likely cause of resident Canada geese congregation in the hotspots identified by the Goose Model, followed by a high access to breeding and nesting habitats, and the provision of supplemental food by humans in urban areas.

The application of chemical repellents (such as Methyl-Anthranilate-Rejex-It) was recommended as the most prevalent Best Management Practice to solve the problem related to the goose population infestation of grassfields. Such chemicals deter the quality of the grass resources consumed by Canada geese and therefore discourage these animals from using the grassfields. This study suggested the spray of EPA-approved chemical repellents on grassfields (100 meters buffer around waters). Given that chemical repellent is a non-lethal prescription, it would only preserve the resources and not reduce the goose population. Therefore harvesting breeding adult geese and egg depredation were recommended by the DSS for wetlands hotspots.

The DSS also suggested building exclosures/fences around small wetlands (such as Kingman and Heritage Islands) to prevent the nuisance geese from accessing the planted marsh vegetation, and to discourage geese from using these lands for nesting and rearing goslings.

Finally, the DSS suggested the ban of goose feeding in urban areas (or enforcement of such policies, if any). This is because lethal roundup management prescriptions would drop the current goose population to a “non problematic” levels while the non-lethal practices would more likely keep geese away from human interfaces while receiving support from animal right advocates.

The application of the goose control strategies presented by the Expert System was predicted to reduce the occurance of goose congregation hotspot by 90% in the study area. Based on the results of this study, it is concluded that the system is a promising new tool to help in the development of spatial control plans for autonomous bioagents in heterogeneous natural environments.

CHAPTER 7:
SUMMARY AND CONCLUSION

7.1 Summary

The spread of invasive species and human disease outbreaks have been of great concern for ecologists and public health specialists in recent years. Because these bioagents affect biodiversity, ecosystems, and human environments, there is a need for science-based decision-making tools for controlling them.

The aim of this research was to develop a Decision Support System (DSS) for the spatial control of invasive bioagents, exemplified in this study by the resident Canada goose species (*Branta canadensis*). The population of this pest species has increased in the past few years in the United States in general, and in the District of Columbia metropolitan area in particular. For this reason, the U.S. Department of Interior and partner agencies are working toward an Environmental Impact Statement for resident Canada goose management in the District of Columbia (D.C.). This plan is expected to provide sets of decisions and actions, and the current study could contribute to this aim.

Three specific objectives were targeted in this research:

(1) developing a Canada goose model of a Fisher-type (Arditi *et al.*, 2001), which predicts the dynamics of the goose population in the study area;

(2) developing of a goose Expert System that diagnoses the most probable causes of goose infestation of the Anacostia - D.C. system, and that prescribes Goose Control Strategies at each identified hotspot based on the diagnoses; and

(3) combining the goose model, expert systems, and geographic system into a single flow system (Decision Support System) that would seamlessly assist managers and other decision makers in controlling invasive bioagents in space and time.

The model results indicated that both the goose and resource dynamics fluctuated in the opposite directions (Lotka-Volterra-type model), but with no identifiable cycles or period of fluctuations. This may be due to the model assumptions and parameterization (there is almost no or very limited literature on goose population dynamics). While the goose population at Kingman led the populations elsewhere (Kenilworth, Anacostia, and Heritage), all populations stabilized before the fourth year. This prediction is an eventual steady-state of goose population densities, and the predicted levels of these populations at four survey sites were in agreement with field observations of Canada geese in the study area. The goose model was used to identify hotspots in the study area, which were further analyzed by the Expert Systems in the GIS environment.

The Expert System developed showed that high accessibility to resources (water bodies and feeding sites) was the most likely cause of resident Canada geese congregation at hotspots. Other probable causes of high geese congregation were the high accessibility to breeding and nesting habitats, and the provision of supplemental food by humans in developed areas. Like the Diagnosis, the prescriptions made by the Prescription Expert System varied on a pixel basis and the application of chemical repellents (such as Methyl-Anthranilate-Rejex-It) on grassfields was recommended as the most prevalent Goose Control Strategy for the issue related to high access to resources.

Such chemicals would lower the quality of goose food and therefore discourage geese from using the treated feeding sites. Given that chemical repellent application is a non lethal prescription, it would only protect the resources (grassfields, pasture hay, etc.) from being consumed by geese rather than reducing the goose population. Egg depredation was the recommended GCS for breeding and nesting habitats, or for field grounds located near roadways, inside parks used for picnic.

The expert systems suggested harvesting breeding adult geese as GCS for hotspots found on, or near, water bodies. Egg depredation and harvesting were the two lethal prescriptions, and as such, they are expected to shrink the goose population densities in the affected areas and the overall Anacostia system. The DSS suggested building exclosures or fences around small wetlands (*e.g.,* Kingman and Heritage) to prevent the nuisance geese from accessing the restoration marsh and to discourage geese from nesting and rearing goslings there. Finally, the expert systems selected the ban of goose feeding as a default GCS.

Introducing such legislations (or enforcement of the regulations in place) would restrict people from providing (unnecessary) artificial food to resident Canada geese in urban areas. This provision usually causes geese to be reluctant in leaving human properties and interfaces.

The Geographical Information System served as a database to store and represent geo-referenced data on platforms suitable for mapping, image processing, data management, and hotspot analysis. Overall, this study demonstrated that a GIS-based Decision Support System that combines both a predictive model and rule-based Expert Systems could be very effective and promising in controlling invasive bioagents. Over 90% of goose-infested areas were eliminated through the DSS developed in this study.

The Canada goose DSS presented in this study has many benefits, five of which are listed below:

- it is an available and usable net decision checklist;
- it is a stable tool despite any eventual changes in the staff;
- it is a transparent, easy-to-use map instrument available to end users;

- it is an effective communication device for a better explanation of recommended GCSs to the public; and

- it could be applied for the control of many other invasive species (such as Asian Longhorned Beetle, Light Brown Apple Moth, etc.) and disease-caused agents (such as avian influenza, HIV/AIDS, Ebola virus, etc.)

7.2 Research Limitations

While the study's goal was achieved, it is useful to remind the reader of some limitations that remain as considerations in future work:

1. *Limitation due to the model type and structure*: The modeling approach used in this research is population-based. As such, it dealt with the population as a group of individuals, and therefore the behavior of individuals within the population are omitted. For instance, it was assumed under this population-based model that geese would more likely use grassy fields. This assumption also guided the mind of goose surveyors, who found it unnecessary to survey woodlands and shrub lands. Unfortunately, there could be an instance where a few geese use these covers as perching assets. Such an example of population-based limitation is in fact one of the main strengths of the IBMs discussed in early Chapters. This research also (purposedly) omitted to incorporate into its structure other demographic parameters such as age, species life history, and all the factors that keep a population in check (*e.g.,* emigration, diseases, harvesting, and egg depredation), which may be considered while modeling population dynamics (Preuss *et al*., 2009). Moreover, the model was simplified by considering only one type of resource (grass) assumed to be the most relevant beside other resources such as water, shelter, soil minerals, and protein found in insects, etc. Factoring these elements within the system could provide a much

better result, but the downside of such complexity would be the difficulty to adequately parameterize and run the system.

2. *Limitations due to parameterization assumptions*: The literature offered little information and data necessary to parameterize the system of equations developed in this study. Therefore, some model parameters were estimated from the literatures related to research on other animal species, or carried out in homogeneous/laboratory settings. The model parameterization along with the model assumptions (*e.g.*, initial conditions) are key aspects in the population dynamics modeling.

3. *Data verification and validation*: The verification and validation of any model would require quality datasets. The field data collected during the goose survey had some outliers. Some datasets were inconsistent (lack of patterns), but this may have been caused by the variability of the tides and other weather conditions recently observed in the region (Hammershlag, *pers. Comm*.). Moreover, on one hand the goose surveys were carried on land cover types assumed to be goose preferable habitats (grasslands), and in other hand the model parameterization was not perfect due to assumptions. For these reasons, there could be some missing counts in the survey data, or some omissions in the model predictions.

4. *Hardware-Software limitations*: In the initial runs of the model, it could take a couple of weeks to display solutions for a one-year simulation. This probably had to do with the computer hardware and software used. It had been found that a large size of the study domain coupled with a high image resolution would require a (high) number of image pixels and nodes during the meshing processes. This would consequently use significant computer memory causing long delays in the solution display as well as “out of memory” error messages.

7.3 Future Work

The current work is certainly not perfect, and therefore the following improvement recommendations are suggested for future work:

1. *Model Validation and Parametrization:* It would be useful to survey resident Canada geese for a longer time period, in order to build a more complete database for model parametrization and validation.

2. *Additional Model Processes:* It is suggested that the goose behavior model be extended to consider additional resources (especially water) and additional processes, such as flying and migration. The goal would be to develop an enhanced model that can account more accurately for all factors relevant and necessary in the population dynamics modeling (Preuss *et al.,* 2009).

3. *Goose Foraging Behavior:* Although resident Canada geese are likely generalist or omnivorous (have varied diet), it would be useful to investigate their optimal foraging behavior, that is, what specific food items are selected in the environment first, second, etc. and why? In ecology, such a study is called optimal foraging theory, and it helps understand the way foraging animals find, capture and consume food items in order to maximize their net energy intake per unit time. This could help redefine the model's response functions (reaction terms) but also make decisions based on such foraging behaviors.

4. *Participatory Natural Resource Management:* The goose control strategies prescribed by the current DSS were based on the knowledge acquired from the literature, experts (resource managers) and personal field experience and observations. Involving stakeholders (including local communities) in DSS design and application processes, could enhance its effectiveness. It is suggested that future versions of the system enable tradeoff analysis between

stakeholder desires and prescribed management strategies, to aid in resolving potential conflicts, and produce control strategy plans that are both effective and acceptable by stakeholders.

5. *Friendly Graphical User Interface* (GUI): The ModelBuilder used to manipulate the data in the DSS is more for GIS analysts. Developing a user-friendly interface would be more convenient for end users.

6. *DSS Application:* The DSS developed in this study could be applied in many fields and particularly in Agriculture and Forestry for the management of pest species, some of which are of great interest to USDA APHIS (such as Asian Longhorned Beetle, Light Brown Apple Moth, and brown tree snake).

7. *Economical Considerations:* Future work should also investigate the costs associated with DSS-generated prescription plans, notably cost optimization and cost efficiency tradeoff analyses.

APPENDIX A
GOOSE FIELD SURVEY DATA
(NATIONAL PARK SERVICE, UNPUBLISHED)

Table A-1: Goose Field Survey Data

(goose biomass in Ton/Km². Numbers were converted into biomass assuming that in average, an adult *resident goose weights 12 lb* or 5.5 kg *(MCE, 2003)*.

Source: National Park Service (unpublished).

Dates						Std. Dev.
10-Apr-04	3.3	3.7	1.21	2.99	2.8	1.1
17-Jul-04	6.25	0.84	2.57	2.46	3.03	2.29
11-Sep-04	0.04	3.39	5.46	2.2	2.77	2.27
13-Apr-05	4.76	2.74	2.05	1.83	2.85	1.33
13-Jul-05	6.04	1.16	3.18	3.12	3.38	2.01
31-Aug.-05	0.55	3.39	5.09	5.99	3.75	2.39
13-Apr-06	3.35	3.08	2.22	2.04	2.67	0.64
6-Jul-06	6.81	0	3.06	0.34	2.55	3.15
7-Sep-06	1.06	3.97	3.41	2.34	2.7	1.28
6-Apr-07	3.49	2.45	1.24	1.35	2.13	1.06
10-Jul-07	6.93	0.09	4.02	0	2.76	3.35
11-Sep-07	0.11	4.14	1.96	4.1	2.58	1.93
3-Apr-08	2.51	3.08	0.54	0.38	1.63	1.37
10-Jul-08	7.06	0	2.71	0.18	2.49	3.29
10-Sep-09	0.23	4.77	4.17	4.09	3.32	2.08
April Average	3.48	3.01	1.45	1.72	2.42	0.98
April Std. Dev.	0.81	0.47	0.69	0.96	0.52	-
July Average	6.62	0.42	3.11	1.22	2.84	2.76
July Std. Dev.	0.45	0.54	0.57	1.46	0.37	-
September Average	0.4	3.93	4.02	3.75	3.02	1.75
September Std. Dev.	0.13	0.98	0.91	1.34	0.39	-
Overall mean	3.5	2.45	2.93	2.23	-	-
Overall stdev	2.68	1.62	1.35	1.68	-	-

APPENDIX B
IN A FISH SURVEY OF THE ANACOSTIA RIVER
(NOAA, 2007)

Table B-1: Fish Species and Composition
Observed in a Fish Survey of the Anacostia River

(NOAA, 2007)

Species Type, Fish Species	Scientific Name
Anadromous Species	
Blueback herring/Alewife*	*Alosa* spp.
White perch	*Morone americana*
Gizzard shad	*Dorosoma cepedianum*
Striped bass	*Morone saxatilis*
Estuarine/Euryhaline Species	
Banded killifish	*Fundulus diaphanous*
Inland silverside	*Menidia beryline*
Mummichog	*Fundulus heteroclitus*
Freshwater Resident Species	
Pumpkinseed	*Lepomis gibbosus*
Brown bullhead	*Ameiurus nebulosus*
Spottailed shiner	*Notropis hudsonius*
Other species	

APPENDIX C
AQUATIC BIRDS DOCUMENTED WITHIN THE LOWER ANACOSTIA RIVER WATERSHED: HABITAT USE AND FEEDING STRATEGY (NOAA, 2007)

Table C-1: Aquatic Birds Documented within
the Lower Anacostia River Watershed: Habitat Use and Feeding Strategy (NOAA, 2007)

Bird Type, Common Name	Scientific Name	Feeding Strategy
Resident Over-winter Breeding Duck-Like Birds		
Bufflehead	*Bucephala albeola*	Omnivore
Canvasback	*Aythya valisineria*	Grazer
Gadwall	*Anas strepera*	Omnivore
Goldeneye	*Bucephala clangula*	Invertebrates
Mallard	*Anas platyrhynchos*	Omnivore
Oldsquaw	*Clangula hyemalis*	Invertebrates
Pintail	*Anas acuta*	Omnivore
Ringneck duck	*Aythya collaris*	Grazer
Northern shoveler	*Anas clypeata*	Omnivore
Ruddy duck	*Oxyjura jamaicensis*	Grazer
Blue-winged teal	*Anas discors*	Omnivore
Green-winged teal	*Anas crecca*	Omnivore
American widgeon	*Anas Americana*	Grazer
Wood duck	*Aix sponsa*	Grazer
Canada goose	*Branta Canadensis*	Grazer
Snow goose	*Chen caerulescens*	Grazer
Common merganser	*Mergus merganser*	Piscivore
Hooded merganser	*Lophodytes cucullatus*	Invertebrates
Red-breasted merganser	*Mergus serrator*	Piscivore
American coot	*Fulica Americana*	Grazer
Eared grebe	*Podiceps nigricollis*	Piscivore
Horned grebe	*Podiceps auritus*	Piscivore
Pied-billed grebe	*Podilymbus podiceps*	Piscivore
Red-necked grebe	*Podiceps grisegena*	Piscivore
Common loon	*Gavia immer*	Piscivore
Red-throated loon	*Gavia stellata*	Piscivore
Sora rail	*Porzana Carolina*	Omnivore
Virginia rail	*Rallus limicola*	Omnivore
Common gallinule	*Gallinula chloropus*	Omnivore

Bird Type, Common Name	Scientific Name	Feeding Strategy
	Wading Birds	
American bittern	*Botaurus lentiginosus*	Piscivore/ Invertebrates
Least bittern	*Ixobrychus exilis*	Piscivore/ Invertebrates
Cattle egret	*Bubulcus ibis*	Invertebrates
Great egret	*Casmerodius albus*	Invertebrates
Snowy egret	*Egretta thula*	Invertebrates
Black-crowned night heron	*Nycticorax nyticorax*	Piscivore/ Invertebrates
Great blue heron	*Ardea herodias*	Piscivore
Green heron	*Butorides virescens*	Piscivore/ Invertebrates
Little blue heron	*Egretta caerulea*	Piscivore/ Invertebrates
	Gulls and Terns	
Herring gull	*Larus argentatus*	Omnivore
Laughing gull	*Larus atricilla*	Piscivore
Ring-billed gull	*Larus delawarensis*	Omnivore
Caspian tern	*Sterna caspia*	Piscivore
Forsters tern	*Sterna forsteri*	Piscivore
Least tern	*Sterna antillarum*	Piscivore
	Sandpipers	
Dunlin	*Calidris alpina*	Invertebrates
Sanderling	*Calidris alba*	Invertebrates
Least sandpiper	*Calidris minutilla*	Invertebrates
Pectoral sandpiper	*Calidris melanotos*	Invertebrates
	Semipalmated	
sandpiper	*Calidris pusilla*	Invertebrates
Solitary sandpiper	*Tringa solitaria*	Invertebrates
Spotted sandpiper	*Acitis macularia*	Invertebrates
Stilt sandpiper	*Calidris himantopus*	Invertebrates
	Blackbirds	
Red-ringed blackbird	*Agelaius phoeniceus*	Omnivore
Rusty blackbird	*Euphagus carolinus*	Omnivore

Bird Type, Common Name	Scientific Name	Feeding Strategy
	Other Species	
Double-crested cormorant	*Phalacrocorax auritus*	Piscivore
Belted kingfisher	*Ceryle alcyon*	Piscivore
Osprey	*Pandion haliaetus*	Piscivore

APPENDIX D
MATLAB CODES

Function *elenoderenum*

```
function [e,nc,vc] = elenoderenum(eles,nodes,verts)

uei = unique(eles(:));
rn = zeros(size(nodes,1),1);
rn(uei) = [1:length(uei)];
e = rn(eles);
nc = nodes(uei,:);
vc = verts(uei,:);
```

Driver File

```
% discretize the domain
disp('Domain Discretization')
dt = tmax / (nt-1);
if min(elesizes) <= 0
   error('Some Elements have Negative or Zero Size!')
end
bndrynodes  = onrectface(nodecoords);
bndrycoords = nodecoords(bndrynodes,:);
bndryfaces  = bndry_faces(elements,bndrynodes,nodecoords);

%-------------------------------------------------------------
% set I.C. in initial solution vector
t = 0;
u = eval([finicond '(elements,nodecoords)']);%-----
%--- Calculate and display some information
system_size = size(u,2);
nn = size(nodecoords,1);
ne = size(elements,1);
dim = size(xmin,2);

disp(['Number of Transport Equations = ' num2str(system_size)])
disp(['Number of Spatial Dimensions  = ' num2str(dim)])
disp(['Number of Elements            = ' num2str(ne)])
disp(['Number of Spatial Nodes       = ' num2str(nn)])
disp(['Total Spatial System Size     = ' num2str(system_size*nn)])
disp(['Total System Size             = ' num2str(system_size*nn*nt)])
%--- Store the initial conditions
u_keep = reshape(u',system_size*nn,1);

%-------------------------------------------------------------
% Discretize and Solve Equations
t = 0;
ucentroid = elemean(u,elements);
ugradient = elegradient(u,elements,bf_slopes);
elesourc  = eval([fsource '(ucentroid,elecentroids,t)']);
elecapac  = eval([fcapacitance '(ucentroid,elecentroids,t)']);
elereact  = eval([freaction '(ucentroid,elecentroids,t)']);
eleadvec  = eval([fadvection '(ucentroid,ugradient,elecentroids,t)']);
elediffu  = eval([fdiffusion '(ucentroid,ugradient,elecentroids,t)']);

timemat  = global_timemat(elecapac,nn,elements,elesizes);
sourcvec = global_sourcvec(elesourc,nn,elements,elesizes);
spacemat = global_spacemat(elereact,eleadvec,elediffu,nn,elements,elesizes,bf_slopes);
if linear & constant_coeffs
   %-------------------------------------------------------------
```

```
   % Solution process for linear equations with constant coeffs
   %----------------------------------------------------------------
   rhmat = timemat + dt*(1-theta)*spacemat;
   rfvec = dt*(1-theta)*sourcvec;
   lhmat = timemat - dt*theta*spacemat;
   lfvec = -dt*theta*sourcvec;

   %Calculate and add boundary conditions
   [bcvalue, bctype] = eval([fbndcond ‘(bndrynodes,bndrycoords,t,system_size)’]);
   [rhmat,rfvec] = rhsplicebc(rhmat,rfvec,bndrynodes,bctype,bcvalue);
   [lhmat,lfvec] = lhsplicebc(lhmat,lfvec,bndrynodes,bctype,bcvalue);
   %(0.6)--- reshape initial solution vector
   u = reshape(u’,system_size*nn,1);
   %(0.7)--- step through time
   disp(‘Time Stepping’)
   for k = 1:nt-1
      %(1.1)--- Solve the system of equations
      rhs = rhmat*u + rfvec - lfvec;
      nu  = lhmat \ rhs;
      if min(nu) < 0
         warning([‘Negative Entity Value(s) at Time Step ‘ num2str(k) ‘, min=‘
num2str(min(nu))])
      end
      %--- store the new solution
      u_keep = [u_keep nu];
      %--- make the new solution the current solution
      u = nu;
   end
elseif linear
   %----------------------------------------------------------------
   % Solution process for linear equations with time-dependent coeffs
   %----------------------------------------------------------------
   %(0.4)--- step through time
   disp(‘Time Stepping’)
   for k = 1:nt-1
      disp([‘Time Step = ‘ num2str(k)])
      %(1.0)--- Form right-hand side matrix and vector for previous time
      rhmat = timemat + dt*(1-theta)*spacemat;
      rfvec = dt*(1-theta)*sourcvec;
      %(1.1)--- Calculate and add boundary conditions for previous time
      [bcvalue, bctype] = eval([fbndcond ‘(bndrynodes,bndrycoords,t,system_size)’]);
      [rhmat,rfvec] = rhsplicebc(rhmat,rfvec,bndrynodes,bctype,bcvalue);
      %(1.2)--- get centroidal solution then reshape previous solution
      ucentroid = elemean(u,elements);
      ugradient = elegradient(u,elements,bf_slopes);
      u = reshape(u’,system_size*nn,1);
```

```
      %(1.3)--- Calculate coefficients at new time
      t = t+dt;
      elesourc  = eval([fsource '(ucentroid,elecentroids,t)']);
      elecapac  = eval([fcapacitance '(ucentroid,elecentroids,t)']);
      elereact  = eval([freaction '(ucentroid,elecentroids,t)']);
      eleadvec  = eval([fadvection '(ucentroid,ugradient,elecentroids,t)']);
      elediffu  = eval([fdiffusion '(ucentroid,ugradient,elecentroids,t)']);
      %(1.4)--- Form global matrices for new time
      timemat  =  global_timemat(elecapac,nn,elements,elesizes);
      sourcvec = global_sourcvec(elesourc,nn,elements,elesizes);
      spacemat = global_spacemat(elereact,eleadvec,elediffu,nn,elements,elesizes,bf_slopes);
      %(1.5)--- Form left-hand side matrix and vector for new time
      lhmat = timemat - dt*theta*spacemat;
      lfvec = -dt*theta*sourcvec;
      %(1.6)--- Calculate and add boundary conditions for new time
      [bcvalue, bctype] = eval([fbndcond '(bndrynodes,bndrycoords,t,system_size)']);
      [lhmat,lfvec] = lhsplicebc(lhmat,lfvec,bndrynodes,bctype,bcvalue);
      %(1.7)--- Solve for solution at new time
      rhs = rhmat*u + rfvec - lfvec;
      nu  = lhmat \ rhs;
      if min(nu) < 0
         warning(['Negative Entity Value(s) at Time Step ' num2str(k) ', min='
num2str(min(nu))])
      end
      %--- Store the new solution
      u_keep = [u_keep nu];
      %--- Reshape the new solution and make it the current solution
      u = reshape(nu,system_size,nn)';
   end
else
   %-----------------------------------------------------------
   % Solution process for nonlinear equations
   %-----------------------------------------------------------
   %(0.4)--- step through time
   disp('Time Stepping')
   for k = 1:nt-1
      disp(['Time Step = ' num2str(k)])
      %(1.0)--- Form right-hand side matrix and vector for previous time
      rhmat = timemat + dt*(1-theta)*spacemat;
      rfvec = dt*(1-theta)*sourcvec;
      %(1.1)--- Calculate and add boundary conditions for previous time
      [bcvalue, bctype] = eval([fbndcond '(bndrynodes,bndrycoords,t,system_size)']);
      [rhmat,rfvec] = rhsplicebc(rhmat,rfvec,bndrynodes,bctype,bcvalue);
      u = reshape(u',system_size*nn,1);
      rhs = rhmat*u + rfvec;
      u = reshape(u,system_size,nn)';
```

```
        %(1.2)--- Calculate BC at new time
        t = t+dt;
        [bcvalue, bctype] = eval([fbndcond '(bndrynodes,bndrycoords,t,system_size)']);
        %(1.3)--- Iteratively attempt to solve system for new time
        iter = 0;
        maxerr = allow_error + 1;
        while iter < max_iter & maxerr > allow_error
           %(2.1)--- Evaluate coefficients at new iteration, for new time

           iter = iter + 1;

           ucentroid = elemean(u,elements);
           ugradient = elegradient(u,elements,bf_slopes);
           elesourc  = eval([fsource '(ucentroid,elecentroids,t)']);
           elecapac  = eval([fcapacitance '(ucentroid,elecentroids,t)']);
           elereact  = eval([freaction '(ucentroid,elecentroids,t)']);
           eleadvec  = eval([fadvection '(ucentroid,ugradient,elecentroids,t)']);
           elediffu  = eval([fdiffusion '(ucentroid,ugradient,elecentroids,t)']);%3/12 added ugradient
here to reflect the new model with arctan in the advection component
           %(2.2)--- Form global matrices for new iteration/time
           timemat  =  global_timemat(elecapac,nn,elements,elesizes);
           sourcvec = global_sourcvec(elesourc,nn,elements,elesizes);
           spacemat = global_spacemat(elereact,eleadvec,elediffu,nn,elements,elesizes,bf_slopes);
           %(2.3)--- reshape previous solution vector
           u = reshape(u',system_size*nn,1);
           %(2.4)--- Form left-hand side matrix and vector for new time
           lhmat = timemat - dt*theta*spacemat;
           lfvec = -dt*theta*sourcvec;
           %(2.5)--- Add boundary conditions for new time
           [lhmat,lfvec] = lhsplicebc(lhmat,lfvec,bndrynodes,bctype,bcvalue);
           %(2.6)--- Solve for solution at new time
           nu  = lhmat \ (rhs - lfvec);
           %(2.7)--- Calculate maximum difference between new and old solution

           maxerr = max(abs(nu-u))

           %--- Reshape the new solution and make it the current solution
           u = reshape(nu,system_size,nn)';
        end
        %--- Store the new solution
        u_keep = [u_keep nu];
        if maxerr > allow_error
           warning(['Convergence not reached at Time Step ' num2str(k) ', max err='
num2str(maxerr)])
        end
        if min(nu) < 0
```

```
      warning([‘Negative Entity Value(s) at Time Step ‘ num2str(k) ‘, min=‘ 
num2str(min(nu))])
    end
  end
end
```

Function *advection*

```
function v = M2D_case2aR0_advection(u,gradu,coords,t)
global  Kv dv D maxveloc alpha alpha_max R0 K

% Calculate general problem information:
ne = size(u,1);
sys_size = size(u,2);
dim = size(coords,2);
% Initialize transport velocities to zero
v = zeros(ne,sys_size,sys_size,dim);
% Specify desired non-zero values
Kv = 5*3;
Kv = 5; %20;

Kv = 10; %20;
v(:,1,1,1) = -u(:,3);
v(:,1,1,2) = -u(:,3);
v(:,1,3,1) = -u(:,1);
v(:,1,3,2) = -u(:,1);
v(:,3,2,1) = Kv; %v(:,3,2,1) = 3; %
v(:,3,2,2) = Kv; %v(:,3,2,2) = 3; %
% -----------------------------------------------
```

Function *boundary condition*

```
function [bcval, bctyp] = M2D_case2aR0_bc(nodes,coords,t,sys_size)
% set specic non-zero-flux BCs
x = coords(:,1);
nn = size(coords,1);
dim = size(coords,2);
bcval = zeros(nn,sys_size);
bctyp = zeros(nn,sys_size);
```

Function *capacitance*

```
function c = M2D_case2aR0_capacitance(u,coords,t)
% Calculate general problem information:
ne = size(u,1);
sys_size = size(u,2);
dim = size(coords,2);
% Initialize capacitances to zero
c = zeros(ne,sys_size,sys_size);
% Specify desired non-zero capacitances
for i = 1:sys_size
    c(:,i,i) = 1;
%    c(:,1,1) = 1;
%    c(:,1,2) = 0;
%    c(:,2,1) = 0;
%    c(:,2,2) = 1;
end
```

Function *diffusion*

```
function d = M2D_case2aR0_diffusion(u,gradu,coords,t)
global  Kv dv D maxveloc alpha alpha_max R0

% Calculate general problem information:
ne = size(u,1);
sys_size = size(u,3);
% sys_size = size(u,2);
dim = size(coords,2);
% Initialize diffusion tensors to zero
d = zeros(ne,sys_size,sys_size,dim,dim);

% Specify desired non-zero values
D = 0.8; %0.6
D = 1.6;
% --------------------------
d(:,1,1,1,1) = D; % d(:,1,1,1,1) = 0.08; %
d(:,1,1,2,2) = D; % d(:,1,1,2,2) = 0.08; %

d(:,3,3,1,1) = dv; %d(:,3,3,1,1) = 3; %
d(:,3,3,2,2) = dv; %d(:,3,3,2,2) = 3; %
```

Function *reshape* (Display Solution)

```
% display results statically
u = reshape(u_keep(:),system_size,nn,nt);

kout = round(linspace(1,nt,num_plot_rows^2));
tout = dt*(kout-1);

for ieq = 1:system_size

   iu = squeeze(u(ieq,:,:));

   figure

   for k = 1:num_plot_rows^2

      subplot(num_plot_rows,num_plot_rows,k)

      if dim == 1


         plot(nodecoords,iu(:,kout(k)))

%          axis([xmin(1) xmax(1) xmin(2) xmax(2) 0 umax(ieq)])

if ieq == 1

axis([xmin(1) xmax(1) 0 3.5])

else
%          axis([xmin(1) xmax(1) 0 3]) % axis([xmin(1) xmax(1) 0 42])  %replaced from previous
line 2/24
end
         %axis([xmin(1) xmax(1) 0 3.5]) %replaced from previous line 3/6


         ylabel([‘u’ num2str(ieq)])

      elseif dim == 2

         trisurf(elements,nodecoords(:,1),nodecoords(:,2),iu(:,kout(k))) %,[0.5 0.5 0.5])

         %axis([xmin(1) xmax(1) xmin(2) xmax(2) 0 10])
       %  axis([xmin(1) xmax(1) xmin(2) xmax(2) 0 100])

         %axis equal
```

```
            shading interp
            ylabel(‘y’)
            zlabel([‘u’ num2str(ieq)])
        end
        xlabel(‘x’)
        title([‘t=‘ num2str(tout(k))])
    end
end
%-----------------------------------------------------------
% display results as movie
%-----------------------------------------------------------
fig = figure;
moviein(num_plot_rows^2);
for kt = 1:num_plot_rows^2
    for ieq = 1:system_size
        iu = squeeze(u(ieq,:,kout(kt)));
        subplot(system_size,1,ieq)
        if dim == 1
            plot(nodecoords,iu)
            axis([xmin(1) xmax(1) 0 1])
            ylabel([‘u’ num2str(ieq)])
        elseif dim == 2
            trisurf(elements,nodecoords(:,1),nodecoords(:,2),iu) %,[0.5 0.5 0.5])
```

```
        %axis([xmin(1) xmax(1) xmin(2) xmax(2) 0 10])
        axis([xmin(1) xmax(1) xmin(2) xmax(2) 0 100])
        %axis equal

        shading interp

        ylabel('y')

        zlabel(['u' num2str(ieq)])

      end

      xlabel('x')

   end

   U_Movie(:,kt) = getframe(fig);

end
movie(U_Movie,4,12)
% display results statically
u = reshape(u_keep(:),system_size,nn,nt);
%kout = round(linspace(1,nt,num_plot_rows^2));
kout = round(linspace(1,nt,3));
tout = dt*(kout-1);
umax = [100 100];
uscale = [100 100];
uscale = [1 1];
for ieq = 1:system_size
   iu = squeeze(u(ieq,:,:));
   for k = 1:3
%       subplot(num_plot_rows,num_plot_rows,k)
figure
        trisurf(elements,nodecoords(:,1),nodecoords(:,2),iu(:,kout(k))/uscale(ieq))
        shading interp
        ylabel('y')
        zlabel(['u' num2str(ieq)])
      xlabel('x')
      tt = round(100*tout(k))/100;
      title(['t=' num2str(tt)])
      colorbar
   end
end
```

Function *initial conditions*

```
function u = M2D_case2aR0_inicond(eles, coords)

global kdR1_vec kdR2_vec kgR_vec
%global urban shrub water road grass
global cell_size

% luc 10/30-------------
global cls_img
global kgN kdN kdR1 kdR2 kgR c
global D maxveloc alpha alpha_max R0 Kv dv
global kdR1_vec kdR2_vec kgR_vec
global seasonal_factor
global verts
%global cell_size
cell_size = 0.012
nn  = size(coords,1);

dim = size(coords,2);
% Set system size (number of equations) and background value
sys_size = 3;
%common_value = 1;
common_value = 0;
u = common_value*ones(nn,sys_size);

% Set specialized values, dependent on coordinates
x = coords(:,1);
y = coords(:,2);

load  classified_newlandcover cls_img;
size(x)
size(y)
size(cls_img,1)
cell_size
nodeidx = floor(x / cell_size)*size(cls_img,1) + size(cls_img,1)- (floor(y / cell_size)+476-616) ;

%    ---   IC for Resource   ---

load classified_newlandcover2 cls_img

nodeidx = floor(x / cell_size)*size(cls_img,1) + size(cls_img,1)- (floor(y / cell_size)+476-616) ;
%nodeidx = floor(x / cell_size)*size(cls_img,1) + size(cls_img,1)- (floor(y / cell_size)+476-616)
;
% max(nodeidx)
% min(nodeidx)
```

```
%end 11/20-----------------------------------
padding_value=255;
size_cls_img=size(cls_img);
nearest_2n=ceil(max(log2(size_cls_img)));
cls_img_2n=padding_value+uint8(zeros([2^(nearest_2n) 2^(nearest_2n)]));
cls_img_2n(1:size_cls_img(1), 1:size_cls_img(2))= cls_img;

figure
image(cls_img)

figure
image(cls_img_2n)

%pause

size(cls_img_2n)

nodeidx = max(verts(:,1),1)+(max(verts(:,2),1)-1)*size(cls_img_2n,1);

max(nodeidx)

nodal_landuse = cls_img_2n(nodeidx);

figure
trimesh(eles,verts(:,2),verts(:,1),nodal_landuse)

figure
plot(verts(:,2),-verts(:,1),'.')

figure
[ixx,jyy]=ind2sub(size(cls_img_2n),nodeidx);
plot(jyy,ixx,'k.')

figure
trimesh(eles,jyy,-ixx)

%pause

urban_nodes      = find(nodal_landuse == 2);   % --- luc suggested all 5 lines 10/30 5:00 pm as
shown in DRiver -------
shrub_nodes      = find(nodal_landuse == 3);   %note shrub=wetland
water_nodes      = find(nodal_landuse == 4);
grass_nodes      = find(nodal_landuse == 5);
road_nodes       = find(nodal_landuse == 6
u(urban_nodes, 2)       = 1;
```

```
u(shrub_nodes, 2)       = 2.5;
u(water_nodes, 2)       = 3.5;
u(grass_nodes, 2)       = 9;
u(road_nodes, 2)        = 0;

figure
trimesh(eles,jyy,-ixx,u(:,2))

figure
trimesh(eles,coords(:,1),coords(:,2),u(:,2))

%    ---   IC for Geese   ---

qqq_eles = eles;
qqq_verts = verts;

load classified_newsites cls_newsites_img

padding_value=255;
size_cls_newsites_img=size(cls_newsites_img);
nearest_2n=ceil(max(log2(size_cls_newsites_img)));
cls_newsites_img_2n=padding_value+uint8(zeros([2^(nearest_2n) 2^(nearest_2n)]));
cls_newsites_img_2n(1:size_cls_newsites_img(1), 1:size_cls_newsites_img(2))=
cls_newsites_img;

eles = qqq_eles;
verts = qqq_verts;

nodeidx = max(verts(:,1),1)+(max(verts(:,2),1)-1)*size(cls_newsites_img_2n,1);

nodeidx(1:100)

figure
[ixx,jyy]=ind2sub(size(cls_newsites_img_2n),nodeidx);
plot(jyy,-ixx,'k.')

figure
image(cls_newsites_img)

figure
image(cls_newsites_img_2n)
hold on
plot(jyy,ixx,'k.')
hold off
 nodal_sites = cls_newsites_img_2n(nodeidx);
```

```
size(nodeidx)
size(nodal_sites)
max(nodal_sites)
min(nodal_sites)
unique(nodal_sites)
figure
trimesh(eles,jyy,-ixx,nodal_sites')

figure
plot(jyy,-ixx,'k.')

Kingman_nodes =   find(nodal_sites ==1);
Heritage_nodes =  find(nodal_sites ==2);
Anacostia_nodes = find(nodal_sites ==3);
Kenilworth_nodes = find(nodal_sites ==4);

u(Kingman_nodes,1)   =   3.296;
u(Heritage_nodes,1)  =   2.991;
u(Anacostia_nodes,1) =   1.214;
u(Kenilworth_nodes,1)=   3.702;
figure
trimesh(eles,jyy,-ixx,u(:,1))
figure
trimesh(eles,coords(:,1),coords(:,2),u(:,1))
pause

%--   IC for velocity   ---
u(:,3)= 0;

function r = M2D_case2aR0_reaction(u,coords,t)
%global cls_img
global kgN kdN kdR1 kdR2 kgR c
global seasonal_factor

% Calculate general problem information:
ne = size(u,1);
sys_size = size(u,2);
dim = size(coords,1);
% Initialize reaction rates to zero
r = zeros(ne,sys_size,sys_size);
```

Function *source*

```
function s = M2D_case2aR0_sourceY(u,gradu,coords,t)
% Calculate general problem information:

ne = size(u,1);         % number of elements

sys_size = size(u,2);   % number of equations in PDE system

dim = size(coords,2);   % number of spatial dimensions

% Initialize sources to zero

s = zeros(ne,sys_size);
```

Function *ndrectangle*

```
function coords = ndrectangle_2c(xmin,xmax,nx)
dim = size(xmin,2);
wigfact = 0;
wigfact = 0.5*(xmax-xmin)/(nx-1);
rand('state',512);

   x_vector = linspace(xmin(1),xmax(1),nx(1));
   y_vector = linspace(xmin(2),xmax(2),nx(2));
   [x,y] = ndgrid(x_vector,y_vector);
   xwiggle = wigfact*(rand(size(x))-0.5);
   ywiggle = wigfact*(rand(size(y))-0.5);
   x(2:end-1,2:end-1) = x(2:end-1,2:end-1)+xwiggle(2:end-1,2:end-1);
   y(2:end-1,2:end-1) = y(2:end-1,2:end-1)+ywiggle(2:end-1,2:end-1);
   coords = [x(:) y(:)];
```

Pre-processing File

```
% ---------- CLASSIFICATION PROCESS ---------------

cls_img=ones(size(I)); % this sets the default class to mash (20)

urban=find(I==76);
cls_img(urban)=2;
shrub=find(I==79);
cls_img(shrub)=3;
water=find(I==145);
cls_img(water)=4;
grass=find(I==175);
cls_img(grass)=5;
road=find(I==0);
cls_img(road)=6;
% backgroung=find(I==255);
% cls_img(backgroung)=7;

save classified_landuse cls_img

figure
v_east = [0 cell_size*(size(I,2)-1)];%coords at beging/end of column axis
v_north = [cell_size*(size(I_2n,1)-1) cell_size*(size(I_2n,1)-size(I,1))]; %coords at beging/end
of row axis
image(v_east, v_north, cls_img)
h = gca ;
set(h,'YDir','normal')
colormap([1 1 1;0 0 1;1 0 0;0 1 0;0.5 0.5 0.2;0 0.75 0.5])
axis image
%trisurf(elements)
%axis image
xlabel('Easting (Km)');
ylabel('Northing (Km)');
hold on
trimesh(elements,nodecoords(:,1),nodecoords(:,2)); % without "hold on,"

format compact
% Store image in MATLAB

newsites3 = imread('newsites3.tif');

newsites2 = imread('newsites2.tif');
% convert s_color image to grayscale
%  S = .2989*newsites2(:,:,1)...
%     +.5870*newsites2(:,:,2)...
```

```
%     +.1140*newsites2(:,:,3);

S = .2989*newsites3(:,:,1)...
   +.5870*newsites3(:,:,2)...
   +.1140*newsites3(:,:,3);

figure;
colormap(gray(256));
image(S)
size(S)
[uniq_S, ti, tj] = unique(S(:));

pause

cls_newsites3_img=ones(size(S));
Kingman=find(S==175);
cls_newsites3_img(Kingman)=1;

Heritage=find(S==76);
cls_newsites3_img(Heritage)=2;

Anacostia=find(S==226);
cls_newsites3_img(Anacostia)=3;

Kenilworth=find(S==145);
cls_newsites3_img(Kenilworth)=4;
```

Pre-process “sites”

```
format compact
% Store image in MATLAB
sites_img=imread('sampling_sites.GCS');
imagesc(sites_img);
pause
cell_size = 3.1/1000; %3.1 meter i.e 0.0031 km
v_east = [0 cell_size*(size(sites_img,2)-1)]; %coords at beging/end of column axis
v_north = [cell_size*(size(sites_img,1)-1) 0]; %coords at beging/end of raw axis
cls_img=ones(size(sites_img)); % this is a 1500 X 1400 matrix of ones.
cls1=find(sites_img==20);       %finds all pts of sub-img where the
cls_img(cls1)=2;                % kingman
%sites_img(1200, 350) % ans is 249, ie the color intensity of lite red==Heritage site
cls2=find(sites_img==249);     %finds all pts of sub-img where the red intensity == 255
cls_img(cls2)=3;               %  Heritage
%sites_img(1200, 600) % ans is 251, ie the color intensity of lite lite2red==east anacostia site
cls3=find(sites_img==251);         %finds all pts of sub-img where the green intensity =128
```

```
cls_img(cls3)=4;              %East_Anacostia
%sites_img(550, 950) % ans is 196, ie the color intensity of orange==kenilworth site
cls4=find(sites_img==196);
cls_img(cls4)=5;              %  kenilworth
save classified_sites cls_img
figure
imagesc(v_east, v_north, cls_img)
h = gca ;
set(h,’YDir’,’normal’)
colormap([1 1 1;0 0 1;1 0 0;0 1 0;0.5 0.5 0.2;0 0.75 0.5])
axis image
xlabel(‘Easting (Km)’);
ylabel(‘Northing (Km)’);
%-------------------------------------------------------------------
xmin=[1.25 0.15]; %min coords of lowest point of the photo image
xmax=[3.25 4.75]; %max coords of highest point of the photo image
nx=[40 20];
rotangle = 50/360*2*pi; % rotation angle in RADIANS!!!!!!!
nodecoords = rot_rect_2D(xmin,xmax,nx,rotangle);

hold on
plot(nodecoords(:,1),nodecoords(:,2),’k.’)
hold off

[elements, elesizes, bf_slopes] = elegeoms(nodecoords);

hold on
trimesh(elements,nodecoords(:,1),nodecoords(:,2)); % without “hold on”
hold off
```

Function *rot_rect*

```
function coords = rot_rect_2D(xmin,xmax,nx,alpha)
%
% Returns an n-dimensional discretization of the rectangle
% bounded by xmin and xmax with nx points in each direction
%
dim = size(xmin,2);
wigfact = 0;
%wigfact = 0.1*(xmax-xmin)/(nx-1);
rand('state',512);

% determine Lx and Ly

Ld = sqrt((xmax(1)-xmin(1))^2+(xmax(2)-xmin(2))^2);
beta = acos((xmax(1)-xmin(1))/Ld) - alpha;
Lx = Ld*cos(beta);
Ly = Ld*sin(beta);

% generate horizontal nodes
   x_vector = linspace(0, Lx, nx(1));
   y_vector = linspace(0, Ly, nx(2));
   [x,y] = ndgrid(x_vector,y_vector);
   xwiggle = wigfact*(rand(size(x))-0.5);
   ywiggle = wigfact*(rand(size(y))-0.5);
   x(2:end-1,2:end-1) = x(2:end-1,2:end-1)+xwiggle(2:end-1,2:end-1);
   y(2:end-1,2:end-1) = y(2:end-1,2:end-1)+ywiggle(2:end-1,2:end-1);

% rotate the nodes by 'alpha' and shift them
r = sqrt(x(:).^2+y(:).^2+0.0000000000000000000001);
gama = alpha + acos(x(:)./r);
x = r.*cos(gama) + xmin(1);
y = r.*sin(gama) + xmin(2);


   coords = [x(:) y(:)];
   coords(1,:) = xmin;
```

APPENDIX E
ARCGIS' VBS SCRIPTS FOR LAND COVER

ArcGIS' VBS Scripts for Land Cover

```
' ---------------------------------------------------------------------------
' LandCovers.vbs
' Created on: Tue Jul 06 2010 10:07:06 PM
'   (generated by ArcGIS/ModelBuilder)
' ---------------------------------------------------------------------------
' Create the Geoprocessor object
set gp = WScript.CreateObject("esriGeoprocessing.GPDispatch.1")

' Load required toolboxes...
gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx"
gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management
Tools.tbx"
gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"


' Local variables...
food_poly_shp__2_ = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp"
waters_poly_shp__2_ =
"Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp"
Developed_areas_shp__2_ =
"Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed areas.shp"
Wood_poly_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Wood_poly.shp"
Study_Area_poly__2_ = "Study Area_poly"
Developed_area_shp =
"Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed_area.shp"
Wood_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Wood.shp"
Grass_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Grass.shp"
waters_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters.shp"
Dev_areas_img =
"Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
Dev_areas.img"
Woodlands_img =
"Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_109012
7_01\Woodlands.img"
Grassfields = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Grassfields.img"
Waters_img = "Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Waters.img"
hayherbwetlds = "hayherbwetlds"
Devped_areas_RAS = "Devped_areas_RAS"
Wood_perenls = "Wood_perenls"
waters_ras = "waters_ras"
Roads_ras = "Roads_ras"
Roads_ras__2_ = "Roads_ras"
Waters = "Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Waters.img"
Grasslands = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Grassfields.img"
```

Woodlands =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_1090127_01\Woodlands.img”
Dev_areas =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\Dev_areas.img”

‘ Process: Define Projection...
gp.DefineProjection_management Roads_ras,
“PROJCS[‘NAD_1983_UTM_Zone_18N’,GEOGCS[‘GCS_North_American_1983’,DATUM[‘D_North_American_1983’,SPHEROID[‘GRS_1980’,6378137.0,298.257222101]],PRIMEM[‘Greenwich’,0.0],UNIT[‘Degree’,0.0174532925199433]],PROJECTION[‘Transverse_Mercator’],PARAMETER[‘False_Easting’,500000.0],PARAMETER[‘False_Northing’,0.0],PARAMETER[‘Central_Meridian’,-75.0],PARAMETER[‘Scale_Factor’,0.9996],PARAMETER[‘Latitude_Of_Origin’,0.0],UNIT[‘Meter’,1.0]]”

‘ Process: Raster to Polygon (5)...
gp.RasterToPolygon_conversion waters_ras, waters_poly_shp__2_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (11)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp #;’Study Area_poly’ #,” waters_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (3)...
gp.PolygonToRaster_conversion waters_shp, “FID,” Waters_img, “CELL_CENTER,” “NONE,” “12”

‘ Process: Define Projection (2)...
gp.DefineProjection_management Waters_img,
“PROJCS[‘NAD_1983_UTM_Zone_18N’,GEOGCS[‘GCS_North_American_1983’,DATUM[‘D_North_American_1983’,SPHEROID[‘GRS_1980’,6378137.0,298.257222101]],PRIMEM[‘Greenwich’,0.0],UNIT[‘Degree’,0.0174532925199433]],PROJECTION[‘Transverse_Mercator’],PARAMETER[‘False_Easting’,500000.0],PARAMETER[‘False_Northing’,0.0],PARAMETER[‘Central_Meridian’,-75.0],PARAMETER[‘Scale_Factor’,0.9996],PARAMETER[‘Latitude_Of_Origin’,0.0],UNIT[‘Meter’,1.0]]”

‘ Process: Raster to Polygon (3)...
gp.RasterToPolygon_conversion hayherbwetlds, food_poly_shp__2_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (10)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp #;’Study Area_poly’ #,” Grass_shp, “ALL,” “,” “INPUT”
‘ Process: Polygon to Raster (6)...

```
gp.PolygonToRaster_conversion Grass_shp, “FID,” Grassfields, “CELL_CENTER,” “NONE,”
“12”

‘ Process: Define Projection (3)...
gp.DefineProjection_management Grassfields,
“PROJCS[‘NAD_1983_UTM_Zone_18N’,GEOGCS[‘GCS_North_American_1983’,DATUM[‘
D_North_American_1983’,SPHEROID[‘GRS_1980’,6378137.0,298.257222101]],PRIMEM[‘Gr
eenwich’,0.0],UNIT[‘Degree’,0.0174532925199433]],PROJECTION[‘Transverse_Mercator’],P
ARAMETER[‘False_Easting’,500000.0],PARAMETER[‘False_Northing’,0.0],PARAMETER[‘
Central_Meridian’,-
75.0],PARAMETER[‘Scale_Factor’,0.9996],PARAMETER[‘Latitude_Of_Origin’,0.0],UNIT[‘
Meter’,1.0]]”

‘ Process: Raster to Polygon (7)...
gp.RasterToPolygon_conversion Wood_perenls, Wood_poly_shp, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (4)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Wood_poly.shp
#;’Study Area_poly’ #,” Wood_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (5)...
gp.PolygonToRaster_conversion Wood_shp, “FID,” Woodlands_img, “CELL_CENTER,”
“NONE,” “12”

‘ Process: Define Projection (4)...
gp.DefineProjection_management Woodlands_img,
“PROJCS[‘NAD_1983_UTM_Zone_18N’,GEOGCS[‘GCS_North_American_1983’,DATUM[‘
D_North_American_1983’,SPHEROID[‘GRS_1980’,6378137.0,298.257222101]],PRIMEM[‘Gr
eenwich’,0.0],UNIT[‘Degree’,0.0174532925199433]],PROJECTION[‘Transverse_Mercator’],P
ARAMETER[‘False_Easting’,500000.0],PARAMETER[‘False_Northing’,0.0],PARAMETER[‘
Central_Meridian’,-
75.0],PARAMETER[‘Scale_Factor’,0.9996],PARAMETER[‘Latitude_Of_Origin’,0.0],UNIT[‘
Meter’,1.0]]”

‘ Process: Raster to Polygon (6)...
gp.RasterToPolygon_conversion Devped_areas_RAS, Developed_areas_shp__2_, “SIMPLIFY,”
“VALUE”

‘ Process: Intersect (7)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed
areas.shp’ #;’Study Area_poly’ #,” Developed_area_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (4)...
gp.PolygonToRaster_conversion Developed_area_shp, “FID,” Dev_areas_img,
“CELL_CENTER,” “NONE,” “12”
```

```
‘ Process: Define Projection (5)...
gp.DefineProjection_management Dev_areas_img,
“PROJCS[‘NAD_1983_UTM_Zone_18N’,GEOGCS[‘GCS_North_American_1983’,DATUM[‘
D_North_American_1983’,SPHEROID[‘GRS_1980’,6378137.0,298.257222101]],PRIMEM[‘Gr
eenwich’,0.0],UNIT[‘Degree’,0.0174532925199433]],PROJECTION[‘Transverse_Mercator’],P
ARAMETER[‘False_Easting’,500000.0],PARAMETER[‘False_Northing’,0.0],PARAMETER[‘
Central_Meridian’,-
75.0],PARAMETER[‘Scale_Factor’,0.9996],PARAMETER[‘Latitude_Of_Origin’,0.0],UNIT[‘
Meter’,1.0]]”
```

APPENDIX F
ARCGIS’ VBS SCRIPTS FOR DIAGNOSIS EXPERT SYSTEM

ArcGIS' VBS Scripts for Diagnosis Expert System

```
‘ ----------------------------------------------------------------
‘ diagnosisVBScripts.vbs
‘ Created on: Wed Jul 07 2010 10:33:29 AM
‘   (generated by ArcGIS/ModelBuilder)
‘ ------------------------------------------------------------------------

‘ Create the Geoprocessor object
set gp = WScript.CreateObject(“esriGeoprocessing.GPDispatch.1”)

‘ Load required toolboxes...
gp.AddToolbox “C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx”
gp.AddToolbox “C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx”


‘ Local variables...
food_waters_shp =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\f
ood_waters.shp”
hayherbwetlds = “hayherbwetlds”
waters_ras = “waters_ras”
food_poly_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp”
waters_poly_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp”
Kingman_marsh = “Kingman_marsh”
Heritage_marsh = “Heritage_marsh”
Kingman_Islands_shp =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_109012
7_01\land_use_land_cover\Kingman_Islands.shp”
Devped_areas_RAS = “Devped_areas_RAS”
Developed_areas_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed
areas.shp”
Urban_Extra_feed_shp =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
Urban_Extra_feed.shp”
Study_Area_poly = “Study Area_poly”
Resources_shp = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Resources.shp”
Urban_feeding_shp = “Y:\Personal\UMCP\GooseResearchMap\Urban_feeding.shp”
StudyArea_foodRes_shp = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\StudyArea_foodRes.shp”
Courtyard_sidewalk_shp = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\Courtyard_sidewalk.shp”
Study_area_major_roads = “Study area major roads”
v100m_Rd_buffer_shp =
“Y:\Personal\UMCP\GooseResearchMap\attachments_2010_03_05\100m_Rd_buffer.shp”
```

```
Breeding_nesting_shp = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\Breeding_nesting.shp”
D1_High_access_Res_img = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\D1_High_access_Res.img”
D2_High_access_Breeding_img = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\D2_High_access_Breeding.img”
D3_Urban_feeding_img = “Y:\Personal\UMCP\GooseResearchMap\D3_Urban_feeding.img”
Study_Area_poly__2_ = “Study Area_poly”
Wood_perenls = “Wood_perenls”
Output_Feature_Class = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\tl_2009_11_county_Intersect7.shp”
Output_polygon_features =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Wood_pe1.shp”
LC_woods_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\LC_woods.img”
waters_ras__2_ = “waters_ras”
Output_polygon_features__2_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_waters_1.shp”
Output_Feature_Class__2_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_waters_1_Intersect.shp”
LC_waters_img = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\LC_waters.img”
hayherbwetlds__2_ = “hayherbwetlds”
Devped_areas_RAS__3_ = “Devped_areas_RAS”
Output_polygon_features__3_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Devped_2.shp”
Output_Feature_Class__3_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Devped_2_Intersect.shp”
LC_Dev_area_img =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\LC_Dev_area.img”
Output_polygon_features__4_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_hayherb3.shp”
Output_Feature_Class__4_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_hayherb3_Intersect.shp”
LC_grass_img = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\LC_grass.img”
D3_Urban_feeding = “D3_Urban_feeding”
D2_High_access_Breeding = “D2_High_access_Breeding”
D1_High_access_Res = “D1_High_access_Res”
Output_Feature_Class__5_ =
“Y:\Personal\UMCP\GooseResearchMap\RasterT_D3_Urba1_Intersect.shp”
Output_Feature_Class__6_ = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_D2_High1_Intersect.shp”
Output_Feature_Class__7_ = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_D1_High1_Intersect.shp”
Output_polygon_features__5_ =
“Y:\Personal\UMCP\GooseResearchMap\RasterT_D3_Urba1.shp”
Output_polygon_features__6_ = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_D2_High1.shp”
```

Output_polygon_features__7_ = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\RasterT_D1_High1.shp”
Goose_hot_spots__per_Field_Observation_ = “Goose hot spots (per Field Observation)”
Urb_feed_HS_img = “Y:\Personal\UMCP\GooseResearchMap\Urb_feed_HS.img”
Breeding_HS_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Breeding_HS.img”
Resources_HS_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Resources_HS.img”

‘ Process: Raster to Polygon...
gp.RasterToPolygon_conversion hayherbwetlds, food_poly_shp, “SIMPLIFY,” “VALUE”

‘ Process: Raster to Polygon (2)...
gp.RasterToPolygon_conversion waters_ras, waters_poly_shp, “SIMPLIFY,” “VALUE”

‘ Process: Union (2)...
gp.Union_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp #;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp #,” food_waters_shp, “ALL,” “,” “GAPS”

‘ Process: Intersect (2)...
gp.Intersect_analysis “‘Study Area_poly’ #;Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\food_waters.shp #,” Resources_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster...
gp.PolygonToRaster_conversion Resources_shp, “FID,” D1_High_access_Res_img, “CELL_CENTER,” “NONE,” “0.00082”

‘ Process: Intersect (6)...
gp.Intersect_analysis “‘Study Area_poly’ #;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp #,” StudyArea_foodRes_shp, “ALL,” “,” “INPUT”

‘ Process: Buffer...
gp.Buffer_analysis Study_area_major_roads, v100m_Rd_buffer_shp, “100 Meters,” “FULL,” “ROUND,” “NONE,” ““

‘ Process: Intersect (3)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC Boundary\StudyArea_foodRes.shp’ #;Y:\Personal\UMCP\GooseResearchMap\attachments_2010_03_05\100m_Rd_buffer.shp #,” Courtyard_sidewalk_shp, “ALL,” “,” “INPUT”

‘ Process: Union (3)...

gp.Union_analysis “Kingman_marsh #;Heritage_marsh #,” Kingman_Islands_shp, “ALL,” “,” “GAPS”

‘ Process: Union (5)...
gp.Union_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Courtyard_sidewalk.shp’ #;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_1090127_01\land_use_land_cover\Kingman_Islands.shp #,” Breeding_nesting_shp, “ALL,” “,” “GAPS”

‘ Process: Polygon to Raster (2)...
gp.PolygonToRaster_conversion Breeding_nesting_shp, “FID,” D2_High_access_Breeding_img, “CELL_CENTER,” “NONE,” “0.00082”

‘ Process: Raster to Polygon (4)...
gp.RasterToPolygon_conversion Devped_areas_RAS, Developed_areas_shp, “SIMPLIFY,” “VALUE”

‘ Process: Intersect...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\food_waters.shp #;’Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed areas.shp’ #,” Urban_Extra_feed_shp, “ALL,” “,” “INPUT”

‘ Process: Intersect (5)...
gp.Intersect_analysis “‘Study Area_poly’ #;Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\Urban_Extra_feed.shp #,” Urban_feeding_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (3)...
gp.PolygonToRaster_conversion Urban_feeding_shp, “FID,” D3_Urban_feeding_img, “CELL_CENTER,” “NONE,” “0.00082”

‘ Process: Raster to Polygon (3)...
gp.RasterToPolygon_conversion Wood_perenls, Output_polygon_features, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (4)...
gp.Intersect_analysis “‘Study Area_poly’ #;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Wood_pe1.shp #,” Output_Feature_Class, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (4)...
gp.PolygonToRaster_conversion Output_Feature_Class, “FID,” LC_woods_img, “CELL_CENTER,” “NONE,” “0.00082”

‘ Process: Raster to Polygon (5)...
gp.RasterToPolygon_conversion waters_ras__2_, Output_polygon_features__2_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (7)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_waters_1.shp #;’Study Area_poly’ #,” Output_Feature_Class__2_, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (5)...
gp.PolygonToRaster_conversion Output_Feature_Class__2_, “FID,” LC_waters_img, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (8)...
gp.RasterToPolygon_conversion Devped_areas_RAS__3_, Output_polygon_features__3_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (12)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Devped_2.shp #;’Study Area_poly’ #,” Output_Feature_Class__3_, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (10)...
gp.PolygonToRaster_conversion Output_Feature_Class__3_, “FID,” LC_Dev_area_img, “CELL_CENTER,” “NONE,” “17”

‘ Process: Raster to Polygon (6)...
gp.RasterToPolygon_conversion hayherbwetlds__2_, Output_polygon_features__4_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (8)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_hayherb3.shp #;’Study Area_poly’ #,” Output_Feature_Class__4_, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (6)...
gp.PolygonToRaster_conversion Output_Feature_Class__4_, “FID,” LC_grass_img, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (7)...
gp.RasterToPolygon_conversion D3_Urban_feeding, Output_polygon_features__5_, “SIMPLIFY,” “Value”

‘ Process: Intersect (9)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\RasterT_D3_Urba1.shp #;’Goose hot spots (per Field Observation)’ #,” Output_Feature_Class__5_, “ALL,” “,” “INPUT”

```
‘ Process: Polygon to Raster (7)...
gp.PolygonToRaster_conversion Output_Feature_Class__5_, “FID,” Urb_feed_HS_img,
“CELL_CENTER,” “NONE,” “0.00016”

‘ Process: Raster to Polygon (9)...
gp.RasterToPolygon_conversion D2_High_access_Breeding, Output_polygon_features__6_,
“SIMPLIFY,” “Value”

‘ Process: Intersect (10)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_D2_High1.shp’ #;’Goose hot spots (per Field Observation)’ #,”
Output_Feature_Class__6_, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (8)...
gp.PolygonToRaster_conversion Output_Feature_Class__6_, “FID,” Breeding_HS_img,
“CELL_CENTER,” “NONE,” “0.00016”

‘ Process: Raster to Polygon (10)...
gp.RasterToPolygon_conversion D1_High_access_Res, Output_polygon_features__7_,
“SIMPLIFY,” “Value”

‘ Process: Intersect (11)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_D1_High1.shp’ #;’Goose hot spots (per Field Observation)’ #,”
Output_Feature_Class__7_, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (9)...
gp.PolygonToRaster_conversion Output_Feature_Class__7_, “FID,” Resources_HS_img,
“CELL_CENTER,” “NONE,” “0.00016”
```

APPENDIX G
ARCGIS’ VBS SCRIPTS FOR PRESCRIPTION EXPERT SYSTEM

ArcGIS' VBS Scripts for Prescription Expert System

```
' ----------------------------------------------------------------
' PrescriptionsVBScripts.vbs
' Created on: Wed Jul 07 2010 10:34:32 AM
'   (generated by ArcGIS/ModelBuilder)
' ------------------------------------------------------------------------

' Create the Geoprocessor object
set gp = WScript.CreateObject("esriGeoprocessing.GPDispatch.1")

' Check out any necessary licenses
gp.CheckOutExtension "spatial"

' Load required toolboxes...
gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx"
gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"


' Local variables...
D1_Resources_shp =
"Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
D1_Resources.shp"
hayherbwetlds = "hayherbwetlds"
waters_ras = "waters_ras"
food_poly_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp"
waters_poly_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp"
Kingman_marsh = "Kingman_marsh"
Heritage_marsh = "Heritage_marsh"
Kingman_Islands_shp =
"Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_109012
7_01\land_use_land_cover\Kingman_Islands.shp"
Devped_areas_RAS = "Devped_areas_RAS"
Developed_areas_shp = "Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed
areas.shp"
D3_Extra_food_shp =
"Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
D3_Extra_food.shp"
Study_Area_poly = "Study Area_poly"
food_water_Res_shp = "Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\food_water_Res.shp"
StudyArea_extra_feed_shp = "Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\StudyArea_extra_feed.shp"
StudyArea_foodRes_shp = "Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\StudyArea_foodRes.shp"
```

P4_Ban_feeding_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\P4_Ban_feeding.img”
P1_Chem_deter_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\P1_Chem_deter.img”
P2_Egg_depr_img__2_ = “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\P2_Egg_depr.img”
Roadway_feed_shp = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Roadway_feed.shp”
Study_area_major_roads = “Study area major roads”
v100m_Rd_buffer_shp = “Y:\Personal\UMCP\GooseResearchMap\attachments_2010_03_05\100m_Rd_buffer.shp”
D2_Breeding_nest_shp = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\D2_Breeding_nest.shp”
Wetlands = “Wetlands”
StudyAreaWetland_poly_shp = “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\StudyAreaWetland_poly.shp”
harvest_BA_shp = “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\harvest_BA.shp”
P5_Fencing = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_1090127_01\P5_Fencing”
Kingman_nests_img = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_1090127_01\Kingman_nests.img”
P3_harvest_BA = “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\harvest_BA_P.img”
hayherbwetlds__2_ = “hayherbwetlds”
waters_ras__2_ = “waters_ras”
food_poly_shp__2_ = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp”
waters_poly_shp__2_ = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp”
Devped_areas_RAS__2_ = “Devped_areas_RAS”
Developed_areas_shp__2_ = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed areas.shp”
Study_Area_poly__2_ = “Study Area_poly”
Waters_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Waters.img”
Dev_areas_img = “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\Dev_areas.img”
Woodlands_img = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_1090127_01\Woodlands.img”

Grassfields = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Grassfields.img”
Wood_perenls = “Wood_perenls”
Wood_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Wood.shp”
Wood_poly_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Wood_poly.shp”
Developed_area_shp =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed_area.shp”
Study_area_major_roads__2_ = “Study area major roads”
Grass_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Grass.shp”
waters_shp = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters.shp”
Devped_areas_RAS__3_ = “Devped_areas_RAS”
Output_polygon_features =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Devped_2.shp”
Output_Feature_Class =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Devped_2_Intersect.shp”
Dev_area_img = “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Dev_area.img”
Ban_Feed_HS_img = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\Ban_Feed_HS.img”
P1_Chem_deter__2_ = “P1_Chem_deter”
P2_Egg_depr__2_ = “P2_Egg_depr”
P3_harvest_BA__3_ = “P3_harvest_BA”
P4_Ban_feeding__2_ = “P4_Ban_feeding”
P5_Fencing__3_ = “P5_Fencing”
Output_polygon_features__7_ = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_P1_Chem1.shp”
Output_polygon_features__8_ = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\RasterT_P4_Ban_1.shp”
Output_polygon_features__9_ =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
RasterT_harvest1.shp”
Output_polygon_features__10_ =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
RasterT_P2_Egg_1.shp”
Output_polygon_features__11_ =
“Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_109012
7_01\RasterT_P5_Fenc1.shp”
Goose_hot_spots__per_Field_Observation___2_ = “Goose hot spots (per Field Observation)”
Chem_HS_poly_shp = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\Chem_HS_poly.shp”
Egg_Depr_HS_poly_shp =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
Egg_Depr_HS_poly.shp”
Harv_HS_poly_shp =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
Harv_HS_poly.shp”
Ban_Feed_HS_poly_shp = “Y:\Personal\UMCP\GooseResearchMap\DC
Boundary\Ban_Feed_HS_poly.shp”

```
Chem_HS_img = “Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Chem_HS.img”
Egg_Depr_HS_img =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
Egg_Depr_HS.img”
Harv_HS_img =
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
Harv_HS.img”

‘ Process: Raster to Polygon...
gp.RasterToPolygon_conversion hayherbwetlds, food_poly_shp, “SIMPLIFY,” “VALUE”

‘ Process: Raster to Polygon (2)...
gp.RasterToPolygon_conversion waters_ras, waters_poly_shp, “SIMPLIFY,” “VALUE”

‘ Process: Union (2)...
gp.Union_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp
#;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp #,”
D1_Resources_shp, “ALL,” “,” “GAPS”

‘ Process: Raster to Polygon (4)...
gp.RasterToPolygon_conversion Devped_areas_RAS, Developed_areas_shp, “SIMPLIFY,”
“VALUE”

‘ Process: Intersect...
gp.Intersect_analysis
“Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
D1_Resources.shp #;’Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed
areas.shp’ #,” D3_Extra_food_shp, “ALL,” “,” “INPUT”

‘ Process: Intersect (5)...
gp.Intersect_analysis “‘Study Area_poly’
#;Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\
D3_Extra_food.shp #,” StudyArea_extra_feed_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (7)...
gp.PolygonToRaster_conversion StudyArea_extra_feed_shp, “FID,” P4_Ban_feeding_img,
“CELL_CENTER,” “NONE,” “96”

‘ Process: Intersect (6)...
gp.Intersect_analysis “‘Study Area_poly’
#;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp #,”
StudyArea_foodRes_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (8)...
gp.PolygonToRaster_conversion StudyArea_foodRes_shp, “FID,” P1_Chem_deter_img,
“CELL_CENTER,” “NONE,” “96”
```

‘ Process: Buffer...
gp.Buffer_analysis Study_area_major_roads, v100m_Rd_buffer_shp, “100 Meters,” “FULL,” “ROUND,” “NONE,” ““
‘ Process: Intersect (3)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC Boundary\StudyArea_foodRes.shp’ #;Y:\Personal\UMCP\GooseResearchMap\attachments_2010_03_05\100m_Rd_buffer.shp #,” Roadway_feed_shp, “ALL,” “,” “INPUT”

‘ Process: Union (3)...
gp.Union_analysis “Kingman_marsh #;Heritage_marsh #,” Kingman_Islands_shp, “ALL,” “,” “GAPS”

‘ Process: Union (5)...
gp.Union_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC Boundary\Roadway_feed.shp’ #;Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\land_use_land_cover_NLCD_1090127_01\land_use_land_cover\Kingman_Islands.shp #,” D2_Breeding_nest_shp, “ALL,” “,” “GAPS”

‘ Process: Polygon to Raster (9)...
gp.PolygonToRaster_conversion D2_Breeding_nest_shp, “FID,” P2_Egg_depr_img__2_, “CELL_CENTER,” “NONE,” “96”

‘ Process: Polygon to Raster...
gp.PolygonToRaster_conversion Kingman_Islands_shp, “FID,” Kingman_nests_img, “CELL_CENTER,” “NONE,” “2.4”

‘ Process: Reclassify...
gp.Reclassify_sa Kingman_nests_img, “VALUE,” “0 1;0 1 2;1 2 3,” P5_Fencing, “DATA”

‘ Process: Intersect (8)...
gp.Intersect_analysis “Wetlands #;’Study Area_poly’ #,” StudyAreaWetland_poly_shp, “ALL,” “,” “INPUT”

‘ Process: Intersect (2)...
gp.Intersect_analysis “‘Study Area_poly’ #;Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\D1_Resources.shp #,” food_water_Res_shp, “ALL,” “,” “INPUT”

‘ Process: Intersect (9)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\StudyAreaWetland_poly.shp #;’Y:\Personal\UMCP\GooseResearchMap\DC Boundary\food_water_Res.shp’ #,” harvest_BA_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (2)...
gp.PolygonToRaster_conversion harvest_BA_shp, “FID,” P3_harvest_BA, “CELL_CENTER,” “NONE,” “0.00082”

‘ Process: Raster to Polygon (5)...
gp.RasterToPolygon_conversion waters_ras__2_, waters_poly_shp__2_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (11)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\waters_poly.shp #,” waters_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (3)...
gp.PolygonToRaster_conversion waters_shp, “FID,” Waters_img, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (6)...
gp.RasterToPolygon_conversion Devped_areas_RAS__2_, Developed_areas_shp__2_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (7)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Developed areas.shp’ #;’Study Area_poly’ #,” Developed_area_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (4)...
gp.PolygonToRaster_conversion Developed_area_shp, “FID,” Dev_areas_img, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (7)...
gp.RasterToPolygon_conversion Wood_perenls, Wood_poly_shp, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (4)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\Wood_poly.shp #;’Study Area_poly’ #,” Wood_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (5)...
gp.PolygonToRaster_conversion Wood_shp, “FID,” Woodlands_img, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (3)...
gp.RasterToPolygon_conversion hayherbwetlds__2_, food_poly_shp__2_, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (10)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\food_poly.shp #,” Grass_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (6)...
gp.PolygonToRaster_conversion Grass_shp, “FID,” Grassfields, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (8)...
gp.RasterToPolygon_conversion Devped_areas_RAS__3_, Output_polygon_features, “SIMPLIFY,” “VALUE”

‘ Process: Intersect (12)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\nlcd_dc_utm18\RasterT_Devped_2.shp #;’Study Area_poly’ #,” Output_Feature_Class, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (10)...
gp.PolygonToRaster_conversion Output_Feature_Class, “FID,” Dev_area_img, “CELL_CENTER,” “NONE,” “96”

‘ Process: Raster to Polygon (15)...
gp.RasterToPolygon_conversion P4_Ban_feeding__2_, Output_polygon_features__8_, “SIMPLIFY,” “Value”

‘ Process: Intersect (20)...
gp.Intersect_analysis “‘Y:\Personal\UMCP\GooseResearchMap\DC Boundary\RasterT_P4_Ban_1.shp’ #;’Goose hot spots (per Field Observation)’ #,” Ban_Feed_HS_poly_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (15)...
gp.PolygonToRaster_conversion Ban_Feed_HS_poly_shp, “FID,” Ban_Feed_HS_img, “CELL_CENTER,” “NONE,” “0.00016”

‘ Process: Raster to Polygon (14)...
gp.RasterToPolygon_conversion P5_Fencing__3_, Output_polygon_features__11_, “SIMPLIFY,” “VALUE”

‘ Process: Raster to Polygon (18)...
gp.RasterToPolygon_conversion P1_Chem_deter__2_, Output_polygon_features__7_, “SIMPLIFY,” “Value”

‘ Process: Intersect (17)...
gp.Intersect_analysis “‘Goose hot spots (per Field Observation)’ #;’Y:\Personal\UMCP\GooseResearchMap\DC Boundary\RasterT_P1_Chem1.shp’ #,” Chem_HS_poly_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (12)...

gp.PolygonToRaster_conversion Chem_HS_poly_shp, “FID,” Chem_HS_img, “CELL_CENTER,” “NONE,” “12”

‘ Process: Raster to Polygon (17)...
gp.RasterToPolygon_conversion P2_Egg_depr__2_, Output_polygon_features__10_, “SIMPLIFY,” “Value”

‘ Process: Intersect (18)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\RasterT_P2_Egg_1.shp #;’Goose hot spots (per Field Observation)’ #,” Egg_Depr_HS_poly_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (13)...
gp.PolygonToRaster_conversion Egg_Depr_HS_poly_shp, “FID,” Egg_Depr_HS_img, “CELL_CENTER,” “NONE,” “0.00016”

‘ Process: Raster to Polygon (16)...
gp.RasterToPolygon_conversion P3_harvest_BA__3_, Output_polygon_features__9_, “SIMPLIFY,” “Value”

‘ Process: Intersect (19)...
gp.Intersect_analysis “Y:\Personal\UMCP\GooseResearchMap\DC_MD_shapefile_wetlands\DC_shapefile_wetlands\RasterT_harvest1.shp #;’Goose hot spots (per Field Observation)’ #,” Harv_HS_poly_shp, “ALL,” “,” “INPUT”

‘ Process: Polygon to Raster (14)...
gp.PolygonToRaster_conversion Harv_HS_poly_shp, “FID,” Harv_HS_img, “CELL_CENTER,” “NONE,” “0.00012”

APPENDIX H
UNPAIRED *T*-TEST COMPARING GOOSE DENSITIES IN TIME (PER SEASON) AND LOCATION (PER SURVEY SITE)

Unpaired *t*-test comparing goose densities in time (per season) and location (per survey site)

Unpaired t test results for April and July populations

APRIL vs JULY

P value and statistical significance:
The two-tailed P value equals 0.6143
By conventional criteria, this difference is considered to be not statistically significant
(i.e. 60% chance that pop. Densities btw APR-JUL are same)

Confidence interval:
The mean of APRIL minus JULY equals -0.8500
95% confidence interval of this difference: From -4.7652 to 3.0652

Intermediate values used in calculations:
t = 0.5312
df = 6
standard error of difference = 1.600

Group	APRIL	JULY
Mean	2.3225	3.1725
SD	0.9246	3.0636
SEM	0.4623	1.5318
N	4	4

Unpaired t test results for July and September populations

JULY vs SEPTEMBER

P value and statistical significance:
The two-tailed P value equals 0.8708
By conventional criteria, this difference is considered to be not statistically significant.
(i.e. 87% chance that pop. Densities btw SEP-JUL are same)

Confidence interval:
The mean of SEPT minus JULY equals -0.2950
95% confidence interval of this difference: From -4.5468 to 3.9568

Intermediate values used in calculations:
t = 0.1698
df = 6
standard error of difference = 1.738

Group	SEPT	JULY
Mean	2.8775	3.1725
SD	1.6406	3.0636
SEM	0.8203	1.5318
N	4	4

Unpaired t test results for September and December populations

SEPTEMBER vs DECEMBER

P value and statistical significance:
The two-tailed P value equals 0.5660
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of DEC minus JULY equals 1.4400
95% confidence interval of this difference: From -4.3637 to 7.2437

Intermediate values used in calculations:
t = 0.6071
df = 6
standard error of difference = 2.372

Group	**DEC**	**JULY**
Mean	4.6125	3.1725
SD	3.6217	3.0636
SEM	1.8109	1.5318
N	4	4

Unpaired t test results population densities at different locations

KINGMAN vs KENILWORTH

P value and statistical significance:
The two-tailed P value equals 0.3553
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of KG minus KW equals 1.5775
95% confidence interval of this difference: From -2.2772 to 5.4322

Intermediate values used in calculations:
t = 1.0014
df = 6
standard error of difference = 1.575

Group	KG	KW
Mean	3.53	1.9525
SD	2.9548	1.0934
SEM	1.4774	0.5467
N	4	4

Unpaired t test results population densities at different locations

KINGMAN vs ANACOSTIA

P value and statistical significance:
The two-tailed P value equals 0.8052
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of KG minus EA equals -0.5075
95% confidence interval of this difference: From -5.3250 to 4.3100

Intermediate values used in calculations:
t = 0.2578

df = 6
standard error of difference = 1.969

Group	KG	EA
Mean	3.53	4.0375
SD	2.9548	2.6027
SEM	1.4774	1.3013
N	4	4

Unpaired t test results population densities at different locations — KINGMAN vs HERITAGE

P value and statistical significance:
The two-tailed P value equals 0.3202
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of KG minus HR equals 1.7625
95% confidence interval of this difference: From -2.2183 to 5.7433

Intermediate values used in calculations:
t = 1.0834
df = 6
standard error of difference = 1.627

Review your data:

Group	KG	HR
Mean	3.53	1.7675
SD	2.9548	1.3622
SEM	1.4774	0.6811
N	4	4

Unpaired t test results population densities at different locations — ANACOSTIA vs HERITAGE

P value and statistical significance:
The two-tailed P value equals 0.1732
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of EA minus HR equals 2.2700
95% confidence interval of this difference: From -1.3240 to 5.8640

Intermediate values used in calculations:
t = 1.5455
df = 6
standard error of difference = 1.469

Review your data:

Group	EA	HR
Mean	4.0375	1.7675
SD	2.6027	1.3622
SEM	1.3013	0.6811
N	4	4

Unpaired t test results population densities at different locations — ANACOSTIA vs KENILWORTH

P value and statistical significance:
The two-tailed P value equals 0.8490
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of EA minus KW equals 0.3875
95% confidence interval of this difference: From -4.3828 to 5.1578

Intermediate values used in calculations:
t = 0.1988
df = 6
standard error of difference = 1.950

Review your data:

Group	EA	KW
Mean	4.0375	3.65
SD	2.6027	2.9032
SEM	1.3013	1.4516
N	4	4

Unpaired t test results population densities at different locations — HERITAGE vs KENILWORTH

P value and statistical significance:
The two-tailed P value equals 0.2849
By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The mean of HR minus KW equals -1.8825
95% confidence interval of this difference: From -5.8060 to 2.0410

Intermediate values used in calculations:
t = 1.1740
df = 6
standard error of difference = 1.603

Review your data:

Group	HR	KW
Mean	1.7675	3.65
SD	1.3622	2.9032

SEM	0.6811	1.4516
N	4	4

BIBLIOGRAPHY

Bibliography

ADF (Arbor Day Foundation). 2006. Hardiness zones. Available online at www.arborday.org/media/zones.cfm . Accessed in August, 2010.

Alver, M.O., J. A. Alfredsen and Y. Olsen. 2006. An individual-based population model for rotifer (*Brachionus plicatilis*) cultures. Hydrobiologia, 560:93–108.

Ankney, C. D. 1996. An embarrassment of riches: too many geese. Journal of Wildlife Management 60: 217-223.

Arditi, R., Y. Tyutyunov, A. Morgulis, V. Govorukhin, I. Senina. 2001. Directed movement of Predators and the emergence of density-dependence in predator-prey models. Theoretical Population Biology, 5:207-221.

Ayto, J. 1989. 20th Century Words. Cambridge University Press, NY, NY, USA.

Baeumer, B., M. Kovacs and M.M. Meerschaert. 2008. Numerical solutions for fractional reaction–diffusion equations. *Computers and Mathematics with Applications*, 55:2212–2226. Available online at http://www.stt.msu.edu/~mcubed/opsplit.pdf. Accessed on October 19, 2010.

Balkcom, G.D. 2010. Demographic Parameters of Rural and Urban Adult Resident Canada Geese in Georgia; Journal of Wildlife Management 74(1):120-123.

Baran, E. and T. Jantunen. 2004. Stakeholder Consultation for Bayesian Decision Support Systems in Environmental Management. Proceeding of the regional conference on ecological and environmental modeling (ECOMOD 2004). University Sains Malaysia, 15-16, September 2004, Penang, Malaysia. In Press.

Belant, J. L., L.A. Tyson and T.W. Seamans. 1999. Use of Alpha-Chloralose by the wildlife services program to capture nuisance birds. Wildlife Society Bull. 27:938-942.

Bjergo, C., C. Boydstun, M. Crosby, S. Kokkanakis and R. Sayers. 1995. Non-native Aquatic Species in the United States and Coastal Waters. Pages 428-430 in LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ, eds. *Our Living Resources: a Report to the Nation on the Distribution, Abundance, and Health of U.S. Plants, Animals and Ecosystems.* Washington, DC.: U.S. Department of the Interior, National Biological Service.

BNWR (Blackwater National Wildlife Refuge). 2000. Environmental Assessment for the Management of conflicts associated with non-migratory (resident) Canada geese. U.S. Fish and Wildlife Service, Dorchester County, Maryland. 37 pp.

Bos, D. 2002. Grazing in coastal grasslands. Brent geese and facilitation by herbivory. PhD thesis, University of Groningen, The Netherlands.

Boudewijn, T. 1984. The role of digestibility in the selection of spring feeding sites by Brent geese. Wildfowl, 35:97-105.

Bradley, F.B., R.A. Dolbeer, J.L. Belant and T.W. Seamans. 1998. Anthraquinone formulation (Flight Control) shows promise as avian feeding repellent. The J. of wildlife management. 62(4):1558-1564. ISSN: 0022-541X.

Caton, B.P., T.C. Foin and J.E. Hill. 1999. A plant growth model for integrated weed management in direct-seeded rice. Development and sensitivity analyses of monoculture growth. Field Crops Research, 62(1):129-143

CDC (Centers for Disease Control). 2009. FluView 2009-2010 Influenza Season Week 48 ending December 5, 2009. Available online at http://www.cdc.gov/flu/weekly. Accessed in December, 2009.

Chakraborti, A. 2006. Numerical study of biological problems in a predator-prey system. Msc. Thesis, Swinburne University of Technology, Melbourne VIC, Australia.

Chakraborty, A., M. Singh, D. Lucy, P. Ridland. 2007. Predator-prey model with prey-taxis and diffusion. Mathematical and Computer Modelling, 46(2007):482-498.

Cleary, E.C., S.E. Wright and R.A. Dolbeer. 1997. Wildlife strikes to civil aircraft in the United States 1992–1996. DOT/FAA/AAS/97-3. Fed. Aviation Admin., Office of Airport Safety and Standards, Washington, DC, pp. 30.

Clevenger, A.P., J. Wierzchowski, B. Chruszcz and K. Gunson. 2002. GIS-generated, Expert-based models for identifying wildlife habitat linkages and planning mitigation passages. Cons. Biol. 16(2):503-514.

Clinton, W. J. 1999. Executive Order 13112 of February 3, 1999: Invasive Species. *Federal Register.* 64(25):6183-6186.

Cohen, T. 1992. Pests with redeeming qualities. Technology Review.

Conroy, M.J. and L.A. Powell. 2001. Development of a monitoring program for sustainable harvest and control of resident Canada geese in Georgia. Final Report Contract between Georgia DNR and University of Georgia. Pp. 55 Wildlife soc. Bull. 00(0):000-000

Cowie R.H. 2002. Apple snails (Ampullariidae) as agricultural pests: their biology, impacts and management. In: Barker GM, eds. Molluscs as crop pests. Wallingford (UK): CABI Publishing. Pp. 145-192.

Curtis, P.D and A.S. Jirka. 1994. Assessment of Methyl Anthranilate (RejeX-It AG-36 TM) for reducing Canada goose use of turf grass areas; Department of Natural Resources, Cornell University, Ihaca, NY 14853. Available online at www.canadageese.org/rejet-it.pdf. Accessed on October 19, 2010.

DDOT (District Department of Transportation). 2007. Final Environmental Impact Statement of the 11th Street Bridges Project, Washington, D.C

Deijfen, M. 2003. Asymptotic shape in a continuum growth model. *Adv. Appl. Prob. 35:303-318.*

DFG (Department of Fish and Game). 2008. Geese in Massachussetts. Massachusetts Division of Fisheries and Wildlife online publication. Available online at www.mass.gov/dfwele/dfw/wildlife/facts/birds/waterfowl/winter_waterfowl_survey.htm. Accessed on October 19, 2010.

DiFazio, S.P., G. Slavov, J. Burczyk, S. Leonardi and S.H. Strauss. 2004. Gene flow from tree plantations and implications for transgenic risk assessment. Trivandrum, India. Research Signpost 37/661 (2):405-422.

Djodjick, F., H.J. Montas, A. Shirmohammadi, L. Bergstrom and A. Gustafson. 2000. Decision Support System for GCS Selection and Evaluation in a small Swedish Agricultural Watershed. An ASAE Meeting Presentation; Paper N0 002196 presented at the 2000 ASAE/CSAE-SCGR Annual International Meeting, Milwaukee, Wisconsin.

DOI FWS (Department of Interior Fish and Wildlife Service). 2010. Migratory bird hunting; final frameworks for late-season migratory bird hunting regulations.

DOI FWS, 50 CFR Parts 20; Federal Register 75(184) / Thursday, September 23, 2010/Rules and Regulations. Available online at http://www.gpo.gov/fdsys/pkg/FR-2010-09-23/pdf/2010-23751.pdf . Accessible on October 19, 2010.

DOI FWS (Department of Interior Fish and Wildlife Service). 2006. Migratory Bird Hunting and Permits; Regulations for Managing Resident Canada Goose Populations; Final Rule. DOI FWS, 50 CFR Parts 20 and 21; Federal Register 71(154) / Thursday, August 10, 2006/Rules and Regulations.

Dornbush, C., G. Feigelson, D. Gruskin, B. Hedges and A. Turner. 1996. Non-Lethal Controls for Resident Canada Geese. Available online at http://www.canadageese.org/report1.html**.** Accessible on October 19, 2010.

Doupe, R.G. and A.J. Lymbery. 2003. Toward the Genetic Improvement of Feed Conversion Efficiency in Fish. The *J. of world aquac. Soc. 34(3)XXX-YYY*.

Druzdzel, M. J. and R. R. Flynn. 1999. Decision Support Systems. Encyclopedia of Library and Information Science. A. Kent, Marcel Dekker, Inc., NY, NY.

Dunkley, L. and M.R.L. Cattet. 2003. Acomprehensive review of the ecological and human social effects of articial feeding and baiting of wildlife. Canadian Cooperative Wildlife Health Center, pp. 69. Available online at http://www.ccwhc.ca/wildlife_health_topics/wildlife_baiting.pdf . Accessible on October 19, 2010.

Durako, M.J., J.J. Shup, C.J. Andress and D. Tomasko. 1993. Restoring Seagrass Beds: Some New Approaches with Ruppia maritima L. (Widgeon-Grass). Proc. 20th Annual Conf. Wetlands Restoration and Creation, pp. 88–101.

Durant, D., L. Desnouhes, H. Fritz, M. Guillemain and F. Mesléard. 2009. Size-related consumption of Scirpus maritimus tubers by greylag geese Anser anser explained by their functional response. Behavioral processes, 80:39-45.

Ekelund, F., H.B. Frederiksen and R. Ronn. 2002. Population Dynamics of Active and Total Ciliate Populations in Arable Soil Amended with Wheat. *Appl. & env. Microbiology, 68(3):1096–1101.*

Engelmore, R. S. and E. Feigenbaum. 1993. Expert Systems and Artificial, Chapter 1. Available online at http://www.wtec.org/loyola/kb/c1_s1.htm. Accessed on October 19, 2010.

EPA (Environmental Protection Agency). 2008. Urban River Restoration Initiative. **Anacostia River Restoration Fact Sheet,** Spring 2008. Available online at http://www.epa.gov/reg3wapd/anacostia.htm. Accessed on October 19, 2010.

ESRI. 2002. Getting started with ArcGIS 8.0. ISBN 1-58948-061-9.

Finlay, P. N. 1994. Introducing decision support systems; 2nd ed., Oxford, UK: NCC Blackwell; Cambridge, Mass., USA: Blackwell Publishers, c1994. 274 p. ISBN 1855543142.

Forbes, J.E., 1996. Bird Strikes. Reducing the chance of disaster. Airports North America, 14–15.

Fort, J. and V. Mendez. 2002. Wavefronts in time-delayed reaction–diffusion systems. Theory and comparison to experiment. *Rep. Prog. Phys.,* **65**:895–954.

French, L. and J. Parkhurst. 2001. Managing wildlife damage: Canada goose (Branta Canadensis). Virginia Cooperative Extension 420-203. Available online at http://www.ext.vt.edu/pubs/wildlife/420-203/420-203.html. Accessed on October 19, 2010.

Gardner, C.L., J.W. Jerome and D.J. Rose. 1989. Numerical Method for the Hydrodynamic Device Model: Subsonic Flow. IEEE Transactions on Computer-Aided Design, 8(5)xxx-yyy.

Garvie, M.R. 2007. Finite-Difference Schemes for Reaction–Diffusion Equations Modeling Predator–Prey Interactions in MATLAB. *Bulletin of Mathematical Biology*, 69(2007):931–956.

Georgiou. 2005. Hydro-ecological modeling of Lower Mississipi River, *Proc. of the 14th Biennial Coastal Zone Conf., New Orleans, Louisiana July 17 to 21, 2005*. Available online at http://www.csc.noaa.gov/cz/CZ05_Proceedings/pdf%20files/posters/Meselhe-hydro.pdf. Accessed on October 19, 2010.

Georgoussis, H., C. Babajimopoulos, A. Panoras, G. Arampatzis, E. Hatzigiannakis, A. Ilias and D. Papamichail. 2009. Regional scale irrigation scheduling using a mathematical model and GIS. *Desalination, 237(1-3):*108-116.

Giaccari, L. 2009. Structured Triangular Mesh Generation. MATLAB Central. Available online at http://www.mathworks.com/matlabcentral/fileexchange/23916-structured-triangular-mesh-generation. Accessed on October 19, 2010.

Gómez-Revuelto, L. E. García-Castillo, D. Pardo and L. F. Demkowicz. 2007. A Two-Dimensional Self-Adaptive hp Finite Element Method for the Analysis of Open Region Problems in Electromagnetics I. *IEEE Transaction on Magnetics*. 43(4):1337-1340.

Goss-Custard, D. John, N.H.K. Burton, N.A. Clark, P.N. Ferns, S. McGrorty, C. J. Reading, M.M. Rehfisch, R. A. Stillman, I. Townend, A.D. West and D. H. Worrall. 2006. Test of a behavior-based Individual-based model: Response of shorebird mortality to habitat loss. *Ecol. Appl.*, 16:2215–2222

Graham, G. 2003. Expert Systems for Marine Oil Spill Response Operations. *Proceedings*, Georgia Basin/Puget Sound Research Conference, March 31 – April 3, Vancouver, BC, Canada, 5pp.

Granholm, S. 1990. Canada geese: Distribution, Abundance, and Seasonality. CWHRS, CDFG, CIWTG. Available online at rm.dfg.ca.gov/FileHandler.ashx?DocumentVersionID=17613. Accessed on October 19, 2010.

Greer, J. and D. Terlizzi. 1999. Exotics in the Chesapeake: An Introduction. Understanding species invasions. Fact sheet 1. Maryland Sea Grant, Publication UM-SGEP-99-01, 4 pp.

Grimm, V. and S. F. Railsback. 2005. Individual-based modeling and ecology. Published by Princeton University Press, 41, William Street, Princeton, New Jersey 08540. Available online at http://press.princeton.edu/chapters/s8108.pdf. Accessed on October 19, 2010.

Gudla, P.R. 2005. Texture-based segmentation and finite element mesh generation for heterogeneous biological image data. PhD Dissertation, University of Maryland College Park. College Park, MD.

Gudla, P.R., H.J. Montas, H. Samet and A. Shirmohammadi. 2001. Quadtree-Based Triangular Mesh Generation for Finite Element Analysis of Heterogeneous Spatial Data. *Paper Number: 01-3072 w*ritten for presentation at the 2001 ASAE Annual International Meeting sponsored by ASAE, Sacramento Convention Center, Sacramento, CA.

Hammerschlag, R.S., A. H. Baldwin, C.C. Krafft, J. S. Hatfield, M. M. Paul, K.D. Brittingham and K.D. Brittingham. 2002. Year 3 Annual Reports For the Kingman Monitoring Project, USGS Patuxent Wildlife Research Center, Laurel, MD.

Hammerschlag, R.S., C. C. Krafft, M. M. Paul and K. Phyillaier. 2000. First Year Annual Report for the Kingman Marsh Monitoring Project, USGS Patuxent Wildlife Research Center, Laurel, MD. Available online at http://www.pwrc.usgs.gov/resshow/hammerschlag/Kingman%202000%20Annual%20Report.pdf. Accessed on October 19, 2010.

Hanna, K.N. 2006. Integrated economic decision support system model for determining irrigation application and projected agricultural water demand on a watershed scale. PhD Dissertation, University of Maryland College Park, College Park, MD.

Harbaugh, A.W., E.R. Banta, M.C. Hill and M.G. McDonald. 2000. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model-User Guide to Modularization Concepts and the Ground-Water Flow Process. Available online at http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-92.pdf . Accessed on October 19, 2010.

Harris, Hannah B. 2002. The impact of resident Canada geese on wetlands restoration, and an evaluation of available mitigation techniques. Technical Report Prepared for the *Anacostia Watershed Society*. *Anacostia Watershed Soc.*, Bladensburg, Maryland. 43 pp.

Hastings, A. 1996. Model of spatial spread: a synthesis. Biol. Cons. 78:143-148.

He, C., C. Shi, C. Yang and B.P. Agosti. 2001. A Window-based GIS-AGNPS interface. The *J. of American Water Res. Ass., 37(2):XXX-YYY*.

Hellweger, F. L. 2008. Spatially explicit individual-based modeling using a fixed super-individual density. *Computers and Geosc. 34(2):144-152*.

Heusmann, H.W. 1999. Special hunting seasons and resident Canada goose populations. Wildlife Soc. Bull. 27: 456-464.

Hiebeler, D. 1994. The Swarm simulation system and Individual-based modeling. Paper presented at and to appear in the proceedings of Decision Support 2001: Advanced Technology for Natural Resource Management, Toronto, Canada.

Higgins, S. and S. Guinn. 2009. Options for controlling Canada geese. Cooperative Extension Service, Univ. of Kentucky. Available online at http://www.ca.uky.edu/agc/pubs/id/id174/id174.pdf . Accessed on October 19, 2010.

Hodder, A.I. Houston, A. Lang and J. Webb. 2000. Spatially explicit, individual-based, behavioural models of the annual cycle of two migratory goose populations. The J. of *Appl. Ecol. 37:103-135*

Holsapple, C. and A.B. Whinston. 1996. Decision Support Systems. A knowledge-based approach; Course Technology Cambridge, MA; ISBN 0-314-06972-0.

Hooten, M. and C. Wikle. 2008. A hierarchical Bayesian nonlinear spatio-temporal model for the spread of invasive species with application to the Eurasian Collared-Dove. *Env. and Ecol. Stat*., 15:59–70.

HR (House of Representatives). 2005. A Bill to establish marine and freshwater research, development, and demonstration programs to support efforts to prevent, control, and eradicate invasive species, as well as to educate citizens and stakeholders and restore ecosystems. *109th Congress, 1st Session, H.R. 1592.* 25 pp.

Hutchinson, B. 2010. USDA Wildlife Canada Goose Mitigation. News Center. Available online at http://www.gocho.com/airport/news/usda-wildlife-canada-goose-mitigation. Accessed on October 19, 2010.

Jorgensen, E. and A.R. Kristensen. 1995. An Object Oriented Simulation Model of a Pig Herd with Emphasis on Information Flow. In: FACTs 95 March 7, 8, 9, 1995, Orlando, Fl. *Farm An. Comp. Tech. Conf.*, Pp. 206-215.

Joshi R.C., E.C. Martin, T. Wada and L.S. Sebastian. 2005a. Role of the golden apple snail in organic rice cultivation and weed management; In: Proceedings of the Conference on "Researching Sustainable Systems," 15th IFOAM World Organic Congress, 21-23 Sep 2005, Adelaide, Australia. Pp. 112-115.

Joshi, R.C., K.M. Meepagala, G. Sturtz, A.G. Cagauan, C.O. Mendoza, F.E. Dayan and S.O. Duke. 2005b. Molluscicidal activity of vulgarone B from Artemisia douglasiana Besser to the invasive, alien mollusc pest, Pomacea canaliculata Lamarck, 21-23 Sep 2005, Adelaide, Australia. Pp. 112-115.

Kaur, Jagjit; DePinto, Joseph V.; Bierman, Victor J.; Feist, Timothy J. 2004. Modeling ecosystem changes caused by Zebra Mussel invasion in Saginaw Bay, Lake Huron. Proceedings of Water Env. Fed., Watershed 2004, pp. 491-506(16).

Keitt, T.H., M.A. Lewis and R.D. Holt. 2001. Allee Effects, Invasion Pinning, and Species Borders. *The American Naturalist, 157(2):203-216.*

Kilgore, J.L. 1997. Development and evaluation of a GIS-based spatially distributed unit hydrograph model. MSc. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Kooijman, S. A. L. M. 2000. Dynamic Energy and Mass Budgets in Biological Systems (2nd ed.). Cambridge University Press, Great Britain, ISBN 0-521-78608-8.

Kreft, J., G. Booth and J.W.T. Wimpenny. 1998. BacSim, a simulator for individual-based modelling of bacterial colony growth. *Microbiology* 144:3275-3287.

Krol, O., N. Weiss, T. Bernard and F. Sawo. 2009. Including Expert Knowledge in Finite Element Models by Means of Fuzzy Based Parameter Estimation *Proceedings of the COMSOL Conference,* Milano 14 – 16 October 2009. 12 pp.

Letcher, B. H., J.A. Priddy, J.R. Walters and L.B. Crowder. 1998. An individual-based, spatially-explicit simulation model of the population dynamics of the endangered red-cockaded woodpecker (*Picoides borealis*). *Biol. Cons., 86(1):1-14.*

Liebhold, A. 2000. Detection and monitoring of invasive species. USDA APHIS FS CPHST, *Tech. Bull*., Plant Health Conference Raleigh, NC, Oct. 24-25, 2000.

Lien, R. 2000. Urban Wildlife: Urban Canada goose management in Wisconsin; Wisconsin Urban and Community Forests, DNR Forestry Division, Newsletter 8(2):XXX-YYY.

Limno-Tech. 2002. Descriptive Inventory of Models with Prospective Relevance to Ecological Impacts of Water Withdrawals. *Technical Report*, October 14, 2002.

Lui, R. 1989. Biological growth and spread modeled by systems of recursions. II Biological theory; Mathematical Bioscences, 93:297-312.

Mack, R. N., D. Simberloff, W.M. Lonsdale, H. Evans, M. Clout and F.A. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences and control. *Ecol. Appl., 10:689–710.*

Malecki, R. E., and R. A. Trost. 1990. A breeding ground survey of Atlantic flyway Canada geese in northern Québec. *Can. Field Nat.*, 104:575-578

Malthus, T. 1798. An Essay on the Principle of Population. Printed for J. Johnson, in St. Paul's Church-Yard, 1998, Electronic Scholarly Publishing Project. Available online at *http://www.esp.org/books/malthus/population/malthus.pdf.* Accessed on October 19, 2010.

Mansingh, G., H. Reichgelt and K.O. Bryson. 2007. CPEST: An expert system for the management of pests and diseases in the Jamaican coffee industry. *Exp. Syst. with Appl*. 32(1):184-192.

Marakas, G. M. 1999. Decision support systems in the twenty-first century. Upper Saddle River, N.J., Prentice Hall. Available online at http://diuf.unifr.ch/ds/courses/dss2002/pdf/DSS.pdf. Accessed on October 19, 2010.

Martha, L.F. 1997. Volume Contouring of Generic Unstructures Meshes. *J. of Braz. Comp. Soc.,* 3(3):43-51 ISSN 0104-6500.

MCB (Maryland Coastal Bays). 2009. Invasive species. Available online at http://www.mdcoastalbays.org/bayissues-invasive-species. Accessed on October 19, 2010.

McCann, K. and P. Yodzis. 1994. Biological Conditions for Chaos in a Three-Species Food Chain. *Ecol. 75(2),* pp. 561-564.

MCD (Missouri Conservation Department). 2002. Controlling Conflicts with Urban Canada Geese in Missouri. Available online at http://mdc4.mdc.mo.gov/Documents/255.pdf. Accessed on October 19, 2010.

MCE (Maryland Cooperative Extension). 2003. Canada Geese. Fact Sheet 612, UMCP-Eastern Shore. Available online at http://extension.umd.edu/publications/pdfs/fs612.pdf. Accessed on October 19, 2010.

McKindley-Ward, S. 2006. The Anacostia Goose Situation: Questions and Answers. Selected article, Anacostia Watershed Society, Bladensberg, MD.

MD DNR (Maryland Department of Natural Resources). 2010. Maryland Migratory Game Bird Hunting Seasons 2009-2010; Pub. 03-7142009-404. Available online at http://www.dnr.state.md.us/huntersguide/pdfs/MGB_Flier_2009_2010.pdf. Accessed on October 19, 2010.

MD DNR (Maryland Department of Natural Resources). 1999. When Resident Geese Become A Problem. Press release available online at www.dnr.state.md.us/dnrnews/pressrelease/33099goose.html. Accessed on October 19, 2010.

MDNRE (Michigan Department of Natural Resource and Environment). 2010. Canada Geese, selected article. Available online at http://www.michigan.gov/dnr/0,1607,7-153-10370_12145_25065-59467--,00.html. Accessed on October 19, 2010.

Merland, R. 2008. Model generation and interpretation. Nancy-Université, France. Available online at http://www.gocad.org/www/studentchapter/Data/Images/romain_voronoi.png. Accessed on October 19, 2010.

Meselhe, E.A., E. Habib, A.G. Griborio, S. Gautam, J.A. McCorquodale, I. Y. MGS (Maryland Geological Survey). 2001. A brief description of geology of Maryland. State of Maryland DNR. Available online at www.mgs.md.gov/esic/brochures/mdgeology.html. Accessed on October 19, 2010.

Miller G. T. 2004. Sustaining the Earth (6th ed.). Thompson Learning, Inc. Pacific Grove, California. Chapter 9, Pp. 211-216

MISC (Maryland Invasive Species Council). 2005. Resident Canada Goose is the Invader of the Month. *News Release,* Oct 21, 2005. http://www.mda.state.md.us/article.php?i=1564 Available online at http://www.mda.state.md.us/article.php?i=156. Accessed on October 19, 2010.

MISC (Maryland Invasive Species of Concern). 2003. Invasive Species of Concern. Available online at http://www.hgic.umd.edu/_media/documents/publications/misc1.pdf. Accessed on October 19, 2010.

Molnar, A. 1990. The influence of high temperature on food intake and transformation of geese during the laying period. *Bull. of the Univ. of agr. Sci.*, Godollo, Hungary. Pp 105-111.

Montas, H.J. 2004. Nonpoint Source Pollution Control (in Transition towards: Spatial Control of Biological Agents). Course ENBE 633, spring 2004. University of Maryland College Park. College Park, MD.

Montas, H.J. 2003. FEM implementation: The flexibility of a high-level language approach. ASAE Paper No. 033100. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA.

Montas, H.J. 1990. A Decision Support System for soil conservation planning. M.Sc. These, McGill University, Montreal, Canada. Available online at http://webpages.mcgill.ca/staff/deptshare/FAES/066-Bioresource/Theses/theses/133HubertMontas1990/133HubertMontas1990.pdf. Accessed on October 19, 2010.

Montas, H.J. and C.A. Madramootoo. 1992. A Decision Support System for Soil Conservation Planning. *Comput. Electron. Agr*., 7:187−202.

Montas, H.J. and C.A. Madramootoo. 1989. Use of Expert System to select soil conservation practices. American Society of Agricultural Engineering and the Canadian Society of Agricultural Engineering (CSAE/SCGR), Quebec, June 25-28, 1989. Quebec, Canada.

Montas, H.J., A.P. Nejadhashemi, E.R. Turner and A. Shirmohammadi. 2003. Evaluation of a Decision Support System for Phosphorus Management at the Watershed Scale. ASAE Annual International Meeting, Las Vegas, Nevada, USA.

Montas, H.J., A. Shirmohammadi, J. S. Butler, T. W. Chu, P. Okelo and A. M. Sexton, 1999a. Decision Support for Precise BMP Selection in Maryland. . ASAE Paper No. 993049 presented at the ASAE/CSAE-SCGR Annual International Meeting, July 18-21, 1999, Toronto, Ontario Canada. ASAE, St.-Joseph, MI, 49085.

Montas, H.J., A. Shirmohammadi, P. Okelo, A. M. Sexton, J. S. Butler, and T. W. Chu, 1999b. Targeting Agrichemical Export Hotspots in Maryland using Hydromod and GIS. ASAE Paper No. 993123 presented at the ASAE/CSAE-SCGR Annual International Meeting, July 18-21, 1999, Toronto, Ontario Canada. ASAE, St.-Joseph, MI, 49085.

Mulatu, H. 2006. Land covers change detection using expert system and hyperspectral imagery in the Islands of Schiermonnikoog, The Netherlands. Msc. Thesis, Intern'l. Inst. for Geo-Informatic Sc. And Earth Observ. (ITC). Enschede, The Netherlands.

Murray, J.D. 2002. Mathematical Biology: I. An Introduction, Third Ed. Interdisciplinary Applied Mathematics, vol. 17. Springer, NY. ISBN 0-387-95223-3

Murray, J.D. 1989. Mathematical Biology. Springer Verlag. Pp. xiv + 767, Berlin.

Murty, K.G. 2005. Optimization Models for Decision-making; Junior Level Self-Teaching Web-Book, vol. 1, Department of Industrial and Operations Engineering University of Michigan, Ann Arbor, MI-48109-2117, USA.

Murua, G. and E., Virla. 2004. Population parameters of *spodoptera frugiperda* (Smith) (Lepnoctuidae) fed on corn and two predominant grasses. *Acta Zoologica Mexcicana (n.s.) 20(1): 199-210*

MWCG (Metropolitan Washington Council of Government). 2009. Anacostia River Hydrography. Available online at www.anacostia.net/history/hydrology.html. Accessed on October 19, 2010.

Narasimhan, T.N. 2004. Fick's Insights on Liquid Diffusion; *Eos, 85(47).* Available online at http://www.olemiss.edu/sciencenet/saltnet/fick_insights_EOS.pdf. Accessed on October 19, 2010.

Nejadhashemi, A.P., E.R. Turner, H.J. Montas, A. Shirmohammadi. 2003. Evaluation of a Decision Support System for Phosphorus Management at the Watershed Scale. ASAE Annual International Meeting, Las Vegas, Nevada, USA.

Neter, J., W. Wasserman and M. H. Kutner. 1990. Applied Linear Statistical Models. IRWIN, Boston, MA.

Neubert, M.G. and Parker, I.M. 2004. Projecting Rates of Spread for Invasive Species. Risk Analysis, 24(4):XXX-YYY.

Newell S.Y. and R. E. Hicks. 1982. Direct-count estimates of fungal and bacterial biovolume in dead leaves of smooth cordgrass (*Spartina alterniflora* Loisel) Estuaries, 5(4):246-260.

NOAA (National Oceanic Atmospheric Administration). 2007. NOAA Damage Assessment, Remediation, and Restoration Program. Anacostia River Watershed Database and Mapping Project. Web-based article, last updated: February 2, 2007. Accessed on October 20, 2010. http://mapping2.orr.noaa.gov/portal/AnacostiaRiver/envsetting_landuse.html

NOAA (National Oceanic Atmospheric Administration). 2004. Climatology of the United States No. 20:1971-2000. Available online at www.ncdc.noaa.gov/normals.html. Accessed on October 19, 2010.

NPS (National Park Service). 2010. Anacostia. Web-based article, last updated: February 17, 2010. Available online at http://www.nps.gov/anac/index.htm. Accessed on October 19, 2010.

Nyerges, T.L. 1993. Understanding the scope of GIS: Its relationship to environmental modeling. In Goodchild, M.F., Parks, B.O. and Steyaert, L.T. (eds.), *Environmental Modeling with GIS*, p. 75-93. Oxford Univ. Press, 488 p.

Okubo, A. 1980. Diffusion and ecological problems: mathematical models: *Biomathematics*, v. 10. Springer-Verlag, NY.

Okuma M., Y. Fukushima and K. Tanaka. 1994a. Feeding habitat of apple snail

Partington, G. 2001. Qualitative research interviews: Identifying problems in technique. *Issues In Educational Research, 11(2001):XXX-YYY..*

Pettifor, R.A., R.W.G. Caldow, J.M. Rowcliffe, J.D. Goss-Custard, J.M. Black, K.H. Pimentel, D., L. Lach, R. Zuniga and D. Morrison. 2000. Environmental and Economic Costs of Nonindigenous Species in the United States. American Institute of Biological Sciences - *Bioscience* 50(1): 53-65.

Pimentel, D., S. McNair and J. Janecka. 2001. Economic and environmental threats of aliens plant, animal, and microbe invasions. *Agric., Ecos., and Env*. 84 (1):1-20.

Pinto, G. R. M., K.M. P. Micchi de Barros Ferraz, H. T. Zarate do Couto and L. M. Verdade. 2006. Detectability of capybaras in forested habitats. *Biota Neotropica*, 6(1). Available online at http://www.biotaneotropica.org.br/v6n1/pt/fullpaper?bn01906012006+en. Accessed on October 19, 2010.

Pomykalski, J. J., W.F. Truszkowski, and D.E. Brown. 1999. Expert System. Wiley Encyclopedia for Electrical and Electronics Engineering. J. Webster (Editor). Available online at http://agents.gsfc.nasa.gov/papers/pdf/es.pdf. Accessed on October 19, 2010.

Power, D.J. 2007. A Brief History of Decision Support Systems. Version 4.0. Available online at http://DSSResources.com/history/dsshistory.html. Accessed on October 19, 2010.

Preuss, T.G., M. Hammers-Wirtz, U. Hommen, M.N. Rubach and H. T. Ratte. 2009. Development and validation of an individual based *Daphnia magna* population model: The influence of crowding on population dynamics. *Ecol. Modelling, 220(3):310-329.*

Prins, H.H.T. and R.C. Ydenberg. 1985. Vegetation growth and seasonal habitat shift of the barnacle goose Brenta leucopsis. *Oecologia 66:122-125.*

Ratanov, N. 2004. Reaction–advection random motions in homogeneous media. *Physica D: Nonlinear phenomena, 189(1-2):130-140.*

Ray, G. 2005. Invasive animal species in marine and estuarine environments: Biology and Ecology. Environmental Laboratory, Aquatic Nuisance Species Research Program, U.S. Corps of Engineers, ERDC/EL TR-05-2.

Rejmanek, M. 1989. Invasibility of plant communities. Pages 369-383 *in* J. A. Drake, H. A. Mooney, F. di Castri, R. H. Groves, F. J. Kruger, M. Rejmanek, and M. Williamson, editors; *Biological invasions: a global perspective*, SCOPE 37; John Wiley, New York, New York, USA.

Reynolds, C.1999. Individual-Based Models. Available online at http://www.red3d.com/cwr/ibm.html. Accessed on Oct. 19, 2010.

Riddington, R., M. Hassall and S. J. Lane. 1997. The selection of grass swards by brent geese *Branta b. bernicla*: Interactions between food quality and quantity. *Biol. Cons. 81(1-2):153-160*.

Rogers, S.M.D., M.L. Dahmer and D.W. Stair. 1993. Characterization of Buffelgrass (*Cenchrus ciliaris* L.) Cell Suspension Cultures. *In Vitro Cell. Dev. Biol. 29:51-54.*

Rowcliffe, J.M., A.R.Watkinson and W.J. Sutherland. 2001. The depletion of algal beds by geese: a predictive model and test. *Oecologia 127:361-371*.

Sadegh Zadeh, K., H.C. Elman, H.J. Montas and A.Shirmohammadi. 2007. A finite element model for protein transport in vivo. *Biomed Eng Online*, 6: 24.

Salomon, J. A. and C.J.L. Murray. 2001. Modelling HIV/AIDS epidemics in sub-Saharan Africa using seroprevalence data from antenatal clinics. *Bull. of the WHO, 79 (7), Ref. No. 99-0139.*

Sapoukhina, N., Y. Tyutyunov and R. Arditi, 2003. The role of prey taxis in biological control: A spatial theoretical model. *The American Naturalist, 162(1):61-76.*

Schlossberg, M. 2006. Nitrogen fertilization of putting greens cohabited by Penn "A-4" creeping bentgrass and annual bluegrass. Pennsylvanya Turfgrass Council Annual Report, Penn State University. 5 pp. Online access on Oct. 19, 2010 at http://cropsoil.psu.edu/turf/research/annual-reports/2005/schlossberg1.pdf

Shigesada, N. and Kawasaki, K. 1997. Biological invasion: Theory and Practice (1st eds.), Oxford, UL: Oxford University Press, USA.

Spahr, S. L., L. R. Jones and D. E. Dill.1988. Expert Systems - Their Use in Dairy Herd Management. *Journal of Dairy Sci* 71:879-885.

Starfield, A.M. and A.L. Bleloch. 1991. Building Models for Conservation and Wildlife Management. Second edition, The Burgess Press, Edina, Minnesota.

Stewart, R.E. 2009. Technical Aspects of Wetlands: Wetlands as bird habitats. USGS *Water Supply Paper 2425*. Available online at http://water.usgs.gov/nwsum/WSP2425/birdhabitat.html. Accessed on October 19, 2010.

Stewart, R. M. and W. A. Boyd. 1999. The Grass Carp Stocking Rate Model *Aquatic Plant Control Technical Note MI-03*. Available online at http://el.erdc.usace.army.mil/elpubs/pdf/apcmi-03.pdf. Accessed on October 19, 2010.

Stockwell. D.R.B.1993. LBS: Bayesian learning system for rapid expert system development; *Expert Systems with Applications, 6(2):137-147*.

Sui, G., M. Fan, I. Loladze and Y. Kuang. 2007. The dynamics of a stoichiometric plant-herbivore model and its discrete analog. *Math. Bio. And eng. 41 (1): 20-46.*

Takafuji, A., E. Kuno and H. Fujimoto. 1997. Reproductive interference and its Consequences for the competitive interactions between two closely related *Panonychus spider* mites. *Experimental and Applied Acarolog*y, 21:379-391.

Teague, J., L. Sneddon, R. Simmons, J. Parrish, M. Tice and M. Strong. 2006. Upper Anacostia Watershed Plant Communities of Conservation Significance. NatureServe, Arlington, Virginia. Available online at http://www.natureserve.org/library/Upper_Anacostia_Plant_Communities_Final_Report.pdf. Accessed on October 19, 2010.

Titchenell, M.A. and W.E. Lynch Jr. 2010. Coping with Canada geese: Conflict management and damage prevention strategies; The Ohio State University Agricultural and Natural Resources Fact Sheet W-3-10, Pp.8. Available online at http://ohioline.osu.edu/w-fact/pdf/0003.pdf. Accessed on October 19, 2010.

Torchin, M.E., K.D. Lafferty, A.P. Dobson, V.J. McKenzie and A.M. Kuris. 2003. Introduced species and their missing parasites. *Nature 421: 628-630.*

Tronstad, R., R. Gum, D. Ray and R. Rice. 1993. Range Cow Culling: Herd Performance. In *Arizona Ranchers' Management Guide*, eds., R. Tronstad, J. Sprinkle, and G.

Ruyle, pp. 27S31. *Pub. No. AZ1279, Coop. Ext. Ser.*, University of Arizona. Available online at http://ag.arizona.edu/arec/pubs/rmg/ranchers.html. Accessed on October 19, 2010.

Turban, E. 1995. Decision support and expert systems : Management Support Systems. Englewood Cliffs, N.J., Prentice Hall.

Turchin, M.E., K.D. Lafferty, A.P. Dobson, V.J. McKenzie and A.M. Kuris. 2003. Introduced species and their missing parasites. *Nature* 421: 628-630.

Turner, M.G., Y. Wu, L.L. Wallace, W.H. Romme and A. Brenkert. 1994. Simulating Winter Interactions Among Ungulates, Vegetation, and Fire in Northern Yellowstone Park. *Ecological Applications*, 4(3):472-496.

USDA APHIS. 2010. National Invasive Species Information Center Online publication, last update: June 24, 2010. Available online at http://www.invasivespeciesinfo.gov/animals/main.shtml. Accessed on October 19, 2010.

USDA APHIS. 2009. Maryland State summary of top ten species calls Wildlife Services received by County or jurisdiction. Appendix A and B (1998-2008), Annapolis, MD.

USDA APHIS WS. 2009. Management of Canada goose nesting. Selected article, Available online at http://www.aphis.usda.gov/wildlife_damage/downloads/canada_goose.pdf. Accessed on October 19, 2010.

USFWS. 2009. Draft Environmental Impact Statement: Resident Canada Goose Management. Available online at http://www.fws.gov/migratorybirds/CurrentBirdIssues/Management/cangeese/finaleis.htm. Accessed on October 19, 2010.

Vakeva, J. and H. Saarenmaa. 1992. A rule-based expert system for the diagnosis of biotic damage on *Pinus sylvestris.* Scandinavian *Jr. of forest research, 7(1-4):533 – 546.*

Vandermeer, J.H. and D.H. Boucher. 1978. Varieties of Mutualistic Interaction in Population Models. *J. theor. Biol. 74:549-558.*

Van Langevelde, F., M. Drescher, I.M.A. Heitkonig and H.T. Prins. 2008. Instantaneous intake rate of herbivores as function of forage quality and mass: effects on facilitative and competitive interactions. *Ecol. Modelling* 213:273-284

Van Oene, H., E. J. M. Van Deursen, and F. Berendse. 1999. Plant-Herbivore Interaction and Its Consequences for Succession inWetland Ecosystems: A Modeling Approach. Ecosystems (1999) 2: 122–138.

Vickery, J.A., W.J. Sutherland, A.R. Watkinson, S.J. Lane and J.M. Rowcliffe. 1995. Habitat switching by dark-bellied brent geese Brenta b. bernicla (L.) in relation to food depletion. *Oecologia* 103:499-508.

Volpert, A.I., V.A. Volpert and Vl. A. Volpert. 1994. Traveling wave solutions of parabolic systems. Translations of Mathematical Monographs, 140. *American Mathematical Society*, Providence, RI, 1994, pp. xii+448. Available online at http://www.ams.org/online_bks/mmono140/mmono140.pdf. Accessed on October 19, 2010.

Wada T, Joshi RC, Yusa Y. 2002. Experiences of Japanese rice farmers with apple snail, Pomacea canaliculata (Lamarck) for paddy weeding in transplanted rice: a video documentation. Paper presented at the Seventh International Congress of Medical and Applied Malacology, 21-24 Oct 2001, Los Baños, Laguña, Philippines. 22 p.

Wangersky, P.J. 1978. Lotka-Volterra population models. *Ann. Rev. Ecol. Syst., 9:189-218*. Available online at http://www.annualreviews.org/doi/pdf/10.1146/annurev.es.09.110178.001201. Accessed on October 19, 2010.

Warren, P.L. 1999. Virginia Integrated Pest Management Expert for Wheat. M.S. Thesis, Virginia Tech, Blacksburg, Virginia

Watson, B. M. 2005. Washington areas winters: snow, wind, ice and cold. NOAA, National Weather Service Forecast Office, December 30, 2005. Available online at http://www.erh.noaa.gov/er/lwx/Historic_Events/va-winters.htm. Accessed on October 19, 2010.

WHO (World Health Organization). 2009. Pandemic (H1N1) 2009 - update 78. Available online at http://www.who.int/csr/don/2009_12_11a/en/index.html. Accessed on October 19, 2010.

WHO (World Health Organization). 2003. Severe acute respiratory syndrome (SARS): Status of the outbreak and lessons for the immediate future. Available online at http://www.who.int/csr/media/sars_wha.pdf. Accessed on October 19, 2010.

Wilcove, D.S., D. Rothstein and J. Dubow. 1998. Quantifying threats to imperiled species in the United States; *Bioscience* 48 (8), 607-615.

Wilson, W.G. 1998. Resolving discrepancies between deterministic population models and individual-based simulations. *Am. Nat*. 151(2):116-34.

Wolfe, L. M. 2002. Why alien invaders succeed: support for the escape-fromenemy hypothesis. *Am. Nat.160, 705-711.*

Woodruff, R.A. and J.S. Green. 1996. Livestock herding dogs: a unique application for wildlife damage management. Pp. 43-45 in R.E. Masters and J.G. Huggins, eds. Twelft Great Plains Wildlife Damage Control Workshop Proceedings published by Noble Foundation, Ardmore, Oklahoma.

Xiao, H. 2003. An integrated GIS-AnnAGNPS modeling interface for nonpoint source pollution assessment. *Proceedings of the 23rd Annual ESRI international GIS* User Conference, July 7-11, 2003, San Diego, CA, USA. Available online at http://gis.esri.com/library/userconf/proc03/index.html.

Xu, Q. and B. Huang. 2001. Lowering soil temperatures improves creeping bentgrass growth under heat stress. *Crop and sc.* 41:1878-1883.

Ydenberg, R.C. and H.H.T Prins. 1981. Spring grazing and manipulation of food quality by Barnacle geese; *J. Appl. Ecol.*18: 443-453. Body size and consumer-resource dynamics *Am. Nat. 139:1151-1175.*