Final Report - December 2006

SERDP Sustainable Infrastructure

Project Number 1259

A Regional Simulation to Explore Impacts of Resource Use and Constraints

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14. ABSTRACT
The Regional Simulator (RSim), designed to integrate land-use changes with ecological effects of changes in noise, water and air quality and species of special concern and their habitats. RSim projects land-use changes, its impacts for the five counties in Georgia surrounding and including Fort Benning, is applicable to other regions and a diversity of resource managers. Data layers that are widely available are being used in the model. Four scenarios implemented: urban growth, road-influenced urbanization, a new military training area, and hurricane impacts. Projections from the various scenarios suggest that urban growth will continue along the northern border of Fort Benning and may have impacts on noise, water, and air quality. Declines in habitat of gopher tortoise as a likely result of land-use changes because urban growth and other land-use changes are highly likely on lands that now provide this habitat. Habitat for red cockaded woodpecker is not likely to be affected by projected land-cover changes under the urban growth and new military training scenarios because most of the limited habitat remaining for this species is under federal protection.

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RSim Final Report – 2006
SERDP Conservation project 1259

Table of Contents

Final Report - December 2006

SERDP Conservation CSSON-01-03

A Regional Simulation to Explore Impacts of Resource Use and Constraints
Project Number 1259
http://www.esd.ornl.gov/programs/SERDP/RSim/index.html

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Overview

The goal of this project was to design computer simulation model, the Regional Simulator (RSim), which integrates land-use changes with ecological effects of changes in noise, water and air quality and species of special concern and their habitats. RSim projects land-use changes and its impacts for the five counties in Georgia surrounding and including Fort Benning and is applicable to other regions and a diversity of resource managers. Data layers that are widely available are being used in the model. Four scenarios have been implemented. (A) The urban growth submodel in RSim consists of spontaneous growth of new urban areas and patch growth (growth of preexisting urban patches). (B) The road-influenced urbanization submodel focuses growth on areas near existing and new roads by considering the proximity of major roads to newly urbanized areas. (C) The new digital multipurpose range complex (DMPRC) at Fort Benning is an example of the pressures that are now being placed on military land for more use. (D) Spatially explicit impacts of a hurricane impact from a storm moving northward from the Gulf of Mexico are based on a storm that impacts the South Caroline coastal system. Projections from the various scenarios suggest that urban growth will continue along the northern border of Fort Benning and may have impacts on noise, water, and air quality. Declines in habitat of gopher tortoise as a likely result of land-use changes because urban growth and other land-use changes are highly likely on lands that now provide gopher tortoise habitat. Habitat for red cockaded woodpecker are not likely to be affected by projected land-cover changes under scenarios A, B and C for two reasons: (1) only 3% of the original habitat remains and (2) most of those remaining sites are on federally protected land that is managed for red cockaded woodpecker.

During this year of the project, we worked to place the RSim effort within the context of the region, ongoing military issues, and current theory. We specifically considered RSim in relation to future plans for the five-county region, transboundary issues at military installations, and the ecological theories relating to environmental security, ecological risk, and land use planning. We also began development of a user friendly interface for RSim so that the transfer of the final product will go smoothly and provide a worthwhile technology. This task involved planning by our computer design team and discussions with personal at Fort Benning and The Nature Conservancy. We continue to publish aspects of the work as it is completed, for submitting the work to peer review is the established method to gain scientific credibility necessary to have confidence that the methods are appropriate for resource management

RSim integrates various stressors and receptors through the linkages depicted in Figure 1. Stressors can act directly on receptors (e.g., noise acting on gopher tortoise or ozone acting on pines), or stressors can act indirectly on receptors via their habitat (e.g., ozone acting on red-cockaded woodpecker by adversely affecting pines). Integration can occur at the level of exposure, for example, if there are multiple sources of nitrogen in streams or ozone in air or blast noise. Similarly, the road-based and non-road-based urbanization are integrated in RSim. Or integration can occur at the level of effects (e.g., changes in abundance resulting from multiple causes of habitat removal and fragmentation, or changes in abundance resulting from the multiple stressors of habitat change, noise, and air pollution). Additionally, Figure 2 in "Planning transboundary ecological risk assessments at military installations," Section 10a of this report, depicts how RSim might integrate several stressors that effect pine density, age structure and patch size to estimate changes in the abundance and production of red-cockaded woodpecker.

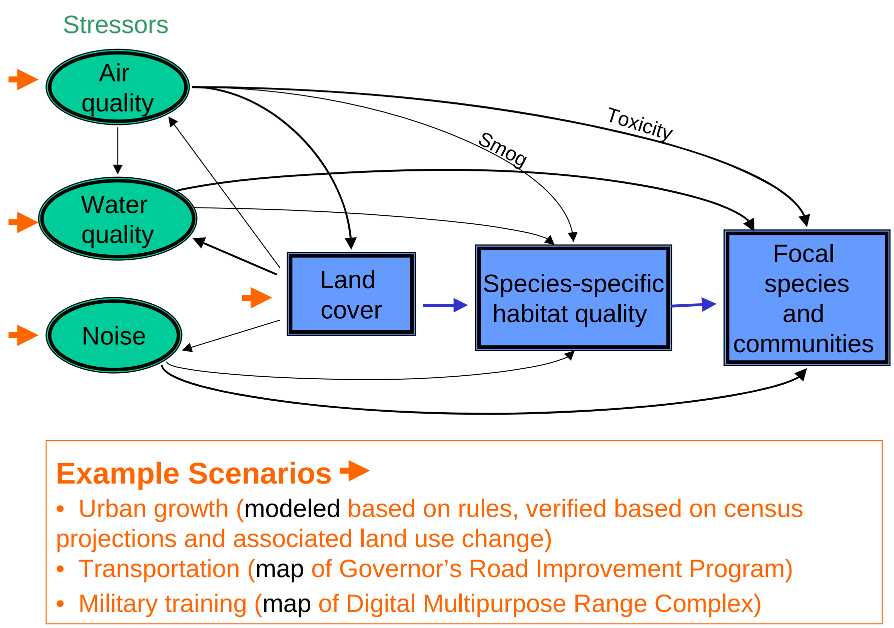

Figure 1. Integrated framework for RSim, showing example scenarios acting on stressors.

Section 2a: Products of RSim Research

November 2006

Summary

Journal articles: 7 (1 in review)
Book chapters and proceedings: 4
Reports: 1
Presentations: 19 (4 in symposia and 4 as plenary lectures)
Posters: 13

Web Site: http://www.esd.ornl.gov/programs/SERDP/RSim/index.html

Publications

Baskaran, L.M., V. H. Dale, and W. Birkhead. 2005. Habitat modeling within a Regional Simulation Model (RSim) environment. Pages 6-16 in the Proceedings of the 4th Southern Forestry and Natural Resource Management GIS Conference, Athens, GA, December 16-17, 2004.

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Theobald, D.M., T. Spies, J. Kline, B. Maxwell, N.T. Hobbs, V.H. Dale. 2005. Ecological support for rural land-use planning and policy. *Ecological Applications* 15(6): 1906-1914.

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Report

Rizy, C.G., D.P. Vogt, and P. Beasley. Economic characterization of RSim counties. ORNL report.

Posters

Aldridge, M. GIScience 2004: Third International Conference on Geographic Information Science, October 20-23, 2004, University of Maryland.

Aldridge, M.L., M.W. Berry, W.W. Hargrove, F.M. Hoffman. Parallelization of a Hoshen-Kopelman Adaptation Using Finite State Machines. Supercomputing 2006. Tampa, Florida, Nov. 11-17, 2006.

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Baskaran, L. Applications of GIS and Remote Sensing: The Regional Simulation Model (RSim) case study. Presentation at the Plateau PC Users Group, Inc in Crossville, TN, October 18, 2004.

Baskaran, L., V. Dale, M. and William Birkhead. Habitat modeling within a Regional Simulation Model (RSim) environment, Fourth Southern Forestry and Natural Resource Management GIS Conference, Athens, GA, December 16-17, 2004.

Chang, M., V. H. Dale, T. Ashwood, L. Baskaran, R. Efroymson, C. Garten, L. Olsen, M. W. Berry, M. Aldridge, and C. Stewart. The challenges in building RSim, a comprehensive resource management model, Presentation at conference on "Emerging Issues Along Urban/Rural Interfaces: Linking Science and Society," Atlanta, Georgia, March 13-16, 2005

Dale, V.H. Ecological Society of America Symposium on Land Use Change, Tucson, AR, August 2002

Dale, V.H. Pardee Symposium at the Geological Society of America, October 27, 2002 in Denver, CO

Dale, V.H. Meeting in Columbus, GA on research in the Fort Benning region, Columbus, GA, October 30, 2002

Dale, V.H. Botany Department, University of Tennessee, Knoxville, TN, November 2002

Dale, V.H. University of Washington, Seattle, WA, March 2003
Dale, V.H. University of Michigan, Ann Arbor, MI, March 2003
Dale, V.H. Keynote presentation for The American Society of Testing and Materials (ASTM International) Biological Effects and Environmental Fate Committee symposium on *Landscape Ecology and Wildlife Habitat Evaluation of Critical information for Ecological Risk Assessment, Land-use Management Activities, and Biodiversity Enhancement Practices.* April 7-9, 2003, Kansas City, KS.
Dale, V.H. Plenary lecture for 34th conference of the Ecological Society of Germany, Austria and Switzerland (GfÖ), Giessen, Germany, September 13-17, 2004
Dale, V.H. School of Agriculture, University of Tennessee, Knoxville, TN, February 2004
Dale, V. Keynote for Fourth Southern Forestry and Natural Resource Management GIS Conference, Athens, GA, December 16-17, 2004
Dale, VH. Plenary speaker for first meeting of the Brazilian Chapter of the International Association for Landscape Ecology, Caxambu, Brazil, November 21, 2005.
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Efroymson, R.A. March 2005. Ecological risk assessment at Oak Ridge National Laboratory. Presentation to students in the Department of Energy's Student Undergraduate Laboratory Internships Program. Oak Ridge National Laboratory, Oak Ridge, TN.

Section 2b Data Requirements for RSim
November 2006

Basic information:

- Land cover – Land cover types at 30 m resolution available from USGS
- Changes in land cover types over time – Land cover data for at least 2 time periods 10 years apart and close to the census periods (e.g., 1980, 1990 or 2000).
- Boundaries of military and other public ownership - available from the state GIS agency or other programs such as the Gap Analysis Program.
- Roads by type (dirt, two-lane, four-lane, interstate) - available from the state GIS agency or the US Census Bureau TIGER data.
- Changes in human population over time - US Census data

Water quality

- Hydrological units (HUCs) - available from USGS
- Region-specific export coefficients for nitrogen and phosphorus from different land cover types -- Some coefficients can be derived from studies already published, but in many cases it would be best to have actual field measurements of N and P exports from watersheds that are dominated by a particular land cover type. So that means measurements and field research similar to what ORNL resaechers have proposed for the watershed management SON at Fort Benning.

Species

- Characterization or location of habitat, foraging area and nesting sites for species of special concern– often this information is better known for rare species than for widely available species.
- Model that identifies habitat for species – Models are available for some rare species (e.g, gopher tortoise, karner blue butterfly, etc.). In cases of widely distributed species, developing such a model may be straight forward. In some case, the habitat to which a species is restricted is not known.

Air quality

- Initial emissions, initial ozone air quality concentrations, and sensitivity coefficients (factors relating changes in air quality concentrations relative to changes in emissions) -- Available from the Fall line Air Quality Study for the entire Eastern United States. Projected changes in future year emissions for all areas are available from the US EPA EGAS4.0 program.

Noise

- Peak noise contours – can be developed for Army installations using SARNAM and BNOISE2. Information needed to run the models include range layouts and operational data. USACHPPM is the tech transfer point for the Army noise models and has already developed Peak noise contours for many of the major Army installations.

Additional stressors of interest

- Fire (both natural and human induced)
- Particulates in air
- Sedimentation
- Invasive species.

Other relevant data

- Soils layers - from the USDA Natural Resources Conservation Service
- Streams data - usually available from the State GIS agency
- Zoning constraints on urbanization, if available

Scenarios

- Type of change
    - Proposed roads and road expansions--often available from state transportation offices
    - Proposed military training and extent--often available from installation.
    - Proposed land purchase or lease by military
    - Proposed environmental regulation
    - Potential disturbance
- Potential impact --often available from the scientific or grey literature. However there is poor documentation of the location, frequency, or intensity of some disturbance (e.g., ice storms).
- Potential extent in application area--can use information from other similar disturbances.

Cost and processing issues:
Most of the listed geographical data sets are inexpensive (there may be a handling charge of $50 or so for some of the data sets based on the state GIS agencies policy of distributing data). However if new data is collected or generated, cost might be an issue. For example if new land-cover data would be needed, the cost of buying satellite data and creating the land-cover classes will be involved. Similarly, there maybe costs for creating the noise contours if the models need to be run at new locations. If field data is needed to be collected, then cost will rise.

The time for collecting geographical data is small and the process is straight forward - that is if data is available (soils, roads, streams, boundaries, basic land cover)! Challenges arise when the appropriate data are not available at the right scale or format.

Section 2c. Coordination with Outside Experts

A formal review of RSim was held on March 16, 2006. A presentation of the model was followed by a live demonstration. Questions and discussion occurred throughout the review, and reviewers were asked to complete an evaluation form.

The reviewers felt that the March version of RSim adequately fulfilled its claim to be able to integrate land-use changes with air quality, water quality, noise and habitat of select species. They anticipated that the final version of RSim (to be completed in the summer of 2006) will do this well. The reviewers were interested in seeing cumulative impacts or other ways to represent the sensitivity of one factor versus others for each output layer.

The reviewers recognize that some modules are further developed than others and that some modules will ultimately be more or less flexible than others. Noise, in particular, is a rather static parameter. They suggested following through on implementation of a burning and forest growth module.

The reviewers thought that the user interface appropriately conveys the information used to project changes and what those changes might be. They suggest that training may be required for uses to learn about the model.

The reviewers thought that RSim will serve as a useful tool for managers to improve their ability to make decisions about resource use and management. One reviewer pointed out that the potential of RSim to be successful now depends upon successful technical transfer and user support.

The reviewers thought that the water quality module in RSim captures changes that might occur over the landscape. This is the most developed module in RSim, and it is very flexible and spatially distributed.

They felt that the air quality module in RSim adequately captures changes that might occur over the landscape. They thought the module was quite detailed and reflects a lot of underlying atmospheric science and chemistry. They appreciated the clever use of off-line intensive model as input to this model.

The reviewers recognized that the noise module in RSim is static and thought that this approach may be totally appropriate for the questions being asked at an annual time step.

The reviewers thought that the red cockaded woodpecker habitat module and the gopher tortoise burrow model seemed to be a good relationship to experimental studies. They suggested that we add the ability to project habitat for trillium even though it is not likely to be as impacted by increased training.

The main suggestion for improving RSim was further development of the user interface. They urged that the next phase of RSim involve input from users (or potential users).

The reviewers identified the key strengths of the RSim approach to be:

a. It gets planners thinking about ecology in more specific terms during comprehensive planning; highly dynamic and responsive to alternative points of view; great for collaborative discussion.'
b. The resolution is incredible
c. It is focused on reasonable number of variables keyed to mission needs and avoids the temptation to develop a universal tool.

Section 2d. Complementarity between RSim and the mLEAM models

WORDING OF ACTION ITEM: In your Final Report, due December 2006, discuss the complementarity between your RSim models and the mLEAM models developed under SERDP project SI-1257 and describe how the two research products can best fit together in a toolkit for DoD land managers. Prepare this portion of your report in coordination with project SI-1257. In this report also include a discussion on how receptive your models will be to different data formats, the degree to which model algorithms have been validated, and what future modeling components may be important to add (for example, the impact of prescribed burns and wildfires on regional air quality).

I. Introduction

This part of the final reportreport discusses the complementarity between the RSim model and the mLEAM models developed under SERDP project SI-1257 and describes how the two research products can best fit together in a toolkit for Department of Defense land managers. The section on complementarity was developed by members of both teams of researchers from SI- 1259 and SI-1257. The report also includes a discussion on how receptive RSim is to different data formats, the degree to which model algorithms have been validated, and what future modeling components may be important to add (for example, the impact of prescribed burns and wildfires on regional air quality).

This report begins with an overview of each of the models as well as a short description of Fort Future, for it may serve as a vehicle for integration. A comparison of end-user delivery approaches of the models is also included, for it points out some of the needs for integration. The report concludes with a section on RSim's data formats, validation and future needs.

II. Complementarity between the RSim model and the mLEAM models

A. Overview of RSim

The Regional Simulator (RSim) is a computer model designed to integrate land-cover changes with effects on noise, water and air quality, and species of special concern and their habitats. The RSim model was developed for the region around Fort Benning, but was designed so that its basic framework can be applied to other military installations and their regions, thus ensuring broad applicability to DoD environmental management concerns. RSim uses nationally available data sets and addresses concerns common to many installations.

Where possible, RSim was built from existing models. Urban growth is based upon the SLEUTH model (Clarke et al. 1998, Clarke and Gaydos 1998, Candos 2002), and transitions for the non-urban land cover are based on change detection of those observed for the five-country region (Baskaran et al. 2006A). The water quality module uses nutrient export coefficients combined with information on the area of different land uses and/or land covers to predict the annual flux of N and P from terrestrial watersheds. The noise module uses GIS data layers of military noise exposure developed by the U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM) as part of the Fort

Benning Installation Environmental Noise Management Plan (IENMP). The Air Quality module estimates the impact of emissions changes on ozone air quality using sensitivity coefficients available the Fall Line Air Quality Study (http://cure.eas.gatech.edu/faqs/index.html). The module that predicts habitat for the gopher tortoise (*Gopherus polyphemus*) was based on analysis of locations of gopher tortoise burrows at Fort Benning and tested for the larger five-country region (Baskaran et al. 2006B). The module predicting habitat for red cockaded woodpecker was based on data from the region.

Numerous future scenarios can be modeled using RSim. These include both civilian and military land-cover changes. RSim includes four specific types of scenarios, along with their impacts on environmental conditions over the next 10 to 40 years: (1) modeled urbanization (conversion of non-urban land cover to low-intensity urban and conversion of low-intensity to high-intensity urban), (2) planned road expansion plus modeled urbanization, (3) a new training area at Fort Benning, and (4) hurricanes of various intensities.

RSim includes a user-friendly interface that also documents the particular components of the model. For example, potential ranges on parameter values are listed and the user is not allowed to enter values that exceed these ranges. Furthermore, the equations and reasoning behind the model are explained. The glossary defines key terms. The use of RSim software involves the following steps:

1. RSim introduction
2. Select scenarios
3. Urban growth model options
4. Land cover transition options
5. Water quality module
6. Air quality module
7. Noise module
8. Species and habitat module
9. Review simulation selections
10. Simulation status
11. Simulation results

As the user moves through the RSim interface, the right part of the screen tracks the current status of the user according to the eleven steps.

Each real-time run of RSim is designed by the users to address their particular needs. The user can choose to include any combination of the modules and change parameter values as well. The code is written in Java with an object-oriented design, and this is not dependent on any particular software and can run on any computer. The spatial resolution is a 30-m pixel and the common temporal resolution across the modules is one year. The interface also provides text, tabular and mapped outputs that the user can save for report development or subsequent analysis.

RSim is intended to be run in learning mode so that users can gain knowledge about potential outcomes of particular decisions and therefore modify decisions and then explore those outcomes. Thus the use and application of RSim are highly related to the users' needs and perspectives.

B. Overview of LEAM

LEAM is short for "Land use Evolution and Impact Assessment Modeling". It is a synthesis of approach and software that allows a regional planning stakeholder community to explore the long-term (20-40) year consequences of proposed regional plans. The LEAM approach has been successfully applied to regions containing Peoria, Illinois; East St. Louis and St. Louis, Missouri; Traverse City, Michigan; and now the Chicago Metropolitan Area extending across Wisconsin, Illinois, and Indiana. It has also been tested with the Fort Benning and Scott Air Force Base communities. Generally speaking, the LEAM approach proceeds as follows:

1. A quick generation of urban growth is completed using nationally available data.
2. Results are presented at a regional planning charrette which then poses the following questions to participants:
    - What is right and what is wrong with the projections?
    - What local data and information is available to replace the national data?
    - What are the perceived encroachment problems/challenges?
    - What are the local drivers to growth?
    - What regional planning ideas should be tested?
3. The LEAM urban growth model is modified, including changes to the source code, to capture the needs identified in the charrette. A 9 or 20 sector economic model is used to project future economic and population growth based on proposed major changes in employment (e.g. installation mission changes).
4. The model is calibrated – often with historic census data
5. Revised model outputs are reviewed by the stakeholder community until they are satisfied with the base model projections.
6. Regional planning proposals are tested with the model
7. As needed/requested, future urban patterns are input into various models such as:
    - Transportation models
    - Habitat fragmentation models
    - Economic impact models
    - Utility (e.g. water, electric grid, and sewer) models
8. Results are captured in a report for general public consumption and presented at regional stakeholder meetings
9. The new localized LEAM model often becomes part of the regular tools of the community to test further regional planning suggestions.

Each full application of LEAM results in an urban growth model specially created to address the specific needs of the target communities. Step 1, above, is accomplished with a generic version of LEAM's land use change model. This software is written in the "C" language and, like RSim, owes its beginnings to the SLEUTH model. It is 30-meter grid-cell based, uses a 1-year time step, and generates future urban patterns across a region based on calculated dynamic attractiveness of undeveloped areas to new urban residential, commercial, and open-space. Raw GIS maps are processed with in-house ESRI GIS scripts to create the needed input files for the LEAM land use change model. Results of the model are further processed with ESRI-GIS for reporting and image production purposes.

LEAM applications are tailored to meet the specific needs of target communities and rely heavily on intensive interactions with multiple stakeholders across a region.

C. Overview of mLEAM

While LEAM provides a powerful approach designed to specifically address the regional planning challenges facing a community composed of many stakeholders, mLEAM provides a very inexpensive and quick, though generic, approach to project residential growth around military installations and forecast the implication of that growth on future military training and testing opportunities. mLEAM analyses begin with a GIS technician downloading free and nationally available data such as land cover (NLCD), elevation (DEM), roads/highways, and state/federal lands. These are processed to generate raster and vector maps in a common UTM projection and common area extending through a defined set of counties. These maps are then loaded with scripts into the Linux/Unix based GRASS GIS and automatically processed. There are three primary steps.

1. LEAMram is the residential attractiveness model that generates a residential attractiveness map based on the combined attractiveness of each 30-meter square area with respect to distances to roads, highways, interstates, intersections, employment, other residential, trees, and water. The attractiveness is measured through an analysis of the current pattern of residential areas across the study area.
2. LEAMluc is a version of the LEAM land use change model. Only residential development is generated however because the primary incompatible land use challenge involves military activities and residential.
3. LEAMtom is the training opportunities module, which runs a number of new GIS analyses that predicts the probability of complaints from residential neighbors in response to military generated noise, dust, and smoke. Night sky illumination due to city lights is also synthesized.

Each of these steps generates results not only within the GRASS GIS, but automatically to a web site for immediate end-user viewing. Posted results include text, map images, urban growth movies, and GIS maps for downloading into a user's local GIS software.

D. Overview of Fort Future - LEAM

Fort Future is a Corps of Engineer's funded R&D program that provides a framework for providing Web-browser based simulation modeling tools that allow installation planners to simulate the consequences of on-installation construction on utility systems, to test the impact of utility failures (e.g. from terrorist attacks), to design new buildings and new sites for buildings, and to run LEAM models. The Fort Future LEAM (FF-LEAM) prototype is expected to be running for demonstration purposes in the Fall of 2006. The interface is expected to allow a user to open a standard browser to access the Fort Future web toolbox site. For FF-LEAM, the user will be provided with a map of the United States showing counties. After zooming to an area of interest, the user will select a coterminous set of counties and request automated mLEAM runs. After validating the request as reasonable (e.g. not too big), the system will schedule simulation runs, run the request, and email the user when the results are completed and posted for viewing. The Fort Future web-based software environment has been designed to accommodate the generation and operation of Web-based GUIs through the construction of XML text files.

E. Comparison of End-User Delivery Approaches

RSim, mLEAM, LEAM, and Fort Future have distinctly different approaches and philosophies for delivering capabilities to end users. RSim and LEAM are designed to deliver final capabilities to a local geographic community by tailoring the software, data, and analyses in direct response to locally unique needs. Therefore, application of RSim or LEAM requires that the development group create a new instance of the capabilities. The RSim interface can be provided to the user via CD or the web, which allows users some latitude in posing scenarios without involving the development group. The user can readily develop reports with text, tables, and maps derived from their particular combination of conditions and scenarios. The interface documents the conditions under which the model can be run and provides suggestions for adaptation of RSim to special applications. LEAM developers deliver results to the user community, but not the models. Results are primarily in the form of color reports filled with images and interpretations, but can include GIS map files. mLEAM, like RSim can be delivered to end users, but is in a form useful only to computer technicians familiar with Unix/Linux and GRASS. A set of technical reports have been published that will help the technicians apply mLEAM to other locations. Fort Future LEAM is designed to allow virtually anyone with a Web browser to run mLEAM (or LEAM) simulations. The development/delivery philosophies for applying the models to a new area can be summarized as follows:

- The RSim philosophy is to provide an end user with the ability to run scenarios on any computer or computer operating system using models specifically tailored for the target area and using nationally available data sets. Adapting the model to a new area can most easily be done by the developers of RSim but could be attempted by others.

- The mLEAM philosophy is to provide an end user with a quick way to generate generic urban growth and military impact analyses using nationally available data sets. Users can contract with developers or work with local GIS techs.

- The LEAM philosophy is to deliver analysis and results of urban growth simulation using models tailored to the needs of local planners, calibrated to local trends, using local data, and through the integration of urban growth impact analyses as needed.

- The Fort Future LEAM philosophy is to allow anyone to run mLEAM-type analyses for anywhere in the country – through their Web browser.

Development of an integrated capability will begin by carefully stating the questions that end users will be able to ask, the expense in time and money the user will accept, the accuracy and detail needed by the user, and the skills of the user. Based on this a product development and delivery approach will be defined – followed by design and development.

III. Receptivity of RSim is to Different Data Format, Model Validations, and

A. Data Format of RSim

This section discusses the data needed to transfer RSim to a new location in terms of its availability, cost, time required, and processes involved.

1. Basic information need to run RSim:

- Land cover – Land cover types at 30 m resolution available from USGS
- Changes in land cover types over time – Land cover data for at least 2 time periods 10 years apart and close to the census periods (e.g., 1980, 1990 or 2000).
- Boundaries of military and other public ownership - available from the state GIS agency or other programs such as the Gap Analysis Program.
- Roads by type (dirt, two-lane, four-lane, interstate) - available from the state GIS agency or the US Census Bureau TIGER data.
- Changes in human population over time - US Census data

2. Water quality

- Hydrological units (HUCs) - available from USGS
- Region-specific export coefficients for nitrogen and phosphorus from different land cover types -- Some coefficients can be derived from studies already published, but in many cases it would be best to have actual field measurements of N and P exports from watersheds that are dominated by a particular land cover type. So that means measurements and field research similar to what ORNL researchers have proposed for the watershed management SON at Fort Benning.

3. Species

- Characterization or location of habitat, foraging area and nesting sites for species of special concern– often this information is better known for rare species than for widely available species.
- Model that identifies habitat for species – Models are available for some rare species (e.g, gopher tortoise, karner blue butterfly, etc.). In cases of widely distributed species, developing such a model may be straightforward. In some case, the habitat to which a species is restricted is not known.

4. Air quality

- Initial emissions, initial ozone air quality concentrations, and sensitivity coefficients (factors relating changes in air quality concentrations relative to changes in emissions) -- Available from the Fall line Air Quality Study for the entire Eastern United States. Projected changes in future year emissions for all areas are available from the US EPA EGAS4.0 program.

5. Noise

- Peak noise contours – can be developed for Army installations using SARNAM and BNOISE2. Information needed to run the models include range layouts and operational data. USACHPPM is the tech transfer point for the Army noise models and has already developed Peak noise contours for many of the major Army installations.

6. Additional stressors of interest

- Fire (both natural and human induced)
- Particulates in air
- Sedimentation
- Invasive species.

7. Other relevant data

- Soils layers - from the USDA Natural Resources Conservation Service
- Streams data - usually available from the State GIS agency
- Zoning constraints on urbanization, if available

8. Scenarios

- Type of change
    - Proposed roads and road expansions--often available from state transportation offices
    - Proposed military training and extent--often available from installation.
    - Proposed land purchase or lease by military
    - Proposed environmental regulation
    - Potential disturbance
- Potential impact --often available from the scientific or grey literature. However there is poor documentation of the location, frequency, or intensity of some disturbance (e.g., ice storms).
- Potential extent in application area--can use information from other similar disturbances.

9. Cost and processing issues:

Most of the listed geographical data sets are inexpensive (there may be a handling charge of $50 or so for some of the data sets based on the state GIS agencies policy of distributing data). However if new data are collected or generated, cost might be an issue. For example if new land-cover data would be needed, the cost of buying satellite data and creating the land-cover classes will be involved. Similarly, there may be costs for creating the noise contours if the models need to be run at new locations. If field data need to be collected, then cost will rise.

The time for collecting geographical data is small and the process is straightforward - that is if data are available (soils, roads, streams, boundaries, basic land cover)! Challenges arise when the appropriate data are not available at the right scale or format.

B. RSim Validation

RSim is a collection of models that simulate changes in the landscape. Validation of this complex set of models can only be done by validation of the models that make up RSim. Where possible, RSim was built upon existing models and thus relies upon model development, testing and validation that has already occurred.

RSim simulates changes in urban land by a well-tested rule-based model (Clarke et al. 1998, Clarke and Gaydos 1998, Candos 2002). The urban growth module of RSim as applied to the five county study region (including and encompassing Fort Benning) was validated by comparing changes in human demographic variables to changes in urban land cover for the five-county study region encompassing Fort Benning (Baskaran et al. 2006A). The RSim urban growth model was run from 1990 for 10 iterations. Each step in the iteration showed an increase in the number or urban pixels. Using the ratio between the population in 1990 (census data) and the urban area in 1990 as a base, the population was estimated for each time step.

The module that predict habitats for the gopher tortoise (*Gopherus polyphemus*) was developed based on analysis of documented locations of gopher tortoise burrows at the Fort Benning military installation in west central Georgia and tested for the five-country region of RSim that falls outside the installation (Baskaran et al. 2006B). Burrow associations with land cover, soil, topography, and water observed within Fort Benning were analyzed with binary logistic regression. This analysis helped generate a probability map for the occurrence of gopher tortoise burrows in the five-county region surrounding Fort Benning. Ground visits were made to test the accuracy of the model in predicting gopher tortoise habitat. The results showed that information on land cover, soils, and distances to streams and roads can be used to predict gopher tortoise burrows for the region.

Nutrient export coefficients have been widely used to predict total N and P losses from landscapes to surface receiving waters (e.g., Beaulac and Reckhow, 1982; Frink, 1991; Johnes, 1996; Mattikalli and Richards, 1996). An export coefficient is the amount of N or P lost annually from a particular land cover type on an area basis (for example, g N m^{-2} yr^{-1}). Export coefficients can be combined with information on the area of different land uses and/or land covers to predict the annual flux of N and P from terrestrial watersheds. Past studies that have compared predicted and measured nutrient loads appear to validate the use of export coefficients for estimating annual watershed losses of both N and P (Johnes, 1996; Johnes et al., 1996; Mattikalli and Richards, 1996).

To understand how noise from military installations may affect the environment, RSim uses GIS data layers of military noise exposure developed by the U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM) as part of the Fort Benning Installation Environmental Noise Management Plan (IENMP). RSim builds upon noise guideline levels developed by the military under the Army's Environmental Noise Program [ENP] (U.S. Army. Army Regulation 200-1. 1997). ENP guidelines define zones of high noise and accident potential and recommend uses compatible in these zones. Local planning agencies are encouraged to adopt these guidelines. IENMP contains noise contour maps developed from three DoD noise simulation models: NOISEMAP, BNOISE, and SARNAM.

- The Army, Navy, and Air Force use NOISEMAP (Version 6.5), a widely accepted model that projects noise impacts around military airfields. NOISEMAP calculates contours resulting from aircraft operations using such variables as power settings, aircraft model and type, maximum sound levels and durations, and flight profiles for a given airfield.
- The Army and the Marines use BNOISE to project noise impacts around ranges where 20-mm or larger caliber weapons are fired. BNOISE takes into account both the annoyances caused by hearing the impulsive noise of weapons and by experiencing house vibration caused by the low frequency sound of large explosions. BNOISE uses operational data on the number of rounds of each type fired from each weapon broken down by day and night firing. Contours show the cumulative noise exposure from both firing point and target noise.
- All the military services use the Small Arm Range Noise Assessment Model (SARNAM) to project noise impacts around small arms ranges. SARNAM is designed to account for noise attenuated by different combinations of berms, baffles, and range structures.

Each model produces noise contours that identify areas where noise levels are compatible or incompatible with noise-sensitive land covers. Based on U.S. Army attempts to validate human annoyance predictions based on noise contours, the Department is considering a new recommendation to use peak sound levels rather than the current metrics.

The Air Quality Module in RSim estimates the impact of those emissions changes on ozone air quality using sensitivity coefficients recently available from another air quality study of middle Georgia (the Fall Line Air Quality Study: http://cure.eas.gatech.edu/faqs/index.html). This study is based on measurements of ozone, as well as models. Sensitivity coefficients from that study relate the changes in emissions to changes in air quality. The final report of the Fall Line Air Quality study presents an uncertainly analysis.

C. Future Modeling Needs for RSim

1. Burning scenario

During discussion with several colleagues at the 2005 SERDP Symposium, we were struck by the importance of burning for forest management at Fort Benning. Locally burning may affect forest development and hence habitats for red cockaded woodpecker. Regionally burning may affect air quality. Yet our initial proposal for RSim did not include a burning scenario.

A burning scenario could be added to RSim by building off of the model of prescribed burning and forest thinning that Garten (in press) developed at Fort Benning. This model allows examination of different levels of fire intensity and return frequency. These effects can be incorporated into the RSim code to affect nitrogen exports, air quality, and land cover changes as well as their subsequent effects on habitat for red cockaded woodpecker and gopher tortoise.

The benefit of including the burning scenario in RSim is that the model can then be used to explore the impacts of burning on several types of environmental impacts. Burning is such a critical management issue at Fort Benning that we suspect the users will be disappointed if RSim does not include this important activity.

2. Testing the general applicability of RSim by transporting it to a new installation and region.

Modifying and applying RSim to another location requires that the general applicability of the model be examined. In that case, stakeholders from the new region would be engaged in the development, testing, and use of RSim throughout the project. A stakeholder analysis will be conducted early to determine the key scenarios to be used in the modeling effort. Relevant scenarios to consider include (but are not limited to) urban and suburban growth, sea level changes, changes in temperature and/or precipitation, hurricanes, introduction and spread of nonnative species, and military training. RSim's forecasting accuracy would be tested by running it using recent historical cases as scenarios and by comparing model output to data already collected for the region. This task would thus require choosing a region where such historical data are already available.

To fully understand how RSim can be used to improve resource management in the new region, RSim would be deployed in three modes: (1) an integration test to examine how well RSim can deal with multiple resource management goals, (2) conservation education and environmental awareness, and (3) support for adaptive management. Technology transfer would best be accomplished by actively engaging stakeholders throughout the study, delivering the RSim model to environmental managers at the installation and holding a workshop with members of the stakeholder community to demonstrate use of the forecasting tool.

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Section 2e. Evaluation of Feasibility and Utility of Synthesizing Tools Provided by SERDP SI 1259 and SI 1257
November 2006

Background:
Research projects SI-1257 and SI-1259 were funded by the Strategic Environmental Research and Development Program (SERDP) to build simulation models that address issues of encroaching development around military installations and their implications on both the installation's mission and the condition of the region. The resulting products, RSim, LEAM, and mLEAM, represent a suite of analysis approaches, software tools, and techniques for helping installations identify, predict, and address encroachment challenges.

To evaluate the feasibility and utility of synthesizing the modeling tools being provided by SERDP SI 1259 and SI 1257, the RSim team held a workshop to identify the strength of the RSim approach and had productive conversations with mLEAM researchers to discuss integration approaches. Because the similar process in the two modeling approaches is urban land cover, the way that urban land cover is modeled by the two approaches needs to be described before the concept of synthesizing the tools can be discussed. The next sections first discuss the utility of a combined approach and then compare the way urban land-cover changes occur in the different models. The last section discusses the technical feasibility of synthesizing the modeling tools.

The Utility of Combing the RSim Approach with the mLEAM Approach:
The value of combining the RSim and the mLEAM approaches is the breadth and diversity of questions that can be addressed, processes evaluated, and decisions considered. RSim focuses on a diversity of outcomes: how land-use decision affects the quality of the air, water, noise and species and their habitat. It can be run under explicit scenarios of urban growth, military use, road development and hurricanes. These changes are underlain by changes in 18 land cover categories (including developed, barren, forested upland, shrubland, non-natural woody land, herbaceous and wetland classes). LEAM connects proposed regional plans with long-term consequences to transportation networks, utilities, habitat fragmentation, and services such as schools. The mLEAM models focus on providing projections of urban residential patterns and their direct impact on suitable military training/testing areas. Together these models cover a great diversity of cause and effects. Because each model allows some feedbacks, the combined model could be used to explore interactions that might display nonlinear dynamics. Combining the capabilities of the model suites could provide installation and regional planners with the following set of capabilities:

- Explore potential outcomes of a variety of decisions under different scenarios of future change.
- Project economic and population changes in regions based on proposed installation mission changes
- Forecast future land-cover changes and patterns across regions
- Forecast effects of changes in the region due to

    - Urban growth (under typical conditions for the region or other scenarios)
    - Natural disturbances such as hurricanes
    - Changes in the road system
    - New military training areas
- Evaluate the impact of future land-cover changes and their patterns on
    - Habitat suitability
    - Military training/testing suitability
    - Water quality
    - Air quality
    - Transportation system loads
    - Economic and social impacts
    - Noise conditions

A Focus on Urban Land-Use Change as a Way to Integrate RSim and mLEAM: The key process that is common to the RSim and LEAM/mLEAM land-use change models is urban land-cover change. Both approaches start with initial conditions of a particular spatial configuration of urban lands and project changes over time in urban land use. However the forces that affect urban land cover are quite different in the two approaches.

The mLEAM models simulate changes in urban patterns in response to local, county and state planning. Planning decisions that can be made by users relate to such features as locations of new highways, construction of highway ramps, major land purchases, purchases of development rights construction of news roads, zoning plans, or installation buffers. Hence the LEAM/mLEAM approach focuses on forecasting results of planning decisions. These planning proposals essentially establish the "playing field" upon which residential developers build new homes and neighborhoods and homebuyers purchase their residences, industrial developers create new industrial/commercial areas, and city planners establish new parks and open spaces. The LEAM land-use change model then forecasts these decisions and resulting regional land-use patterns. (mLEAM uses only the residential projection component.) Based on population projections using a multi-sector economic input-output model, target growth in commercial, residential, and open space is pre-calculated. The LEAM land-use change model then converts developable, but undeveloped land within the region based on the pre-calculated needs and the relative attractiveness of land to each use. The new development then affects the attractiveness of each cell to development, which is recalculated. This process occurs in one-year time steps. The result is captured in two maps. The first is the final land-use map using the National Land Cover Data (NLCD) categories as the starting land-use map. The second captures the time step at which each cell changed. Using these two maps and the starting map, it is simple with a GIS to generate the land use at any time step or to create a movie showing the land-use change over simulation time.

RSim simulates changes in urban land by a rule-based model (Clarke et al. 1998, Clarke and Gaydos 1998, Candos 2002). RSim includes both spontaneous growth or new urban areas and patch growth (growth of preexisting urban patches). Growth occurs in either low-intensity[1] or high intensity[2] urban areas. Any non-urban cells can become low-intensity urban cells according to three rules: spontaneous growth occurs in a set number of random cells; new spreading growth occurs in random cells and two neighboring cells, or edge growth arises from a random number of non-urban pixels with at least three urbanized neighboring cells. This approach to modeling urban growth was derived from the SLEUTH model (http://www.whrc.org/midatlantic/modeling_change/SLEUTH/sltuh_overview.htm).

Low-intensity urban pixels become high-intensity urban cells according to different rules for two types of desired high-intensity urban cells:

- central business districts, commercial facilities, high impervious surface areas (e.g., parking lots) of institutional facilities that are created within existing areas with a concentration of low-intensity urban cells; and
- industrial facilities and commercial facilities (malls) that are created at the edge of the existing clumped areas of mostly low-intensity urban cells or along four-lane roads.

For the first high-intensity category, land-cover changes occur in a manner similar to changes in low-intensity growth, as described above: a spontaneous growth algorithm converts random low-intensity pixels to high-intensity pixels, and an edge growth algorithm converts random low-intensity urban pixels with high-intensity urban neighbors to high-intensity pixels. The second type of conversion from low-intensity to high-intensity urban land use is road-influenced growth.

RSim is initiated with the 1998 land-cover data for the west central Georgia study region that was obtained from the Natural Resource Spatial Analysis Laboratory, University of Georgia and classified into 18 NLCD categories. In addition to considering urban growth, RSim simulates changes in non-urban land cover (i.e., change in forests, cropland, barren area, and so on). In order to incorporate the growth and changes that may happen in non-urban land-cover types, an analysis of past growth trends helped to set specific growth patterns and trends for the future. This approach is based on the assumption that growth trends remain constant over the years of analysis and over the spatial area being considered. Since forest management activities are different within Fort Benning and the surrounding private lands, the transition rules were calculated only for regions outside Fort Benning. The land inside the Fort Benning military reservation is maintained for training exercises.

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[1] Low-intensity urban land includes single family residential areas, urban recreational areas, cemeteries, playing fields, campus-like institutions, parks, and schools.

[2] High-intensity urban land includes central business districts, multi-family dwellings, commercial facilities, industrial facilities, and high impervious surface areas of institutional facilities.

The Technical Feasibility of Synthesizing the Modeling Tools Provided by SERDP SI 1259 and SI 1257:
Using urban land use as a common process, it seems entirely possible to combine the tools provided by RSim and mLEAM. The models have the same spatial resolution (30 m pixels) and temporal resolution (1 year).

One challenge that must be met is using a common computer language and developing a common code. RSim is written in Java with an object-oriented design and thus does not rely on any particular software (although it produces maps compatible with ARC-INFO or with any text editor or spread sheet software). It also was designed to use data sets that are available across the United States. The LEAM/mLEAM land-use change model is written in the C programming language. LEAM relies heavily on Windows-based ESRI-based processing and analysis scripts, while mLEAM relies on Linux/Unix scripts and the GRASS GIS for map analyses and spatial output. Combining the software products would require the expertise of a computer scientist.

Because urban land cover is the common process, the values for urban land cover would serve as the interface between the two modeling approaches. The mLEAM models project changes in three categories of urban cover (residential, commercial, and open space). RSim projects changes in two categories of urban cover (low intensity urban and high intensity urban). In order to relate changes in urban land cover of the RSim and mLEAM models, we will need to carefully define the relationship between the two ways of categorizing urban land. However, once this definition is done, then the computer codes should be able to be modified so that the user would have access to the full abilities of both RSim and mLEAM.

Combining and adopting the full system for the Fort Benning region is the obvious first step. Before the combined model can be deployed to a new location, RSim must be adopted to a new region. Proposals have been developed to do this for Fort Bragg and for Camp Lejeune. mLEAM, on the other hand has already been designed to run in its “quick and dirty’ mode for installations across the United States. Full application of LEAM in a particular region would require detailed work however.

One possibility for a framework in which to house the combined models is Fort Future^{TM}. The data and tools within Fort Future^{TM} are designed to readily interface to help the Department of Defense address its planning requirements.

The development of such a combined approach would likely involve the following steps:
1. Identify an existing or new user panel that represents the target user community and is forward thinking and adapts/adopts new technology.
2. Demonstrate all capabilities to user panel
3. Obtain feedback on what they like, don’t like, want, and need
4. Develop an end-user interface design
5. Present to user panel for acceptance
6. Design the computer architecture that will support the user interface
7. Develop the software

8. Conduct Alpha test
9. Develop the software to address needs identified in the Alpha test
10. Conduct Beta test
11. Refine the software to address needs identified in the Beta test
12. Release the combined product

Model Components that Would be Useful to Add to RSim

During discussion with several colleagues at the 2005 SERDP Symposium, we were struck by the importance of burning for forest management at Fort Benning. Locally burning may affect forest development and hence habitats for red cockaded woodpecker. Regionally burning may affect air quality. Yet our initial proposal for RSim did not include a burning scenario.

Therefore, it would be both feasible and useful to provide a supplement so that a burning scenario can be added to RSim. This addition could be done by building off of the model of prescribed burning and forest thinning that Garten (2006) developed at Fort Benning. This model allows examination of different levels of fire intensity and return frequency. These effects can be incorporated into the RSim code to affect nitrogen exports, air quality, and land cover changes as well as their subsequent effects on habitat for red cockaded woodpecker and gopher tortoise.

The benefit of including the burning scenario in RSim is that the model can then be used to explore the impacts of burning on several types of environmental impacts. Burning is such a critical management issue at Fort Benning, that we suspect the users will be disappointed if RSim does not include this important activity.

We estimate that the cost for adding the burning scenario to RSIM will be about $110,000 for the spatial implementation and interpretation of the new scenario. This budget would cover subcontracts to the University of Tennessee Computer Science Department and the Georgia Institute of Technology, 200 hours each of time for Latha Baskaran and Rebecca Efroymson, 80 hours for Chuck Garten, and 40 hours for Virginia Dale.

In addition, it would be very useful to test the generality of the RSim approach by applying it to a new location. Because of the generality of the data requirements, RSim could be readily transferred to a new site. The main challenge would be obtaining or developing habitat predictors for the habitats of the species of interest in the new location. Thus, it is more straightforward to first move RSim to another location along the Fall Line in the southeastern United States that supports red cockaded woodpecker and gopher tortoise, which are the key species modeled in RSim.

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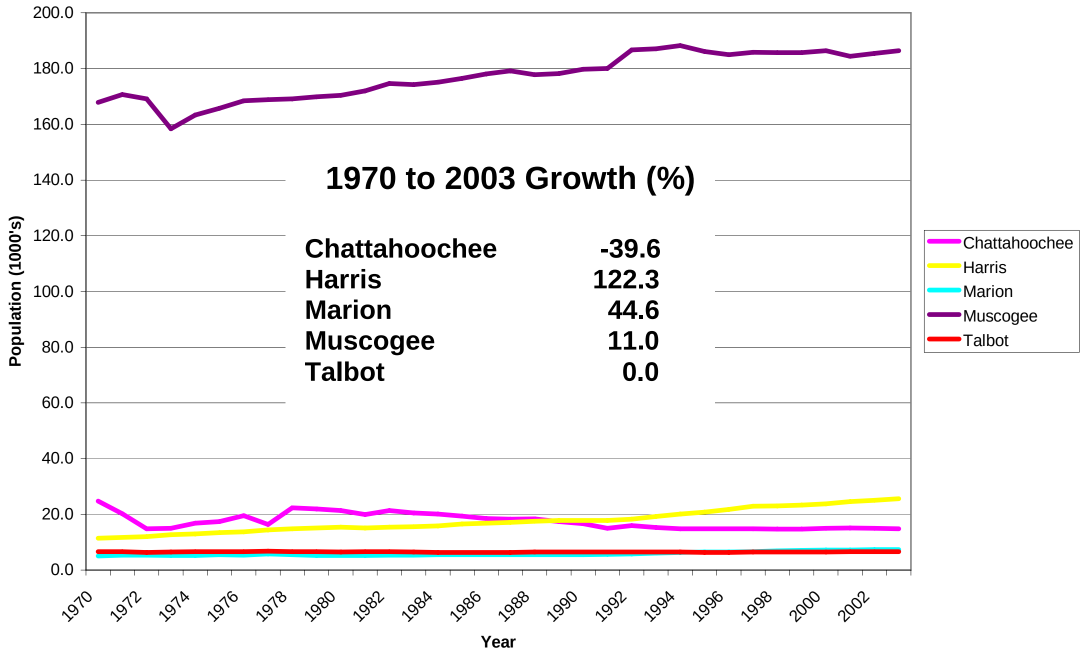
Section 2f. Backcasting Component of RSim and Testing RSim by Comparison to Growth Trends for the Region

Introduction
Growth and development of human settlement is an inherent aspect of societies. With more awareness of the environmental implications of growth and with more regulations in place that are affected by growth, the need to plan any development is important. A good understanding of the implications of such activities can assist in foreseeing negative effects they may have on the environment and society.

The Regional Simulation Model (RSim) explores resource use and constraints as dictated by growth and development issues in and around Fort Benning, Georgia. Four scenarios are considered and simulated in the model – urban growth, proposed road improvement plan in Georgia, a new training area in Fort Benning, and hurricanes. Backcasting was done with RSim in the sense that the model was initiated in 1990 and used to project forward to 1998. The challenge in such an effort is always obtaining consistent data across the time intervals. We were frustrated to find differences in the land-cover categories adopted by different groups of researchers making it impossible to compare model projections using these categories.

Population trends in the study region:
Analyses involving different demographic and economic characteristics such as population, employment in various sectors, market value of commodities, income and commuting patterns, have been done for each of the five counties in the study region for different years by David Vogt and Colleen Rizy, Regional Study Program, Environmental Science Division, ORNL. The major population growth trends within the RSim counties are presented in Figure 1. As can be seen from the graph, the growth trends are vastly different among the counties. Harris County has the fastest growth rate whereas Chattahoochee County has seen a decline in growth. The 1970, 1980, 1990, and 2000 Census data were also used to produce a time-series of detailed (i.e., tract level) economic characteristics, such as urban vs. rural density and housing stats. A grid-based database of economic characteristics of 1990 and 2000 population data was also prepared by Vogt and Rizy.

Figure 1. Total Population, by Rsim County, 1970-2003



Description of 1990 and 1998 landcover:

RSim model runs originate from a base year of 1998. The 1998 land cover data for the study region was obtained from the Natural Resource Spatial Analysis Laboratory, University of Georgia. The 18 class land-cover map was originally generated from Landsat TM images. A description of all the classes is presented in Appendix A. The resolution of the data is 30m.

For model calibration of RSim, the 1990 land-cover data were also used. The 1990 land-cover map was created by the Georgia Department of Natural Resources. This data set has 12 landcover classes and a description of the classes is listed in Appendix B. The map is based on Landsat TM imageries dated 1988 to 1990 and has a resolution of 60m. For this study, the landcover data was resampled to 30m in order to match the 1998 landcover resolution.

Urban growth time step estimation:

Initially the rate of growth was estimated for the whole study region, i.e., the five counties. Subsequently county wise estimates were made. Several approaches for estimating the length of a model run were carried out. Other approaches were not suitable for this study because of data constraints and nature of the study region. However, all the approaches are outlined in the following sections. The primary approach was the one most suitable to calculate the time step of the model.

1. **Primary Approach:**

The RSim model was run from 1990 for about 10 iterations. Each iteration indicated an increase in the number or urban pixels (low intensity urban and high intensity urban classes). Using the ratio between the population in 1990 (Census data) and the urban area in 1990, the population was estimated for each time step. This analysis is shown in table 1.

Comparing the growth in population from 1990 to 2000, with the growth in population from 1990 to the first time step gives an estimate of the number of years for one step (Table 2). In this case, one time step corresponds to approximately 11.7 years.

Table 1: Population estimation based on 1990 urban area and population

Data	Area of Urban (hectare)	Population
Original – 1990	11984.70788	226114
Time step 1	12756.64591	240678.0593
Time step 2	13566.11623	255950.2355
Time step 3	14363.31638	270990.912
Time step 4	15176.39557	286331.1765
Time step 5	16022.67639	302297.8521
Time step 6	16882.31005	318516.4539
Time step 7	17726.42555	334442.2766
Time step 8	18588.58542	350708.5401
Time step 9	19477.09007	367471.8473
Time step 10	20345.02414	383847.0519

Table 2: Time step calculation based on 1990 urban area and population

	Change in population	Number of years
1990 to 2000	12396	10 Years
1990 to timestep1	14564.05927	11.74899909

Similar calculations were carried out by changing the ratio used to estimate the population of each time step. A calculation based on the year 2000 ratio of urban area and population yielded a longer time step of approximately 18 years for one iteration (Tables 3 and 4). The two estimates using 1990 and 2000 population-urban area ratios can be used to bind the timestep by their values of relatively slower growth and faster growth.

Similar analysis using measures such as population within urban pixels and number of people per pixel were attempted but were not appropriate since the estimated values for 2000 were lower than that of 1990. This difference can be due to the way in which population was gridded in the region by the US Census for the different years (2000 population is more widely spread than the 1990 population).

Table 3: Population estimation based on 2000 urban area and population

Data	Area of Urban (hectare)	Population
Original - 1998 (2000)	12244.86	238510
Time step 1	12756.64591	248478.7589
Time step 2	13566.11623	264245.927
Time step 3	14363.31638	279774.092
Time step 4	15176.39557	295611.5551
Time step 5	16022.67639	312095.7321
Time step 6	16882.31005	328840.0007
Time step 7	17726.42555	345282.0007
Time step 8	18588.58542	362075.4757
Time step 9	19477.09007	379382.1042
Time step 10	20345.02414	396288.0512

Table 4: Time step analysis based on 2000 urban area and population

	Change in population	Number of years
1990 to 2000	12396	10 Years
1990 to timestep1	22364.75894	18.04191589

The above calculations were for the summed five county extent in the study region. Similar calculation carried out for individual counties yielded varying results. The population in some of the counties (Chattahoochee and Talbot) has been declining over the past few years. The Census data indicates this change, but the RSim growth rules are not sensitive to such population decline. Hence the urban areas show an increase in all counties. Such a trend is not directly comparable to the population information.
In counties showing an increase in population (Harris, Marion and Muscogee), three different time step rates were obtained. Marion – 4.3 years, Harris – 1.9 years and Muscogee – 17.6 years. These differences can be attributed to the rate of growth of each county and the presence of new or old growth situations

2. **Alternative Approaches**

a. **Population potential:**

A simple way to obtain population potential is by considering the density of each point (pixel) over a fixed region. A regional extent is considered since the original population grid does not exactly identify locations of houses/settlements (they are randomly placed), it would not be appropriate to consider density at each grid. Some kind of smoothing should be done to account for the random placement.

b. **Based on urban and rural population**

By comparing urban areas of the landcover simulations and the urban and rural population information from the Census, estimates of the change in urban population by urban area can be developed and used to identify the time frame of a model run. An example of the urban and rural breakup of the demographic data is presented in Table 5. The definition of each of the Census population categories relating to urban and rural classifications is provided in Appendix C.

This approach was not useful in this study because of differences in definitions of urban area of land-cover data and the definition of urban and rural population by the Census. The land-cover data has two categories for urban areas – low intensity urban and high intensity urban (refer Appendices A and B). These categories of urban area are based on the extent of buildings, roads and concrete as seen by a sensor. It does not entirely imply the population in that region. Hence the urban area land cover could not be equated to the urban population of a region.

Table 5: 1990 and 2000 Urban and Rural Population by County

	Chattahoochee County		**Harris County**		**Marion County**		**Muscogee County**		**Talbot County**	
	1990 - County	2000 – County	1990 - County	2000 – County	1990 - County	2000 – County	1990 - County	2000 – County	1990 - County	2000 – County
Urban:	86%	79%	4%	3%	0%	0%	97%	97%	2%	0%
Inside urbanized areas	86%	79%	0%	0%	0%	0%	97%	97%	0%	0%
Inside urban clusters	0%	0%	4%	3%	0%	0%	0%	0%	2%	0%
Rural:	14%	21%	96%	97%	100%	100%	3%	3%	98%	100%
Farm	0%	0%	3%	1%	7%	4%	0%	0%	5%	6%
Nonfarm	14%	21%	93%	96%	93%	96%	3%	3%	93%	94%

Time step calibration:
The time step estimate of 11 to 18 years for one model run was considered very high for the RSim study. Finer temporal estimates were required. Hence the parameters for the growth rules were adjusted such that growth was much slower. After this calibration, one time step corresponded to approximately one year.

Appendix A: Landcover classes in 1998 landcover data

(1) **Beaches/Dunes/Mud** - This class includes the following categories of information; beaches, exposed sandbars, sand dunes, mud, dredge materials, and exposed lakeshore.

(2) **Open Water** - This class includes all types of waterbodies: lakes, rivers, ponds, ocean, industrial water, and aquaculture, which contained water at the time of image acquisition.

(3) **Transportation** - This class includes roads, railroads, airports, and runways.

(4) **Utility Swaths** - This class includes vegetated linear features, which are maintained for transmission lines and gas pipelines.

(5) **Low Intensity Urban** - This class includes; single family residential areas, urban recreational areas, cemeteries, playing fields, campus-like institutions, parks, and schools.

(6) **High Intensity Urban** - This class includes central business districts, multi-family dwellings, commercial facilities, industrial facilities, and high impervious surface areas of institutional facilities.

(7) **Clearcut/Sparse** - This class includes areas that had been clearcut within the past 5 years, as well as areas of sparse vegetation.

(8) **Quarries/Strip Mines** - This class includes; mines and exposed rock and soil from industrial uses, gravel pits.

(9) **Rock Outcrop** - This class includes geological features such as rock outcrops, and exposed mountaintops.

(10) **Deciduous Forest** - This class is composed of forests, which contain at least 75% deciduous trees in the canopy, deciduous mountain shrub/scrub areas, and deciduous woodlands.

(11) **Evergreen Forest** - This class is composed of forests, which contain at least 75% evergreen trees, pine plantations, and evergreen woodlands.

(12) **Mixed Forest** - This class includes forests with mixed deciduous/coniferous canopies, natural vegetation within the fall line and coastal plain ecoregions, mixed shrub/scrub vegetation, and mixed woodlands.

(13) **Golf Courses** - Golf courses.

(14) **Pasture** - This class includes pastures, and non-tilled grasses.

(15) **Row Crop** - This class includes row crops agriculture, orchards, vineyards, groves, and horticultural businesses.

(16) **Forested Wetland** - This class includes all types of forested and shrub wetlands.

(17) **Coastal Marsh** - Coastal freshwater and brackish marsh.

(18) **Non-forested Wetland** - This class includes all freshwater emergent wetlands.

Appendix B: Landcover classes in 1990 landcover data

(1) **Open Water.** Lakes, reservoirs, coastal waters, ponds and wide stream channels with little or no emergent vegetation are included in this class. On the unclassified imagery, open water appears dark, similar to shadows behind northwest-facing slopes; therefore, some shadow areas are included.

(2) **Clearcut/Young Pine**. The spectral characteristics recently cleared in timber harvest operations and planted to pine or left unplanted are usually quite different from those of other landcover types. The clearcuts are often large in area and regularly shaped. The typical clearcut/young pine stand has widely-spaced woody vegetation with a ground cover of herbs and grasses. This vegetation type can be seen as transitional to closed-canopy coniferous forest. Any cleared land can be spectrally similar to timber clearcuts, including some agricultural land such as abandoned pasture and fallow cropland.

(3) **Pasture**. Pasture land is distinguished from other agricultural land by the presence of low-growing herbaceous vegetative cover year round. This class includes actual pastures, as well as lawns, fields, and other open areas within urban areas. Pasture can be spectrally similar to cultivated fields that have vegetative cover during the winter. Pixels of the clearcut/young pine and cultivated/exposed earth classes are often found intermingled.

(4) **Cultivated/Exposed Earth.** Agricultural fields with no winter vegetation, and any other areas where vegetation has recently been removed, exposing soil or rock, are represented by this class. Exposed banks around reservoirs with low water levels often are included in this class. Some cultivated fields showing winter vegetation are spectrally similar to pasture. This class may be found within urban areas and in conjunction with the pasture and clearcut/young pine classes in other areas.

(5) **Low Density Urban.** The high reflectivity of man-made structures in urban areas provides for some separation of urban classes from the non-urban classes. The low density urban class represents urban areas with moderate vegetative cover. However any area with high reflectivity, such as isolated industrial sites, may fall into this or the high density urban class. The edges of some bodies of water are spectrally similar to this class. It is typical for residential areas to be shown as a matrix of this class and forest class pixels. Low density urban may be interspersed with high density urban.

(6) **High Density Urban.** This class is distinguished from low density urban by an even higher reflectivity of the landcover. Paved areas with buildings and little vegetation are typical of this landcover class. Roads are often shown as linear features composed of high and low density urban pixels. High density urban pixels found outside of urban areas are indicative of any type of highly reflective structure/ feature such as power substations, grain storage bldgs.

(7) **Emergent Wetland.** Emergent wetlands are spectrally and ecologically transitional between open water and scrub/shrub wetlands. Freshwater marsh vegetation with few woody plants interspersed is typical of the cover type. Where clusters of emergent wetland pixels are found, other wetland types and open water are often in proximity. This class may show up in some non-wetland areas with low-reflectivity cover.

(8) **Scrub/Shrub Wetland.** Intended for wetland vegetation dominated by woody plants less than 20 feet in height, this class contains areas in transition between emergent and forested wetlands. This class is usually found in conjunction with other wetland classes. Where uplands with woody vegetation border open water, pixels from this class may be shown. When found singly within a matrix of low urban density and forest pixels, it is more likely that cover spectrally similar to but not actually scrub/shrub wetland is being shown (i.e., scrubby vegetation over some low-reflective surface).

(9) **Forested Wetland**. Where spectral differences are pronounced, this class may be distinguished from scrub/shrub wetland and upland forest types. Where upland tree canopies overhang river banks or edges of water bodies, pixels from this class may show. These edges may or may not be actual wetlands. Areas of swamp are often shown as mixtures of forested wetland and hardwood forest pixels. Individual or small clumps of pixels in this class when found scattered throughout urban areas may be showing non-wetland areas with spectral similarity to wetlands, such as woody vegetation over low-reflective surfaces. Classification of forested wetlands dominated by deciduous trees is probably more accurate than that in areas with evergreen, closed canopies. In the latter case, the low reflectivity of the wet areas underneath the canopy may not be picked up by the sensor, making them difficult to distinguish from upland evergreen forest canopies. Spectral similarity between this class and shadows behind northwest-facing slopes may account for the presence of forested wetland pixels shown on some slopes.

(10) **Coniferous Forest.** The uniformity of large tracts of planted pines provides for accurate classification of this landcover type in upland areas. These stands may be fringed or bisected by the other forest types. Spectral similarity with evergreen hardwood forest in the Coastal Plain may result in difficulty in distinguishing between these two cover types. Where pine canopies are dense, as is often the case, it may be difficult to determine whether the sites are upland or wetland.

(11) **Mixed Forest.** Typically, this class represents mixed stands of hardwood and coniferous trees, neither type exceeding 60-70 percent of the stand. Pine plantations in transition from early stages to forest may be shown in this class, although few if any hardwood trees may be present. Edges of coniferous stands and areas of transition between coniferous and hardwood forest are often shown with this class. Also included may be abandoned cut-over areas.

(12) **Hardwood Forest**. Stands of deciduous hardwoods are generally distinguished from forested wetlands and other forest classes accurately. Evergreen hardwood forests may be spectrally similar to mixed and coniferous classes, and, due to a closed canopy, may be difficult to distinguish from evergreen forested wetlands. River floodplains are often depicted as a mixture of forested wetland and hardwood forest pixels, with drier areas shown as hardwood forest. Cut-over lands with young, shrubby hardwood growth, although not forest, may make up part of this class.

Appendix C: Description of urban and rural descriptors in Census statistics

- **Urbanized Areas** - (UA) An area consisting of a central place(s) and adjacent territory with a general population density of at least 1,000 people per square mile of land area that together have a minimum residential population of at least 50,000 people. The Census Bureau uses published criteria to determine the qualification and boundaries of UAs
- **Urban Clusters** - A densely settled territory that has at least 2,500 people but fewer than 50,000. New for Census 2000.
- **Urban** - All territory, population and housing units in urbanized areas and in places of more than 2,500 persons outside of urbanized areas. "Urban" classification cuts across other hierarchies and can be in metropolitan or non-metropolitan areas.
- **Urban Area** - Collective term referring to all areas that are urban. For Census 2000, there are two types of urban areas: urban clusters and urbanized areas.
- **Rural** - Territory, population and housing units not classified as urban. "Rural" classification cuts across other hierarchies and can be in metropolitan or non-metropolitan areas.
- **Farm Residence** - Dwelling or household located in a rural farm area and concerned with growing crops or raising livestock.
- **Census county division (CCD)** - A subdivision of a county that is a relatively permanent statistical area established cooperatively by the Census Bureau and state and local government authorities. Used for presenting decennial census statistics in those states that do not have well-defined and stable minor civil divisions that serve as local governments.
- **Place** - A concentration of population either legally bounded as an incorporated place, or identified as a Census Designated Place (CDP) including comunidades and zonas urbanas in Puerto Rico. Incorporated places have legal descriptions of borough (except in Alaska and New York), city, town (except in New England, New York, and Wisconsin), or village.

Section 3. Air Quality Emissions Algorthim of RSim

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3.1 About the Air Quality Module

The Air Quality Module (AQM) estimates how demographic and economic growth, technology advances, activity change, and land cover transformations affect ground-level ozone concentrations in the Columbus – Fort Benning, GA area. The AQM was developed at Georgia Tech and is largely based on air quality computer modeling completed during the Fall line Air Quality Study (1999-2004). Unlike the FAQS models though, the design of the AQM removes the computational load of traditional air quality modeling while remaining flexible enough for the user to test various future scenarios.

3.2 Air quality in and around the Columbus and Fort Benning, Georgia area

Fort Benning is located in parts of Muscogee and Chattahoochee counties in the Columbus, Georgia metropolitan area. Presently, there are local concerns about excessively high ozone and fine particulate matter pollutant concentrations that could affect human and ecosystem health, regulatory compliance, and economic development. Though other pollutants are monitored in the region (e.g. sulfur dioxide, lead, and coarse particulate matter), there is no concern at this time that the concentrations of these pollutants are sufficiently high enough to be having any significant health or regulatory impacts. Thus, the focus of this analysis is on ozone and fine particulate matter.

3.2.1 Ozone

Ozone is not directly emitted into the atmosphere from any known source in any significant quantities. It is formed in the atmosphere from other chemical precursors that are emitted into the atmosphere from both human and natural sources. Sunlight provides the energy that drives the atmospheric photochemical reactions, and production peaks in the summer months when the sun's rays are most intense. The Georgia Environmental Protection Division (EPD) has operated two ambient ozone monitors in Muscogee County and near Fort Benning since the early 1980s. Data from the Crime Lab station northwest of Columbus and near the northernmost boundary of Fort Benning (see Figure 3.1) is available for all years between 1981 and present and for the months April through October. Data from the Airport station is available for all years between 1983 and present and the months April through October.

The National Ambient Air Quality Standard (NAAQS) for ozone is 0.085 ppmv averaged over 8 hours. Between 1981 and 2002, the Crime Lab station experienced an average of 2.9 days per year on which the NAAQS was exceeded. The worst year for ozone air quality at this station was 13 exceedance days in 1999. In contrast there have been many years when no violations of

Figure 3.1 Air quality monitoring in the Columbus / Fort Benning region of Georgia.

the 8-hour ozone NAAQS were recorded (1982, 1985, 1989, 1991, 1993, and 2001). The all-time highest 8-hour average ozone concentration recorded at this site is 0.105 ppmv recorded on 18 July 2000. As Figure 3.2 shows, there is a slight seasonal increase in ozone concentrations during the summer months. The average summer daily peak 8-hour average ozone concentration (June, July, August) is 0.050 ppmv.

Between 1983 and 2002, the Airport station experienced an average of 3.4 days per year on which the NAAQS was exceeded. The worst years for ozone air quality at this station were 1986, 1998, and 1999 when ozone concentrations exceeded the standard on 9 days of each year. Like the Crime Lab station however, there were also several years when no violations of the air quality standard were recorded (1985, 1989, 1992, 1993, and 2001). The all-time highest 8-hour average at this site is 0.117 ppmv recorded on 11 July 1983. Like the Crime Lab station, Figure 3.3 shows a slight seasonal increase in ozone concentrations during the summer months at the Airport station. The average summer daily peak 8-hour average ozone concentration (June, July, August) is 0.050 ppmv.

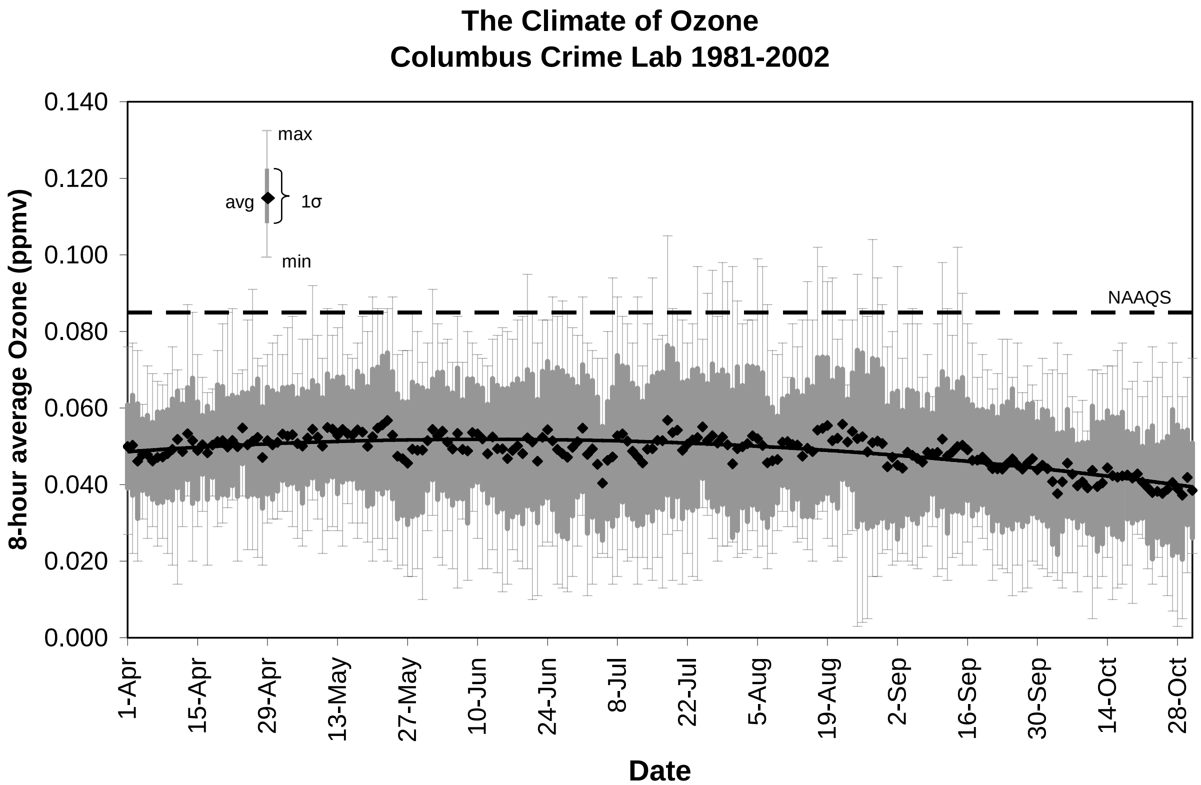

Figure 3.2 Long-term ozone season trends at Columbus Crime Lab station (data, GA EPD).

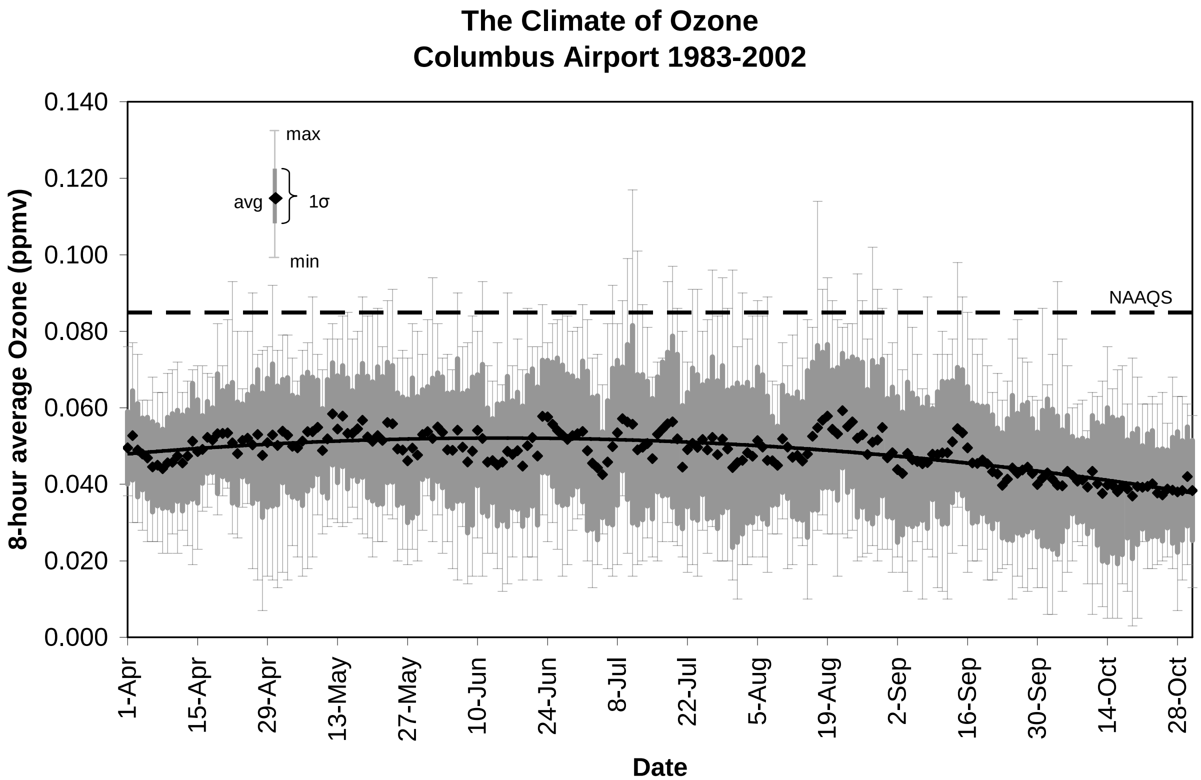

Figure 3.3 Long-term ozone season trends at Columbus Airport station (data, GA EPD).

A third ozone air quality monitor in the region was established in 2000 in the far southwestern corner of Muscogee County at the Oxbow Meadows Environmental Learning Center (see Figure 3.1). This monitor, discontinued in 2004, was part of the Fall line Air Quality Study (FAQS) being conducted by Georgia Tech on behalf of the State of Georgia (Chang et al. 2004). While there were some slight variations with the two long running GA EPD monitors, concentrations and trends were generally the same as the other two sites over the course of operations.

The US EPA designated areas as attainment or nonattainment of the 8-hour ozone NAAQS in April 2004. At that time and using data from 2001-2003, the design value[1] for the Columbus Crime Lab monitoring station was 0.073 ppmv and the design value for the Columbus Airport monitoring station was 0.074 ppmv. As a result of those design values at that time, the Columbus area was designated attainment for the 8-hour ozone NAAQS. Most recently, there were no exceedances of the ozone NAAQS at either the Crime Lab or Airport monitoring stations in 2003, 2004, or 2005. There were, however, three exceedances of the ozone NAAQS in 2006, all at the Airport station. Regarding design values, the Airport station reached a peak of 0.093 ppmv for the period 1998-2000 and during the same time period, the Crime Lab station also reached a peak design value of 0.089 ppmv. See Figure 3.4.

[1] The design value is the 3-year average of the annual 4th highest 8-hour average ozone concentrations. If this value is greater than or equal to 0.085 ppmv, the area would meet the requirements for US EPA to designate it a “nonattainment” area for ozone, subject to the rules and regulations of the Clean Air Act.

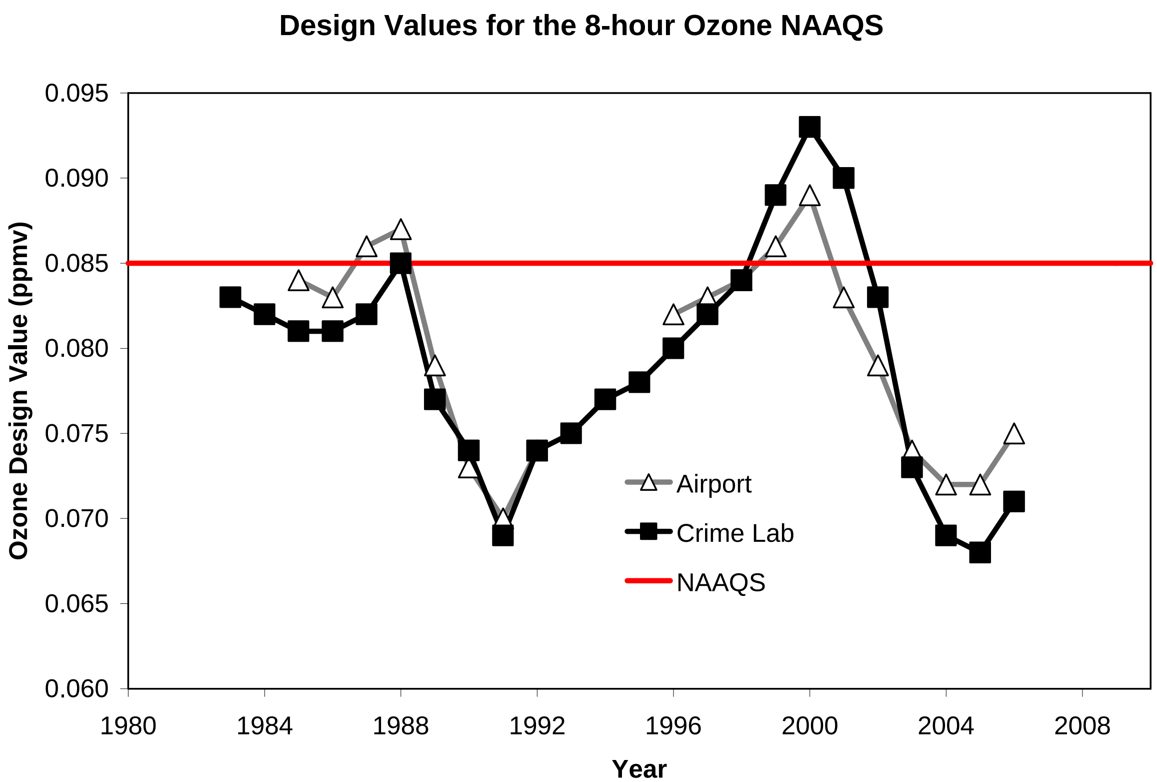

Figure 3.4 8-hour ozone design values in the Columbus, GA area, 1983-2006.

3.2.2 Fine Particulate Matter

Fine particulate matter consists of liquid and solid aerosols having diameters of 2.5 microns or less. It is both emitted directly into the atmosphere as a primary pollutant, and forms in the atmosphere as a secondary pollutant resulting from physical and chemical combinations in the atmosphere. The GA EPD began monitoring fine particulate matter ($PM_{2.5}$) in 1999 at two stations: Cusseta Road School and the County Health Department. See Figure 3.1. Samples at these two stations are collected every 3 days. The NAAQS for $PM_{2.5}$ is 15 $\mu g/m^3$ for an annual average and 65 $\mu g/m^3$ for a daily, 24-hour average[2]. The annual average, peak daily maximum, and 98th percentile concentrations are shown for each year 1999 through 2005 in Table 3.1. Generally, higher concentrations of $PM_{2.5}$ were observed early in the period with lower concentrations following later.

The US EPA designated areas as attainment or nonattainment for the $PM_{2.5}$ NAAQS in December 2005. Using data from 2002-2004, the Columbus area was designated as being in attainment at that time. In September 2006, the US EPA proposed lowering the $PM_{2.5}$ daily NAAQS from 65 $\mu g/m^3$ to 35 $\mu g/m^3$.

[2] The annual standard is met when the three year average of the annual average PM2.5 concentration is less than 15 $\mu g/m^3$. The daily standard is met when the three year average of the 98th percentile PM2.5 concentration is less than 65 $\mu g/m^3$.

Table 3.1 PM2.5 trends in the Columbus / Fort Benning, Georgia region (US EPA).

	County Health Department				*Cussetta Road School*			
	Annual avg	3-yr avg Annual	98% Daily	3yr avg Daily	Annual avg	3-yr avg Annual	98% Daily	3yr avg Daily
1999	18.3		36.9		19.0		41.7	
2000	16.7		31.4		19.3		51.4	
2001	15.4	16.8	34.3	34.2	15.9	18.0	46.4	46.5
2002	14.2	15.4	30.8	32.2	13.8	16.3	31.2	43.0
2003	14.5	14.7	32.4	32.5	13.1	14.3	28.8	35.5
2004	14.7	14.5	37.4	33.5	15.1	14.0	41.4	33.8
2005	15.1	14.8	29.1	33.0	13.6	13.9	29.6	33.3

Continuous (as opposed to every 3 days by the GA EPD monitors) $PM_{2.5}$ measurements conducted during the FAQS in 2001 captured an exceptional event associated with a wildfire at Fort Benning. Figure 3.5 shows short-term $PM_{2.5}$ concentrations in the hazardous range during a three week span in October and November of 2001. Events such as these require further analysis, but suggest that wildfires and perhaps even prescribed burning activities at or near Fort Benning could have a significant short-term impact on local air quality.

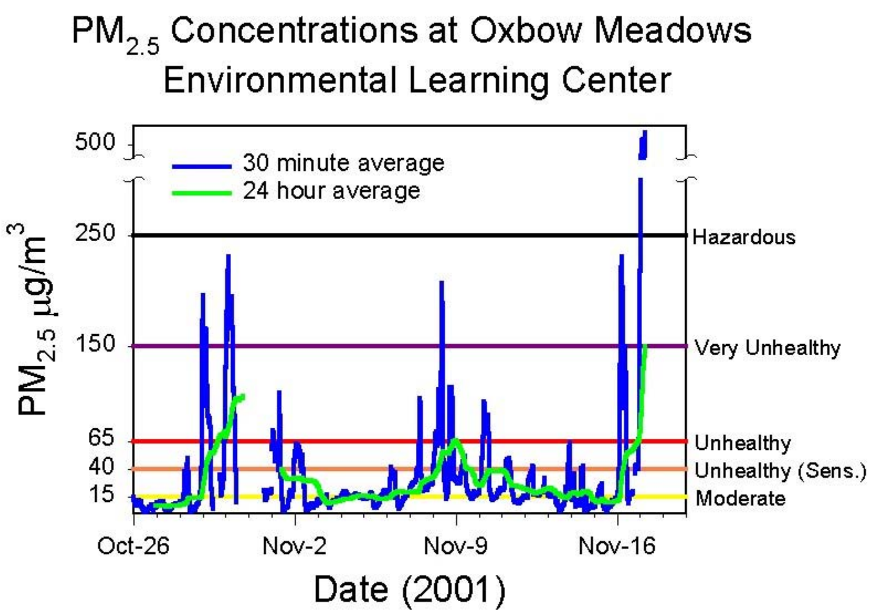

Figure 3.5 $PM_{2.5}$ concentrations at the Oxbow Meadows Environmental Learning Center during a series of wildfire events at Fort Benning.

3.3 Scope of the RSim Air Quality Module

As of October 2006, the Columbus – Fort Benning area is in attainment of all applicable air quality standards. Based on observed pollutant concentrations from the last decade (1996-2005), however, the area has on occasion seen both ozone and fine particulate concentrations that exceed federal air quality standards. Based on this history, it is reasonable to be wary of recurrent risks from both of these pollutants in the future. From its conception though, the RSim was intended to include only the means to assess impacts on future ozone air quality. Thus, RSim at this time, includes only future year impacts on ozone – estimated as the design value and relative to two selected meteorological events from 1999.

As noted previously, ozone concentrations reached historical maxima in the latter half of the 1990s, with 1999 being one of the worst years for the number of days exceeding the 8-hour ozone NAAQS. Meteorology in the southeastern U. S. in the late 1990s can generally be characterized as hot, dry, and stagnant relative to other years – conditions that are conducive to poor ozone air quality. As a historically "worst year," it is practical to assume that 1999 defines the upper limit of expectation for poor air quality, and that if one can "design" a management strategy that succeeds under this worst scenario, one can define a strategy that will be sufficiently effective for all scenarios past, present, and future. Ozone design values in the Columbus area in 1999 (using data from 1997 to 1999) ranged from 0.086 ppmv at the Airport monitoring station, to 0.089 ppmv at the Crime Lab monitoring station. Meteorological episodes for this RSim application were chosen that resulted in ozone concentrations that are near these ozone design values. On 4 August 1999, the Columbus area experienced an ozone event in which the peak 8-hour average ozone concentration was 0.083 ppmv. Several days later on 7 August 1999, the peak observed 8-hour average ozone concentration was 0.089 ppmv. In RSim then, the user can select between a mild ozone event, 4 August 1999, or a more extreme ozone event, 7 August 1999, to simulate air quality outcomes. Under either scenario and as the simulation progresses, the challenge for the user will be to find a means to manage air quality in order to keep the area in attainment or bring it back into attainment under these difficult meteorological conditions.

3.4 The Air Quality Module Algorithm

Air quality (χ) is a function of emissions (**E**), and meteorology (**M**), with $\boldsymbol{\chi}$, **E**, and **M** denoting vector quantities distributed in time and space:

$$\chi = fxn(\mathbf{E}, \mathbf{M})$$

Here meteorology is a constant. That is in RSim, the user selects from two historical ozone pollution episodes: a mild ozone day or a more extreme ozone day as described above. Simulations of future years use the selected meteorology, and any change in air quality relative to the base year is due only to a change in emissions:

$$\Delta\chi = fxn(\Delta\mathbf{E})$$

or

$$\chi_{\text{future}} = \chi_{\text{base}} + fxn(\Delta\mathbf{E})$$

The change in emissions is simply the growth in emissions from the base year (in the case of the air quality module, the base year is 1999):

$$\Delta\mathbf{E} = \mathbf{E}^{T}\mathbf{G}$$

Where

G is a vector of growth factors for each source type by location and future year (e.g. G may specify that mobile source emissions in Muscogee County may be expected to increase by 20% in the year 2030 relative to mobile source emissions in Muscogee County in the year 1999, and in the same location for the same period, industrial sources may only be expected to grow by 13%. As per the conventions of matrix algebra, $\mathbf{E}^{T}$ is the transpose of **E** for the base year.

Finally, the $fxn(\Delta \mathbf{E})$ is defined as:

$$\Delta\chi = fxn(\Delta \mathbf{E}) = \Delta \mathbf{E}^T \mathbf{P}$$

Where

P is a matrix of sensitivity coefficients making up the Area of Influence that relates changes in emissions ($\Delta \mathbf{E}$) to changes in air quality ($\Delta\chi$) and are provided by the full air quality model runs of the Fall line Air Quality Study (that is changes in air quality from the basecase were calculated for every small change in emissions from each source using the fully functional four-dimensional photochemical transport grid model developed for the FAQS and external to RSim).

Thus, the final form of the Air Quality Module is:

$$\chi_{future} = \chi_{base} + \mathbf{E}^T_{base}\mathbf{G}_{future}\mathbf{P}$$

3.4.1 Base Air Quality (χ_{base})

Ambient ozone (O_3) is a product of a series of chemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides (NOx). These reactions are directly activated by the sun's rays, and the more intense the sun, the more active are the chemical reactions. Somewhat indirectly, the sun also works to accelerate the chemical reactions as many of them are heat sensitive – the hotter it becomes, the faster are the reactions. The warmth of the sun also increases the rate of emissions of ozone precursors into the atmosphere, both VOCs and NOx. Thus, ozone formation is more favored on hot, sunny days than it is on cool, cloudy days.

$$\text{NOx} + \text{VOCs} + \text{sunlight} \rightarrow O_3$$

Once ozone is formed, advection and ventilation rates determine whether the pollutant readily disperses or slowly accumulates. On windy days or days when the atmosphere is vertically well mixed, ozone concentrations as measured at ground-level tend to be lower relative to other days when the air is stagnant. In summary, ozone concentrations largely depend on day-to-day meteorology. The goal of the RSim AQM, however, is to allow the user to explore how change in land-cover and land-use will affect air quality over the long-term without the confounding interference of short-term variants like meteorology. For this reason, users select a baseline meteorological episode which is then kept constant throughout the simulation period.

Using a Classification and Regression Tree (CART) technique, ozone and meteorological data for 1712 days between 1996 and 2003 were analyzed. The CART analysis leads to a separation of days into "bins" of similar meteorological conditions and when paired with observations of ground-level ozone, it is possible to identify meteorological regimes that have a higher tendency to coincide with higher concentrations of ozone. For the years 1996 to 2003, each day was classified by its meteorology into one of 31 different bins. Additionally during this period, there were 294 days on which the 8-hour ozone NAAQS was exceeded at one or more monitoring stations in Georgia. In some meteorological classifications (i.e. bins), exceedances of the 8-hour ozone NAAQS were rare. In others, they occurred with more frequency. There was one bin, however, that contained far more exceedance days than any other. In this single bin alone, 65 (22%) of the 294 exceedances were observed. The next most frequent bin contained only 34 (12%) of the exeedance day events. One may conclude from this analysis that the meteorological conditions represented by this one bin are most often associated with exceedances of the 8-hour ozone NAAQS in Georgia, and it is from this pool of 65 days that we selected two meteorological episodes to use in our RSim AQM: 4 August 1999 and 7 August 1999. While these two days are not the worst days for ozone air quality, they are near the 8-hour ozone design value for 1999 (Figure 3.4), and thus are representative of the Columbus – Fort Benning area's air quality relative to the form of the NAAQS (i.e. the 3-year average of the 4th annual daily peak 8-hour average ozone concentration). It is from these episodes that the user can select from for χ_{base}. In the RSim AQM, however, these days are not actually represented directly. They are represented though the air quality model simulations of these days conducted during the Fall line Air Quality Study (Change et. 2004). See for example, Figure 3.6.

Table 3.2 Atmospheric conditions on 4 August 1999 and 7 August 1999 in the Columbus – Fort Benning area.

*Columbus Metro Area**	*4 August 1999*	*7 August 1999*
Peak O_3 (ppb)	83	89
Prior Day Peak O_3 (ppb)	83	97
Max Temp (C)	34	37
Min Temp (C)	24	24
Average Dewpoint (C)	67.5	64.7
Average Wind Speed (mph)	3.4	3.7

* O_3 data from GA EPD at the Crime Lab and Airport stations, meteorological data from the NWS at the Airport station.

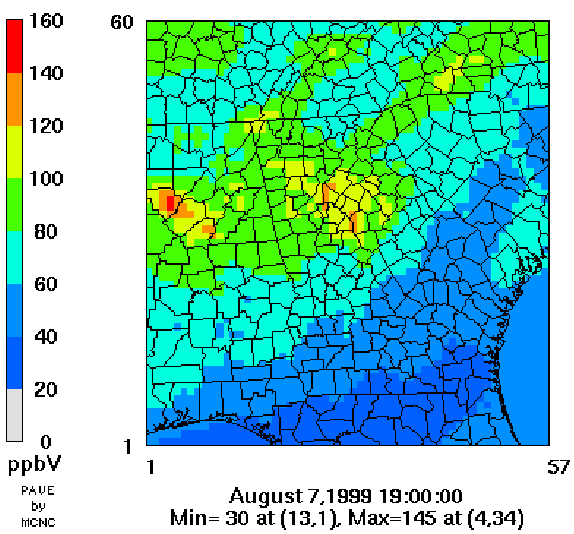

Figure 3.6 FAQS simulation of 8-hour ozone on 7 August 1999.

The air quality models of the Fall line Air Quality Study are fully described elsewhere including evaluations of the model performance (Chang et al. 2004). It is sufficient to say here that the FAQS models are reasonable representations of air quality in the Fall Line cities of Georgia including Columbus. As a model though, there are differences between the simulated concentrations and observed concentrations that should be noted. For example, on 4 August 1999, the simulated peak 8-hour average ozone concentration in the Columbus area was 79 ppb rather than the 83 ppb that was observed. Similarly, on 7 August 1999, the simulated peak 8-hour average ozone concentration in the Columbus area was 81 ppb rather than the

89 ppb that was observed. Differences such as these are typical for almost all air quality models. Nonetheless, we "correct" for these differences in the RSim AQM by scaling the base and future model predicted values to the appropriate observed value. For example, using the mild ozone episode of 4 August 1999, the simulated peak 8-hour average ozone concentration is 79 ppb whereas the observed ozone concentration is 5% higher at 83 ppb. Thus, for this episode, all base and future year simulated ozone concentrations are scaled higher by 5%.

3.4.2 Base Emissions ($\mathbf{E}_{base}$)

Prior to the Fall line Air Quality Study (FAQS), the Columbus, Georgia area was never the focus of an air quality assessment and thus, no emission inventory had been specifically developed for the region. The area has been included peripherally in other large regional studies including the Ozone Transport Assessment Group (OTAG, US EPA, 1998)), the Southern Appalachian Mountain Initiative (SAMI), and the Gulf Coast Ozone Study (GCOS) but at a more coarse resolution than has been done in the FAQS. Here then, the emissions inventories developed for the FAQS (and fully described in Chang et al. 2004) are the bases for the inventories used in RSim.

Emissions are considered in five source categories: point, area, non-road, mobile, and biogenic. Point sources are large stationary industries such as coal fired power plants. Area sources are small stationary ventures and may include sources such as dry cleaners, gas stations, or residential water heaters. Non-road sources include construction, lawn and garden, railroad, and farming equipment. Mobile sources are limited to on-road vehicles, i.e. cars, trucks, and motorcycles. Finally biogenic sources are natural such as trees, crops, lightening, and soil microbes. Table 3.3 summarizes the base year (1999) emissions in the Columbus area and other metropolitan areas in Georgia.

Table 3.3 Episode average daily emissions during August 1999 (tons per day)

	Point		*Area*		*Non-road*		*Mobile*		Biogenic	
	NO_X	VOC	NO_X	VOC	NO_X	VOC	NO_X	VOC	NO	VOC
Augusta	18.73	7.00	3.24	37.38	9.68	6.70	33.93	22.88	2.90	435.12
Columbus	9.76	10.16	2.74	27.25	7.90	4.76	23.21	17.18	1.14	338.04
Macon	173.73	8.42	3.70	38.05	13.48	6.32	47.39	28.87	1.59	313.89
Atlanta	87.37	31.38	48.5	173.66	116.37	77.66	295.58	178.82	2.56	827.08
Georgia	829.98	135.41	111.41	711.44	310.7	188.9	846.98	525.38	64.97	11505.26

It is worth noting the sizable difference in biogenic VOC emissions relative to the other sources of VOCs. Eliminating all VOCs of human origin (i.e. point, area, non-road, and mobile), would have little effect on the total VOCs. Conversely, significantly increasing (e.g. doubling) VOC emissions from any human source would not substantially add to the total VOC load either. Thus, as a means to effect change in ozone concentrations (NOx + VOCs + sunlight $\rightarrow O_3$), VOC change is generally inconsequential. This is a well noted phenomenon for most of the southeastern U. S. (Chameides and Cowling, 1995), and it is for this reason that the RSim AQM focuses only on changes in NOx emissions and how those changes affect ozone concentrations.

3.4.3 Future Growth ($\mathbf{G}_{future}$)

To estimate how emissions will change in the future, emission growth factors for the Columbus, GA area are predicted using two EPA models: the Economic Growth Analysis System (EGAS, US EPA 2004a and 2004b) and NONROAD (US EPA 2006). EGAS "is an emissions activity forecast software model that provides State and local governments with an EPA-approved set of emissions activity growth factors [for point, area, and mobile sources]" (Bowman and Stella, 2001). The NONROAD model is a similar model dealing specifically with emissions from nonroad mobile engines, equipment, and vehicles. With these models it is possible to estimate emissions change for any year for any Source Classification Code (SCC)[3] in any county of the United States. EGAS Version 5.0 provides growth factors out to the year 2035, and NONROAD2005 provides growth factors out to the year 2050. One further point of distinction is that the NONROAD projections include the effects of some federally defined default controls on emissions (e.g. new rules limiting emissions from heavy duty diesel engines). The EGAS projections on the other hand, reflect only changes in future activity relative to the base year and do not include any projected controls on emissions from point, area, and mobile sources.

As implemented here, EGAS Version 5.0 and NONROAD2005 were run offline to generate growth rates for every SCC code for every year available. These growth rates were then aggregated into the broader categories of point, area, nonroad and mobile sources by taking a weighted average for each source category based on the percentage of each SCC source in the county's total base year (1999) emissions. These average growth rates for point, area, nonroad, and mobile sources are then used directly in the RSim AQM to grow the emissions for each source category in each county. For longer term growth projections that extend beyond the scope of growth factors provided by EGAS (i.e. out to the year 2035) or NONROAD (i.e. out the year 2050), a linear extrapolation is used.

One exception to using EGAS or NONROAD as the basis for growth factors is for prescribed burning. Neither model support growth factors for prescribed burning, so in the RSim AQM changes in prescribed burning activity are coupled to changes in forest land cover (LC):

$$G(\text{burning})_{future} = LC(\text{forest})_{future} / LC(\text{forest})_{base}$$

Further, since NOx emissions from prescribed burning accounts for 17% of base year emissions in the area source category, the overall area source growth factor is the weighted accordingly:

$$G(\text{AREA}) = 0.83*(\text{other area sources from EGAS}) + 0.17*G(\text{burning})$$

This combination of land cover surrogates for prescribed burning, and EGAS, NONROAD, and linear extrapolations thereof for all other emissions sources, represent the default emissions projections used by the RSim AQM. The module also allows the user additional opportunities to scale these projections up or down based on the user's own growth

[3] Source Classification Codes uniquely identify different emissions sources in the point, area, nonroad, and mobile source categories. The US EPA maintains a current database of SCCs at http://www.epa.gov/ttn/chief/codes/scc_feb2004.xls.

projections, ideas about future controls, or desires to evaluate the sensitivity of air quality outcomes to different emissions scenarios. On the Air Quality Module interface, see Figure 3.7, the user has the option of entering "Emission Growth Scaling Factors" for point, area, nonroad, and mobile sources. The default scaling factors are 1.0, which means that the default emissions projections, as described above, will be used. Beyond the default, users may input any value from +2 to -2 for a growth scaling factor. The user should understand that the growth scaling factor scales the <u>rate</u> of emission change and <u>not the amount</u> of emissions directly. The effects of different growth scaling factors on the rate of emission change are summarized in Table 3.4. The effects of these scaling factors on the amount of emissions are shown in Figures 3.8 through 3.11.

Figure 3.7 RSim Air Quality Module user interface.

Table 3.4 Effect of different emission growth scaling factors on rate of emissions change.

Emission Growth Scaling Factor, X	Future Emission Trend
1 < X < 2	Emission trend change greater than the default change in emissions
X = 1	Default change in emissions
0 < X < 1	Emission trend change smaller than the default rate of change
X = 0	No change in emissions over time
-1 < X < 0	Emissions change that is opposite of the default change and at a smaller rate
X = -1	Emissions change that is exactly opposite of the default rate of change
-1 < X < 2	Emissions change that is opposite of the default rate of change and greater

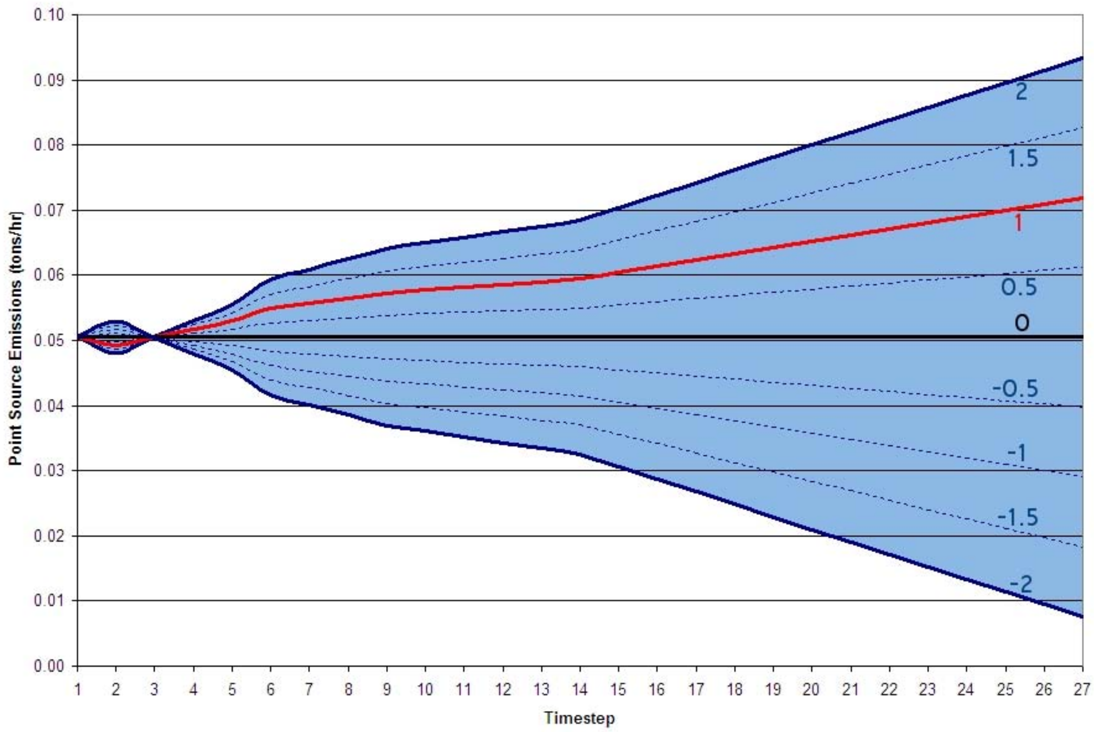

Figure 3.8 Effect of different growth scaling factors on emissions of point sources in the Columbus – Fort Benning area. Note: the default projection is for point source emissions to initially decrease; before year 4, negative scaling factors paradoxically increase emissions.

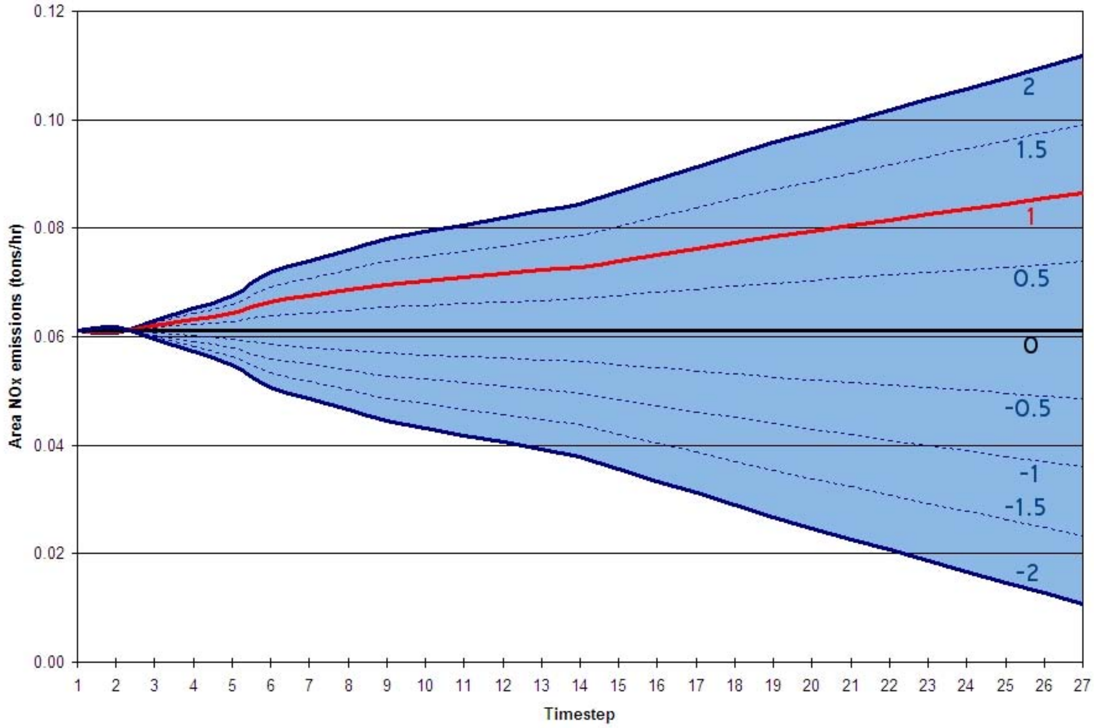

Figure 3.9 Effect of different growth scaling factors on emissions of area sources in the Columbus – Fort Benning area.

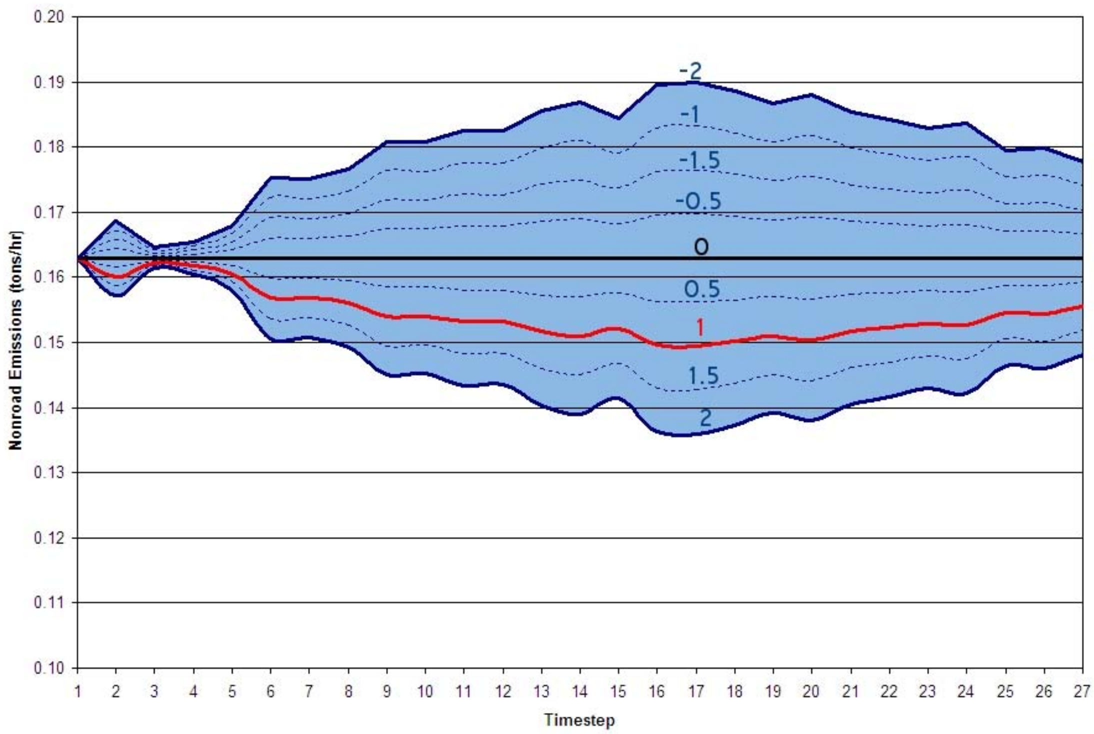

Figure 3.10 Effect of different growth scaling factors on emissions of nonroad sources in the Columbus – Fort Benning area. Note: the default projection is for nonroad source emissions to decrease and the user should notice that negative scaling factors increase emissions.

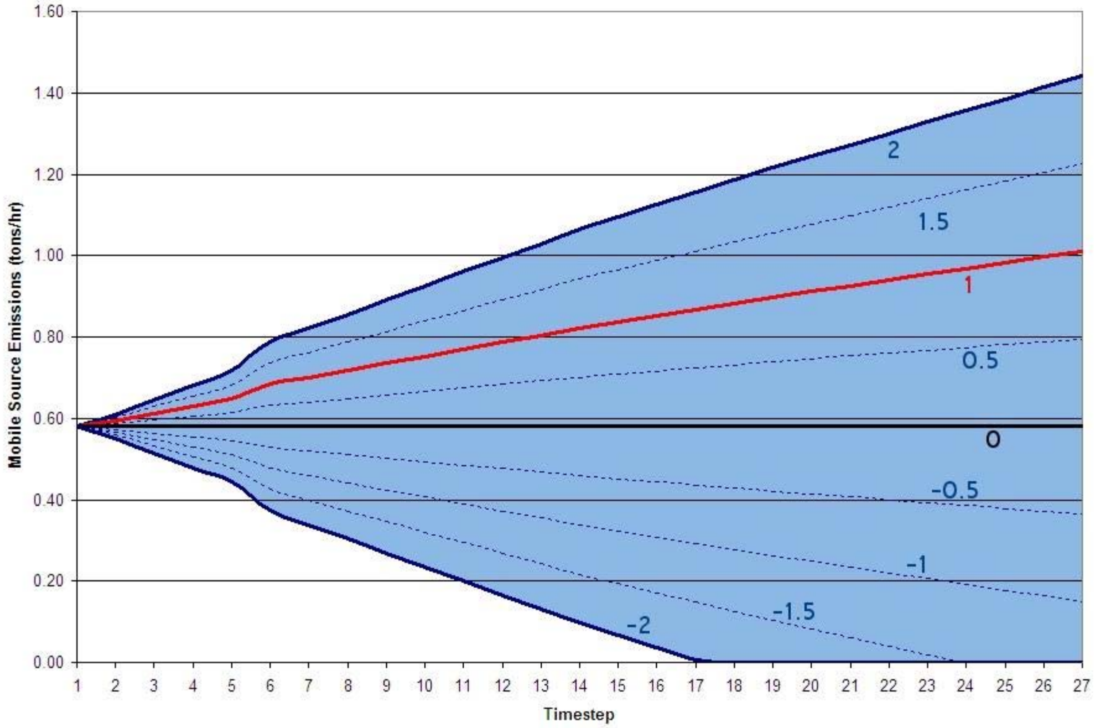

Figure 3.11 Effect of different growth scaling factors on emissions of mobile sources in the Columbus – Fort Benning area.

Example: Using Growth Scaling Factors

- Suppose a user expects that population growth will lead to an increase in vehicle miles traveled (VMT) in the Columbus area that is 25% higher than the default rate of increase. This can be simulated by changing the default emissions growth scaling factor for mobile sources from 1.00 to 1.25.
- Alternatively, suppose the user believes that automobiles will emit 50% less NOx per mile traveled in the future than they do now. This can be simulated by changing the default emissions growth scaling factor for mobile sources from 1.00 to 0.50.
- Finally, suppose that the user expects both an increase in VMT of 25% and a decrease in NOx emissions per mile traveled of 50%. This can be simulated by changing the default emissions growth scaling factor for mobile sources from 1.00 to 0.625 (i.e. 1.25 X 0.50)

3.4.4 Sensitivity Coefficients (**P**)

Sensitivity coefficients (S) measure the change in model response due to a change in some model parameter. Here, we are most interested in the change in ozone concentrations at location i, $(\Delta O_3)_i$, due to changes in emissions from source j at location k, $(\Delta E)_{jk}$.

$$S_{i,jk} = (\Delta O_3)_i / (\Delta E)_{jk}$$

These sensitivity coefficients can be readily and efficiently calculated using a comprehensive 3-dimensional photochemical grid model and were so done in the Fall line Air Quality Study (Cohan et al. 2005, Chang et al. 2004).

Traditionally, sensitivities relate the impact of a change in emissions from a single source on air quality in many locations. For example, Figure 3.12 shows the response of ozone concentrations to emissions of NOx in the Columbus area. These types of sensitivity analyses would, however, require many model runs to determine the impact on air quality in a single location to emissions from many sources. Recent work at Georgia Tech to reinterpret traditional sensitivities has led to a new approach to define an area of influence (AOI) (Habermacher 2006, and Napelenok 2006). The AOI indicates how emissions across the domain impact air quality in a specific area. Figure 3.13 shows how potential NOx sources from across the region may affect air quality in Columbus. For the RSim AQM, it is these AOI coefficients that are used. Calculated external to the RSim AQM using the full FAQS air quality model, this array of sensitivities, **P**, relate changes in air quality at all locations i=1,m to changes in all sources j=1,n at all locations k=1,p.

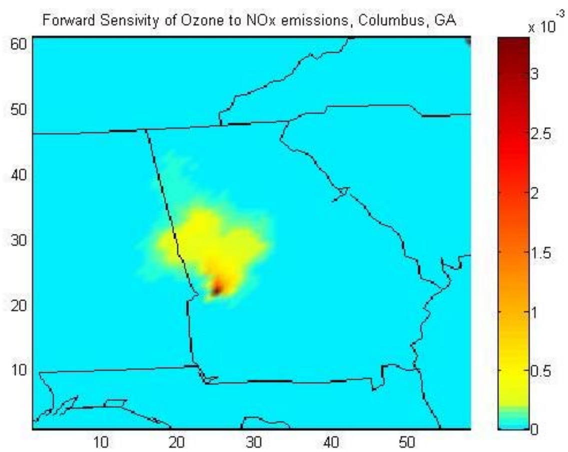

Figure 3.12 Ozone sensitivity to NOx emissions in Columbus, GA on 7 August 1999 (units are ppm O_3 per mole/s of NOx).

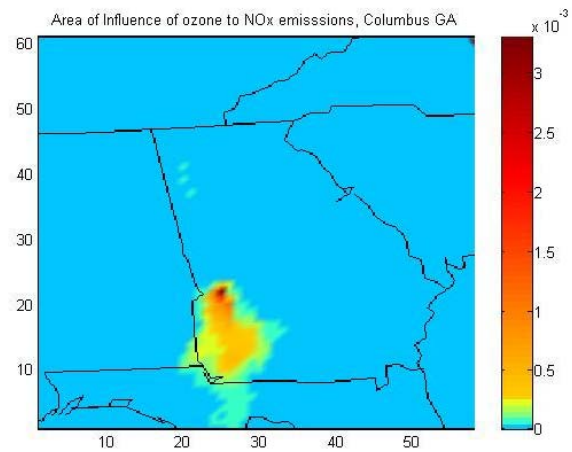

Figure 3.13 Area of Influence affecting ozone concentrations in Columbus, GA on 7 August 1999 (units are ppm O_3 per mole/s of NOx).

3.5 Integration of the AQM into RSim

The description of the Air Quality Module above is a highly simplified version of a stand-alone air quality model in which land use and land cover, as is typical for most air quality modeling applications, are assumed to remain constant. Assuming that land use and land cover remain constant is sufficient for most air quality modeling applications because they mostly deal with relatively short time frames (3 to 7 years) in which land use and land cover, at the regional scale at least, remains relatively unchanged. RSim, however, addresses longer time scales (25 years or more) in which significant land use or land cover changes may occur. Here we describe the three principal ways in which we have accounted for these potential changes and integrated the Air Quality Module into RSim.

In RSim, the urbanization and road development scenarios (using the default model coefficients) represent land use and land cover defaults, and for these default scenarios, future year growth or change in emissions are already accounted for by the EGAS projections described above. Variations from the defaults, however, will lead to increases or decreases in the various classes of land uses and land covers. We use variations in the transportation land cover class to further scale the mobile sources, the largest source of smog forming precursors in the RSim domain. For example, suppose that in the year 2020, EGAS projects that mobile source emissions will increase by 20% over 1999 emissions. This 20% growth rate is valid assuming the default urbanization and road development scenarios. If the model coefficients are changed by the user, however, such that in the year 2020 there is 10% less land covered by the roadway transportation class than in the default scenario, then the default growth rate in emissions should also be reduced by 10% resulting in an emissions growth rate of 18% (i.e. 20% - 10%*20%). Similarly, the selection of the military expansion scenario could also lead to a change in land cover for the transportation class and lead to changes in the mobile source emissions growth rate. (Note: the military expansion scenario may also lead to changes in the nonroad mobile source emissions and this is dealt with separately as per below). The hurricane scenario does not affect the transportation land cover classes and so has no impact on mobile source emissions.

We assume the rate at which forest land cover that is burned each year under prescribed burning programs will remain constant over the modeling period. Therefore, we can tie future prescribed burning emissions directly to the change in total forest land cover as described by our calculations in the previous section. In RSim, the urbanization, road development, military training, and hurricane scenarios all modify the amount of predicted forest land cover and thereby impact our air quality forecasts.

Finally, the selection of the military training scenario may lead to additional nonroad source emissions associated with the training activities themselves (e.g. heavy duty diesel vehicles, field generators, small or heavy arms, obscurants, etc…). As of October 2006, it is not yet understood what, if any, additional scaling factor may be required to account for any such changes in training activity, and so this connection has not been directly coded into the RSim AQM at this time. If this becomes known in the future, it is possible to approximate an increase in training activities by adjusting the emissions growth scaling factor for nonroad sources as described in section 3.4.3.

In summary, changes in land cover or training activity can affect future year emissions from mobile sources, prescribed burning sources, and nonroad mobile sources. By default, the AQM accounts for changes in prescribed burning activity by automatically scaling this source up or down with changes in forest land cover. The effects on air quality from changes in military training activity are not explicitly provided for in the AQM, but they may be approximated by making the appropriate adjustment to the nonroad source emissions growth scaling factor. This leaves only the changes in the transportation land cover class unaccounted for in the AQM. Any such modifications (**L**) are applied to the growth factors (**G**) described above such that:

$$\chi_{future} = \chi_{base} + \mathbf{E}^{T}_{base}[\mathbf{L}^{T}\mathbf{G}_{future}]\mathbf{P}$$

where

L is a vector of modifiers to the growth factors that are derived from changes in the transportation land cover class:

$$LC(transportation)_{future,scenario\ i} / LC(transportation)_{future,default\ scenario}$$

Lastly, it should be noted that RSim recognizes that output from the air quality module can affect the ecology of the RSim domain by including language about ozone causing foliar damage in trees, crops, and other vegetation, as well as other effects. The output page includes a statement regarding the number of simulation years in which the secondary ozone standard is exceeded. Due to the variability of effects across the breadth of flora (and fauna), however, there is no way at this time to provide a more quantitative direct feedback into the RSim land cover (e.g. we could not code into RSim something akin to the following: for every 10 ppb increase in ozone, the forest land cover class will diminish by 1%). We expect such feedbacks to in fact occur, but are unable to justifiably quantify them at this time. Instead, we provide a qualitative statement to alert the user to such possible effects.

We have selected the ozone secondary standard (0.08 ppm) as the ecological risk threshold of importance in RSim. Numerous effects levels for particular crop and tree species are available in the current Ozone Criteria Document. Some thresholds for effects are expressed via the SUM06 metric (Sum of hourly ozone values greater than 0.06 ppm summed over 12 hours [0800-2000] during a 3-month growing season period) rather than ozone concentrations in air. For the Columbus, GA, region, the 4th highest ozone concentration is tightly related to SUM06. The secondary standard of 0.08 ppm is close to a SUM06 value of 20 ppm-hrs. In 1996 the Emission and Effects Task Group of the Southern Oxidant Study Program recommended a secondary ozone standard of 15 to 20 ppm-hrs SUM06 in 1996 (Cowling and Furiness 2004), based on reductions in crop yield at this range, growth effects on natural forest trees (10-15 ppm-yrs), and growth effects on plantation trees (12-16 ppm-hrs). Thus, RSim's result that adverse effects on vegetation growth or yield are likely at 4th highest 8-hr ozone concentrations above 0.08 ppm should be reasonable.

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Section 4: Water quality and Nitrogen and Phosphorus Export

Predictions of Annual Nitrogen and Phosphorus Export

1. Introduction

The purpose of the water quality submodel is to predict changes in annual nitrogen (N) and phosphorus (P) exports from watersheds within the 5-county (Harris, Muscogee, Marion, Chattahoochee, Talbot) RSim region surrounding Fort Benning, Georgia. It is widely established that land use and land cover are principal determinants of nutrient export from terrestrial ecosystems to surface receiving waters. The water quality submodel predicts total (kg yr^{-1}) and normalized (kg ha^{-1} yr^{-1}) losses of N and P from 48 watersheds within the region over the time frame of RSim scenarios. Predicted changes in water quality are strongly coupled to future changes in land cover that result from urbanization, changes in agriculture, and disturbance events.

2. Approach

Calculations of annual N and P export are performed for the 48 12-digit hydrologic units (HUC) that are included within the RSim region (Figure 1). The method is based on land cover area (ha) within each watershed and annual nutrient export coefficients (kg element ha^{-1}) specific to each of the eight land cover types (Table 1). The area (ha) of each land cover category is multiplied by its respective export coefficient (Table 2) and the products are summed for all land covers to estimate the annual flux (kg element yr^{-1}) of N or P from each watershed. The exports (kg yr^{-1}) are also normalized for the size (ha) of the watershed to yield an area-normalized N or P export (kg element ha^{-1} yr^{-1}). The 48 12-digit HUCs range in size from approximately 3200 to 12000 ha.

2.1 Land Cover Classification

Twenty-eight different land cover categories, based on NLCD land cover class definitions, were reclassified into the following broad groups for use in the water quality submodel: (1) wetlands, (2) forests, (3) pasture/grass, (4) row crops, (5) idle, (6) industrial, (7) residential, and (8) business. Permanently or seasonally flooded land covers were classified as wetlands. Forests, other than swamps and forested wetlands, were grouped in a single category. Because of their association with industry, transportation corridors were binned with quarries and strip mines into a single industrial category. Other land cover classifications are described in Table 1.

2.2 Export Coefficients

2.2.1 Export coefficients have been widely used to predict total N and P losses from landscapes to surface receiving waters (e.g., Beaulac and Reckhow, 1982; Frink, 1991; Johnes, 1996; Mattikalli and Richards, 1996). An export coefficient is the amount of N or P lost annually from a particular land cover type on an area basis (for example, g N m^{-2} yr^{-1}). Export coefficients can be combined with information on the area of different land uses and/or land covers to predict the annual flux of N and P from terrestrial watersheds. Past studies that have compared predicted and measured nutrient loads appear to validate the use of export coefficients for estimating annual watershed losses of both N and P (Johnes, 1996; Johnes et al., 1996; Mattikalli and Richards, 1996).

2.2.2 Within certain limits, export coefficients for the 8 different land cover categories in the water quality model can be adjusted to the user's specifications. The lower limit for each category is 0 kg element ha^{-1}. The upper limit is twice the default value. Selecting different parameter settings within the allowed range permits the user to examine the sensitivity of predicted N and P exports to changing export coefficients.

2.2.3 Default export coefficients for total N and P from all land covers except row crops and wetlands (Table 2) were adopted from the North Carolina State University (NCSU) WATERSHEDSS Pollutant Budget Estimation Form that is part of the NCSU WATERSHEDSS Decision Support System for Nonpoint Source Pollution Control (Osmond et al., 1995). Default export coefficients for wetlands were taken from a different source (CH2M HILL, 2001).

2.2.4 Default export coefficients for row crops were calculated as a weighted mean based on (1) crops planted in the 5-county region and (2) export coefficients for specific crop types from the WATERSHEDSS Decision Support System (Table 3). Data from the USDA, National Agricultural Statistics Service, Agricultural Statistics Database on acres of major crop types planted from 1996 to 2000 were compiled for each county in the RSim region. There were no reports for Chattahoochee and Muscogee counties that are mostly occupied by Fort Benning. Peanuts, rye, wheat, soybeans, corn, and cotton were the major crops in the 3 remaining counties. Based on a 5-year average, small grains (e.g., wheat and rye) were planted on ≈44% of the region's agricultural land. Cotton, corn, soybeans, and peanuts were ≈8, 12, 15, and 20%, respectively, of the acres planted. The export coefficient for N from peanuts was set to zero (Table 3). Peanuts are a legume and usually receive no N fertilizer because they are sensitive to fertilizer burn. The weighted average export coefficient for N and P from row crops in the RSim region was 6.3 kg N ha^{-1} yr^{-1} and 2.3 kg P ha^{-1} yr^{-1}, respectively (Table 2).

3. Water Quality Outputs

3.1 RSim predictions of N and P exports (kg element yr^{-1}) over time will vary depending on the changing patterns of land cover within each watershed. Trial runs with the water quality submodel indicate that the annual fluxes of both N and P exhibit a significant ($P \leq 0.001$) positive correlation with size of the hydrologic unit ($r = 0.80$ and $r = 0.48$, respectively). However, size of a watershed, the types of land cover within a watershed, and the export coefficients selected for different land covers all influence predicted N and P exports.

3.2 The total area of the 48 hydrologic units in the RSim region is 3570 km^2. Normalized for land area, and based on 2001 land cover, trial runs with the model indicate the predicted regional N and P export is ≈238 and ≈42 kg km^{-2} yr^{-1}, respectively. These predictions need to be verified and revised using the actual RSim model once it is fully operational.

3.3 Calculated nutrient exports for the 5-county RSim region can be put into perspective using data from other regional studies. Average N export from minimally disturbed watersheds in the US is ≈260 kg N km^{-2} yr^{-1} and is strongly related to annual runoff (Lewis, 2002). Nitrogen export from the Mississippi, Hudson and Delaware Rivers (3 major eastern US tributaries) has been estimated at ≈177, 356, and 518 kg N km^{-2} yr^{-1}, respectively (Caraco and Cole, 1999). Median N export from 16 rivers draining large watersheds (475 to 70189 km^2) in the northeastern US over a 5-year study was 518 kg N km^{-2} yr^{-1} (Alexander et al., 2002). Total N and P export in rivers from the southeastern US has been estimated to be ≈675 and ≈32 kg km^{-2} yr^{-1}, respectively, by Howarth et al. (1996). Predicted N export from the 5-county RSim region (238 kg N km^{-2} yr^{-1}) was in the lower range of reported exports for US rivers and approximately twice that (111 kg N km^{-2} yr^{-1}) for a minimally disturbed watershed (Falling Creek) in central Georgia (Lewis, 2002). Predicted regional P export (42 kg km^{-2} yr^{-1}) agreed reasonably well with previously reported export in the southeastern US. The relatively small percentage of cropland (range 0 to 17%) in the 48 watersheds inside the RSim region is one likely reason why predicted N export is in the lower range of N loadings reported by other studies from the eastern US. Export coefficients applied to agricultural land are greater than those applied to forests for both N and P (Beaulac and Reckhow, 1982; Frink, 1991).

3.4 Aside from the effect of agricultural land use on N export from the land to surface receiving waters, reviews of export coefficients for both N and P indicate the importance of urban development (Beaulac and Reckhow, 1982; Frink, 1991). A recent analysis of 35 large river systems from around the world indicates that river N export exhibits a significant positive correlation with population density (Caraco and Cole, 1999). Urbanization and commercial development along the perimeter of Fort Benning and in surrounding counties (Dale et al., 2005) have the potential to alter future exports of N and P from the 48 watersheds within the RSim region. Population growth, road improvements, and increasing urban land cover are key drivers in various scenarios that are addressed by RSim.

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Table 1. Reclassification of 1998 and 2001 land cover categories for RSim.

Reclassified land cover	1998 Land Cover (code)	2001 Land Cover (code)
Wetland	Open water (11) Forested wetland (91)	Open water (11) Woody wetland (90) Herbaceous wetland (95)
Forest	Deciduous (41) Evergreen (42) Mixed (43)	Deciduous (41) Evergreen (42) Mixed (43)
Pasture	Pasture (80)	Pasture (81) Grassland (71)
Idle	Beach (7) Utility swaths (20) Clear-cut/sparse vegetation (31)	Shrub (52) Barren land (31)
Industrial	Transportation (18) Quarries and strip mines (33)	
Residential	Low intensity urban (22) Parks and recreation (72)	Developed, open space (21) Developed, low intensity (22) Developed, medium intensity (23)
Row crops	Row crops (83)	Cultivated crops (82)
Business	High intensity urban (24) Golf courses (73)	Developed, high intensity (24)

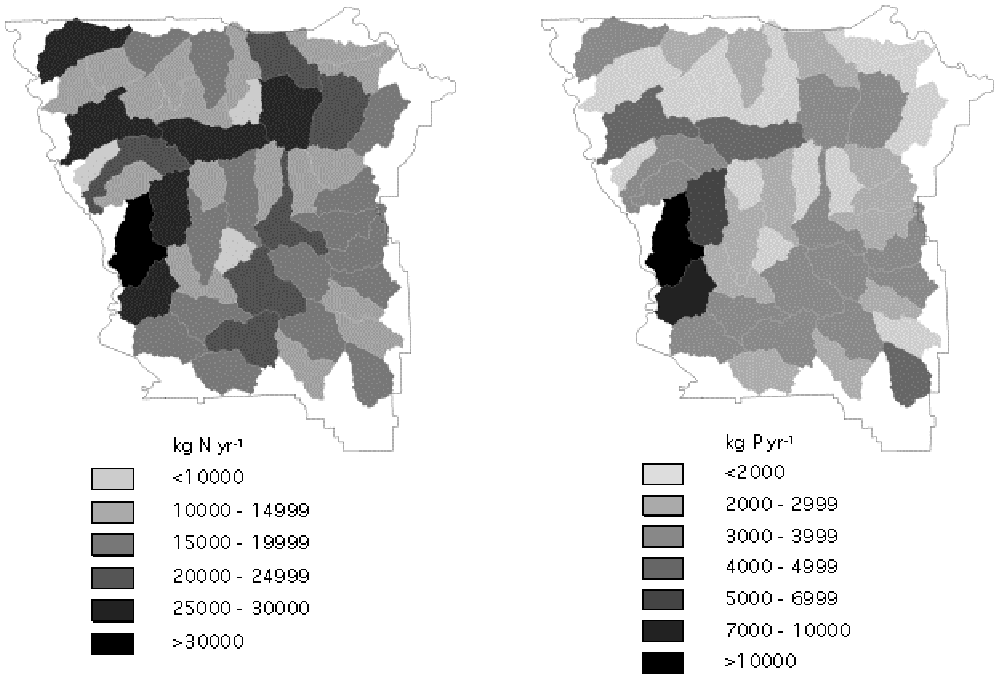
Table 2. Export coefficients for N and P from different land cover categories (from Osmond et al., 1995, and CH2M HILL, 2001).

Revised land cover	Export coefficient	
	kg N ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}
Wetland	5.5	0.25
Forest	1.8	0.11
Pasture	3.1	0.1
Idle	3.4	0.1
Industrial	4.4	3.8
Residential	7.5	1.2
Row crops	6.3	2.3
Business	13.8	3.0

Table 3. Export coefficients for N and P for different agricultural crops (data for corn, cotton, soybeans, and small grains are from Osmond et al., 1995).

	Export coefficient	
Crop type	kg N ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}
Corn	11.1	2.0
Cotton	10.0	4.3
Soybeans	12.5	4.6
Peanuts	0	1.5
Small grain	5.3	1.5

Figure 1. Predicted annual total N export (left panel) and P export (right panel) from 48 12-digit hydrologic units within the 5-county RSim region based on 2001 land cover data.



Landcover Based Predictions of Annual Nitrogen and Phosphorus Export for a Five County Area in Southwestern Georgia, USA

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ABSTRACT

The purpose of this study was to develop a method for estimating annual N and P exports from 48 watersheds within a 5-county region surrounding Fort Benning, Georgia, for use in a regional simulation model (RSim). Export coefficients were combined with data from a geographic information system (GIS) to estimate annual total N and P loads from watersheds within Harris, Muscogee, Marion, Chattahoochee, and Talbot counties. Calculated N loads for the 5-county RSim region (237 kg km^{-2} yr^{-1}) were in the lower range of reported annual exports for US rivers, and calculated P loads (42 kg km^{-2} yr^{-1}) were in good agreement with previously reported annual exports. Stepwise multiple regression analysis indicated that ≥95% of the variance in calculated annual total N or P loads could be explained by the area of forest, industrial, business, and cropland in a hydrologic unit. Urbanization and commercial development along the perimeter of Fort Benning, and elsewhere in the 5-county RSim region, have the potential to alter future N and P exports from affected watersheds. Multiple regression equations for predicting N and P loads on the basis of land cover can be used to assess the effects of future land cover change on regional water quality in the region.

1. INTRODUCTION

This research was undertaken during the development of a spatially-explicit regional simulation model (RSim) to aid military land managers in determining the effects of land use and land cover change on various measures of environmental quality (i.e., noise, air, and water quality). Military installations and the communities that support them have a mutually vested interest in understanding the effects of land use and land cover change on issues related to water quality on private, public, and federal lands. Land use, particularly urbanization and agriculture, is a primary determinant of water quality through controls on nitrogen (N) and phosphorus (P) runoff to surface receiving waters (Carpenter et al., 1998).

Fort Benning, established in 1918, is a primary training facility for the US Army. It is ≈74000 ha in size, and the annual number of troops on-site ranges between 18,000 and 23,000 soldiers. Five Georgia counties

(≈435,000 ha) are either adjacent to or part of the military installation and included in RSim. US census data from 2000 show the population of Harris, Muscogee, and Marion counties increased by 13 to 50% from 1990 to 2000 with the greatest increase around Columbus (Georgia's third largest city) in Muscogee county. Although the population of the two remaining counties (Chattahoochee and Talbot) declined from 1990 to 2000, urbanization is projected to increase in the first half of the 21st century with associated changes in land use and land cover (Dale et al., 2005).

Between 1990 and 2000, Georgia was the sixth fastest growing state in the US. The mix of federal and private ownership in the RSim region leads to complicated land-management issues that may intensify with projected economic growth and development. The purpose of this study was to develop a method for estimating N and P exports from 48 watersheds within a 5-county region surrounding Fort Benning in southwest Georgia for use in the regional simulation model.

2. METHODS

2.1 Land cover map

The method was based on land cover. The land cover map for the 5-county region was derived from a statewide map, produced from Landsat Thematic Mapper satellite data, by the Natural Resources Spatial Analysis Laboratory, Institute of Ecology at the University of Georgia. The map was a mosaic of cloud-free scenes, mostly from 1998 with some data from 1996 and 1997. The statewide map included 28 different land cover categories and had an overall accuracy of ≈85%. The area (ha) of each land cover category in a hydrologic unit was calculated by the GIS.

2.2 Land cover reclassification

The original 28 land cover categories in the 1998 land cover map were reclassified into 8 general land covers for use with N and P export coefficients (Table 1). Permanently or seasonally flooded land covers were classified as wetlands. Forests, other than swamps and forested wetlands, were grouped into a single category. Because of their frequent association with industry, transportation corridors were binned with quarries and strip mines into a single industrial category. High intensity urban areas and golf courses were reclassified into a “business” land cover.

Table 1. Reclassification of 1998 land cover map.

Reclassified land cover	Original land cover (numeric code)
Wetland	Open water (11) Cypress gum swamp (890) Freshwater marsh (930) Shrub wetland (980) Evergreen forested wetland (990)
Forest	Urban forest deciduous (201) Urban forest evergreen (202) Urban forest mixed (203) Hardwood forest (412) Xeric hardwood forest (413) Open loblolly – shortleaf pine (422) Xeric mixed pine – hardwood (432) Mixed pine – hardwood (434) Loblolly – shortleaf pine (440) Sandhill (512) Longleaf pine (620) Bottomland hardwood (900)
Pasture	Pasture, hay (80)
Idle	Beach (7) Utility swaths (20) Clear-cut or sparse vegetation (31)
Industrial	Transportation (18) Quarries and strip mines (33)
Residential	Low intensity urban (22) Parks and recreation (72)
Row crops	Row crops (83)
Business	High intensity urban (24) Golf courses (73)

2.3 Export Coefficients

Export coefficients for total N and P from all land covers except row crops and wetlands were adopted from the North Carolina State University (NCSU) WATERSHEDSS Pollutant Budget Estimation Form[1] that is part of the NCSU WATERSHEDSS Decision Support System for Nonpoint Source

[1] http://www.water.ncsu.edu/watershedss/

Pollution Control (Osmond et al., 1995). Because wetlands have a high affinity for retention of both N and P (Kadlec and Knight, 1996), export coefficients for N and P from wetlands were set to zero (Table 2).

Table 2. Export coefficients for N and P from different land cover categories (from Osmond et al., 1995).

Revised land cover	Export coefficient	
	kg N ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}
Wetland	0.0	0.0
Forest	1.8	0.11
Pasture	3.1	0.1
Idle	3.4	0.1
Industrial	4.4	3.8
Residential	7.5	1.2
Row crops	6.3	2.3
Business	13.8	3.0

Export coefficients for row crops were calculated as a weighted mean based on (1) crops planted in the 5-county region and (2) export coefficients for specific crop types from the WATERSHEDSS Decision Support System (Table 3). Data on acres of major crop types planted from 1996 to 2000 were compiled for each RSim county from the NASS Agricultural Statistics Database. There were no reports for Chattahoochee and Muscogee counties that are mostly occupied by Fort Benning. Peanuts, rye, wheat, soybeans, corn, and cotton were the major crops in the 3 remaining counties. Based on a 5-year average, small grains (e.g., wheat and rye) were planted on ≈44% of the region's agricultural land. Cotton, corn, soybeans, and peanuts were ≈8, 12, 15, and 20%, respectively, of the acres planted. The export coefficient for N from peanuts was set to zero (Table 3). Peanuts are a legume and usually receive no N fertilizer because they are sensitive to fertilizer burn. The weighted average export coefficient for N and P from row crops in the RSim region was, respectively, 6.3 kg N ha^{-1} yr^{-1} and 2.3 kg P ha^{-1} yr^{-1} (Table 2).

2.4 Calculations

The calculations were performed for 48 12-digit hydrologic units (HUCs) that were included within the RSim region (Fig. 1). The area (ha) of each land cover category was multiplied by its respective export coefficient (Table 2) and the products were summed for all land covers to estimate the annual flux (kg element yr^{-1}) of N or P from a watershed. Calculated annual fluxes of N and P for the 48 watersheds were regressed against areas (ha) of the eight land cover types in each watershed using stepwise multiple regression analysis. Multiple regression equations were developed to predict changes in annual N and P loads from the terrestrial environment to surface receiving waters as a result of future land cover change in the RSim region.

Table 3. Export coefficients for N and P for different agricultural crops (data for corn, cotton, soybeans, and small grains are from Osmond et al., 1995).

Crop type	Export coefficient	
	kg N ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}
Corn	11.1	2.0
Cotton	10.0	4.3
Soybeans	12.5	4.6
Peanuts	0	1.5
Small grain	5.3	1.5

3. RESULTS

Over the entire 5-county region the land cover was ≈74% forest, 9% idle, 6% industrial, 5% pasture, 2% crops, 2% wetland or water, 1% residential, and 1% business. The 48 watersheds ranged in size from ≈3200 to 12000 ha. Considering all 48 watersheds, calculated annual total N export ranged from 7188 to 52072 kg yr^{-1} and calculated annual total P export ranged from 1110 to 18137 kg yr^{-1} (Appendix I). Both predicted loads of N and P were positively skewed with the greatest loadings in HUC 30104 that includes Columbus, GA (Fig. 1).

The annual flux of both N and P was positively correlated with size of the hydrologic unit (+0.80, $P \leq 0.001$ and $r = +0.48$, $P \leq 0.001$, respectively). The total area of the 48 hydrologic units in the RSim region was ≈3573 km^2. Total N and P export from all 48 watersheds was estimated at ≈847450 and 150496 kg, respectively. Normalized for land area, and based on 1998 land cover, the predicted regional N loss was ≈238 kg km^{-2} yr^{-1} and the predicted regional P loss was ≈42 kg km^{-2} yr^{-1}.

Stepwise multiple regression analysis indicated that 99.7% of the variance in calculated annual total N flux (Y_N, kg N yr^{-1}) could be explained by a multiple regression equation with 5 independent variables ($F_{5,43}$ = 3206; P $\leq$0.001). The regression equation was:

$$Y_N = 1.78(X_1) + 4.22(X_2) + 6.51(X_3) + 7.50(X_4) + 14.26(X_5)$$

where

X_1 = area (ha) of forest lands
X_2 = area (ha) of idle land
X_3 = area (ha) of industrial land
X_4 = area (ha) of cropland, and
X_5 = area (ha) of business land.

Over 99.9% of the variance in calculated annual total P flux (Y_P, kg P yr^{-1}) was explained by a multiple regression with 4 independent variables ($F_{4,44}$ = 26964; P $\leq$0.001). The regression equation was:

$$Y_P = 0.11(X_1) + 4.14(X_2) + 2.35(X_3) + 3.09(X_4)$$

where

X_1 = area (ha) of forest lands
X_2 = area (ha) of industrial land
X_3 = area (ha) of cropland, and
X_4 = area (ha) of business land.

Coefficients in the regression equations indicated the importance of business, industrial, and agricultural land covers to calculated losses of both N and P from terrestrial environment to aquatic environments. For both elements, the area of forest, industrial, business, and cropland accounted for $\geq$95% of the variation in predicted annual export.

4. DISCUSSION

We combined export coefficients (kg ha^{-1} yr^{-1}) with 1998 land cover data (ha) to estimate the total N and P load (kg yr^{-1}) from 48 watersheds within Harris, Muscogee, Marion, Chattahoochee, and Talbot counties, Georgia. From these data, multiple regressions were developed to predict N and P export based on land cover area in watersheds of varying size in the 5-county RSim region. Export coefficients have been widely used to predict total N and P losses from landscapes to surface receiving waters (e.g., Beaulac and

Reckhow, 1982; Frink, 1991; Johnes, 1996; Mattikalli and Richards, 1996). An export coefficient is the amount of N or P lost annually from a particular land cover type on an area basis (e.g., g N m^{-2} yr^{-1}). Export coefficients can be combined with information on the area of different land uses and land covers to predict the flux of N and P from terrestrial watersheds. Empirically derived export coefficients do not convey critical information about the natural processes or human activities that contribute to stream nutrient loads. Despite this shortcoming, some recent studies that compared predicted and measured loads appear to validate the use of export coefficients for calculating annual watershed losses of both N and P (Johnes, 1996; Johnes et al., 1996; Mattikalli and Richards, 1996).

There were insufficient data to compare calculated total N and P exports with observed annual nutrient loads in waterways throughout the RSim region. However, the calculated loads can be placed in perspective using data from other studies of nutrient export. Average N export from minimally disturbed watersheds in the US is ≈2.6 kg N ha^{-1} yr^{-1} and is strongly related to annual runoff (Lewis, 2002). Nitrogen export from the Mississippi, Hudson and Delaware Rivers (3 major eastern US tributaries) has been estimated at ≈177, 356, and 518 kg N km^{-2} yr^{-1}, respectively (Caraco and Cole, 1999). Total N and P export in rivers from the southeastern US has been estimated to be ≈675 kg N km^{-2} yr^{-1} and ≈32 kg P km^{-2} yr^{-1} (Howarth et al., 1996). Median N export from 16 rivers draining large watersheds (475 to 70189 km^2) in the northeastern US over a 5-year study was 518 kg N km^{-2} yr^{-1} (Alexander et al., 2002). Predicted N loads for the 5-county Rsim region (237 kg N km^{-2} yr^{-1}) were in the lower range of reported exports for US rivers and predicted P loads (42 kg P km^{-2} yr^{-1}) were in good agreement with previously reported loadings for US rivers.

The relatively small percentage of cropland (range 0 to 17%) in the 48 watersheds inside the RSim region is one likely reason why predicted N loads are in the lower range of N loads reported in other studies from the eastern US. Export coefficients from forests are less than those from agricultural land for both N and P (Beaulac and Reckhow, 1982; Frink, 1991). Previous studies have shown that N export from predominantly agricultural watersheds exceeds export from mainly nonagricultural catchments (Hill, 1978; Neill, 1989). Mean N losses tend to increase as a function of the percentage of ploughed area in a watershed (e.g., Neill, 1989).

Aside from the probable influence of agricultural land use on N losses to surface receiving waters, reviews of export coefficients for both N and P indicate the importance of urban development (Beaulac and Reckhow, 1982; Frink, 1991). A recent analysis of 35 large river systems from around the world indicates that river N export exhibits a significant positive correlation with population density (Caraco and Cole, 1999). Population growth, road improvements, and increasing urban land cover are key drivers in future scenarios that will be addressed by RSim. Urbanization and commercial development along the perimeter of Fort Benning, and elsewhere in the 5-county RSim region, (Dale et al., 2005) have the potential to alter future N and P loads from affected watersheds. Multiple regression equations for predicting N and P loads on the basis of land cover can be used to assess the effects of future land cover change on regional water quality.

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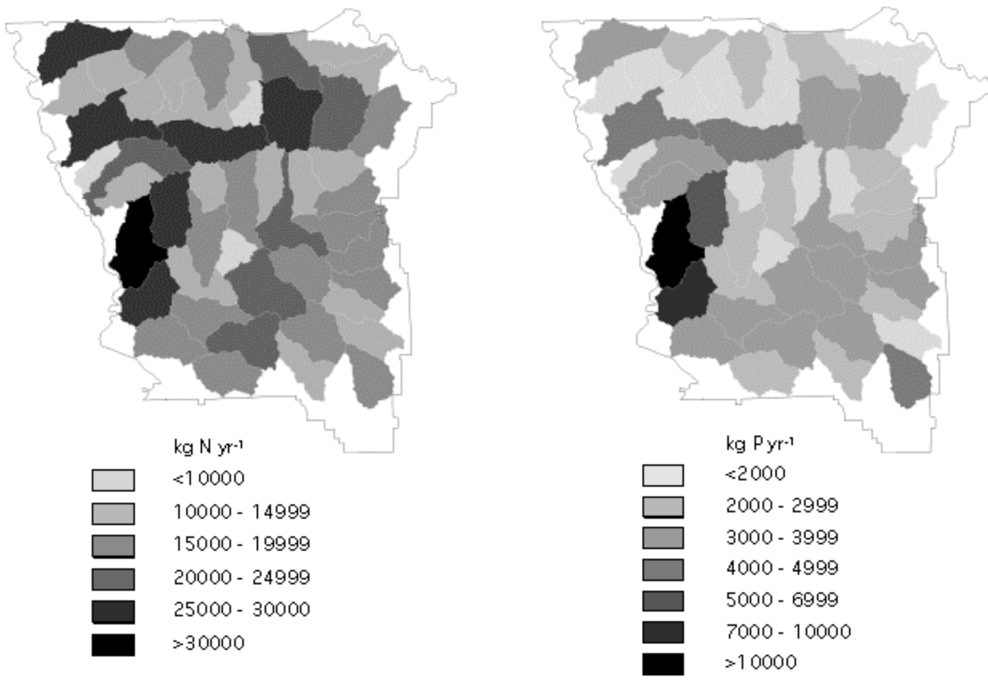
Spooner, J. Wells, J.C. Walker, L.L. Hargrove, M.A. Foster, P.D. Robillard, and D.W. Lehning. (1995) WATERSHEDSS: Water, Soil, and Hydro-Environmental Decision Support System (http://www.water.ncsu.edu/watershedss/)

Figure 1. Predicted annual total N export (left panel) and P export (right panel) from 48 12-digit hydrologic units in the 5-county RSim region.



APPENDIX I. Land area, and calculated N and P export from subwatersheds (12-digit HUCs) in the RSim study region. The first 7 digits for each hydrologic unit are the same (i.e., 0313000).

HUC code	Area (ha)	kg yr^{-1}			HUC code	Area (ha)	kg yr^{-1}	
		N	P				N	P
21008	10586	25007	3517		30208	3742	7188	1165
21102	6049	15037	2849		30301	8049	18767	3089
21103	5645	12614	1714		30302	11684	23478	3416
21104	6139	12858	1990		30303	4737	11846	1852
21201	3172	7219	1220		30304	8463	16770	2821
21202	5879	12608	1829		30305	6583	13398	2472
21203	8344	18613	2577		30306	9527	20147	3619
21204	5193	12488	1987		30307	7405	15796	3901
21205	6588	14204	1983		30308	8038	25727	7025
21206	11815	28347	4558		30602	8314	17805	3476
21207	4805	10842	1740		30603	7616	17042	2756
21208	12230	26811	4129		50801	8799	20279	2871
21302	9354	21127	3183		50802	12024	26135	3319
21303	5559	14149	3171		50803	11510	24939	3502
21304	3419	7855	1110		50804	6054	14583	1975
30103	9092	29707	6574		50805	4972	10598	1359
30104	10823	52072	18137		51102	7866	16456	1828
30201	5904	14880	2063		60201	6430	17444	3883
30202	5469	11996	1463		60202	5654	15907	3115
30203	6392	16030	2387		60203	4836	12727	2462
30204	6817	16729	2731		60205	5864	13381	1930
30205	8457	20335	3596		70101	8653	19102	3186
30206	5596	12140	1537		70102	6050	14559	2231
30207	8946	19820	2591		70701	6785	19887	4606

Section 5: Noise in RSim

Latha Baskaran
Rebecca Efroymson
Catherine Stewart

Noise

The principal way that noise impacts on wildlife have been studied in the past is through field studies at specific sites, where noise levels are measured in conjunction with measures of animal behavior or reproduction, usually at nest or burrow locations. Through the noise and risk assessment components of RSim, we plan to estimate impacts of noise on wildlife at Fort Benning without conducting any new field studies, with the acknowledgment that any uncertainties in field data will be transferred to model outputs. We have anticipated that exposure-response relationships for noise would include:

1. the transferal of effects thresholds from other sites and species to related wildlife at Fort Benning,
2. use of GIS to infer apparent noise thresholds for particular species, based on overlaying noise contours on species presence/absence maps, and/or
3. addition of noise to an existing habitat model to determine if including noise as a variable improves predictions.

We have made progress on the noise component of RSim in the past calendar year. CHPPM generated peak noise contours for blast noise at Fort Benning, both before and after construction of the Digital Multipurpose Range Complex, using the BNOISE model. We converted these files to grid maps in ArcView. Fort Benning staff provided us with survey data for many wildlife species, including deer harvest data, quail harvest data, rare species survey data (bald eagle, wood stork, American alligator), and LCTA data. We already had RCW nest locations and gopher tortoise burrow locations from Fort Benning, as well as gopher tortoise burrow predictions for the region from our habitat model. Unfortunately, nest or burrow locations are not available for other species. We have plotted survey data for groups of species on noise contour maps (as explained in Section 6), and many of these locations are in high-blast-noise areas, but because these surveys were not tied to range activities, it is unclear if animals were present during times of high blast noise. Therefore, the noise component of RSim will be limited to our focal species, RCW and gopher tortoise. For future implementations of RSim, it is important that nest or burrow locations be surveyed, as these are the most long-term, reliable indicators of effects from noise (based on method 2 above) for species whose behavior has not been specifically studied in relation to noise and for which audiograms are not available.

Noise and RCW

The primary exposure metrics for noise are the peak noise contours mentioned above, as well as day-night average sound levels that were calculated prior to this year. In the near future, we may also simulate sound using a downy woodpecker weighting, a surrogate for

RCW. It should be noted that the primary use of noise contours is in land-use planning zones. The use of these values in a simulation model like RSim raises uncertainties regarding units that are a challenge to overcome. However, noise contours are the best available estimate of exposure to noise for use in a regional model.

Thresholds for effects of sound on RCW will be taken primarily from Delaney et al. (2002). These thresholds have been checked, and some have been modified, in response to a comment at the SERDP in-progress review (Table 1).

Table 1. Risk assessment outputs for red-cockaded woodpecker (RCW) that are under consideration for use in RSim.

Stressor	Exposure	Effect	Relevance to endpoint	Threshold	No Observed Effects Level	Reference
Blast noise	artillery simulator in experimental test	Flushing from nest	Ft. Stewart population of RCW	91.4 m distance, 74-101 dB SEL[1,2]	152.4 m distance 65dBW SEL, 72 dB SEL unweighted	Delaney et al. 2002
Continuous noise	.50 caliber blank fire in experimental test	Flushing from nest	Ft. Stewart population of RCW	121.9 m distance, 84-89 dB SEL[3]	152.4 m distance, 68 dBW, 80 dB unweighted	Delaney et al. 2002
Continuous noise	Small-caliber (M-16) live fire event	Flushing from nest	Ft. Stewart population of RCW		400 m distance, 51 dbW SEL, 76 dB unweighted SEL	Delaney et al. 2002
Continuous noise	Military helicopter overflights	Flushing from nest	Ft. Stewart population of RCW		30 m distance, 84 dBW SEL, 102 dB unweighted SEL	Delaney et al. 2002
Continuous noise	Large-caliber live fire event	Flushing from nest	Ft. Stewart population of RCW	500-600 m distance 77-79 dBW SEL; 105-108 dB SEL unweighted sometimes	700 m SEL, 59dBW SEL, 102 dB SEL unweighted	Delaney et al. 2002
Continuous noise	Military/civ-ilian vehicles	Flushing from nest	Ft. Stewart population of RCW	15-30m, 58-110 dB SEL unweighted, 56-91 dBW SEL	>50 m distance, <55dBW SEL, 75 dB SEL unweighted	Delaney et al. 2002
Blast noise	Missile launches	Flushing from nest	Ft. Stewart population of RCW		750 m, 25 dBW SEL, 69 dB unweighted SEL	Delaney et al. 2002
Blast noise	Grenade simulator	Flushing from nest	Ft. Stewart population of red-cockaded woodpecker	100 m, 92-95 dB SEL unweighted, 78-84 dBW SEL unweighted	200 m, 47dBW SEL, 82 dBW unweighted SEL	Delaney et al. 2002

Continuous noise	Fixed wing aircraft	Flushing from nest	Ft. Stewart population of RCW		600 m, 62 dBW SEL, 90 dB SEL unweighted	Delaney et al. 2002
Continuous and blast noise	Firing of small arms and artillery	Numbers of eggs, nestlings, adults, return rates of adults feeding young, masses of nestlings and adults	Ft. Benning population of RCW		82 dB Lmax, but control noise at similar level	Doresky et al. 2001, Nature Conserv-ancy of Georgia 1996
Habitat fragmentation	Simulated, fragmented landscapes	Population crash—Allee effect	Simulated North Carolina Sandhills population of RCW	Randomly distributed and moderately clumped populations of 25 groups, and randomly distributed populations of 100 groups declined	Populations of 25 territories stable when territories were highly aggregated, moderately clumped populations of 100 groups were stable	Schiegg et al. 2002
Habitat fragmentation	Simulated demograph-ic and environ-mental stochasticity	Population crash—Allee effect	Simulated North Carolina Sandhills population of RCW	Populations of 25, 49, 100 territories ranged from rapidly declining to stable depending on territory density and level of aggregation	Populations of 250, 500 territories stable regardless of level of territory aggregation	Walters et al. 2002
Habitat fragmentation	Spatial distribution of territories	Population crash—Allee effect	Simulated North Carolina Sandhills population of RCW	Populations of 169 or fewer highly dispersed territories	Populations of 49 or more highly aggregated territories	Letcher et al. 1998
Habitat fragmentation	Loss of territories	Population crash—Allee effect	General population of RCW	Less than 400 territories	400 territories	USDA 1995, U. S. Army 1996

[1]Range of values associated with distance LOAEL; distance at which RCW flushed only 1/16 times discounted from LOAEL but not included in NOAEL
[2] Dose-response relationship between stimulus distance and flush frequency is available.
[3]Range of values associated with distance LOAEL; no significant decrease in effect with distance

Table 2 shows some of the disconnects between units of exposure and units of effects that are being resolved in the coming weeks. Conversions will be checked with Larry Pater and/or David Delaney at CERL.

Table 2. Differences in units of exposure and effect levels for noise for RSim implementation at Fort Benning.

	Exposure	Effect level
Blast noise—large caliber	1) Unweighted Peak sound level contours 2) CDNL 3) downy-woodpecker-weighted contours (possible)	Unweighted SEL for RCW flushing/not flushing from nest
Small arms	ADNL	Unweighted SEL for RCW flushing/not flushing from nest
Helicopter	ADNL for total aircraft	Unweighted SEL for RCW not flushing from nest
Fixed wing	ADNL for total aircraft	Unweighted SEL for RCW not flushing from nest
	Peak sound level contours	Peak sound level for desert tortoise (surrogate for gopher tortoise) not exhibiting acoustic threshold shift

Noise and gopher tortoise

Effects of noise on gopher tortoise have not been tested in the field at Fort Benning or elsewhere. Therefore, the noise module of RSim will only be able to infer effects of noise, based on studies of related species or based on relationships between noise and burrow locations. While behavioral effects on desert tortoise were primarily due to sonic booms (Bowles et al. 1997a, not relevant to Fort Benning), we may use a peak sound level, no effects level for temporary hearing loss in desert tortoise from simulated aircraft overflights. Regarding noise and burrow locations, we plan to include noise as a variable in the gopher tortoise habitat model and simulate probable burrow locations based on noise as a variable.

Bowles, A. E., S. A. Eckert and L. Starke. 1997a. Effects of simulated sonic booms and low-altitude aircraft noise on the behavior and heart rate of the desert tortoise (*Gopherus agassizii*). The Desert Tortoise Council. Abstracts for the Twenty-Second Annual Meeting and Symposium, Las Vegas, NV.

Bowles, A. E., J. K. Francine, J. Matesic Jr. and H. Stinson. 1997b. Effects of simulated sonic booms and low-altitude aircraft noise on the hearing of the desert tortoise (*Gopherus agassizii*). The Desert Tortoise Council. Abstracts for the Twenty-Second Annual Meeting and Symposium, Las Vegas, NV.

Delaney, D. K., L. L. Pater, R. H. Melton, B. A. MacAllister, R. J. Dooling, B. Lohr, B. F. Brittan-Powell, L. L. Swindell, T. A. Beaty, L. D. Carlile and E. W. Spadgenske. 2002. *Assessment of training noise impacts on the red-cockaded woodpecker: final report*. U. S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory, Champagne, IL.

Peak noise grids for Fort Benning

Catherine Stewart provided the 2003 operational data used to create peak noise contours for Fort Benning. Using the NOISEMAP software, closely spaced peak noise contours were created by setting the contour with primary grid spacing as 1, and setting 10 secondary grid spacings between the primary contours. These contours were then converted to a shape file and brought in to ArcView®. Using the contourgridder script (http://arcscripts.esri.com/details.asp?dbid=12531), the contours were converted to a 30 m grid dataset. Figure 1 illustrates the peak noise contour grids for 2003.

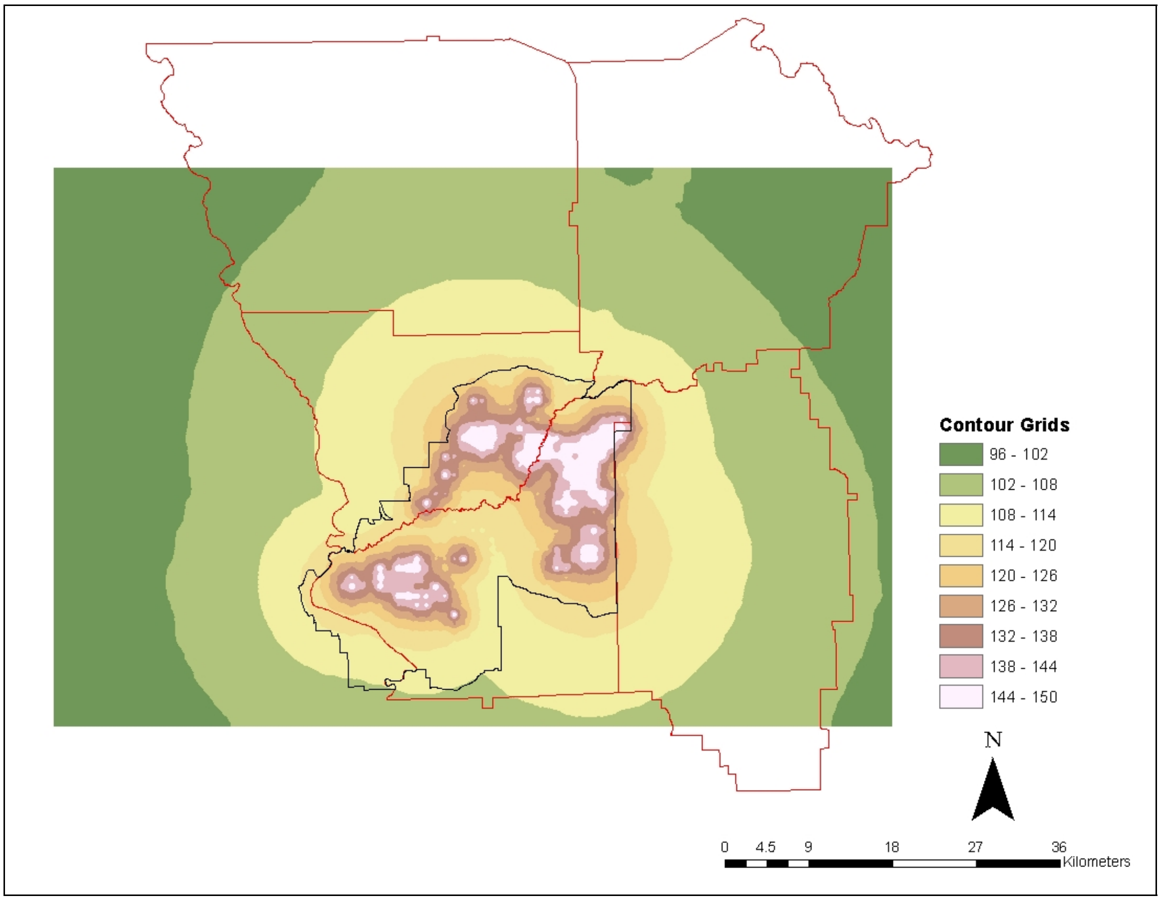
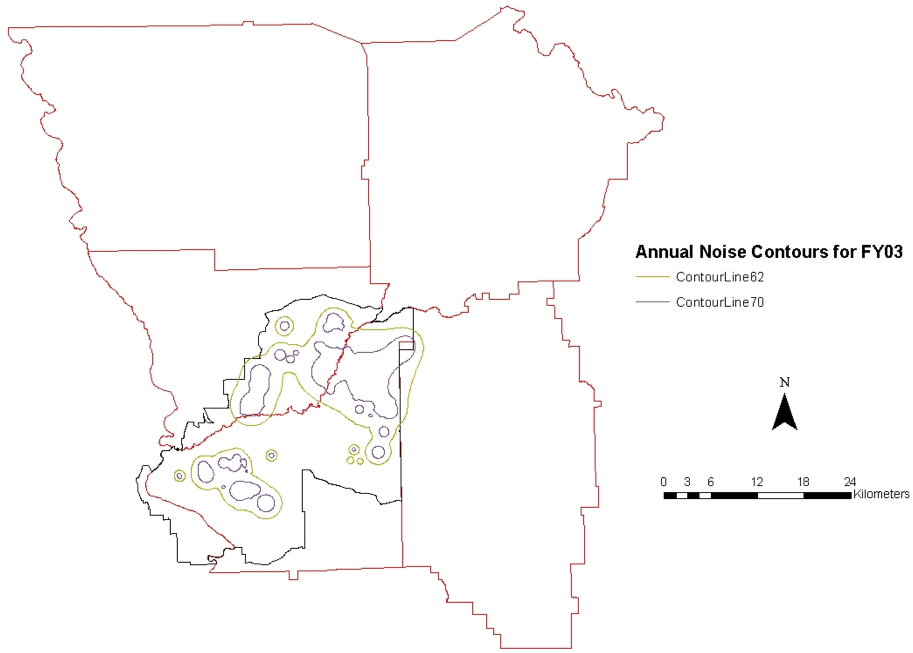


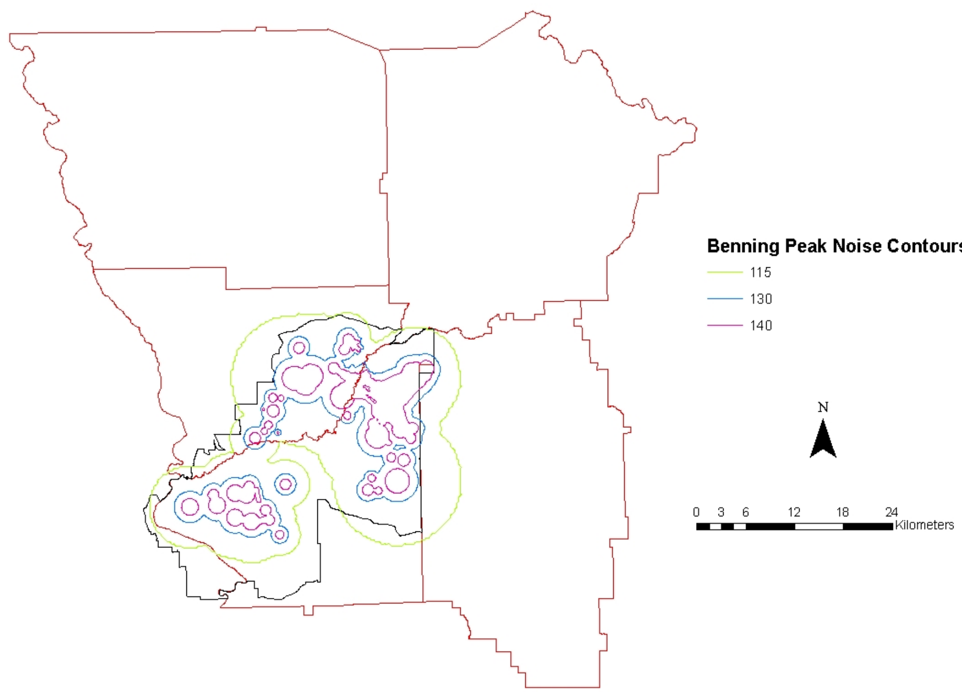
Figure 1: Peak noise contour grids for Fort Benning

Other noise data from Catherine Stewart:

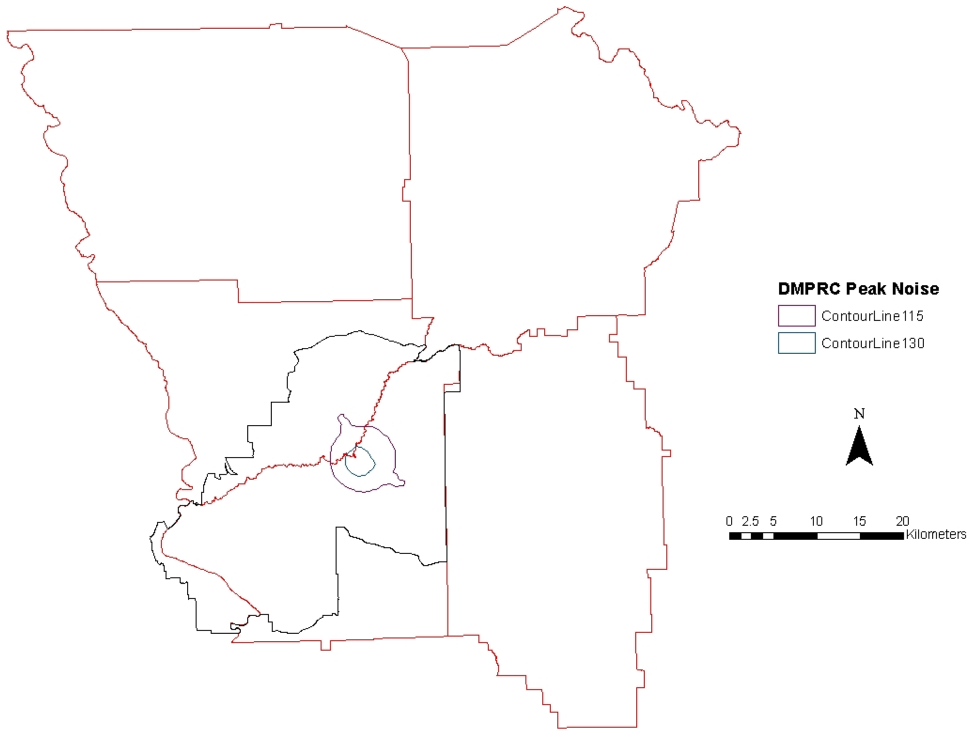
- Annual noise contours for Fort Benning in 2003



- Noise contours for Fort Benning with the Digital MultiPurpose Range Complex (DMPRC)



- Peak noise contours for DMPRC



Adequate noise thresholds for behavioral or reproductive effects are not available for gopher tortoise or red-cockaded woodpecker. Therefore, we have replaced ecological risk assessment output for noise simulations in RSim with human annoyance output. These thresholds are based on Larry Pater's Blast Noise Guidelines that are likely to be adopted as new Army regulations (Table 1)

Table 1. Blast Noise Guidelines from Pater (1976)[1].

Predicted Sound Level, dBP[2]	Risk of Complaints
< 115	Low risk of noise complaints.
115 – 130	Moderate risk of noise complaints.
130 – 140	High risk of noise complaints, possibility of damage
> 140	Threshold for permanent physiological damage to unprotected human ears. High risk of physiological and structural damage claims.

[1] Pater, L. 1976. "Noise Abatement Program for Explosive Operations at NSWC/DL", presented at the 17th Explosives Safety Seminar of the DOD Explosives Safety Board and presented in fact sheet at http://chppm-www.apgea.army.mil/dehe/morenoise/TriServiceNoise/document/DoDFS.pdf
[2] peak decibels

Section 6: Species at Fort Benning

Introduction:

The focus of RSim is on the rare species: gopher tortoise (see section 6a) and red cockaded woodpecker (see section 6b). Data on several more common species at Fort Benning were collected and analyzed to check if they could be used to study noise impacts on wildlife using the RSim model. Survey information on locations and habitats of several species were collected from the Integrated Natural Resources Management Plan (INRMP) of Fort Benning and communication with Fort Benning personnel. However it was found that none of these species had sufficient information to be able to identify noise related impacts. A listing of the species data currently available in Fort Benning, and their shortcomings (with respect to analyzing noise related effects) is provided in section 6c.

We have incorporated an ecological patch size threshold for gopher tortoise. Mature individuals in Florida have been observed to abandon habitat patches of less than 2 ha (McCoy & Mushinsky 1988). The RSim user can select the size of the threshold patch area, but the default value is 2 ha.

RSim output for red-cockaded woodpecker is expressed with respect to the breeding cluster number goal (361) set forth in the FWS Biological Opinion and the Installation RCW management plan.

Am. Midl. Nat. 155:335–351

Habitat Modeling Within a Regional Context: An Example Using Gopher Tortoise

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ABSTRACT.—Changes in habitat are often a major influence on species distribution and even survival. Yet predicting habitat often requires detailed field data that are difficult to acquire, especially on private lands. Therefore, we have developed a model that builds on extensive data that are available from public lands and extends them to surrounding private lands. This model is applied for a five-county region in Georgia to predict habitats for the gopher tortoise (*Gopherus polyphemus*), based on analysis of documented locations of gopher tortoise burrows at the Fort Benning military installation in west central Georgia. Burrow associations with land cover, soil, topography and water observed within the military installation were analyzed with binary logistic regression. This analysis helped generate a probability map for the occurrence of gopher tortoise burrows in the five-county region surrounding Fort Benning. Ground visits were made to test the accuracy of the model in predicting gopher tortoise habitat. The results showed that information on land cover, soils, and distances to streams and roads can be used to predict gopher tortoise burrows. This approach can be used to better understand and effectively carry out gopher tortoise habitat restoration and preservation activities.

INTRODUCTION

Land-use practices and land cover affect environmental conditions within a local area and the ability of an area to support particular species can be influenced by conditions of the surrounding region (*e.g.,* Steffan-Dewenter, 2003; Winton and Leslie, 2004). Habitat for a species of concern and the resources required by its population can be improved or compromised by the environmental conditions of a landscape (*e.g.,* Hanowski *et al.*, 1997; Collinge *et al.*, 2003; Cederbaum *et al.*, 2004; Donnelly and Marzluff, 2004; Moffatt *et al.*, 2004). Understanding and predicting how the pattern of land use and land cover affects habitat at multiple scales is a key concern of conservation biology (Saunders *et al.*, 1991).

Predicting the presence of suitable habitat across diverse land ownerships can be a challenge. Such predictions often rely on detailed field data, but collection of such data can be expensive and time consuming, and so habitat information may not be readily available. The Gap Analysis Program of the U.S. Geological Survey provides an assessment of the degree to which native animal species and natural communities are, or are not, represented on existing conservation lands (*e.g., see* Pearlstine *et al.*, 2002), but private lands also offer hospitable habitat (Scott *et al.*, 2001). However dealing with different ownerships can raise a variety of management issues (*e.g.,* Thompson *et al.*, 2004). Often data collected on

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public land may be detailed, but little may be known about conditions on private lands. Therefore, we developed a procedure that uses the detailed information about species and their habitat on public land (in this case a military base) and show how it can be extended to private land and thus incorporate the diversity of ownerships across a region.

Military installations and their environs offer a special case for examining how activities on the land can affect habitat, because these lands can have ecological importance and the military adopts a proactive management approach. Military installations support a number of endangered and threatened plant and animal species (Leslie *et al.*, 1996). In many cases, the military installations support more native species, and especially more rare species, than the surrounding lands (Groves *et al.*, 2000; NatureServe, 2004). Some reasons for this relative abundance of native and rare species on military lands as compared to the surrounding region likely lie in differences in land cover and land-use practices. Department of Defense lands provide oases for numerous species, through protection from the widespread urban, exurban, and rural development. This phenomenon is also observed on many Department of Energy lands (Mann *et al.*, 1996; Dale and Parr, 1998) and park lands (*e.g.*, Rivard *et al.*, 2000).

Typically, the military collects considerable information about rare species within their installations; yet protection of species requires understanding the distribution of habitat for rare species inside and outside the installation boundaries (Efroymson *et al.*, 2005). Therefore, we have developed a procedure for using the detailed information on species within an installation to predict habitat in the surrounding region. The procedure is illustrated using data on gopher tortoise (*Gopherus polyphemus*) from the Fort Benning military installation in west central Georgia, United States. Fort Benning maintains several rare or threatened plant and animal species, including the gopher tortoise. The procedure described here could be adapted for use in any situation where there are local habitat data, yet the natural resources management questions are regional.

Gopher tortoises are found in the southeastern United States, from southern South Carolina to southeastern Louisiana (Auffenberg and Franz, 1982). Their typical habitat includes longleaf pine (*Pinus palustris*) forests, sandhills, scrub oak woodlands, xeric hammocks, pine flatwoods, dry prairies, coastal grasslands and dunes and mixed hardwood-pine communities where the soils have a high sand content (Auffenberg and Franz, 1982; Kushlan and Mazzotti, 1984; Diemer, 1986). They prefer open-canopied and sparse understory regions. The name *gopher tortoise* derives from their tendency to dig deep burrows. The gopher tortoise is considered to be a keystone species, and up to 300 other species have been recorded in their burrows (Hubbard, 1893; Lago, 1991; Frank and Layne, 1992; Wilson *et al.*, 1997; Alexy *et al.*, 2003).

The gopher tortoise is federally listed as threatened in its western populations in Louisiana, Mississippi and western Alabama, and is listed as threatened by the state of Georgia. Over 80% of the population has been lost in past decades due to activities such as farming, fire suppression and habitat degradation (Hermann *et al.*, 2002). However, gopher tortoises are locally abundant on suitable soils at Fort Benning, where more than 8000 burrows were identified between 1996 and 1999 (USFWS, 1999).

Land use and land-management practices are important determinants of gopher tortoise burrows (Russell *et al.*, 1999; Hermann *et al.*, 2002; Jones and Dorr, 2004) and their abandonment (Aresco and Guyer, 1999). Farming and urban development, habitat changes, such as forest conversions, habitat loss and human exploitation, have a negative impact on the survival of this species (Wilson *et al.*, 1997; Aresco and Guyer, 1999). The impact of the proximity of gopher tortoise burrows to roads and streams is not clear. The presence of roads with heavy traffic can be detrimental to a sustainable gopher tortoise population because of road kills (Auffenberg and Franz, 1982). In a number of cases, however, gopher tortoises are found close to roads (Hal Balbach, U.S. Army Engineer Research and Development Center, pers. comm., 22 March 2004). Studies by Kushlan and Mazzotti (1984) show that gopher tortoises avoid burrowing in areas subject to flooding or overwash. However, other findings imply that the tortoises use moist burrows near riverbeds during winter months (McRae *et al.*, 1981; Means, 1982).

Understanding gopher tortoise habitat is important for the conservation and preservation of the species. Gopher tortoises can benefit from management that is focused on ecosystem processes and habitat structure (Hermann *et al.*, 2002). Management efforts may include restoration of the longleaf pine ecosystem, habitat maintenance through controlled burning and establishment of reserves (Landers *et al.*, 1995; Wilson *et al.*, 1997; Eubanks *et al.*, 2003). Several populations of gopher tortoises have also been relocated from their current declining habitat to potentially sustainable habitats. During relocation, repatriation, and translocation of species, it is important to characterize biological, habitat, biophysical and demographic constraints (Dodd and Seigel, 1991; Witz *et al.*, 1991). Hence, a good understanding of the potential habitat is vital.

Within the study area, burrows are predominantly located in areas supporting longleaf pine stands and a relatively sparse canopy cover and understory. However, vegetation structure is not sufficient to predict potential gopher tortoise habitat, since land cover, which mostly indicates current vegetation, does not indicate the long-term sustainability of a species (Mann *et al.*, 1999). Other factors such as soil and terrain type also contribute to the occurrence and persistence of a population. Gopher tortoises are known to inhabit well-drained sandy soils (Auffenberg and Franz, 1982) and to avoid clay soils, probably due to the difficulty of burrowing (Jones and Dorr, 2004). At a large geographical scale, topographic relief has also been found to be an important factor affecting the burrow distribution, with burrows oriented in the primary direction of relief (McCoy *et al.*, 1993).

The purpose of our study was to develop a means of predicting gopher tortoise habitat in a five-county region surrounding Fort Benning. Animal habitat is a better factor to model than animal location, since it is more consistent over time than demographics (Aebischer *et al.*, 1993). Furthermore, the number and density of gopher tortoise burrows can be used to estimate numbers of tortoises, provided that a reliable conversion factor can be determined (McCoy and Mushinsky, 1992). Our model of habitat for gopher tortoises was based on the presence of burrows within Fort Benning and then field-tested for the five-county region surrounding the installation.

METHODS

STUDY AREA AND DATA

Our study was conducted on a five-county region (Harris, Muscogee, Chattahoochee, Marion and Talbot) containing Fort Benning (Fig. 1). Much of this land is forested or used for agriculture. This region also includes the city of Columbus and several other smaller communities. Human activity in this region has been intense and of long duration (Kane and Keeton, 1998; Dale *et al.*, 2005). For example, longleaf pine forests have been declining for decades, and only 4% of the original pine forest remains in the southeastern United States (Noss, 1989).

At Fort Benning, the military has put much effort into identifying locations of burrows to avoid destruction of gopher tortoise habitat. Locations of gopher tortoise burrows from 1996 to 1999 were collected in a survey undertaken for the U.S. Fish and Wildlife Service (USFWS, 1999). This survey identified about 8100 active, inactive and abandoned

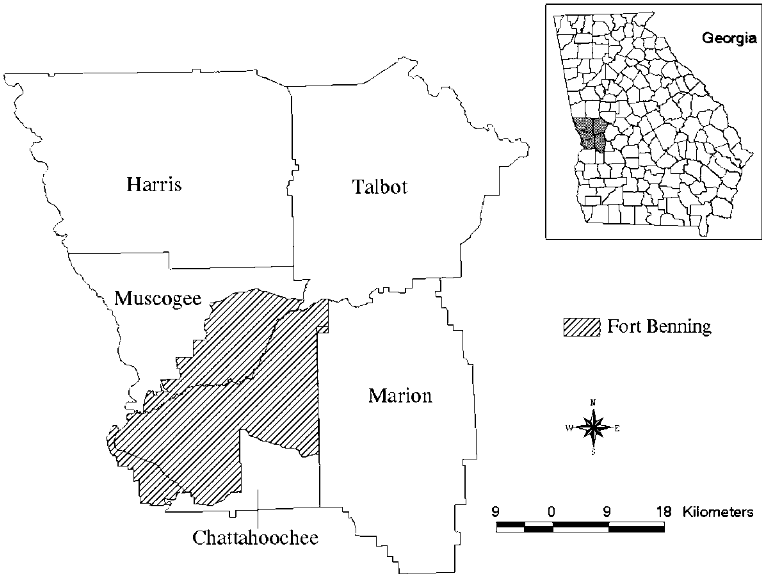

FIG. 1.—Map of the five-county study region in Georgia

burrows. Active burrows were defined as those currently maintained by a gopher tortoise. Inactive burrows were those that have been unoccupied for some time but still had a clear burrow entrance. Abandoned burrows were defined as unoccupied burrows where the entrance was covered by plants and nearly closed (Auffenberg and Franz, 1982). All three types of burrows were considered in our analysis, because it was important to identify potential habitats.

To identify resources and other factors vital for the gopher tortoise burrow, the probability of a resource unit (habitat variable) being used had to be determined. Resource selection functions provided a theoretical framework to identify such probabilities of use (Alldredge *et al.*, 1998; Boyce *et al.*, 2002; Manly *et al.*, 2002). In our study, the data on presence and absence of burrows in Fort Benning were used as the basis to model the resource selection function. One thousand locations of burrow presence and 1000 locations of burrow absence were selected. Since all the locations with burrows had been identified in Fort Benning from extensive surveys by the U. S. Fish and Wildlife Service, the remaining areas were assumed to be non burrow locations. The non burrow locations were randomly selected such that they were at least 90 m from the burrow locations to avoid any overlap with gopher tortoise habitats. Hence a random selection of locations with burrows and locations without burrows helped to obtain unbiased estimates of coefficients and, in turn, probabilities of use (Keating and Cherry, 2004).

The variables considered for our gopher tortoise burrow model were distance to roads, distance to streams, slope, soil texture, percentage of clay in the upper soil layer (0 to 5 cm) and 12 land-cover categories (including transportation corridors, utility corridors, low- and high-intensity urban areas, clear-cut areas, deciduous forests, evergreen forests, mixed forests, pasture land, areas planted in row crops, golf courses and forested wetlands) (Table 1). These factors were identified through a review of existing literature that examined attributes associated with gopher tortoise behavior and life-history characteristics, such as

TABLE 1.—Variables entered into the model

Type	Variable	Habitat characteristics
Terrain variable	Slope	Terrain orientation and slope can influence gopher tortoise burrows.
Distance variables	Distance to streams	Gopher tortoises are known to burrow in moist soils; they also avoid wetlands and regions close to streams.
	Distance to roads	Roads can be detrimental to gopher tortoises because of the increased chances of road kills by vehicles (Auffenberg and Franz, 1982). However, land cover adjacent to roads may also be favorable for digging and hence for gopher tortoise habitation.
Soil variable	Percentage of clay in the first soil layer	Gopher tortoises avoid clayey regions to make burrows because of the difficulty in digging in these regions.
Land–cover variables	Transportation land-cover class	In addition to the distance-to-roads variable, the transportation land cover variable is included, since gopher tortoises may be present very close to the roads and within the 30-m land cover pixel extent.
	Utility swaths	Clearings for transmission lines may be suitable gopher tortoise habitats because of the absence of dense vegetation that prohibits sunlight.
	Clear-cut regions	Clear-cut regions and regions with sparse vegetation could support gopher tortoises because of their open-canopy landscape.
	Deciduous, evergreen, and mixed forests	Forests without closed canopies and thick understories may be suitable gopher tortoise habitat. But dense forests may decrease the amount of sunlight reaching the ground and may limit the herbaceous understory required for gopher tortoise foraging (Hermann *et al.*, 2002).
	Pastures and non tilled grasses; row-crop fields	Cultivated areas, grazed lands, mowed lands, and pastures can accommodate gopher tortoises (Hermann *et al.*, 2002).
	Low-intensity urban	Some low-intensity urban areas such as farms or house yards could support gopher tortoise burrows.
	High-intensity urban	Gopher tortoise burrows are not expected in dense urban areas.
	Golf courses	Golf courses may not be good gopher tortoise habitats because of the frequent maintenance and disturbance in such locations.
	Forested wetlands	Gopher tortoises usually avoid wetlands (Kushlan and Mazzotti, 1984)

the need for open areas for basking and movement, appropriate forage and suitable soil and topography for digging burrows (Diemer, 1986; Wilson *et al.*, 1997; Boglioli *et al.*, 2000; Hermann *et al.*, 2002). Distance-based measures have been found to be useful in quantifying habitat use for animals (Conner *et al.*, 2003). However, the association between gopher tortoise burrows and distances from roads and streams is not clear (McRae *et al.*, 1981; Auffenberg and Franz, 1982; Means, 1982; Kushlan and Mazzotti, 1984). Thus, the effects of distances to roads and streams were evaluated in our analysis. Burrows can occur very close to roads, such as on road edges. Hence, a land-cover category indicating transportation features was included to accommodate the probability of gopher tortoises on road, railroad, trail and runway land-cover pixels.

Data sets describing land cover, soils and distance to roads and streams were analyzed in conjunction with data on burrow locations. Soil characteristics, such as percentage of clay, were obtained from the State Soil Geographic (STATSGO) database (Miller and White, 1998). The land-cover categories were derived from classification of a 1998 Landsat TM image (Natural Resources Spatial Analysis Laboratory, University of Georgia). The spatial resolution of the remotely sensed land cover was 30 m. Hence, all the analyses were carried out at that resolution. The habitat model was developed with a geographic information system (GIS) to examine the regional distribution of gopher tortoise habitat.

ANALYSIS

The prediction of the locations of gopher tortoise burrows (active, inactive and abandoned) based on physical conditions and land cover was done using binomial logistic regression in SPSS®. Logistic regression describes the relationship between a set of continuous and discrete independent variables and a binary or dichotomous outcome (Hosmer and Lemeshow, 1989; Trexler and Travis, 1993). With a random sampling design in a use—non use scenario, logistic regression can be used to establish the resource selection functions and variable relationships (Keating and Cherry, 2004).

Since the land-cover maps were available in 30-m resolution, all the variables were converted to the same spatial resolution. The land-cover classes were each considered separately as binary variables to be able to leave out classes, such as water, that were not useful in the analysis. The land-cover pixels were unique and did not overlap. The percentage of clay was used as an explanatory variable. The percentage of sand was not used because it is related to the percentage of clay. The distance variables were generated by calculating the nearest distance to a road or stream for every pixel. This approach was essentially a gridded contour of the distance to the roads or streams at 30-m intervals.

For each gopher tortoise burrow location used to build the model, corresponding explanatory variable features were extracted using GIS functionalities such as *spatial analyst*, that aid in obtaining the pixel value at a point. The variables observed at the model building points, *i.e.,* the burrow locations, were entered into the logistic regression analysis. During iterations of the model, some variables that did not significantly contribute to the variance explained were removed using stepwise backward logistic regression, which drops variables based on the order of their significance using the likelihood-ratio test (Hosmer and Lemeshow, 1989). Backward logistic regression was used instead of forward logistic regression, since the latter may fail to include important variables (Leung and Tran, 2000). The variables removed were slope, low- and high-intensity urban areas, golf courses and forested wetlands. For the slope variable, non linear relationships (square and cubed values of slope) were tested for their impact in the model. However they were found to be insignificant in effectively modeling the habitat of the tortoise.

ACCURACY ASSESSMENT WITHIN FORT BENNING

The model was tested by examining predictions of gopher tortoise burrow sites within Fort Benning against 1000 burrow locations that had been randomly selected for the analysis and then removed from the data set that was used to develop the model. A cut-off or threshold, which is the critical amount of evidence favoring the presence of the burrow (Swets, 1988), was used for assigning a modeled location to a burrow or non–burrow category. Accuracy assessment techniques are often used for validating maps produced from remote sensing as compared with in situ data (*e.g.*, Foody, 2002; Ramsey *et al.*, 2002). Based on the observed and predicted data, the sensitivity, specificity and overall accuracy of the model were determined. Sensitivity, or the true positive fraction, and specificity, or the true negative fraction, measure the proportion of sites at which the observations and predictions are in agreement (Pearce and Ferrier, 2000). In addition to these indices that evaluate the discrimination performance of wildlife habitat models, an accuracy measure that is unbiased to the cut-off used to classify the outcome was required. The receiver operating characteristic (ROC) curve, which is a plot between the false positive fraction (1 minus the specificity) and the sensitivity at various cut–offs, provided such an accuracy measure (Swets, 1988). The area under the ROC curve (AUC) is an indication of the accuracy of the model. AUC values of 0.5 to 0.7 indicate poor models, 0.7 to 0.9 are reasonably good models and greater than 0.9 indicates high accuracy models (Swets, 1988).

VALIDATION OF THE MODEL IN THE REGION AROUND FORT BENNING

Following the accuracy analysis within Fort Benning, the regression model was used to predict gopher tortoise habitat for the five-county study region around Fort Benning. This application was done in ArcView 3.1® using *spatial analyst* and *grid modeling* functionalities.

The ability of the model to correctly predict the presence of burrows outside Fort Benning was tested by field visits to a sample of sites that the model predicted to be gopher tortoise habitat at different levels of probability. Five categories of probabilities were divided equally based on their numeric range, from of 0 to 1 (Fig. 2). Site selection for testing was done by stratifying the study region outside Fort Benning into blocks that represented the major soil types of the area. Random points were located within each of these blocks. The points selected also occurred in all the probability categories of the predicted model. The sites were located using a global position system (GPS) and visited in May 2004. At each location the surrounding 30×30 m area was visually scanned for burrows or evidence of tortoises such as tortoise track marks. Land cover and land use in the local area were also recorded. Using the data obtained from the ground survey, the validity of the model to predict burrows was tested. The observed and predicted data were compared using accuracy statistics.

RESULTS

Several iterations of the logistic regression model were considered using different methods for selecting input variables. The backward stepwise logistic regression model which had the smallest (–2)log likelihood value and maximum percentage of regions correctly classified, was selected for the final model (Table 2). The Wald statistic provided the statistical significance of each coefficient (B) in the model. The percentage of clay was the most significant variable present, followed by the land-cover category of pastures and the

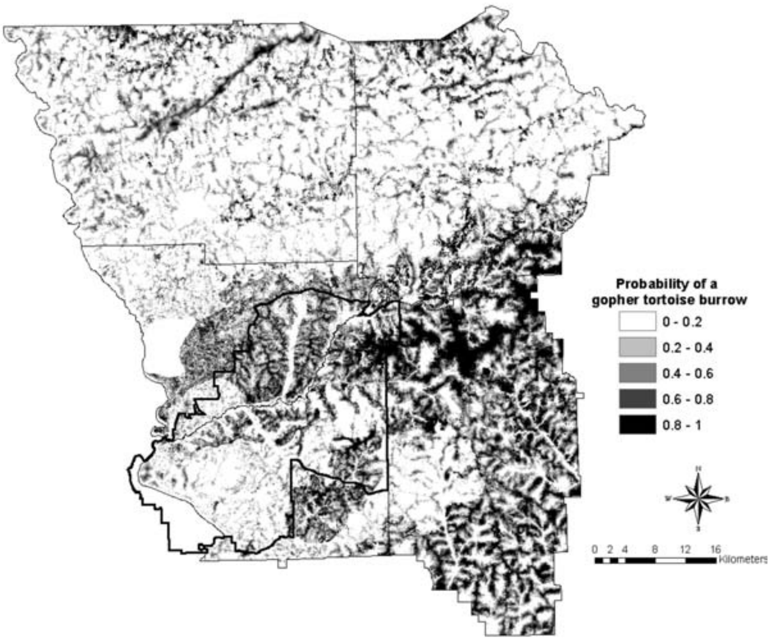

FIG. 2.—Predicted gopher tortoise habitat distribution map for the five-county study region

land-cover category of clear-cut or sparse regions. The equation of the model was summarized as

$$\text{Probability of a gopher tortoise burrow} = \frac{Exp(A)}{1 + Exp(A)}, \tag{1}$$

where

$$A = \begin{pmatrix} (Dist2strms * 0.004) - (Dist2rds * 0.003) - (\%\ clay * 0.152) \\ + (Transportation * 1.751) + (Utilityswaths * 2.327) \\ + (Clearcut * 2.684) + (Decid * 1.913) + (Evergreen * 1.004) \\ + (Mixed * 1.8) + (Pasture * 3.987) + (Rowcrop * 2.435) - 0.757 \end{pmatrix}. \tag{2}$$

Parameters are defined in Table 2.

ACCURACY ASSESSMENT OF THE MODEL WITHIN FORT BENNING

The sensitivity and specificity of the model were 77.4% and 78.9%, respectively (Table 3). Overall accuracy of the model was 78.15%. To identify the threshold independent accuracy, the ROC curve was plotted (Fig. 3). The area under the curve was 0.858. Since this value is within the reasonable model range (0.7 to 0.9), and very close to the very good model threshold (greater than 0.9), the model is considered to be good for prediction within Fort Benning.

TABLE 2.—Variables in the backward stepwise regression model for gopher tortoise burrow locations

Variable	Explanation	B*	SE*	Wald*	Exp (B)*
Dist2strms	Distance to streams	0.004	0.000	65.738	1.004
Dist2rds	Distance to roads	−0.003	0.001	33.808	0.997
%clay	Percentage of clay in the first soil layer	−0.152	0.011	178.898	0.859
Transportation	A land cover category consisting of roads, railways and runways	1.751	0.303	33.409	5.761
Utility swaths	Vegetated linear features maintained for transmission lines and gas pipelines	2.327	1.159	4.030	10.246
Clearcut	Areas that have been clear-cut within the past 5 years, as well as areas of sparse vegetation	2.684	0.297	81.627	14.643
Decid	Deciduous forests, which contain at least 75% deciduous trees in the canopy, deciduous mountain shrub/scrub areas, and deciduous woodlands	1.913	0.284	45.404	6.776
Evergreen	Forests with at least 75% evergreen trees, pine plantations, and evergreen woodlands	1.004	0.269	13.972	2.729
Mixed	Forests with mixed deciduous/ coniferous canopies, natural vegetation within the fall line and coastal plain ecoregions, mixed shrub/scrub vegetation, and mixed woodlands	1.800	0.276	42.418	6.048
Pasture	Pastures and non tilled grasses	3.987	0.357	124.857	53.915
Row crop	Agricultural row crops, orchards, vineyards, groves, and horticultural businesses	2.435	0.562	18.793	11.416
Constant	Constant in the logistic regression equation	−0.757	0.279	7.349	0.469

* B = Beta coefficient; SE = standard error; Wald = Wald statistic; Exp (B) = exponential function of B

VALIDATION OF THE MODEL FOR THE FIVE-COUNTY REGION

A map (Fig. 2) of the predicted probabilities for the presence of gopher tortoise burrows in the region was created to assess how well the model performed in predicting gopher tortoise habitat outside Fort Benning. Reference data were collected on 42 sites in the study area. The burrow status on the ground was compared to the model-predicted probability (Table 4). The land use recorded in the region helped in understanding the reasons for varying predictions.

TABLE 3.—Observed and predicted number of gopher tortoise burrows at Fort Benning

	Observed		
Predicted	No burrow	Burrow	Total
No burrow	789	226	1015
Burrow	211	774	985
Total	1000	1000	2000

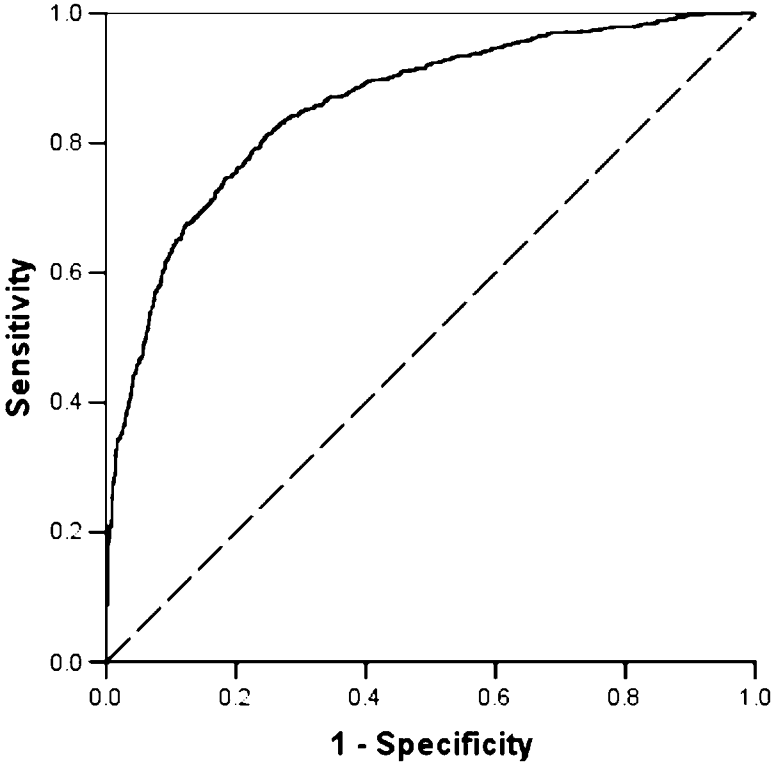

FIG. 3.—Receiver operating characteristics (ROC) curve for model prediction within Fort Benning

The difference between the predicted measures and the actual conditions in parts of the five-county region was tested using different cut–off values (Fig. 4). At a cut–off of 0.5, which is the typical center point threshold, the sensitivity of the model, which indicates the positive predictive power of a model, was 100%. But the specificity or negative predictive power of the model was 48.57%, which showed that the model overestimated possible gopher tortoise habitats. At a cut–off of approximately 0.8, the overall accuracy, the burrow presence and burrow absence predictive values were maximum (Fig. 4). The sensitivity, specificity and overall accuracy of the model at that threshold were 71.43%, 80% and 78.57, respectively (Table 5). Hence, a cut–off value of 0.8 was considered the appropriate threshold for this analysis.

DISCUSSION

Regression analysis provided an appropriate means to determine the influence of environmental variables on the ability to predict gopher tortoise habitat. In a logistic regression, the beta (B) coefficient does not provide much direct interpretation of the effect of each variable on the probability of the dependent variable occurrence. However, the exponential function of B [Exp(B)] indicates a change in odds of the probability of occurrence of the dependent variable.

TABLE 4.—Data collected in regions around Fort Benning listed by predicted probability

Location number	Burrow	Burrow status	Predicted probability	Land use
1	Present	Two abandoned burrows	0.96	Native sandhill habitat, mixed pine, xeric
2	Absent	Not a good habitat—no foraging vegetation	0.95	Lawn, open area (pasture)
3	Present	Two active burrows	0.94	Power lines (utility lines)
4	Present	One active burrow	0.92	Sand pine forests, open, savannah-like canopy
5	Present	Two abandoned burrows	0.91	Native sandhill habitat, open canopy
6	Absent	Possible habitat	0.85	Planted longleaf and loblolly pine forests
7	Absent	Not a good habitat—human intervention	0.77	Pasture, houses (lawns), mowed fields
8	Absent	Possible habitat	0.69	Hardwood to the north, planted pine to the south
9	Absent	Possible habitat	0.68	Planted pine to the southeast, thinned planted pine to the northeast
10	Present	Two abandoned burrows	0.56	Young longleaf pine forests with sparse understory
11	Absent	Not a good habitat	0.48	Edge of planted pine and riparian hardwood
12	Absent	Not a good habitat—wetland	0.37	Mesic hardwood forests, next to two ponds
13	Absent	Not a good habitat—wetland	0.29	Wetland with a creek nearby and also next to riparian hardwood forests

INFLUENCE OF VARIABLES

The effect of each variable on the occurrence of a gopher tortoise burrow can have several interpretations, based on our model. The probability of finding a burrow decreased as the clay percentage in the top soil layer increased. This result is logical, because gopher tortoises require well-drained sandy soils to dig burrows. Regions with clay soils are not suitable habitat because of respiratory limitations and difficulty of burrowing (Wilson *et al.*, 1997).

The probability of a burrow being present increased when the land cover was a transportation corridor; a utility swath; a clear-cut or sparse region; deciduous, evergreen or mixed forest; a pasture, or a row crop. This effect was most significant for pastures and clear-cut or sparse regions. This result is in agreement with a previous observation from scrub and flatwoods in Florida that gopher tortoise habitat is associated with high herbaceous cover providing food for tortoises (Breininger *et al.*, 1994).

Contrary to the expectation that road-influenced mortality causes a decline in gopher tortoise population, the probability of finding a burrow decreased as the distance from the road increased. This association of gopher tortoises with roads occurred at Fort Benning but was also observed elsewhere, such as at Camp Shelby, MS (Hal Balbach, U.S. Army Engineer Research and Development Center, pers. comm., 22 March 2004). Such a pattern was

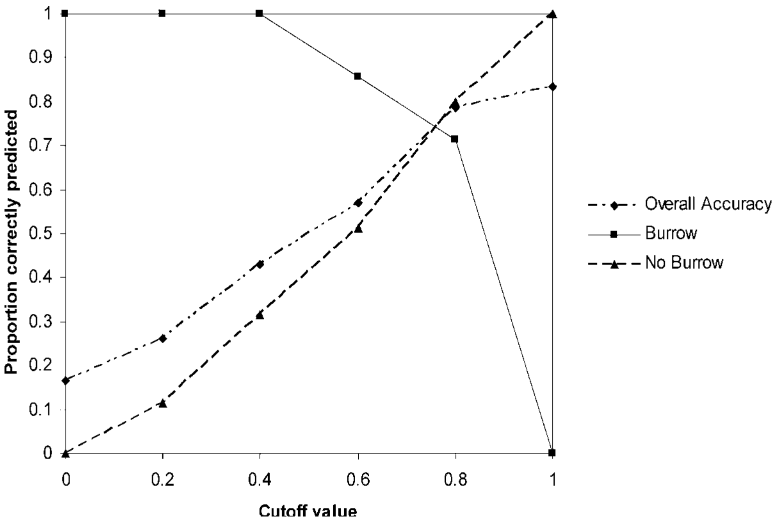

FIG. 4.—Prediction accuracies at different cut–offs (by definition, the extreme points indicate either a complete prediction of burrows at 0, or a complete absence of burrows at 1)

consistent with the positive relationship between gopher tortoise burrow probability and the presence of a transportation land-cover class. Road edges often have herbaceous cover and low tree cover, as well as a sunny exposure that may be favored by tortoises, and this association of burrows with roads has been observed in other species such as the desert tortoise (*Gopherus agassizii*) (Boarman *et al.*, 1997; Lovich and Daniels, 2000). Further, roads and trails occur along ridge tops and avoid wetland areas since such regions represent a stable path with low erosion and reduced requirements for fill (Hugh Westbury, Fort Benning, GA, pers. comm., 03 January 2005). Since gopher tortoises also avoid wetlands and clayey regions (Kushlan and Mazzotti, 1984), regions along the roads are favorable for burrowing. In some cases, gopher tortoises are forced into marginal habitats (such as those near roads) because fire suppression has resulted in canopy closure and in land-use changes that are unfavorable for the gopher tortoise (McCoy *et al.*, 1993). Alternatively, tortoises may burrow near roads to avoid predation by species that avoid roads. For example, it has been hypothesized that prairie dog colonies are found at high densities in urbanized areas because predator densities are low (Johnson and Collinge, 2004).

The probability of finding a burrow increased as the distance to streams increased. Some authors have suggested that gopher tortoises like to burrow in moist soils (McRae *et al.*,

TABLE 5.—Observed and predicted gopher tortoise burrows around Fort Benning

	Observed		
Predicted	No burrow	Burrow	Total
No burrow	28	2	30
Burrow	7	5	12
Total	35	7	42

1981; Means, 1982), but in our study area, gopher tortoises avoided moist regions for burrowing, consistent with observations by Kushlan and Mazzotti (1984).

EVALUATION OF MODEL

The overall accuracies of the model within and outside Fort Benning were 78.15% and 78.57%, respectively. There are several possible explanations for the approximately 22 % of false predictions from the gopher tortoise habitat model both within and outside the installation. Since locations of burrows within Fort Benning are clearly known, the predictions within the installation were analyzed relative to certain characteristic information, such as detailed soil data, land–use data and forest inventory data that is available only for Fort Benning.

First, the model predicted a higher probability of a burrow being present in a pasture, but the definition of pasture land from remote sensing imagery is ambiguous. Areas identified as pasture land within Fort Benning included areas managed as wildlife openings. Such regions supported gopher tortoise burrows, but in the region surrounding Fort Benning, pasture land supported animal grazing or hay cultivation. Furthermore, grazing land may not support gopher tortoise burrows because of disturbance by livestock and/or the removal of tortoises by humans. Such misclassifications occurred for locations 2 and 7 (Table 4), where although the model predicted a high probability of gopher tortoise burrow presence (0.95 and 0.77), no burrows were observed owing to the use of land for pastures.

Second, slope was a parameter initially entered in the model, but it was not retained as a significant variable. However, other topographic parameters, like elevation, could be of importance, since gopher tortoise burrows were more common along ridges than flat terrain. But it is unclear whether topographic features could be useful at a 30-m resolution for the relatively flat or gently sloping areas of central Georgia.

The locations of false positive predictions were analyzed for Fort Benning and showed that about 31% of falsely predicted regions lay in areas of high military use (training areas, ranges, etc.). The military uses were not categorized as such in the satellite images; rather, areas used actively by troops were classified as clear-cut regions, pastures, forests, etc. It is likely that these locations did not support gopher tortoise burrows because of the intense military activities.

About 10% of the false positive prediction regions in Fort Benning lay in areas with tree basal areas >70 m^2/ha. Such areas are unsuitable for gopher tortoise burrows since Florida gopher tortoises are known to abandon areas with tree basal areas ≥ 70 m^2/ha and areas with ≥ 1400 trees/ha (Aresco and Guyer, 1999). A high basal area is related to high tree density and high canopy cover. Mature gopher tortoises also abandon areas with greater than 50% tree canopy (Wilson *et al.*, 1997). This behavior explains about 10% of the false predictions in Fort Benning.

Mature individuals are known to abandon habitat patches of <2 ha (Wilson *et al.*, 1997). Approximately 19% of the predicted habitats were in regions that were less than 2 ha in area. The size of a patch is not included in the model as a predictor variable, and hence, such small areas, though not suitable and sustainable habitats for gopher tortoises, were predicted as potential habitats. This might be a significant factor, but it conflicts with our attempt to build on land-cover data based on landsat imagery.

Finally, the model considered the percentage of clay in the upper soil layer (0 to 5 cm). However, gopher tortoise burrows are up to 2 m deep and, thus, soil conditions below the first soil layer may also affect ease of burrowing.

Even though the model prediction of gopher tortoise habitat might be improved with additional data, better refinement of land-use categories, or finer resolution, we present this version in Eq. (1), because it can easily be adopted by resource managers, and it uses data that are readily available. The use of this approach should help managers better identify potential sites of gopher tortoise burrows. A field visit or the use of recent aerial images in conjunction with the model predictions is warranted if actions are planned that would irrevocably jeopardize the suitability of a site for gopher tortoise habitat. The model can be used to alert resource managers to potential gopher tortoise sites, to monitor changes in potential habitat, to plan field surveys for gopher tortoise, and to guide habitat restoration efforts.

CONCLUSIONS

This study developed a quantitative habitat model for the gopher tortoise using the extensive data available on a military installation and extended it across the surrounding private lands. The model indicated that the probability of finding a gopher tortoise burrow increased when soils contain a low percentage of clay; the distance to a road is low; the distance to a stream is high; and land cover is a transportation cover, utility swath, clear-cut or sparse region, a deciduous, evergreen or mixed forest, a pasture or a row crop. The model may best be used as a planning tool to identify areas of importance for restoration, conservation, relocation, etc.

Natural resource management and military activities at Fort Benning are designed to avoid jeopardizing federal- or state-listed species. Conserving the habitat of rare species is of great importance to planners and developers at Fort Benning and in the surrounding regions in order to avoid the constraints on management that would occur if habitat were to become rare. The habitat model developed here will aid planning activities of resource managers and become part of a more comprehensive simulation model of environmental impacts in the region (RSim) (Dale *et al.*, 2005; Dale *et al.*, *in press*). One of the main indicators of the environmental effects of development is the response and alteration of the habitats of focal species. The gopher tortoise model will be an important component in RSim, enabling it to project impacts of changes in land use and cover on gopher tortoise habitat. The approach of developing a model based on the extensive data on public lands and then testing it on private lands illustrates how our understanding of habitat can be used across a variety of land ownerships.

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Section 6b. Red Cockaded Woodpecker (RCW) and Longleaf Pine Habitat

The habitats for RCW's were identified from three sources:

- Hugh Westbury of Fort Benning, GA provided the location of RCW's within Fort Benning
- Jonathan Ambrose, Program Manager, Georgia Natural Heritage Program provided site specific information on the occurrence of RCW's as shape files. Only one location was identified by this data in Talbot County.
- Personal communication with Thomas Greene, Nature Conservancy helped to identify a few areas of longleaf pine strands. The locations were identified on a map of Benning and the 5 counties. They were later digitized as points using ArcView 3.1 to make a shape file.

The above three sources of data were combined to create the layer of RCW habitat (Figure 1).

Longleaf pine habitats have been obtained from the following sources

- SEF database – Neil Burns from EPA provided the Southeastern Ecological Framework data which had a layer for locations of longleaf pine for the whole of the Southeastern region.
- Callaway gardens – LuAnn Craighton, Director of Stewardship at Callaway Gardens might be able to give specific locations of longleaf pine data within Callaway gardens. A project is underway for this, and is expected to be carried out in winter.
- GA GAP Alliance level mapping – The Alliance level mapping results will include a longleaf pine unit. This data will be useful to identifying the habitat within RSim study region.

Most of the RCW and longleaf pine habitat in the five country region fall within Fort Benning. Not surprising, RSim projections show that risk of change to these habitats is greatest due to activities within the installation.

RSim output for red-cockaded woodpecker is expressed with respect to the breeding cluster number goal (361) set forth in the FWS Biological Opinion and the Installation RCW management plan.

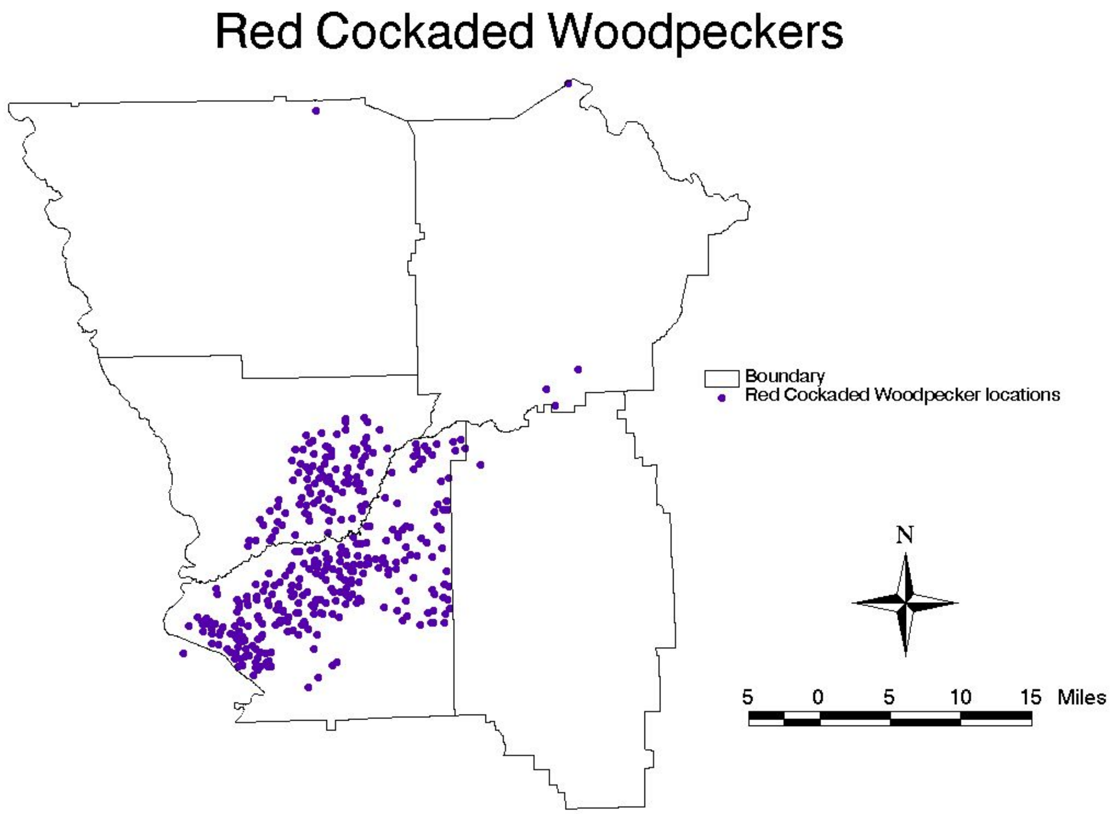

Figure 1: Location of red cockaded woodpeckers in the study region

Section 6c: Evaluation of Species Susceptible to Noise at Fort Benning

Latha Baskaran
Virginia Dale
Rebecca Efroymson

Introduction:

Data on several common species at Fort Benning were collected and analyzed to determine if they could be used to evaluate noise impacts on wildlife using the RSim model. Survey information on locations and habitats of several species were collected from the Integrated Natural Resources Management Plan (INRMP) of Fort Benning and communication with Fort Benning personnel. However it was found that none of these species had sufficient information to be able to identify noise related impacts. A listing of the species data currently available in Fort Benning, and their shortcomings (with respect to analyzing noise related effects) is provided below:

Data available on species in Fort Benning:

- Wood Stork, Bald Eagle and American Alligator: Since these species are fairly specific in the types of habitat they prefer, their locations are known in Fort Benning (Figure 1, mostly down in the backwaters of the Chattahoochee river) (personal communication with Rob Addington, Fort Benning, GA). However there is no data on their distribution or movement patterns within that habitat. For bald eagle, there is one nest along the river that is monitored for activity and breeding status. Wood stork is a transient species that tends to return to the same ponds year after year. Hence spatial data for these species is just a dot on the map showing the location of the nest or pond location. The same is the case for American alligators as well.

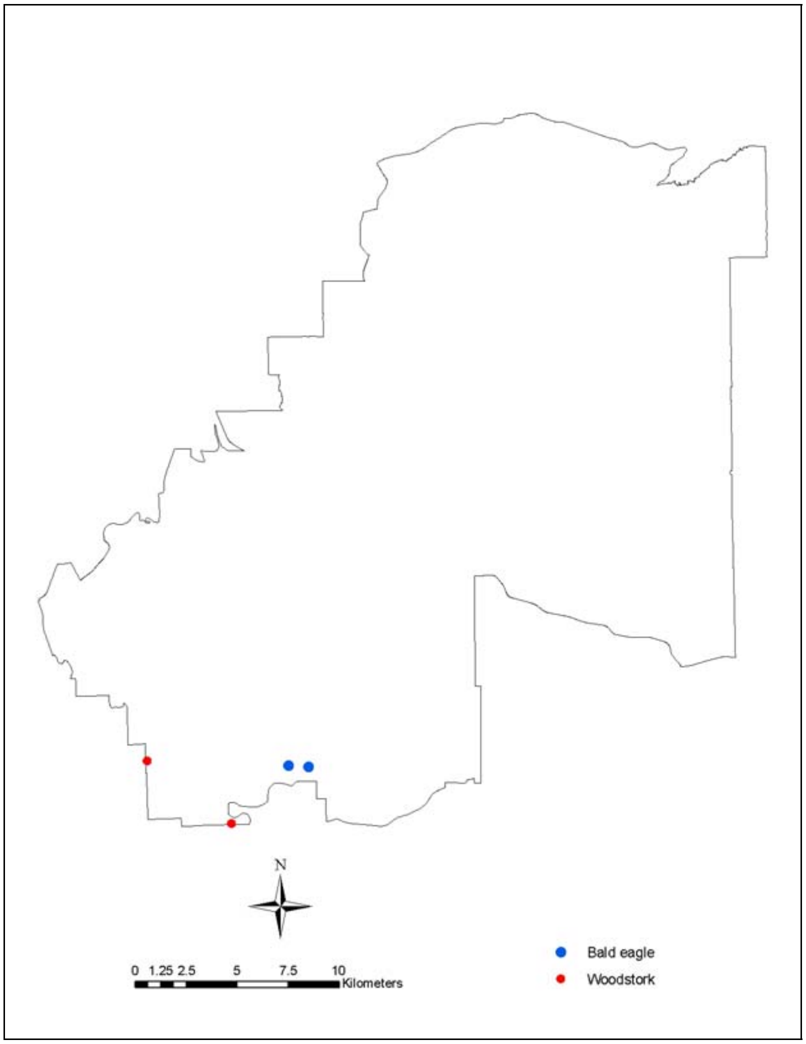

Figure 1: Bald eagle nests and wood stork location in Fort Benning

- Songbirds: Data on songbirds were available from the LCTA report.

- Birds and Mammals data from the LCTA report: The LCTA report represents a summary of wildlife data collected from 1991 through 1995 on sixty Land Condition Trend Analysis (LCTA) wildlife core plots at Fort Benning, Georgia. The surveys include winter inventories of birds and small mammals and spring inventories of birds.
  The numbers of bird and mammals sightings per plot are available in an access database. Information on a few relevant species and orders were extracted from the database and displayed in ArcMap. The species locations were overlaid on the noise grid and any possible associations with high or low noise levels was checked for (Figures 2, 3 and 4). The following information from Neil Giffen, Oak Ridge National Laboratory was used to identify some key species that may be affected by noise in Fort Benning.

- Waterfowl: Large flocks of waterfowl (ducks and geese) congregated on refuges have been known to flush as the result of low flying military aircraft. Waterfowl are most often noted in the literature as being particularly impacted by aircraft overflights. There are numerous accounts on National Wildlife Refuges. Similar behavior has been seen in areas with large congregations of shorebirds.
- Colonial Waterbirds: Based on the LCTA list of species, there may be some colonial waterbird (egret and/or heron) colonies on the installation. Some studies in Florida have shown that low altitude military training flights had no impact on the establishment, size or reproductive success of the colonies. However, there is speculation that reductions in colonies of magnificent frigatebirds at the Key West National Wildlife Refuge may be due to frequent flyovers of tour planes coupled with low altitude military overflights. So, flights of military aircraft over any existing egret/heron rookeries could be a concern at Benning.
- Gamebirds: A study done on the reaction of wild turkeys to sonic booms showed a limited alarm response not severe enough to result in decreased productivity.
- Passerine Bird Species: For some studies conducted on common passerine species, measurements of nesting success between habitats subjected to military overflights and control areas were not appreciably different. Also, species richness and abundance did not show appreciable differences. (The Bachman's sparrow, listed as rare in the state of Georgia, is present at Fort Benning according to the list and would be a species of concern)
- Raptors: The swallow-tailed kite is listed as rare in Georgia. Fort Benning appears to be a bit north of its breeding range. Studies done on snail kites in southern Florida found no evidence that overflights from nearby airports had adverse impacts on breeding success and behavior. Similarly, a four year study conducted by the USFWS on bald eagles in Arizona showed no adverse impacts to breeding bald eagles due to overflights of small propeller aircraft and helicopters. Also, ospreys in frequently overflown areas appear to habituate to the activity; however, flight/fright behavior has been seen in nesting ospreys in areas with only infrequent overflights.
- Studies of raptors in Colorado did show shifts in home range during times of military activity, with some species actually leaving the area. Other work has shown that red-tailed hawks not previously exposed to Army UH-1 helicopter overflights showed a stronger avoidance response than those that had already been exposed; although no differences were found in nesting success. The Fort Benning species list includes the red-tailed hawk along with other buteos (high soaring hawks) - the red-shouldered hawk and the broad-winged hawk. The Fort Benning list also includes the northern harrier, which winters throughout the south. A study conducted in Mississippi on a U. S. Navy bombing range noted a harrier hunting throughout a bombing event. Between bombing runs the bird hunted over a larger area of the bombing range; however, during bombing the harrier seemed to focus more on the

target area. It was deduced that the harrier was probably taking small mammals and birds flushed from cover by the bombing.

- Mammals: Some studies have shown that desert mule deer will habituate rapidly to jet aircraft noise. White-tailed deer at Fort Benning may be expected to similarly habituate to any disturbance, because they are generally known as a very adaptable species. Some work has shown that coyotes will change their daily activity in response to military training maneuvers.

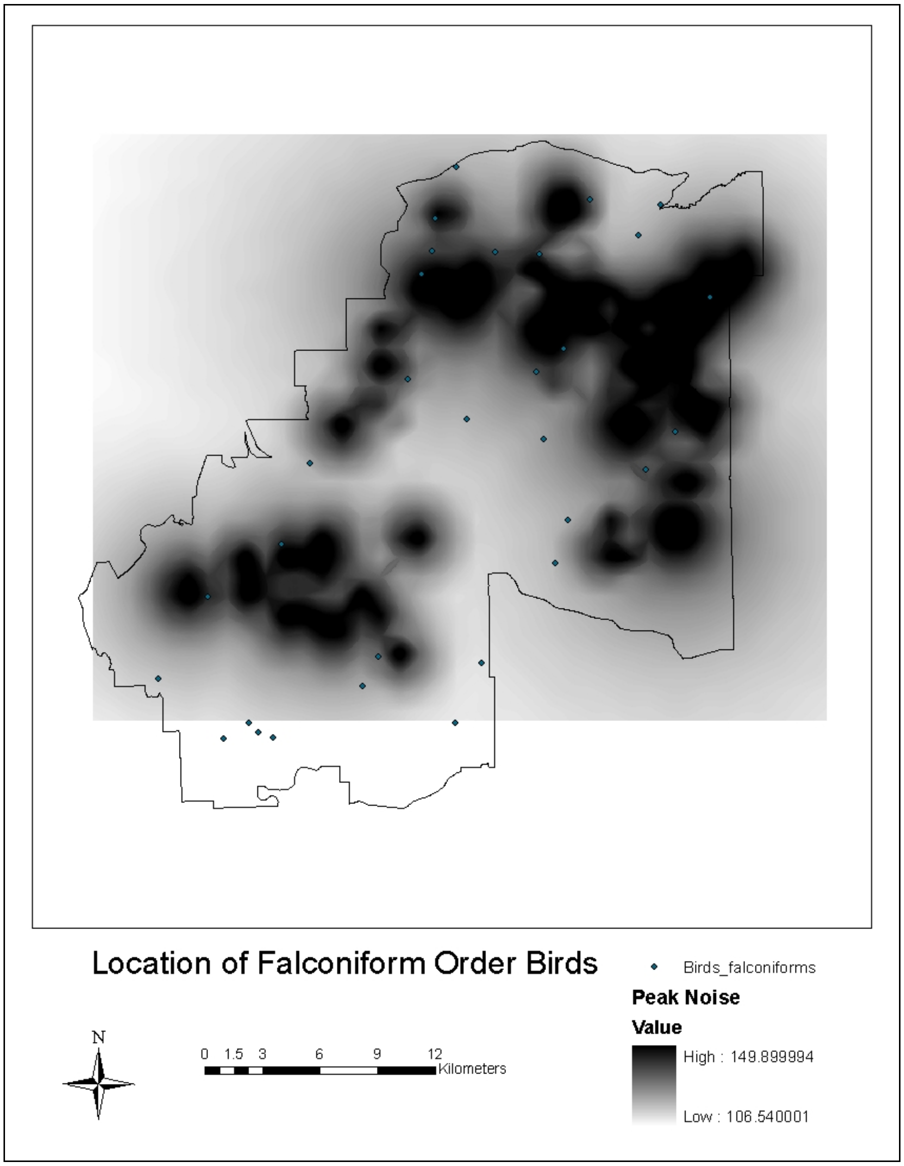

Figure 2: Falconiform order bird survey data overlaid on peak noise grids

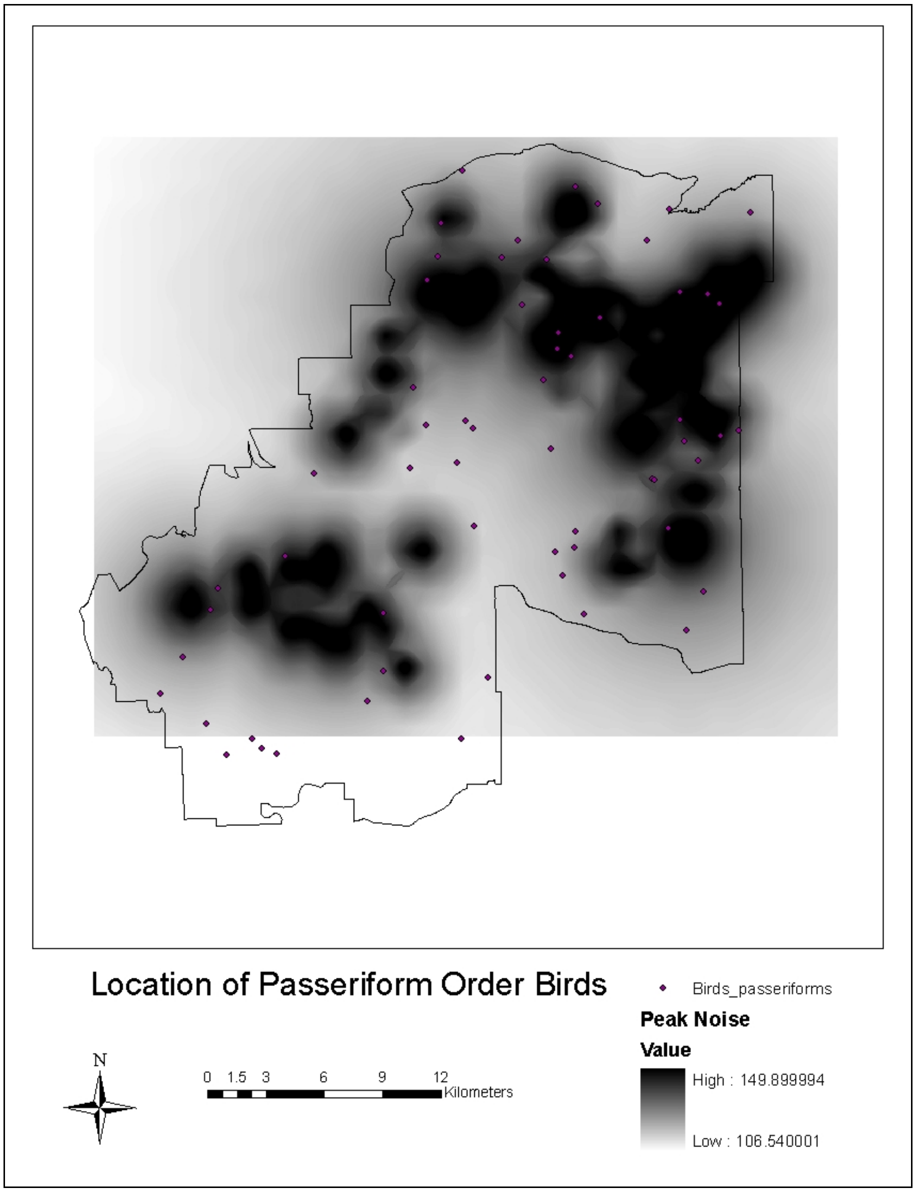

Figure 3: Passeriform order bird survey data overlaid on peak noise grids

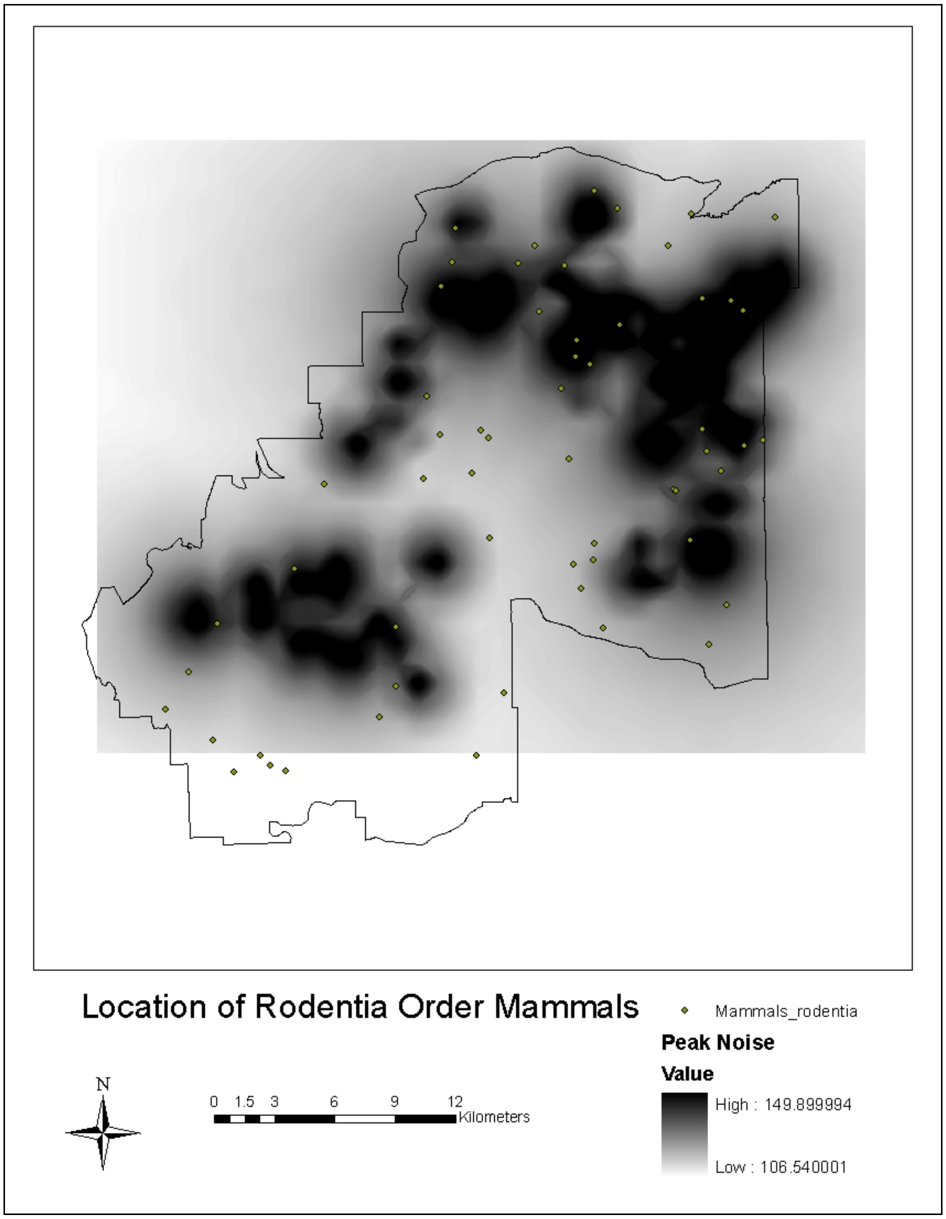

Figure 4: Rodentia order mammal survey data overlaid on peak noise grids

On a general observation of the LCTA survey data over the noise grids, it was found that species occurrence was not affected by noise since there were sightings in high noise and low noise regions. However this result could be a function of the type of data which reports sightings and not nest/habitat locations. Data on nest/habitat locations and temporal status of the species in their nests/habitats would be a useful indicator to identify possible effects of noise on species.

- White Tailed Deer (Game species): Deer harvest records are available by training compartment for the year 2003-2004. A map of the deer harvest concentrations is presented in figure 5. The white areas on the map represent zero deer harvested, generally because they overlap with ranges or other areas where hunting is not allowed and not because there are no deer there. The red areas are dud areas where no hunting is allowed. However this data may be biased by how often and when the training compartments were open for hunting (Mark Thornton, Fort Benning, GA). Hence the deer harvest estimates may not be reliable estimates of deer population in Fort Benning.

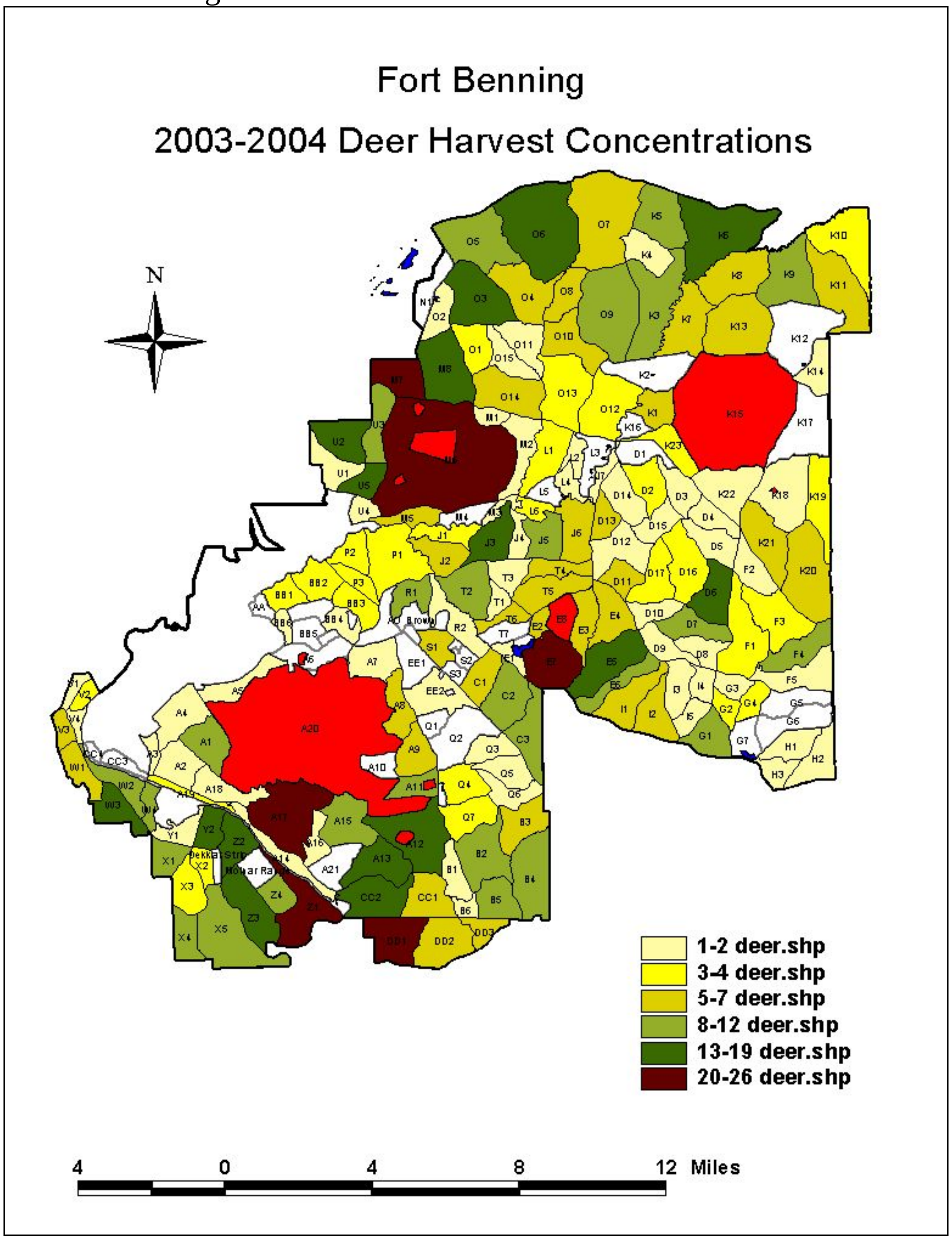

Figure 5: Deer harvest concentrations in Fort Benning by training area

- Bobwhite Quail (Game species): Quail count survey data were obtained from Fort Benning. Figure 6 shows the routed on which the quails were surveyed on. The quail count data provides locations on these routes where quail whistles were heard in 2003, 2004 and 2005. Since this data is not comprehensive in Fort Benning, and since it did not contain information on habitat or nest locations, the data could not be used for analysis in RSim.

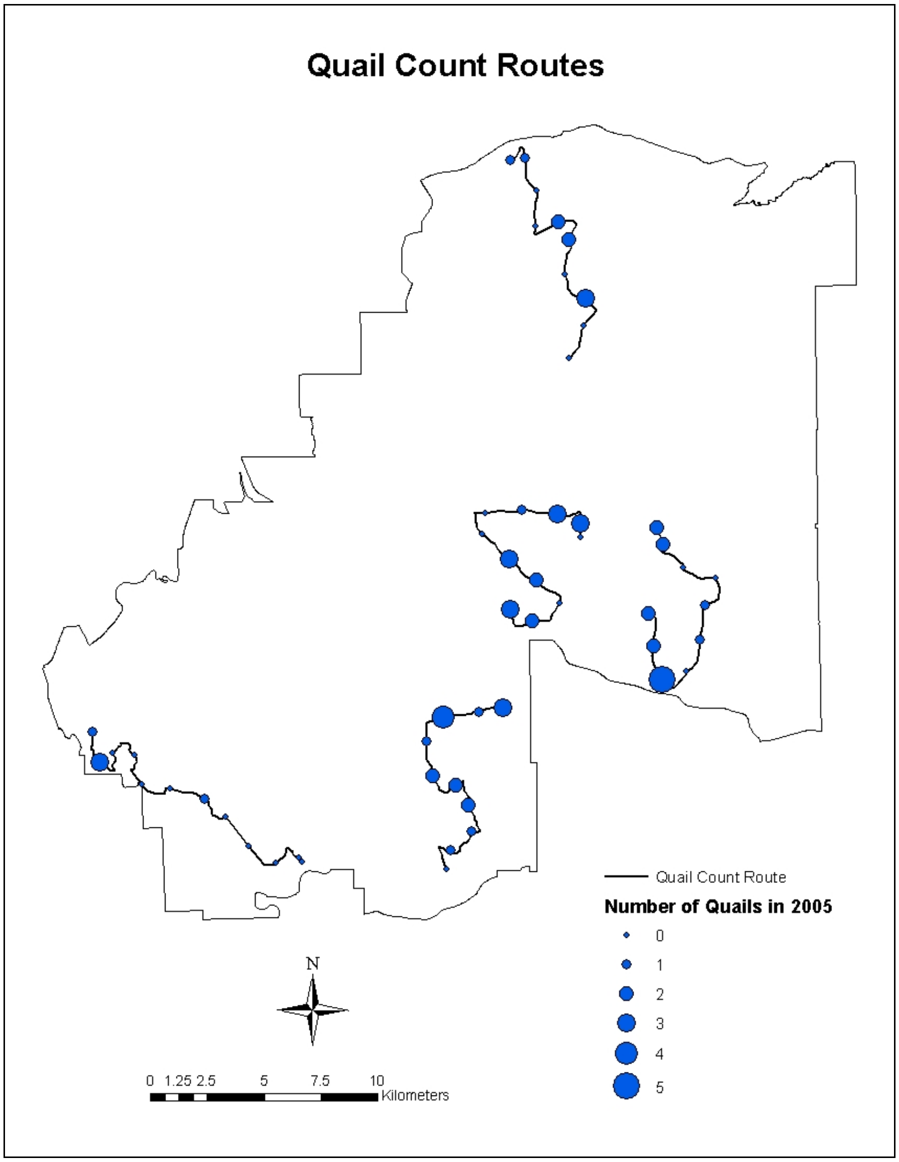

Figure 6: Quail count data in Fort Benning

Discussion:

The results of the survey data for groups of species were plotted on noise contour maps, and many of these locations are in high-blast-noise areas, but it is still unclear if animals were present during times of high blast noise. For this reason, we believe that nest or burrow locations would be more reliable indicators of effects from noise. Hence it was found that none of the data were suitable for RSim applications. This indicates the shortcomings of available data and the type of data required.

Section 7. Habitat Patches in RSim

Critical habitat patch size is an important concept in ecology and ecological risk assessment (Carlsen et al. 2004). Habitat patches below a certain size may not support individuals or populations of particular species. We have developed algorithms within RSim to identify boundaries of habitat patches. Essentially, patches of contiguous land with identical land-cover or habitat suitability designations are identified using a modification of the Hoshen-Kopelman algorithm (Berry et al. 1994; Constantin et al. 1997). This computationally intensive algorithm gives a unique label to each spatially discontinuous habitat patch. Alternative rules for defining adjacency, such as whether or not diagonally adjacent cells of the same land-cover designation are in the same patch or whether cells a certain distance apart should be considered to be within the same patch, may influence the outcome of patch-finding algorithms.

The first implementation of this patch-finding algorithm is to identify habitat patches that are of a threshold size below which mature gopher tortoises have been observed to abandon (less than 2 ha, McCoy & Mushinsky 1988), but are otherwise suitable for gopher tortoise, according to our habitat model.

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Section 8: Scenarios in RSim

A. Urban growth scenario

Our methods for simulating population growth generated new urban pixels in land-cover maps for the five-county region around Fort Benning. Urban growth rules are applied at each iteration of RSim to create new urban land cover. The subsequent RSim modeling step then operates off a new map of land cover for the five-county region. The computer code (written in Java) has been built from the spontaneous, spread center, and edge growth rules of the urban growth model from Sleuth [[i], [ii], [iii], [iv]].

The urban growth submodel in RSim includes both spontaneous growth of new urban areas and patch growth (growth of preexisting urban patches). We have focused first on generating low-intensity urban areas (e.g., single-family residential areas, schools, city parks, cemeteries, playing fields, and campus-like institutions). Three sources of growth of low-intensity urban pixels are modeled: spontaneous growth, new spreading center growth, and edge growth. First, an exclusion layer is referenced to determine those pixels not suitable for urbanization. The exclusion layer includes transportation routes, open water, the Fort Benning base itself, state parks, and a large private recreational resort (Callaway Gardens). Spontaneous growth is initiated by the selection of *n* pixels at random, where *n* is a predetermined coefficient. These cells will be urbanized if they do not fall within any areas defined by the exclusion layer. New spreading center growth occurs by selecting a random number of the pixels chosen by spontaneous growth and urbanizing any two neighboring pixels. Edge-growth pixels arise from a random number of non-urban pixels with at least three urbanized neighboring pixels.

Low-intensity urban pixels become high-intensity urban cells according to different rules for two types of desired high-intensity urban cells:

- central business districts, commercial facilities, high impervious surface areas (e.g., parking lots) of institutional facilities that are created within existing areas with a concentration of low-intensity urban cells; and
- industrial facilities and commercial facilities (malls) that are created at the edge of the existing clumped areas of mostly low-intensity urban cells or along four-lane roads.

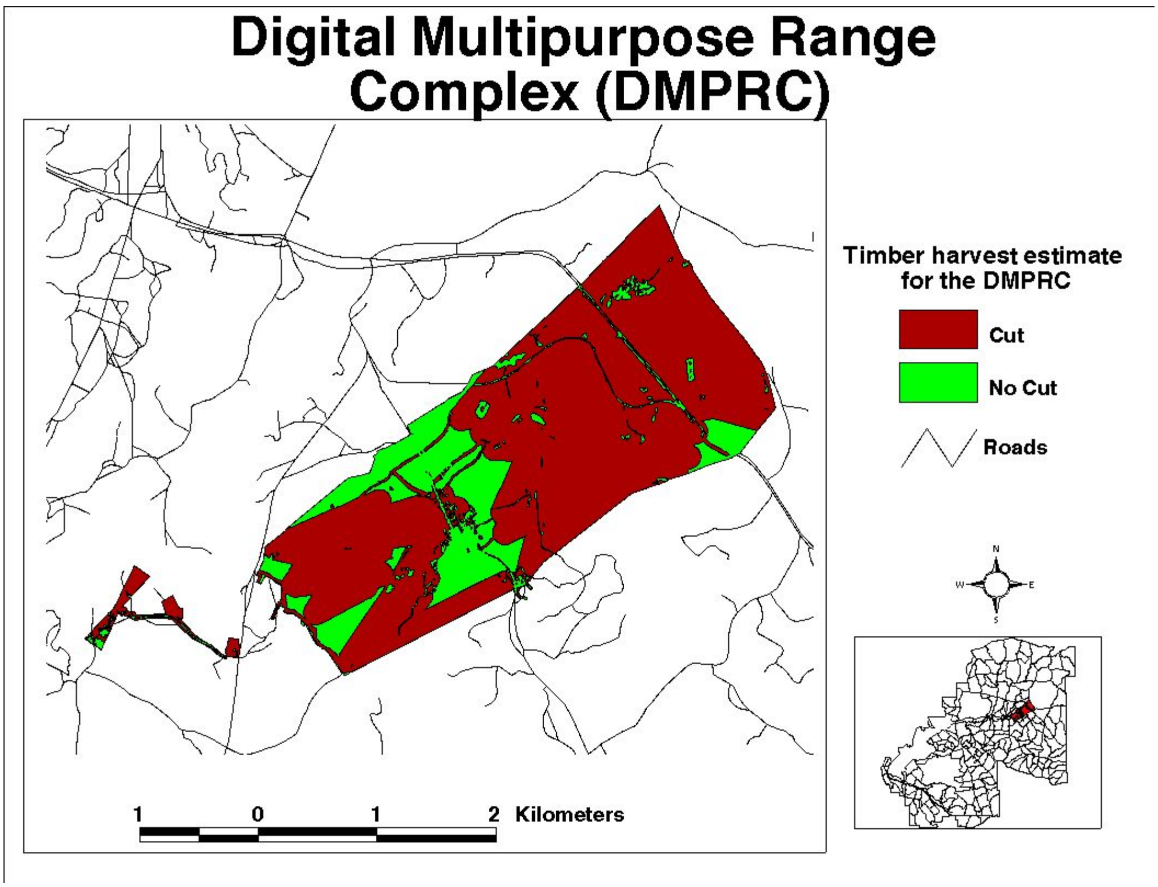
For the first high-intensity category, land-cover changes occur in a manner similar to changes in low-intensity growth, as described above: a spontaneous growth algorithm converts random low-intensity pixels to high-intensity pixels, and an edge growth algorithm converts random low-intensity urban pixels with high-intensity urban neighbors to high-intensity pixels. The second type of conversion from low-intensity to high-intensity urban land use is road-influenced growth and is described in the next section.

B. Military training scenario in RSim– the Digital Multi Purpose Range Complex (DMPRC)

Fort Benning is in the process of constructing a Digital Multi Purpose Range Complex (DMPRC) to provide a state-of-the-art range facility, in order to meet the Installation's training needs for conducting advanced gunnery exercises in a realistic training environment. The DMPRC construction will be incorporated within the RSim model and the impact of this training range on air, water, noise and habitat of species will be estimated.

As of now, the data for the regions where trees are cut for the DMPRC has been obtained and added in the RSim model. About 1500 acres of the region will be cleared of trees, shrubs and other vegetation. This clearing work started in October 2004.

The attached map indicates the DMPRC site with cut and no cut regions. The 'cut' category refers to vegetation that is being cleared. The 'no cut' category refers to regions that are not cleared.



C. New road scenario

The road-influenced urbanization submodel of RSim consists of growth in areas near existing and new roads by considering the proximity of major roads to newly urbanized areas. The new-road scenario makes use of the Governor's Road Improvement Program (GRIP) data layers (as described above) for new roads in the region. Upon each iteration (time step) of RSim, some number of non-urban pixels in a land-use land-cover map are tested for suitability for urbanization according to spontaneous and patch growth constraints. For each pixel that is converted to urban land cover, an additional test is performed to determine whether a primary road is within a predefined distance from the newly urbanized pixel. This step is accomplished by searching successive concentric rings around the urbanized pixel until either a primary road pixel is found or the coefficient for a road search distance is exceeded. If a road is not encountered, the attempt is aborted.

Assuming the search produces a candidate road, a search is performed to seek out other potential pixels for urbanization. Beginning from the candidate road pixel, the search algorithm attempts to move a "walker" along the road in a randomly selected direction. If the chosen direction does not lead to another road pixel, the algorithm continues searching around the current pixel until another road pixel is found, aborting upon failure. Once a suitable direction has been chosen,the walker is advanced one pixel and the direction selection process is repeated.

In an effort to reduce the possibility of producing a road trip that doubles back in the opposite direction, the algorithm attempts at each step of the trip to continue moving the walker in the same direction in which it arrived. In the event that such a direction leads to a non-road pixel, the algorithm's search pattern fans out clockwise and counterclockwise until a suitable direction has been found, aborting upon failure. Additionally, a list of road pixels already visited on the current trip is maintained, and the walker is not allowed to revisit these pixels.

The road trip process continues until it must be aborted due to the lack of a suitable direction or the distance traveled exceeds a predefined travel limit coefficient. The latter case is considered a successful road trip. To simulate the different costs of traveling along smaller two-lane roads and larger four-lane roads, each single-pixel advancement on a two-lane road contributes more toward the travel limit, allowing for longer trips to be taken along four-lane roads such as the GRIP highways.

Upon the successful completion of a road trip, the algorithm tests the immediate neighbors of the final road pixel visited for potential urbanization. If a non-urban candidate pixel for urbanization is found, it is changed to a low-intensity urban type, and its immediate neighbors are also tested to find two more urban candidates. If successful, this process will create a new urban center that may result in spreading growth as determined by the edge growth constraint.

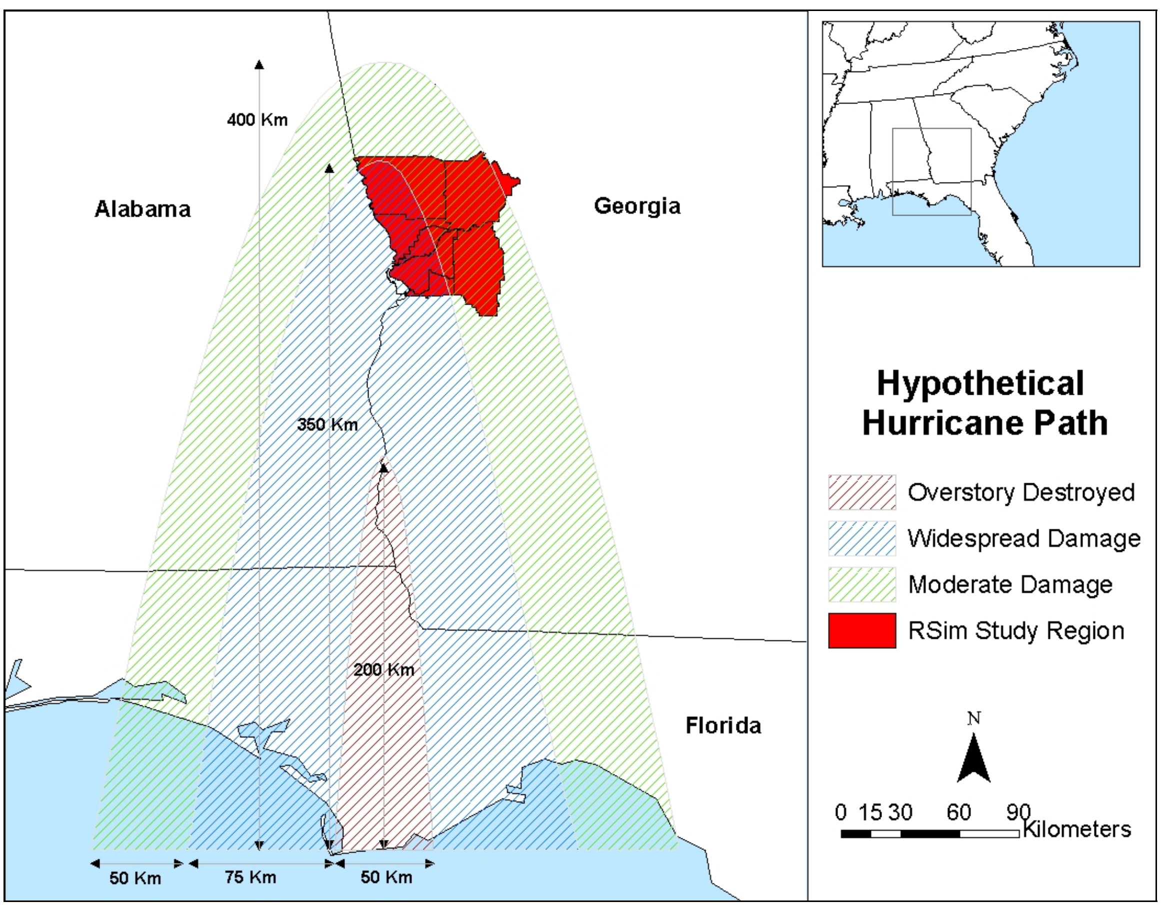
Roads also influence the conversion of low-intensity urban land cover to high-intensity urban land cover. For the second high-intensity urban subcategory (industry and malls), the RSim code selects new potential high-intensity-urbanized cells with a probability defined by a breed coefficient for each cell. Then, if a four-lane or wider road is found within a given maximal radius (5 km, which determines the road_gravity_coefficient) of the selected cell, the cells adjacent to the discovered four-lane or wider road cell are examined. If suitable, one adjacent cell is chosen for high-intensity urbanization. Hence, the new industry or mall can be located on the highway, within 5 km of an already high-intensity urbanized pixel

D. Hurricane Scenario for RSim

Hypothetical hurricanes with direct north hits, in a westerly and easterly path with respect to the study region, are to be simulated in RSim. The extent and depth of hurricane path from the coast is similar to that of Hurricane Hugo on the South Carolina coast (Conner, 1998). 3 zones of damage are identified after the hurricane

- Overstory destroyed – 100% of the forest landcover are destroyed and converted to clearcut/sparse landcover.
- Widespread damage - 50% of the forest landcover are destroyed and converted to clearcut/sparse landcover.
- Moderate damage - 25% of the forest landcover are destroyed and converted to clearcut/sparse landcover.

10 years after the hurricane damage, the original forest landcover is restored by increments of 10% restoration (or re-growth) every year. It is assumed that only the forest land covers change after the hurricanes.



Reference:

Conner, W. H. 1998. Impact of hurricanes on forests of the Atlantic and Gulf coasts. Pages 271-277 in A.D. Laderman (ed.) Coastally Restricted Forests. Oxford University Press, New York, NY.

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[i] Gigalopolis model website: http://www.ncgia.ucsb.edu/projects/gig/index.html

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[iii] Clarke K C, Gaydos L J. Loose-coupling a cellular automation model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore, *Geographical Information Science* 1998; 12(7):699-714.

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Section 9. Development of transition rules for non-urban land-cover classes

Latha Baskaran

Introduction

The RSim model initially included urban growth rules. In order to incorporate the growth and changes that may happen in non urban land-cover types, the land cover changes of the region was observed for past years. The land cover trend was determined by using change detection procedures in ArcGIS 9.0® that helped in identifying changes from one land-cover type to another. Changes to and from urban classes were not considered in the results since they were being dealt with using different growth rules. Based on the land cover changes happening over a period of time, the annual rate of change was calculated. These changes were incorporated in the form of a transition matrix from which the transition growth rules were derived.

Since forest management activities are different within Fort Benning and the surrounding private lands, the transition rules were calculated separately for Fort Benning and regions outside Fort Benning. Outside Fort Benning, National Land Cover Datasets (NLCD) of 1992 and 2001 were used. The 2001 data set covers only the northern part of the RSim study region. The data for the remaining regions is yet to be released. Hence currently, the changes observed in the northern portion are assumed to be representative of changes in all areas outside Fort Benning in the 5 County study region. Within Fort Benning, landcover data sets from 2001 and 2003 were used to derive the transition rules.

This report describes the processes carried out for analyzing the change between two sets of landcover data sets for the RSim study region (the counties of Chattahoochee, Harris, Marion, Muscogee and Talbot). Land cover data for the study region were available for 4 different time periods – 1992, 1998, 2001 and 2003 (Figures 1, 2, 3 and 4). Landcover data for 1972, 1983/86, 1991, 2001 and 2003 were also available for Fort Benning. The results of the change detection carried out for the RSim region, regions outside Fort Benning and within Fort Benning are explained below.

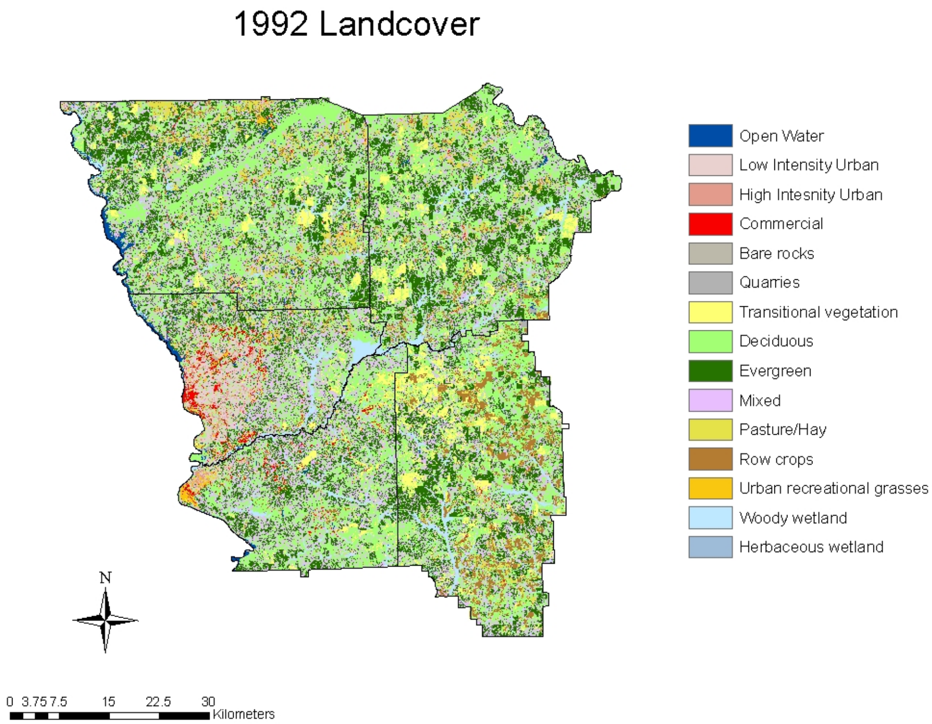

Figure 1: MRLC 1992 landcover

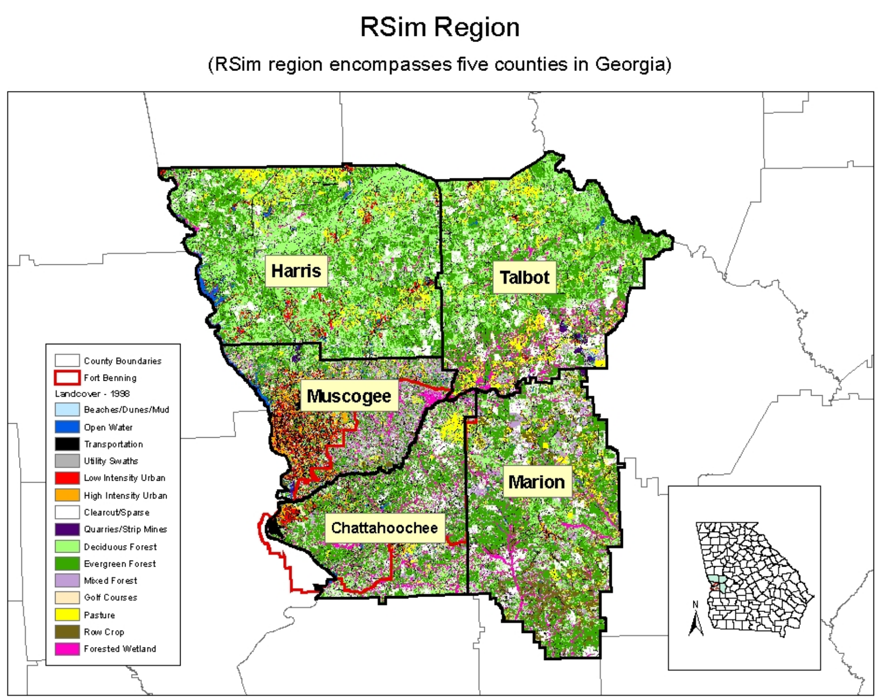

Figure 2: 1998 landcover from University of Georgia

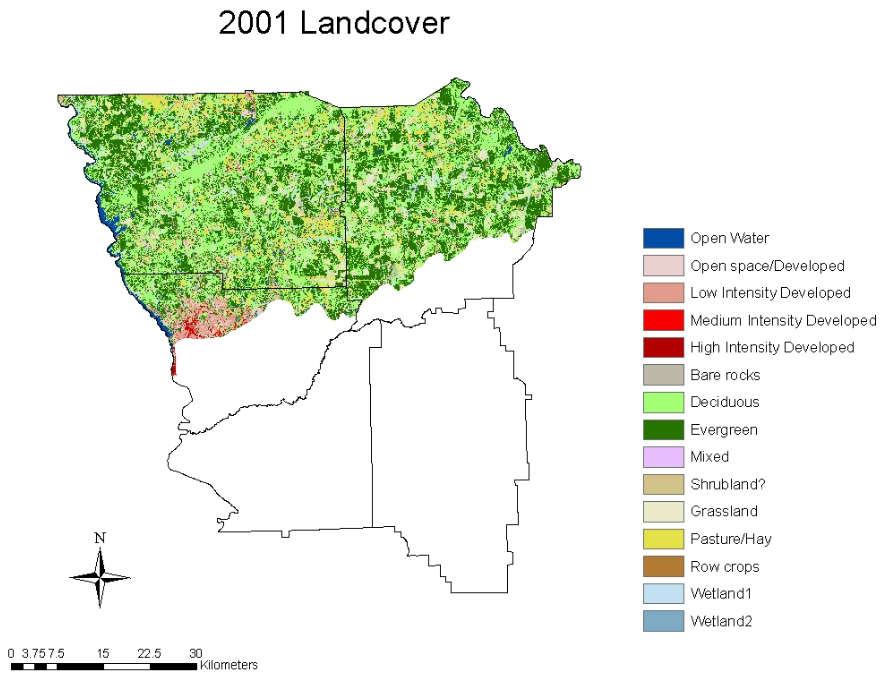

Figure 3: MRLC 2001 Landcover

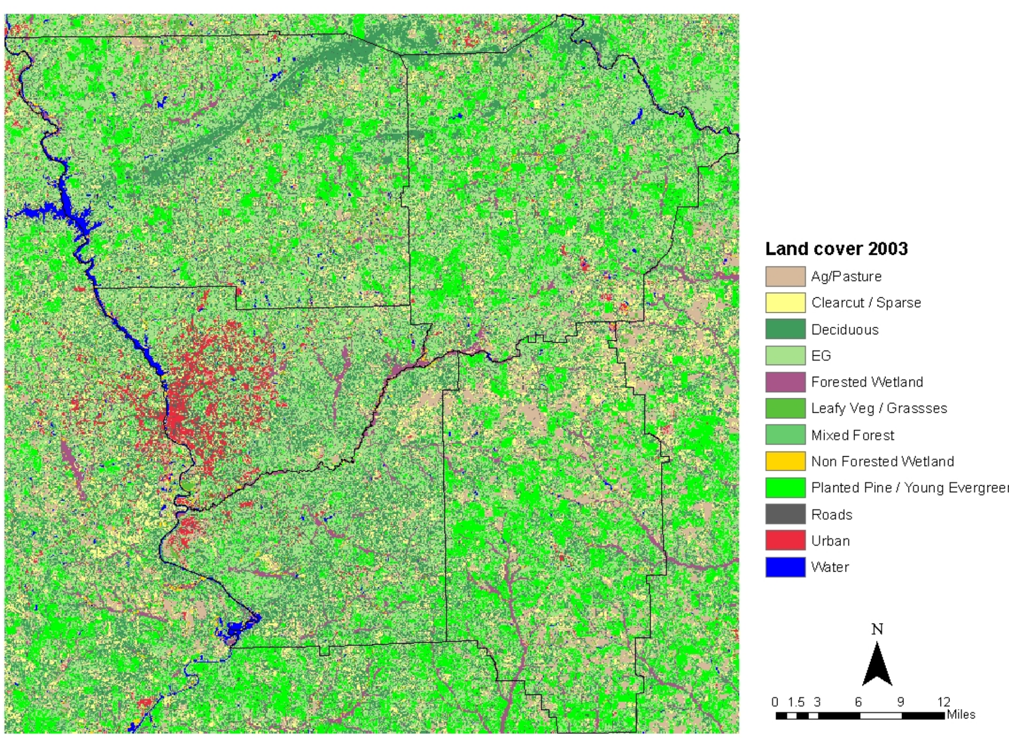

Figure 4: 2003 Landcover from Georgia Institute of Technology

Change Detection between 1998 and 2003 landcover data

The first dataset, a 1998 landcover map, was created by Natural Resources Spatial Analysis Laboratory (NARSAL), at the University of Georgia. The second dataset, a 2003 landcover map was created by researchers at Georgia Institute of Technology and provided by Wade Harrison. This 2003 dataset has just been completed, and hence does not have detailed metadata to describe it. Discussions with Wade Harrison were useful in performing the change detection analysis for these data sets.

Some of the issues to be clarified before performing the change detection are:

1. Resolution. The 2003 landcover data set has a resolution of 15 m whereas the 1998 data set has a 30 m resolution. For comparison, the 2003 data set was converted to a 30 m resolution.
2. Class definitions. The 1998 and 2003 landcover maps were prepared by different organizations. Hence they followed different classification schemes. The 1998 landcover dataset has 15 classes in the study region and the 2003 landcover gas 12 classes. An attempt to compare classes is presented in Table 1. The 1998 landcover classes ‘Utility swaths’, ‘Beaches/dunes’ and ‘Mines/Quarries’ are not directly comparable to any classes of the 2003 landcover. The distribution of those classes in the 2003 landcover is given in Table 2. They are not discussed in detail in the analysis.

Table 1: Mapping between classes of the two landcover data sets

<table>
<tr><th>1998 Landcover category</th><th>2003 Landcover category</th></tr>
<tr><td>Deciduous forest</td><td>Deciduous forest</td></tr>
<tr><td>Mixed forest</td><td>Mixed forest</td></tr>
<tr><td rowspan="2">Evergreen forest[a]</td><td>Planted pine/Young evergreen</td></tr>
<tr><td>Evergreen</td></tr>
<tr><td>Clearcut/Sparse vegetation</td><td>Clearcut/Sparse</td></tr>
<tr><td>Row crop</td><td>Ag/Pasture</td></tr>
<tr><td>Pasture</td><td rowspan="2">Leafy veg/Grasses[b]</td></tr>
<tr><td>Golf courses</td></tr>
</table>

[a] The ‘Planted pine/Young evergreen’ and ‘Evergreen’ classes of the 2003 landcover have been considered similar to the ‘Evergreen forest’ class of 1998.

[b] The 2003 landcover data has an ‘Ag/Pasture’ class and a ‘leafy vegetation/grasses’ class that can be combined to represent agricultural land as a whole. The ‘leafy veg/grasses’ class is primarily comprised of winter grass areas. Anything with a lot of active chlorophyll that is not part of the planted pine class will show up in this class (personal communication with Wade Harrison). Hence it is being considered as part of the agricultural land class. Similarly in the 1998 data set, there are three separate classes – pasture, row crops and golf courses, which in general represent agricultural land. These three classes are comparable to

Open water	Water Non forested wetland[c]
Low intensity urban High intensity urban	Urban[d]
Forested wetland	Forested Wetland
Transportation	Roads

Table 2: Percentage distribution of 'Utility swaths', 'Beaches/Dunes' and 'Mines/Quarries' landcover areas in 1998 with respect to the 2003 landcover

	2003 Landcover class								
1998 Land cover class	*Deciduous*	*Mixed*	*Evergreen*	*Clear cut/ sparse*	*Ag land*	*Water*	*Urban*	*Forested wetland*	*Roads*
Utility swaths	14.63	1.4	39.13	15.8	21.24	1.2	2.96	2.61	1.04
Mines/ Quarries	6.69	0.60	17.51	8.23	25.73	7.21	32.15	1.15	0.73
Beaches/ Dunes	10.30	0.81	22.49	4.61	1.63	28.73	1.36	29.81	0.27

Results:

Using the nine classes listed in Table 1, the change detection analysis was carried out and the results are shown in tables 3 and 4. The analysis was carried out in Arcview 3.1 using the spatial analyst extension. Maps indicating the areas of change and no change for each landcover class are also included.

The results of certain classes such as open water, urban areas and roads (Maps 6, 7 and 9) are not very useful and accurate and hence are not discussed in detail.

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the 'Ag/pasture' and 'Leafy veg/grasses' combined class which will be known as 'Ag land' in further discussion.

[c] There is no 'non-forested wetland' class in 1998. When the 2003 non forested wetland area was analyzed with respect to the 1998 data, it was found that 35% of the non forested wetland area in 2003 was water in 1998; 20% was forested wetland; 15% was deciduous forest; and 13% was evergreen forest. Since 'open water' of 1998 comprised most of the non forested wetland, the 'non forested wetland' class has been combined with the 'water' class of 2003, and it is comparable to the 'open water' class of 1998.

[d] The 1998 landcover data has two urban classes – low intensity urban and high intensity urban. Since the 2003 landcover has just one 'urban' class, the two 1998 landcover classes have been combined to represent urban land.

Deciduous – There has been a small decrease in the amount of deciduous forest between 1998 and 2003. However, when looking at the percent distribution of the 1998 landcover in 2003 (table 4), it can be seen that only 29% of the area classified as deciduous forest in 1998 remained as deciduous forest (Map 1). About 44% of the area was converted to evergreen classes. Such a change is not very likely to happen, and hence the results of this class analysis are not very reliable.

Mixed forests – According to the change detection results, the amount of mixed forests reduced from 7.2% to about 1.6%. Further, 50% of the area classified as mixed forests in 1998 were classified as evergreen in 2003 (Map 2). The reliability of this class result is also questionable.

Evergreen – The percentage of evergreen forests increased from 32% in 1998 to about 49% in 2003. About 72% of the original area remained the same, and about 14% were converted to deciduous forests (Map 3). This is a larger increase than expected. Some of the increase may be mixed forest in '98 reclassified as evergeen in '03 (Wade Harrison, TNC).

Clearcut/Sparse – There was a reduction in the clearcut/sparse areas from 10% to about 9%. According to table 4, 50% of the clearcut area in 1998 is considered as evergreen in 2003 and only about 13% of the area remained as clearcut (Map 4). From table 5, it can be seen that most of the clearcut area in 2003 was deciduous and evergreen forests in 1998.

Ag land – There has been an increase in the agricultural land from about 8% to 9% in the RSim region. Results in table 5 suggest that a considerable part of this increase could be from clearcut regions, deciduous and evergreen forests. About 51% of the Ag land in 1998 remained the same in 2003 (Map 5).

Based on calculations from the data from the NASS Census of Agriculture (Table 6), there was a 13% increase in the land in farms between 1997 and 2002. This approximately matches the change observed in the landcover maps. But when individual counties are considered, the change trend does not match between the landcover maps and the agricultural census in most of the counties (refer to table 6). Hence it is not clear if the results of the Ag land can be considered as accurate.

Forested wetland – According to the table 3, there is a decrease in the percentage of forested wetlands from about 6.3% to 4.8%. Only 27% of the forested wetland in 1998 remained the same in 2003 (Map 8). Remaining areas were classified as deciduous or evergreen forests in 2003. Similarly from table 5, it can be seen that a large portion of the land classified as forested wetland in 2003 was classified as deciduous, mixed or evergreen forest in 1998. Such results indicate a mix of class definitions during classification of the two landcover data sets. This makes the results of the forested wetland class irrelevant.

Table 3: Change in percentage area of landcover classes from 1998 to 2003

Land cover class	**% in 1998**	**% in 2003**
Deciduous	24.06	19.91
Mixed forest	7.27	3.32
Evergreen	32.76	49.41
Clearcut/Sparse	10.11	8.26
Ag land	8.26	8.61
Water & non forested wetland	1.56	1.83
Urban	2.77	1.87
Forested wetland	6.31	3.72
Roads	6.42	3.07

Table 4: Percentage distribution of 1998 landcover classes in 2003

	2003 LANDCOVER CLASS								
1998 LANDCOVER CLASS ↓	*Deciduous*	*Mixed*	*Evergreen*	*Clearcut/ sparse*	*Ag land*	*Water & non for wetland*	*Urban*	*Forested wetland*	*Roads*
Deciduous forest	29.01	3.64	43.65	12.48	4.27	0.77	0.37	5.32	0.49
Mixed forest	25.59	1.37	50.43	10.15	5.55	0.38	0.87	4.89	0.78
Evergreen	13.94	0.88	72.12	5.01	3.44	0.69	0.45	2.81	0.66
Clearcut/sparse	18.11	1.22	50.60	13.35	11.19	0.44	1.53	2.22	1.33
Ag land	9.19	0.51	21.75	13.46	50.91	0.65	1.59	0.76	1.17
Open water	5.34	0.25	15.55	2.23	1.92	69.65	1.00	3.77	0.28
Urban	12.86	0.56	21.84	12.46	13.40	1.18	29.16	2.10	6.42
Forested wetland	28.74	2.44	31.85	4.81	1.61	3.48	0.21	26.56	0.29
Transportation	11.59	0.54	29.46	6.84	8.84	0.39	5.94	1.50	34.89

- No change

Table 5: 'From-To' matrix of landcover conversions from 1998 to 2003

	2003 LANDCOVER CLASS (TO) (Area in hectares)									
1998 LANDCOVER CLASS (FROM) ↓	*Deciduous*	*Mixed*	*Evergreen*	*Clearcut/ Sparse*	*Ag land*	*Water & non for wetland*	*Urban*	*Forested Wetland*	*Roads*	***Total area***
Deciduous forest	30876.12	3874.32	46458.63	13279.68	4541.85	821.25	397.35	5667.48	523.35	106440.03
Mixed forest	8225.46	441.54	16213.14	3263.67	1783.26	120.87	278.64	1571.76	250.11	32148.45
Evergreen forest	20195.37	1271.07	104502.69	7266.60	4988.07	998.01	649.62	4076.91	954.09	144902.43
Clearcut/Sparse	8103.42	545.58	22636.89	5972.04	5005.26	196.65	683.28	994.95	596.52	44734.59
Ag land	3305.97	184.41	7828.65	4844.16	18321.57	235.26	572.13	274.14	421.20	35987.49
Open water	368.37	17.46	1072.17	153.72	132.39	4801.5	69.12	259.56	19.26	6893.55
Urban	1575.09	68.76	2673.63	1526.04	1641.33	144.45	3570.48	257.67	786.51	12243.96
Forested wetland	8027.46	681.12	8896.59	1344.60	450.72	973.35	57.60	7420.23	81.45	27933.12
Transportation	3291.48	153.99	8367.21	1942.92	2510.64	110.34	1686.78	426.96	9908.46	28398.78
Total area	83968.74	7238.25	218649.60	39593.43	39375.09	8401.68	7965.00	20949.66	13540.95	**439682.4**

(yellow) - No change

Table 6: Agricultural land cover change comparison with change in land area of farms (from agricultural census data)

Region	**Area of land cover in agriculture (hectares)**		**Based on landcover**	**Land use based on census of Agriculture**
	1998	*2003*	*% change from 1998 to 2003*	*% change from 1997 to 2002*
Talbot	9025	7230	-24.84	15.85
Harris	7663	10160	24.58	23.58
Muscogee	3049	3304	7.71	28.98
Marion	14006	15306	8.49	-2.86
Chattahoochee	2240	4136	45.85	-18.09
RSim region	35984	40136	10.35	13.70

Aggregated land cover change detection:

The above results are not accurate and logical mainly because of the class differences between the two data sets. Further, since the classifications were carried out by different organizations, methodology differences and classification biases may affect the results. To negate some of the biases and class difference errors, the land cover classes were aggregated to more general classes and the changes between 1998 and 2003 landcover were tested. The following broad categories were created by combining classes:

Forest – The deciduous forests, evergreen forests, mixed forests and forested wetlands were combined to form one forest category in both the 1998 and 2003 datasets

Ag/Open – In the 1998 landcover, the row crops, pastures, golf courses, utility swaths and clearcut/sparse classes were combined to form the Ag/Open category. In the 2003 landcover, the ag/pasture, leafy veg/grasses and clearcut classes were combined.

Water – For the 2003 landcover, the non forested wetland and the water classes were combined to form the broader water category. The open water class of 1998 was not combined with any other class.

Urban/Transportation – The low intensity urban, high intensity urban and transportation classes of 1998 were combined to create the urban /transportation category. In the 2003 landcover the urban and roads classes were combined.

The results of the change detection analysis using these classes are:

Table 7: Change in percentage area of landcover classes from 1998 to 2003

Land cover class	**% in 1998**	**% in 2003**
Forest	70.40	76.30
Ag/Open	18.65	16.82
Urban/Transportation	1.56	1.8

Water	9.19	4.88

Table 8: Percentage distribution of 1998 landcover categories in 2003

	2003 LANDCOVER CATEGORY			
1998 LANDCOVER CATEGORY	*Forest*	*Ag/Open*	*Urban/Transportation*	*Water*
Forest	87.69	10.4	1.03	0.88
Ag/Open	55.01	41.68	2.86	0.45
Urban/Transportation	42.14	18.11	39.25	0.5
Water	27.46	3.69	1.28	67.57

Table 9: 'From-To' matrix of landcover category conversions from 1998 to 2003

	2003 LANDCOVER CATEGORIES (TO) (Area in hectares)				
1998 LANDCOVER CATEGORIES (FROM)	*Forest*	*Ag/Open*	*Urban/transportation*	*Water*	***Total area***
Forest	273103	32382.81	3192.21	2745.99	311424.03
Ag/Open	45392.58	34389.09	2358.45	373.32	82513.44
Urban/transportation	17128.44	7360.2	15951.5	202.59	40642.74
Water	1892.97	254.16	88.38	4658.04	6893.55
Total area	337517	74386.26	21590.6	7979.94	**441473.76**

Discussion:

The information from the change detection analysis is to be used to estimate future changes in land cover for the deciduous forests, mixed forests, evergreen forests, clearcut/sparse regions and agricultural land. But it is not clear how reliable these comparisons are, largely because of the differences in the 1998 and 2003 classes. Aggregation of classes did not produce reasonable results. Hence these change detection results are unsuitable for generating non urban land cover change rules for RSim.

Change Detection between 1992, 1998 and 2001 landcover data

Land cover data for the years 1992, 1998 and a 2001 (Figures 1, 2 and 3) were available. The 1992 dataset was created by the Multi-Resolution Land Characteristics (MRLC) Consortium. The 1998 landcover map was created by Natural Resources Spatial Analysis Laboratory (NARSAL), at the University of Georgia. The third dataset, a 2001 landcover map was also created by MRLC consortium. However, only part of this data set is currently available. The data covering the northern portion of RSim has been completed. The data for the southern regions are yet to be released. Hence change detection using the 2001 data set was carried out only for the northern RSim region.

Change detection was carried out between each of the years 1992 and 2001, 1998 and 2001 and 1992 and 1998. The results are as follows:

Table 10: Change detection results from 1992 to 2001

Percentage distribution of 1992 landcover classes in 2001								
	2001 LANDCOVER							
1992 LANDCOVER	*Water*	*Developed*	*Barren*	*Deciduous*	*Evergreen*	*Mixed*	*Herb veg*	*Wetland*
Water	**84.918**	1.562	0.263	6.776	2.476	0.197	1.647	2.160
Developed	2.083	**78.623**	0.636	4.304	7.117	0.365	6.576	0.296
Barren	0.302	4.455	**1.397**	11.386	68.795	0.578	12.389	0.698
Deciduous	0.802	5.405	0.348	**60.949**	15.802	0.542	11.643	4.509
Evergreen	0.355	4.655	2.033	11.263	**62.014**	0.591	18.704	0.385
Mixed	0.496	7.333	0.692	36.724	37.439	**1.150**	13.988	2.179
Herb veg	0.322	13.460	0.283	6.570	10.419	0.254	**68.532**	0.160
Wetland	2.093	1.287	0.449	33.865	13.671	1.181	8.647	**38.808**

Table 11: Change detection results from 1992 to 1998

Percentage distribution of 1992 landcover classes in 1998								
	1998 LANDCOVER							
1992 LANDCOVER	*Water*	*Developed*	*Barren*	*Deciduous*	*Evergreen*	*Mixed*	*Herb veg*	*Wetland*
Water	**73.542**	2.662	0.723	5.428	10.413	0.607	0.767	5.859
Developed	3.223	**65.140**	5.348	6.728	12.629	2.708	3.594	0.630
Barren	0.419	9.892	**13.518**	26.854	35.289	7.868	5.213	0.947
Deciduous	0.861	6.601	6.919	**56.504**	19.152	3.058	3.607	3.299
Evergreen	0.409	6.122	13.148	13.944	**61.030**	2.796	1.941	0.610
Mixed	0.679	8.197	8.635	34.132	38.345	**4.713**	3.484	1.815
Herb veg	0.715	15.128	11.150	10.898	8.085	1.528	**52.143**	0.353
Wetland	2.078	2.076	6.388	41.821	19.880	2.895	0.783	**24.081**

Table 12: Change detection results from 1998 to 2001

Percentage distribution of 1998 landcover classes in 2001								
	2001 LANDCOVER							
1998 LANDCOVER	*Water*	*Developed*	*Barren*	*Deciduous*	*Evergreen*	*Mixed*	*Herb veg*	*Wetland*
Water	**66.092**	3.964	0.461	12.827	8.260	0.276	6.069	2.051

Developed	0.857	**39.237**	0.840	16.433	24.414	0.461	16.969	0.790
Barren	0.394	5.913	**0.911**	23.612	20.018	0.436	47.746	0.970
Deciduous	0.512	3.139	0.444	**59.096**	20.739	0.874	10.230	4.965
Evergreen	0.881	4.810	1.516	21.767	**58.887**	0.630	9.986	1.522
Mixed	0.698	8.037	0.696	33.261	42.969	**1.047**	11.254	2.037
Herb veg	0.543	8.067	0.357	13.512	12.146	0.413	**64.510**	0.452
Wetland	5.010	1.951	0.592	40.555	15.376	1.094	7.750	**27.672**

Table 13: Percentage of landcover classes in 1992, 1998 and 2001

Percentage of Landcover			
	1992	**1998**	**2001**
Water	1.79	2.05	2.13
Developed	2.06	8.63	7.55
Barren	4.14	9.27	0.89
Deciduous	34.26	33.99	34.29
Evergreen	24.56	33.58	33.60
Mixed	23.62	3.42	0.68
Herb veg	7.14	6.58	17.67
Wetland	2.43	2.48	3.18

Based on the class definitions for data of each year, it was decided that the change from 1992 to 2001 was most appropriate and suitable. The change detection results from 1992 to 2001 were used to develop a list of probabilities of change for one landcover class to change to another class in one year (annual change) (Table 14).

Table 14: Annual rates of change outside Fort Benning

Annual Changes (percentage) outside Fort Benning - based on data from 1992 to 2001							
	Deciduous	***Evergreen***	***Mixed***	***Clearcut***	***Pasture***	***Row crops***	***Forested wetland***
Deciduous		1.76	0.06	0.76	0.53	0.00	0.50
Evergreen	1.25		0.07	1.59	0.48	0.01	0.04
Mixed	4.08	4.16		1.03	0.52	0.00	0.24
Clearcut	1.28	7.78	0.07		0.73	0.00	0.08
Pastures	0.69	1.04	0.03	0.39		0.02	0.02
Row crops	0.82	1.39	0.02	0.97	5.64		0.02
Forested wetland	3.79	1.52	0.13	0.74	0.20	0.00	

Assumptions made while deriving the non urban growth rules are:

- There is no change in the following categories –
    - Open water
    - Beaches
    - Utility swaths
    - Quarries/Strip mines
    - Golf courses

- The changes in the following categories is taken care of other growth rules
    - Low intensity Urban
    - High intensity Urban
    - Transportation
- For changes outside Fort Benning, the transitions are derived from the northern part of RSim region only (since the 2001 landcover is available for that region only)
- Changes within Fort Benning were derived separately using different data sets available for the Fort Benning region.

Change Detection within Fort Benning

The 2001 and 2003 land cover data of Fort Benning were created by U. S. Army Engineer Research and Development Center (ERDC), Fort Benning. The 1974, 1983/86 and 1991 classifications were created by Lisa Olsen, Oak Ridge National Laboratory from the North American Landscape Characterization (NALC) triplicate data (Olsen et al., i*n review*). The change detection results carried out among these datasets are presented in Tables 15 to 17.

Table 15: Change detection results within Fort Benning from 2001 to 2003

Fort Benning: Percentage distribution of 2001 landcover classes in 2003										
	Water	***EG/Planted***	***EG***	***Decid***	***Shrub***	***Herbaceous***	***Bare ground***	***Mixed***	***Roads***	***Urban***
Water	**71.92**	0.36	13.40	7.83	4.10	0.31	0.41	1.40	0.13	0.11
EG/Planted	0.00	**59.43**	20.03	4.21	9.42	2.61	0.00	4.30	0.00	0.00
EG	0.05	9.13	**54.23**	8.84	2.39	1.42	0.16	23.61	0.12	0.05
Decid	0.10	1.24	12.36	**47.46**	2.04	0.46	0.05	36.19	0.07	0.03
Shrub	0.06	0.15	2.81	70.86	**14.09**	1.76	0.12	10.12	0.03	0.00
Herbaceous	0.12	0.06	1.89	19.76	44.09	**26.68**	3.69	3.05	0.39	0.27
Bare ground	0.06	0.09	1.16	5.46	10.34	35.57	**43.22**	1.25	0.58	2.28
Mixed	0.05	0.37	20.01	37.60	2.94	1.18	0.14	**37.57**	0.10	0.04
Roads	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**100.00**	0.00
Urban	0.26	0.17	4.14	4.63	9.49	4.51	6.52	2.43	4.90	**62.91**

Table 16: Change detection results within Fort Benning from 1974 to 1983/86

Fort Benning: Percentage distribution of 1974 landcover in 1983/86						
	Urban	***Clearcut***	***Deciduous***	***Mixed***	***Evergreen***	***Water***
Urban	**44.69**	43.46	1.41	8.05	2.27	0.12
Clearcut	13.15	**47.72**	5.34	24.18	9.31	0.29
Deciduous	0.84	8.06	**38.96**	29.21	22.85	0.07
Mixed	1.52	12.91	21.96	**34.02**	29.44	0.14
Evergreen	1.14	5.79	13.96	32.76	**46.06**	0.30
Water	0.00	0.00	0.00	0.00	0.00	**100.00**

Table 17: Change detection results within Fort Benning from 1983/86 to 1991

Fort Benning: Percentage distribution of 1983/86 landcover in 1991						
	Urban	***Clearcut***	***Deciduous***	***Mixed***	***Evergreen***	***Water***
Urban	**45.99**	44.20	2.12	4.50	1.38	1.81
Clearcut	8.14	**60.97**	6.10	18.81	5.73	0.25
Deciduous	0.32	2.91	**58.48**	17.83	20.40	0.06
Mixed	1.05	15.15	22.01	**28.71**	32.62	0.46
Evergreen	0.80	6.49	17.29	25.64	**49.55**	0.23
Water	4.11	7.91	2.80	8.65	5.55	**70.98**

Fort Benning is a public land which is under routine forest management. Since there are moves to increase the long leaf pine habitats, management using fires is a common practice. Under such a scenario, it will be expected that the mixed forests and deciduous forests become evergreen in the course of a few years with fire management.

Analyzing the results of the change detections and based on the above premise, it was found that the change from 2001 to 2003 was most appropriate to derive non urban growth rules. The annual rates of change within Fort Benning from the 2001 to 2003 change detection results are presented in Table 18.

Table 18: Annual rates of change within Fort Benning

Annual Changes (percentage) - based on changes from 2001 to 2003							
	EG/Planted	***EG***	***Decid***	***Shrub***	***Herbaceous***	***Bare ground***	***Mixed***
EG/Planted	**29.72**	10.02	2.10	4.71	1.30	0.00	2.15
EG	4.56	**27.12**	4.42	1.20	0.71	0.08	11.81
Decid	0.62	6.18	**23.73**	1.02	0.23	0.02	18.10
Shrub	0.08	1.40	35.43	**7.04**	0.88	0.06	5.06
Herbaceous	0.03	0.95	9.88	22.04	**13.34**	1.85	1.52
Bare ground	0.05	0.58	2.73	5.17	17.78	**21.61**	0.62
Mixed	0.18	10.01	18.80	1.47	0.59	0.07	**18.78**

References:

Olsen LM, Dale VH, Foster T. Landscape patterns as indicators of ecological change at Fort Benning, Georgia. Landscape Urban Planning [in press].

Section 10. Risk Approach

The risk assessment component of RSim is being developed to present expected ecological effects of noise, air quality, total nitrogen in water, and habitat disturbance (from prescribed burns, wildfires, training, roads and/or logging). Background levels of these stressors are considered, as well as levels associated with future, hypothetical scenarios. Potentially susceptible and valued ecological receptors of concern include (1) fish or invertebrate communities (N in water), (2) forest communities (urbanization, ozone, wildfires), (3) red-cockaded woodpecker (RCW, *Picoides borealis*) population (noise and/or habitat disturbance) and (4) gopher tortoise (*Gopherus polyphemus*) population (noise and/or habitat disturbance). Continuous exposure-response models are probably not available for any combinations of these stressors and receptors. Therefore, effects models are primarily thresholds, and exceedences of these thresholds are displayed in RSim. Examples of risk outputs in RSim include

- Map of RCW clusters where woodpeckers may temporarily flush from nests because of noise
- Map of gopher tortoise burrows where animals are potentially immobilized because of blast noise
- Map of habitat areas with burrows that gopher tortoises may potentially abandon because of predicted tree cover changes
- Area of otherwise suitable habitat for gopher tortoise that is unsuitable because of small patch size
- General stability of installation population of RCW, based on number of territories (compared to effects threshold)
- Map of streams where amphibian growth or development may be impaired (if we have estimates of nitrate concentrations)
- Map of areas around roads that are likely to have low abundances of particular songbirds
- Probability that the abundance of a random bird population is reduced, based on distance from the nearest road
- Map of vegetation with potentially injured foliage due to ozone exposure
- Map of vegetation predicted to have at least a 20% reduced yield due to ozone exposure

We made progress in four principal risk assessment areas: (1) compilation of thresholds for effects of noise and vegetation change on red-cockaded woodpecker and gopher tortoise, (2) compilation of thresholds for effects of nitrate in surface water on amphibians, (3) compilation of thresholds for vertebrate disturbance by roads, (4) review of EPA report that summarizes threshold concentrations for ozone on vegetation, and (5) developing a framework for transboundary risk assessments at military installations and on a habitat model for gopher tortoise. The risk assessment framework is justified because of the species, stressors, and management goals that cross installation boundaries. The risk assessment framework paper focuses on the problem formulation or planning phase. Components of the framework include: (1) regional management goals such as installation Integrated Natural Resources Management Plans and land acquisition, (2) involvement of multiple stressors, and (3) large-scale assessment endpoint entities.

Challenges of selecting measures of exposure include: quantifying exposure to aggregate stressors, describing land cover consistently in the region, describing rates of land-cover transition, scaling local measurements to a region, and aggregating or isolating exposures from within and outside of the installation. Measures of effect that are important to transboundary or regional ecological risk assessments at military installations are those that represent: effects at a distance from the stressor, large-scale effects, effects of habitat change or fragmentation, spatial extrapolations of localized effects, and integrated effects of multiple stressors. These factors are reflected in conceptual models. The transboundary approach is described in the paper in section 10a.

The second paper describes a habitat model of the gopher tortoise for a five-county region in Georgia based on analysis of documented locations of gopher tortoise burrows at Fort Benning (detailed in section 6a). Using burrow associations with land cover, soil, topography and water observed at Fort Benning, potential gopher tortoise habitats were analyzed with binary logistic regression. We generated a probability map for the occurrence of gopher tortoise burrows in the five-county region surrounding Fort Benning. An accuracy assessment was performed for select locations outside Fort Benning.

Section 10a. Planning transboundary ecological risk assessments at military installations

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Running head: Transboundary risk assessments at military installations

Abstract

Ecological risk assessments at military installations that are performed to support natural resources management objectives rely on information from the surrounding region. Stressors such as noise, ozone, and ozone precursors cross installation boundaries, and effects of urbanization and highway development are regional in scale. Ecological populations are not limited to one side of the installation boundary. Therefore a framework for transboundary ecological risk assessment at military installations is under development. This paper summarizes the problem formulation stage. Components include: (1) regional management goals such as installation Integrated Natural Resources Management Plans and land acquisition, (2) involvement of multiple stressors, and (3) large-scale assessment endpoint entities. Challenges of selecting measures of exposure include: quantifying exposure to aggregate stressors, describing land cover consistently in the region, describing rates of land-cover transition, scaling local measurements to a region, and aggregating or isolating exposures from within and outside of the installation. Measures of effect that are important to transboundary or regional ecological risk assessments at military installations are those that represent: effects at a distance from the stressor, large-scale effects, effects of habitat change or fragmentation, spatial extrapolations of localized effects, and integrated effects of multiple stressors. These factors are reflected in conceptual models.

Key words: ecological risk assessment, regional risk assessment, problem formulation, military, scaling

INTRODUCTION

Ecological risk assessment frameworks for military training and testing activities have been developed in the past few years, both for general military programs (Suter *et al.* 2002) and specific activities such as low-altitude aircraft overflights (Efroymson *et al.* 2001a; Efroymson and Suter 2001). These frameworks are elaborations of the US Environmental Protection Agency (EPA) framework for ecological risk assessment (EPA 1998). Risk assessment frameworks for military applications provide approaches to assessing risks to animal populations, plant communities, and ecosystem processes within the boundaries of military installations as well as in outlying, affected areas (e.g., below military-controlled airspace). Another military environmental assessment framework provides metrics for assessing the resiliency of generic environmental settings to explosive-residue contamination, based on factors that influence the fate and transport of contaminants (Houston *et al.* 2001). The nature and scale of on-base disturbances associated with training activities are described in Demarais *et al.* (1999), Efroymson *et al.* (submitted), and the risk assessment frameworks mentioned above. However, the regional scale of many stressors created by installations or by development in surrounding jurisdictions, as well as the regional scale of potentially affected receptors, deserves more emphasis in ecological risk assessment.

Although risk managers have tended to manage risk on a local scale, reasons for examining risks at the regional scale are becoming more evident. Stressors and effects cross the boundaries of military installations. Air pollutants and water pollutants can travel long distances, and compliance with the Clean Air Act and Clean Water Act requires knowledge of the source of the pollutants, even if they are on the opposite side of the military base boundary. Military airspace typically crosses over civilian lands. Vertebrate populations and metapopulations do not observe the boundaries of installations, and management of species under the Endangered Species Act may require habitat management on both sides of the fence. For example, 34 listed (threatened or endangered) and one candidate species on or adjacent to 32 U.S. western, arid military installations are threatened by habitat loss and degradation from various sources of mostly off-base land-use change and other stressors (Table 1, data from Tazik and Martin 2002). Moreover, "the interests of the Army and the RCW [red-cockaded woodpecker, *Picoides borealis*] are best served by encouraging conservation measures in areas off the installation" (Department of the Army 1996). Clusters of the federally endangered RCW that are located off-base but demographically connected to on-base populations are included in counts toward U.S. Army Regional Recovery Goals (Beaty *et al.* 2003).

In a non-military example, grizzly bear, elk, moose, bighorn sheep, bison, and grey wolf in Yellowstone National Park depend on lands outside of park boundaries to support their populations (Kelson and Lilieholm 1999). Similarly, forest bird species richness on agricultural lands is a linear function of the log of the size of adjacent, remnant forest (Freemark and Merriam 1986). Moreover, invasive plants move across institutional boundaries.

Encroachment

Many of these transboundary issues from the military perspective are encompassed in the term "encroachment." Encroachment is defined by DoD as "the cumulative result of any and all outside influences that inhibit normal military training and testing" (GAO 2002). The U. S. General Accounting Office (GAO) has identified eight encroachment issues: compliance with endangered species legislation on military installations, application of environmental statutes to unexploded ordnance and munitions, competition for radio frequency spectrum, required consultation with regulators regarding activities potentially affecting protected marine resources, competition for airspace, the application of the Clean Air Act to base-generated air pollution, the application of noise abatement rules to training and testing activities, and urban growth around military installations (GAO 2002). According to the GAO (2002), the impact of encroachment on training ranges has increased over the past several years, and over forty percent of installations have reported encroachment issues (USAEC 2003a).

Encroachment related to the Endangered Species Act (ESA) affects various aspects of military training and testing. The example that is most often cited in the popular press is the designation of 10 percent of Camp Pendleton as critical habitat for several endangered species, which limits the area of beach available for amphibious assaults, off-road vehicle use, the digging of fighting positions, the number of days of weapon systems use, and nighttime helicopter operations (GAO 2002). Similarly, critical habitat designation for the desert tortoise (*Gopherus agassizii*) has hindered Fort Irwin's ability to expand training activities (Tazik and Martin 2002). The military training schedule, approved training area, and fire management of grassland at Fort Huachuca are affected by the distribution of agave cactus species, one of the primary food resources for the lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae* Petryszen) (Tazik and Martin 2002). In another example, the Sonoran pronghorn (*Antilocapra americana sonorienisis*), an endangered subspecies, has hindered training at the Barry M. Goldwater Range in Arizona. High explosive ordnance deliveries have been canceled in seven percent of missions and moved in another 26 percent between 2000 and 2002. Ironically, the animals often prefer the watering holes and young vegetation found in craters of bombing ranges (Tobin 2004).

Urban development encroaches on the military mission, including the management of natural resources at many installations. For example, the frequent understory burns of longleaf pine forests that are required to maintain habitat for RCW have been thought to contribute to the poor air quality of Columbus, GA, the city adjacent to Fort Benning (Ledger Enquirer 2000). Furthermore, individuals and populations of rare species are often concentrated in isolated vegetation community remnants on military land. Large areas of undeveloped land on military installations often provide a refuge for rare species that were once abundant, but whose habitat was destroyed or compromised by development of lands surrounding the installation. As a result, military lands support a higher number of rare species per land area than most other federal lands in the US (Leslie *et al.* 1996). This rarity means that habitat changes on military lands can be associated with high risk to rare species.

The encroachment of environmental regulations leads to at least two situations that may recommend transboundary ecological risk assessments. (1) DoD or regional planners may be interested in attributing the causes of noncompliance to off-base or on-base sources, whichever is appropriate. (2) DoD may implement mitigation measures such as land swaps or conservation easements to facilitate compliance with environmental statutes. These latter options are part of the Private Lands Initiative (USAEC 2003a) and are authorized in the current National Defense Authorization Act.

Regional risk assessment

Regional-scale ecological risk assessments have been conducted for a variety of purposes. The U. S. Environmental Protection Agency's Office of Research and Development has a program on Regional Vulnerability Assessment [(ReVA), EPA 2004], the goal of which is to develop an approach for comparing near-term and long-term vulnerabilities of regions such as watersheds and multi-state areas (Carpenter and Lunetta 2000). A challenge in ReVA is to develop stressor profiles for various stressors that act at the regional scale. In the mid-Atlantic study area, these stressors include: acid deposition, coal mining, human population, landscape pattern, agricultural nitrogen, ozone, pesticide applications, soil redistribution, and ultraviolet B radiation (Carpenter and Lunetta 2000).

In another implementation of regional risk assessment, conceptual models have been developed for use in attributing causes of adverse conditions in South Florida and evaluating restoration options (Gentile *et al.* 2001). The stressors that are the subject of these models include natural events, such as hurricanes, droughts, freezes, fires, sea-level rise and variability in precipitation, as well as anthropogenic stressors, such as modification of habitats and hydrology, nutrient harvesting, recreation, toxic chemicals and climate change (Gentile *et al.* 2001).

Other examples of risk models illustrate their versatility and utility. Graham *et al.* (1991) conducted a regional ecological risk assessment for a forest impacted by ozone to demonstrate (1) the importance of using a spatially explicit model, (2) the importance of contingent effects (ozone, followed by bark beetle attacks), and (3) the link between terrestrial and aquatic effects. Relative risk models were used to rank and sum risks from multiple stressors in assessments in Port Valdez, Alaska (Wiegers *et al.* 1998) and a Tasmanian agricultural catchment (Walker *et al.* 2001). A similar risk-ranking model was used to evaluate relative spatial risks associated with land-use change in and near a Brazilian rain forest reserve (Moraes *et al.* 2002).

These models and frameworks for regional risk assessment highlight the importance of regional-scale risk assessments to address questions related to regional-scale stressors, landscape features, hydrology, or nutrient cycles. Landis and Wiegers (1997) note that assessment at the regional scale "requires additional consideration of scale, complexity of structure, and the regional spatial components: sources that release stressors, habitats where the receptors reside, and impacts to the assessment endpoints." The problem formulation stage of assessment becomes increasingly important as the complexity and scale of analysis and number of stakeholders increase.

Objective

This study calls attention to the potentially unique features of transboundary ecological risk assessments in the vicinity of military installations that should be considered in the planning stage of assessment, or, in risk assessment jargon, the *problem formulation* stage. Aspects of regional or transboundary risk assessment that are elaborated here, beyond the general guidance that is published elsewhere, include:

- Management goals that are unique to the military or to regional institutions in proximity to military installations,
- The wide range of physical stressors that are present and often controlled at the regional scale,

- The large spatial scale of potential assessment endpoint entities, and factors that increase their susceptibility to particular stressors,
- Indirect effects and exchanges between the installation and region that are represented in the conceptual model,
- Measures of exposure, such as land-cover categories, transition rates between land-cover types, and data interpolation methods, and
- Measures of effect, such as remotely sensed information, habitat suitability models, and monitoring protocols.

In addition, prescriptive aspects of these assessments are described, such as: the need for cooperation and collaboration among institutional entities, the need to integrate risks from multiple stressors, the need for consistency in measures of exposure and effects on both sides of the installation fence, and the potential need to attribute causality to stressors on one side of the fence or the other (or to apportion blame appropriately). In the remaining text we elaborate on typical components of ecological risk assessment frameworks, as described in EPA (1998) and, more specifically for military activities (Suter *et al.* 2002a), with particular emphasis aspects on the problem formulation. Attention to detail during the problem formulation stage of a risk assessment leads to more rigorous analyses.

IDENTIFICATION OF MANAGEMENT GOALS

The practice of regional ecological risk assessment around military installations is applicable to many scenarios in which land uses change. These may include the development of new training or testing ranges on an installation; the alteration of natural resources management activities, such as prescribed burns; land acquisition by military installations; the development of new highways and other roads in the region; residential development; and commercial and industrial development. Changes in pollutant releases may occur even in areas where land-use categories are not changing, and regional predictions of regulated chemical concentrations are needed to influence calculations of Total Maximum Daily Loads of pollutants that meet water quality standards. Land-use change outside of installations may remove habitat for threatened or endangered species, thus forcing military installation managers to commit more resources to species management. Most scenarios involve prospective applications of risk assessment. Practitioners of transboundary risk assessment at military installations would include land managers or their agents on both sides of the base boundary.

Management goals for particular installations are set forth in Integrated Natural Resources Management Plans (INRMPs). These plans describe the balance between mission goals and environmental goals, management goals (including recreational land uses) and timeframes, recommended projects (e.g., ecological restoration or wetland protection) and expected costs, environmental legal requirements, and the ecoregional context of the installation's resources. INRMPs are developed with input by the U.S. Fish and Wildlife Service, state wildlife agencies, and the general public, and they are used by installation natural resource managers, planners, and others conducting environmental assessments for proposed agency actions (DoD and USFWS 2002).

On installations, risk assessments could be conducted to support environmental impact statements or other environmental assessments for new training or testing activities, INRMPs, endangered species recovery plans, decisions concerning environmental restoration, or decisions about which lands adjacent to the installation to lease or purchase. McKee and Berrens (2001) discuss the economics of habitat acquisition: "to achieve a cost-effective land acquisition program, the Army must know beforehand the quantity and quality of land that it will require to ensure the survival of the species."

The DoD Private Lands Initiative (PLI) involves cooperative agreements between the U.S. Army and non-governmental organizations to purchase land titles or conservation easements for conservation or training buffer purposes (USAEC 2003a). The National Defense

Authorization Acts for Fiscal Year 2003 and Fiscal Year 2004, codified at 10 USC 2684a, authorize the Secretary of Defense or the Secretary of a military department to enter into agreements with states, cities, counties or private entities concerned with conservation of land or natural resources "to address the use of development of real property [i.e., to acquire land or other interest in a property] in the vicinity of a military installation for purposes of (1) limiting any development or use of the property that would be incompatible with the mission of the installation; or (2) preserving habitat on the property in a manner that (a) is compatible with environmental requirements; and (b) may eliminate or relieve current or anticipated environmental restrictions that would or might otherwise interfere, whether directly or indirectly, with current or anticipated military training, testing, or operations on the installation." The U.S. Army refers to this program as the Army Compatible Use Buffer (ACUB). Under this authority Ft. Irwin, CA, is expanding by 118,000 acres into prime desert tortoise habitat, and the Army is providing $75 million for tortoise conservation (Gerwin 2004). ACUB and related land acquisition efforts would benefit from transboundary ecological risk assessments.

In practice, private, commercial land managers outside of military installations may conduct qualitative risk assessments to ensure that they do not improve habitat for threatened or endangered species, if ESA restrictions would reduce their production [e.g., timber companies with land in North Carolina at risk of RCW habitat designation, Drake and Jones (2002)]. However, the management goals of most large-scale land managers include increasing or at least maintaining the abundance of species of special status.

Retrospective regional risk assessments might also be undertaken if adverse ecological effects are observed, but the responsible stressor or institutional entity is not easily identified. The USEPA's *Stressor Identification Guidance Document* and related papers (Suter *et al.* 2002b; Cormier *et al.* 2003; Norton *et al.* 2003) provide principles for (1) determining causality in aquatic ecosystems and (2) supporting conclusions with evidence that are useful for conducting transboundary or other regional risk assessments. For example, they recommend an evaluation of the association of measurements of exposure and effects, including spatial co-occurrence, spatial gradients, temporal relationships and temporal gradients, as well as the association of effects with mitigation or manipulation of causes. Retrospective risk assessments may also be undertaken to determine comparative or relative risk associated with stressors acting in different spatial areas (Landis and Wiegers 1997), and prospective or retrospective assessments may evaluate risk from different remedial or restoration actions [e.g., net environmental benefit analysis, Efroymson *et al.* 2004].

Regional or transboundary ecological risk assessments could be undertaken to serve other regional planning purposes. For example, Florida and Georgia have passed legislation defining Developments of Regional Impact (DRI). Development projects of sufficient size (based on published thresholds) to have an impact beyond a local government's jurisdiction are subject to review by adjacent jurisdictions in order to avoid potential conflict. DRI projects in Florida include large residential developments, airports, power plants, and large shopping centers (Kolakowski *et al.* 2000). Nineteen categories of developments in Georgia that are potentially subject to DRI considerations are described in GDCA (2002). Types of impact that are considered under the Florida Environmental Land and Water Management Act of 1972 include environmentally sensitive areas, transportation, capital facilities, emergency services, historical resources, the economy, recreation, energy, education, and housing (Kolakowski *et al.* 2000).

Although military installations are not specifically mentioned in DRI legislation (to our knowledge), they are increasingly being notified about regional developments. For example, the Growth Management Act of Florida was recently amended to require counties and municipalities to notify commanding officers of military installations if the comprehensive zoning plan and land development regulations may affect the "intensity, density or use of land adjacent to the military base." In addition, local governments must alter comprehensive plans by June of 2006 to include criteria to improve compatibility of adjacent or proximate lands with military installations

(Florida DCA 2004). Transboundary ecological risk assessments may be useful in the context of future regional planning at military installations.

Cooperation among institutional entities

Clearly, the conservation of wide-ranging populations depends on cooperation of institutional entities that own property comprising habitat, as well as regulatory entities and other stakeholders that have an interest in their survival. Regional or transboundary ecological risk assessments depend on the cooperation and collaboration of institutional entities to provide information to support the characterization of exposure and effects, as well as information on future or past ecological management goals. The problem formulation stage of an ecological risk assessment is the appropriate stage for stakeholders to become involved (EPA 1998).

Cooperation among stakeholders is recommended for conservation, training, and development purposes. INRMPS include procedures for consultation with "all interested groups and individuals that represent an interest in natural resources" (Legacy Resource Management Program 2002). For example, Ober *et al.* (2000) and Tazik and Martin (2002) note that the conservation of lesser long-nosed bats is dependent on the cooperation of a large number of landowners in the region of Fort Huachuca, because they feed over a large area with patchy locations of forage (agaves, *Agave* L. spp.; yucca, *Yucca* L. spp; and saguaro, *Carnegia gigantea*). In its *Management Guidelines for the Red-Cockaded Woodpecker on Army Installations*, the Department of the Army (1996) recommends that if RCW nesting areas are located on installation lands and foraging areas are located offsite (or vice versa), the U.S. Fish and Wildlife Service (FWS) and installations "should initiate cooperative management with these landowners, if such efforts would compliment [sic] installation RCW conservation initiatives." Moreover, the FWS and installations should participate in promoting cooperative RCW conservation plans, solutions, and efforts with other federal, state, and private landowners in the surrounding area" (Department of the Army 1996).

Similarly, land-acquisition programs (and any future risk assessments associated with them) demand cooperation among stakeholders. For example, the North Carolina Sandhills Conservation Partnership, including the US Army, the North Carolina Chapter of The Nature Conservancy, the North Carolina Department of Transportation, the North Carolina Wildlife Resources Commission, the Sandhills Area Land Trust, the Sandhills Ecological Institute, and the U.S. Fish and Wildlife Service have jointly purchased land and conservation easements around Fort Bragg, NC, to preserve the longleaf pine-wiregrass ecosystem and RCW. This arrangement permits use of additional areas on Ft. Bragg for training and increases public recreation opportunities (USAEC 2003b; Dale *et al.* submitted).

DEFINITION OF STRESSORS

Stressors are defined in the problem formulation stage of an ecological risk assessment. Stressors that cross military-civilian boundaries (or whose impacts cross these boundaries) and the activities that produce these stressors are listed in Table 2. Many of the listed activities occur on both sides of the installation boundary, but most are predominantly found on one side or the other. For example, explosions occur on military lands, and most urban expansions occur beyond the boundaries of installations, but in both cases, ecological impacts may cross installation boundaries.

Tracked and wheeled vehicle movement, explosions, troop movements, and road construction can erode soil, leading to sedimentation in streams. Nitrogen runoff is high on agricultural lands and lower on most installations, so the net transport would be expected to move onto installation lands if topography permits these flows. Emissions of volatile organic compounds (VOCs) and oxides of nitrogen (NOx) from both military installations and the surrounding regions mix in the atmosphere and undergo photochemical transformations to form ozone. Similar sources and chemical processes can also lead to increased concentrations of airborne particulate matter. Smokes and obscurants may be comprised of metals, chlorinated hydrocarbons, or oils in various formulations and may be used as munitions (i.e., grenades or projectiles) or produced from stationary generators. Stressors include the smoke material and its breakdown products (Sample *et al.* 1997). Noise from aircraft overflights, explosions, or highways may cross installation boundaries. The visual stressors associated with aircraft overflights can also be significant for some wildlife such as raptors (Efroymson and Suter 2001). Wildlife populations that cross installation boundaries may be impacted by local events such as road kills (Forman *et al.* 2003). New training ranges, roads or other development may fragment habitat for particular species. Many of these stressors (urban encroachment, industrial and commercial development, air pollution, and roads) have also been listed as primary threats to national parks (Kelson and Lilieholm 1999).

Urbanization, which exceeds the national average rate near 80 percent of installations in the U.S. (GAO 2002), is a stressor that directly affects species habitat and populations [e.g., decreases in grassland nesting songbird density (Haire *et al.* 2000) and decreases in avian diversity and increases in avian biomass (Crooks *et al.* 2004)]. Urbanization alters hydrology and nutrient mass balance, especially at the boundaries of urban areas that consist of edges of paved areas. For the purpose of risk assessment, urbanization must often be decomposed into component stressors, such as paved surface, urban runoff, noise, heat, or nighttime light. These component stressors are most often the exposure parameters in exposure-response relationships.

The challenge of attributing sources of ozone to either side of the installation fence may be illustrated by a description of the chemistry of ozone. Low concentrations of ground-level ozone exist naturally in the atmosphere; however, concentrations may increase as a result of a series of complex photochemical reactions involving VOCs and NOx. Anthropogenic sources of VOCs include most civilian and military activities and processes that involve fuels, paints, and solvents. Biogenic sources of VOCs include trees, crops, and other types of vegetation on both sides of the installation fence. Where these latter sources are abundant, biogenic VOC emissions can sometimes eclipse anthropogenic VOC emissions. All significant sources of NOx involve combustion. These include, for example, burning of fuels for transportation, generating electricity, industrial processes, and construction equipment. Biomass burning from prescribed and wild fires on military installations and in surrounding areas can also generate significant emissions of NOx. Emissions of VOCs and NOx from both military bases and the surrounding regions are readily mixed in the atmosphere and undergo photochemical transformations to form ozone. Clearly, the sources of ozone and its precursors in particular locations are sometimes difficult to identify.

SELECTION OF ASSESSMENT ENDPOINTS

Assessment endpoints are defined as ecological entities (populations, communities, or ecosystem processes), properties (e.g., production, abundance), and levels of effect that are deemed important. Criteria for the selection of assessment endpoints are described in Suter *et al.* (2000) and include policy goals and societal values, ecological relevance, susceptibility, appropriate scale, operational definability, and practical considerations. Regarding scale, assessment endpoint entities for transboundary ecological risk assessments would include vegetation communities (Table 3), wide-ranging populations such as birds that cross installation boundaries, as well as more localized populations that are potentially impacted by stressors that cross installation boundaries.

For example, the endangered RCW flies across installation boundaries in many locations in the southeastern United States. Four of the ten largest RCW populations (i.e., clusters of cavity trees) are on military installations (Fort Bragg, NC; Fort Benning, GA; Fort Stewart, GA; and Eglin Air Force Base, FL), and several other military installations (e.g., Fort Gordon, GA; Fort Polk, LA; Fort Jackson, SC; Camp LeJeune, NC; Peason Ridge, LA; and Military Ocean Terminal Sunny Point) also contain woodpecker clusters (James 1995; Beaty *et al.* 2003). The clusters present on most installations do not constitute viable populations. Therefore management efforts would benefit from the modeling of woodpecker populations within a risk assessment context on combinations of military, other public, and private lands. Since 1996 Fort Benning, Fort Bragg, and Fort Stewart have moved over 110 RCWs to other federal, state, and private forests to help stabilize very small populations (Beaty *et al.* 2003). U.S. Fish and Wildlife Service has prepared a recovery plan for the RCW that proposes regional, population-level and cluster-level criteria for delisting the species that include regional population sizes, numbers of populations that should include particular numbers of clusters, and plans for habitat management and population monitoring (USFWS 2003).

Similarly, the only population of Sonoran pronghorn, an endangered subspecies, ranges across southwestern Arizona and Mexico. At the end of 2000 about 40% of the home range of the 99 Sonoran pronghorns in the U.S. was on the Barry M. Goldwater Range, a bombing and gunnery range, with the rest in the Cabeza Prieta National Wildlife Refuge and Organ Pipe Cactus National Monument (Krausman and Harris 2002). This subspecies is of the appropriate scale for regional assessment, is valued by society, and is potentially susceptible to ordnance delivery, aircraft overflights, and collisions with ground vehicles (Krausman and Harris 2002).

Ecological properties of potential wildlife assessment endpoint entities that increase susceptibility to military and nonmilitary stressors are summarized in Table 4. Of these, properties that increase susceptibility to the noise or visual stressors of aircraft overflights were previously described in Efroymson and Suter (2001). Based on these criteria, generic assessment endpoint entities for training or testing activities involving aircraft overflights may include groups of animals such as raptors, waterfowl, amphibians, ungulates, small mammals, cetaceans, and pinnipeds. The desert tortoise, for example, is especially sensitive to habitat loss and fragmentation caused by highways, utility rights-of-way, off-road vehicle use, construction activities and cattle grazing (Tazik and Martin 2002). In addition, vegetation communities are susceptible to erosion, air pollution, and changes in hydrology. Aquatic communities are susceptible to sedimentation from soil disturbance that may be associated with tracked vehicle movement and troop training.

DEVELOPMENT OF CONCEPTUAL MODEL

Conceptual models are developed during the problem formulation stage of a risk assessment to represent the relationships between sources of chemicals or physical stressors and effects (Suter *et al.* 2000). Most conceptual models for ecological risk assessments of contaminants represent processes of fate and transport (including biological uptake), as well as toxicity to assessment endpoint entities. An example of a published conceptual model for effects of smokes and obscurants on RCW on a military installation is presented in Figure 1.

As Suter (1999a) notes, conceptual models for multiple activities involving chemical and physical stressors can be challenging because of the level of detail that is required to illustrate all connections to assessment endpoints, including indirect effects. Indeed, regional risk assessments tend to emphasize indirect effects on populations, e.g., habitat alterations rather than direct mortality and chemical toxicity (although regional-scale air and water pollutants can have regional toxicity). Transboundary ecological risk assessments at military installations need to have conceptual models that reflect spatial locations of stressors and receptors because of the multiple land-management institutions involved. Limburg *et al.* (2002) provide references to support the assertion that "there will be tighter coupling among processes and components with similar rates and overlapping spatial scales." Our conceptual model in Figure 2 distinguishes between on-base and off-base stressors, although the linkages and processes are expressed in more detail on the installation side of the graphic. In this particular example, the RCW population on an installation is the assessment endpoint entity of concern, but the model could just as easily have depicted exposure pathways for the regional metapopulation.

Additional modular models could be constructed in a hierarchical manner (as described in Suter 1999b and Suter *et al.* 2002a) to investigate all of the exposure pathways resulting from the off-base activities of logging, highway construction, vehicle movement, urban development, and conversion to agricultural production. Suter (1999b) recommends three types of conceptual models for use in complex risk assessments: activity-specific models (e.g., for a proposed range or development), site models (e.g., hydrologic models, food web models), and receptor models (i.e., for a particular assessment endpoint). In the problem formulation (and therefore the conceptual models) of a regional risk assessment, it is important to note all connections between stressors, for example, whether similar stressors are produced by multiple activities (e.g., noise), whether stressors overlap in space and time, whether effects are additive, and whether exposures are additive (e.g., habitat loss from multiple sources) (Suter 1999b).

DEVELOPMENT OF ANALYSIS PLAN

The analysis plan is the final stage of the problem formulation in which hypotheses related to exposure and effects are evaluated to identify data and models that are required for analysis (EPA 1998). Key components of the analysis plan are measures of exposure and measures of effects.

Measures of Exposure

Measures of exposure are described in the problem formulation. These measures may include chemical concentrations, area of compacted soil, size and distribution of habitat patches, noise contours, lengths of roads, etc. Particular challenges that are associated with exposure metrics for regional or transboundary risk assessments at military installations include:

- Quantifying exposure to aggregate stressors, such as “urbanization,” in a way that is predictive of effects,
- Describing land cover in sufficient and consistent detail on and off the installation to delimit wildlife habitat,
- Describing rates of land-cover transition accurately,

- Identifying boundaries, sizes, and numbers of patches of similar land-cover or habitat types,
- Scaling point or local measurements to a region (or scaling regional measurements to particular locations), and
- Summing or disaggregating exposures from within and outside of the installation.

Although urbanization and road development are significant stressors that encroach on military missions, including conservation, these stressors may have to be disaggregated into component stressors for exposure-response relationships to be meaningful. Urbanization consists of changes in paved area, vegetation cover, wildlife habitat, soil nutrients, water quality, air quality, structures (physical and visual stressor), noise, nighttime light, heat, vehicle movement, etc. Exposure-response relationships are available for many of these stressors, but few are available for urbanization, in general. For example, a broad study of avian assemblages along a gradient of urbanization was designed to investigate the role of habitat fragmentation rather than other aspects of urbanization (Crooks *et al.* 2004). Similarly, Johnson and Collinge (2004) studied the effect of urbanization, as measured by percent of landscape area occupied by anthropogenic features, on numbers of burrow entrances of black-tailed prairie dogs (*Cynomys ludovicianus*) in the Colorado Front Range. Component stressors associated with roads are a subset of those associated with urbanization, and many studies of the impacts of roads cannot attribute causation to particular variables. An exception is a study of the effects of automobile traffic on breeding bird densities, which empirically separated noise from the visual stressor of automobiles and examined literature to determine the relevance of roadkills and pollution to species abundance (Reijnen *et al.* 1995).

Many military installations support a variety of land-cover classes and include their attributes in geographic information systems that are available for use in risk assessments. However, it is rare that data at a comparable level of detail are available for private and public lands in the surrounding region. For example, at Fort Benning, Georgia, over 40 classes of forest stand data are available, with attributes including many features that are variables in wildlife habitat models, e.g., date of planting, area of stand, radial growth within five years, radial growth within ten years, hardwood basal area within stand, pine basal area in forest stand, site index, stand condition, number of stems per acre in stand, and number of longleaf pine stems per acre (SEMP 2004).

In contrast, the most detailed land-cover data for the five counties of Georgia surrounding Fort Benning, obtained from the University of Georgia's Natural Resources Spatial Analysis Lab (part of the Georgia Gap Analysis Program) include just over 20 tree classes (based on 30-m Landsat TM remotely sensed data) without any detailed temporal or spatial attributes. It is also notable that Fort Benning crosses two states, and the land cover data in Alabama are far less detailed than those in Georgia (USGS 2004a). [Land cover data from the Alabama Gap Analysis Program are incomplete (USGS 2004b).]

Spatially-explicit transition models use rules to specify change in land-cover types for a particular situation (e.g., Debussche *et al.* 1977; Turner 1988; Dale *et al.* 2002). The maps produced from these models can illustrate how changes might occur over time. For example, a map produced from a transition model for Fort McCoy depicts patches of wild lupine (*Lupinus perennis*), which is the obligate host for the larvae of the federally endangered Karner blue butterfly (*Lycaecides melissa samuelis*), at risk of change with tracked and wheeled vehicle training in maneuver areas (Dale *et al.* 2002). When applied to military lands, these models can be use to inform exposure assessment.

The Regional Simulator model (RSim) for use in environmental assessments in the region of military installations is being designed to simulate land-cover changes caused by urban development, road development and changes in military training activities, as well as resulting ecological risks (Dale *et al.* submitted). In this model, rules have been developed to describe transitions to low-intensity and high-intensity urban land-cover classes, and highway development and new military ranges are digitized based on construction plans. In addition, the model will be able to identify patches of contiguous land with identical land-cover or habitat suitability designations, using a modification of the Hoshen-Kopelman algorithm (Berry et al. 1994; Constantin et al. 1997). This computationally intensive algorithm gives a unique label to each spatially discontinuous habitat patch. Alternative rules for defining adjacency, such as whether or not diagonally adjacent cells of the same land-cover designation are in the same patch or whether cells a certain distance apart should be considered to be within the same patch, may influence the outcome of patch-finding algorithms. Exposure metrics such as patch area (Carlsen et al. 2004) and number of territories (Walters et al. 2002) are related to demographic profiles, abundances and extinction probabilities of various species of wildlife.

The spatial and temporal scales of the analysis of exposure are the scales at which the exposure-response model is most relevant. Limburg *et al.* (2002) define the scale of an ecological property as the scale at which the property has "greatest coherence." Few measurements of environmental stressors are from monitoring networks that were designed with the regional scale in mind. As Andelman and Willig (2004) note, most ecological measurements are performed at spatial scales of 10 m^2 or less and durations of five years or less. Often, the regional assessor must make due with measurements at point locations and methods to interpolate between points (and sometimes extrapolate) to larger regions. Spatial interpolation is a challenge if the land-cover categorization varies within the region, e.g., if installation and off-installation land-cover categorizations are different. Even within a land-cover category, various spatial interpolation methods of exposure are only appropriate if certain assumptions are met; Woodbury (2003) discusses Thiessen polygons and kriging in this context.

Air quality monitors and networks of air quality monitors are deployed by state and federal regulatory agencies to determine compliance with National Ambient Air Quality Standards. They are designed, sited, and operated to take air quality samples that are representative of a large area. Thus, they are suited to regional risk assessments if the region roughly coincides with the area represented by one or more monitors. Air quality monitors are poorly suited however, for characterizing local air quality and its effects (except at the location of a monitor). As such, there is some question as to whether these air quality monitors provide effective air pollutant exposure metrics of individual human health or local vegetation growth and survival. Another concern about these monitoring stations is that while they are fairly representative of a large area in the layer of the atmosphere near the land's surface, they do not capture the variability in pollutant concentrations with altitude. This omission makes it difficult for atmospheric scientists to understand how pollutants and pollutant precursors mix and are transported.

Finally, the issue of aggregation of exposure may be illustrated with reference to noise. Exposures to noise may be measured or modeled. Modeled exposures to noise can be added only if the noise exposures have similar frequency and temporal characteristics. For example, Wasmer Consulting (2003) provides instructions for adding noise from contours independently calculated for military and civilian aircraft in the same region. However, methods are not available to integrate wildlife exposures to sources of various types of sound in a region. That is, the decibel results from models used to estimate impulsive blast noise exposures [e.g., BNOISE2 (ERDC 2004, USACHPPM 2004)] cannot be added to the decibel results from models used to estimate continuous sound, such as NOISEMAP (AFCEE 2004), which is used to model overflight sound. Frequency differences in the sounds would need to be determined before a true noise addition could occur (Efroymson *et al.* 2001b). Also, peak sound levels are probably more closely related to ecological effects than the day-night or annual average sound levels that are typically produced from these models, but peak sound levels are usually modeled based on one source. Many sources of sound in the regions of military installations (highway noise; tank noise, especially loud during small radius turns) are rarely modeled.

Measures of Effects

Measures of effects are "statistical or arithmetic summaries of observations used to estimate the effects of exposure on the assessment endpoint" (Suter *et al.* 2000). Examples of measures of effect are: (1) a sound pressure level that results in a bird flushing from its nest, (2) the proportion of habitat lost that leads to the extinction of a population, (3) the minimum number of reproducing pairs needed to sustain a population, or (4) SUM06, a summary statistic for ozone effects on vegetation, calculated as the sum of all hourly values greater than 0.06 ppm (ppm-hrs) (EPA 1996). These measures are developed as part of the problem formulation for an ecological risk assessment. Measures of effect that are uniquely important to transboundary or regional ecological risk assessments at military installations are those that represent: effects at a distance from the stressor or source of the stressor, large-scale effects, indirect effects such as from habitat change or fragmentation, spatial extrapolations of localized effects, and integrated effects of multiple stressors.

For example, effects of noise and visual stressors from aircraft overflights and vehicles on roads can occur at a distance from their sources. Thresholds and other ecological response models for noise and visual stressors of aircraft overflights are available in Efroymson and Suter (2001), and estimates of road-effect zones are provided by Forman and Deblinger (2000). Similarly, ozone and other air pollutants act at a distance from their sources.

Measures of large-scale effects can be computed with data available since the 1970s from satellites and even earlier from some other remote sensing platforms. Underwood *et al.* (2003) developed hyperspectral techniques for monitoring iceplant (*Carpobrotus edulis*) and jubata grass (*Cortaderia jubata*), two invasive species in the coastal zone of Vandenberg Air Force Base in California. Moreover Leyva *et al.* (2002) have used Light Detection and Ranging (LIDAR) data to map the vertical distribution of vegetation supporting black-capped vireo (*Vireo atricapillus*) at Fort Hood, Texas. Washington-Allen *et al.* (submitted) used the Soil-Adjusted Vegetation Index derived from historical Landsat imagery to assess the effects of military training and testing activities and drought on vegetation at National Guard Camp W. G. Williams in Utah from 1972 to 1997. All of these applications could be regional in scope, and data from these remote-sensing technologies are not limited to military installations.

As with exposure, spatial extrapolation or aggregation of effects is a challenge. Rastetter *et al.* (1992) caution ecological assessors about aggregation errors that can arise when fine-scale equations are used to predict coarse-scale behavior. For example, Woodbury *et al.* (2002) examined the sensitivity of tree basal area predictions by the ECLPPS ozone-tree model to the choice of cell size. This vegetation property varied with cell size because of an aggregation error in the algorithm used to calculate shading.

Habitat models can be considered measures of exposure (of individual animals or populations to disturbance) or measures of effects (on species-specific habitat). Habitat suitability indices are estimates of carrying capacity (USFWS 1981), and other habitat suitability models can be used to estimate the presence or absence of a given species. Based on available land-cover data, habitat models for use on-base and off-base would probably require different parameters, which means that uncertainty might be much larger in poorly studied regions outside of military installations than within installations with strong conservation programs. Habitat models may not be necessary for the estimation of current species locations on-base, where locations for threatened, endangered, and other valued species are periodically surveyed. For example, dynamic models of vegetation growth can provide much of the vegetation growth data that are available on Fort Benning for outlying areas, but these models are highly dependent on management assumptions. Yet models can greatly reduce field efforts [e.g., identification of threatened calcareous habitat at Fort Knox Military Preserve (Mann *et al.* 1999)]. Models can also identify habitats on sites that may not be accessible because of unexploded ordnance [e.g., potential locations at Fort McCoy of wild lupine (Dale *et al.* 2000)].

Simulation models may incorporate thresholds and other measures of effects for use in ecological risk assessments. As stated above, RSim is designed to simulate (1) land-cover changes caused by urban development, road development, and changes in military training activities; (2) resulting changes in air quality, water quality, soil nutrients, and noise; and (3) changes in vertebrate populations and their habitats (Dale *et al.* submitted). The model will include thresholds for ecological effects and continuous exposure-response relationships. Examples of effects that will be estimated and mapped for the Fort Benning, GA, case study include RCW clusters where woodpeckers may temporarily flush from nests because of noise, gopher tortoise (*Gopherus polyphemus*) burrows where animals are potentially immobilized because of blast noise, areas around roads that are likely to have low abundances of particular songbirds, and vegetation predicted to have at least a 20% reduced yield due to ozone exposure.

CONCLUSIONS

Many of the natural resources management goals of military installations and other lands in the region involve physical and chemical stressors and ecological populations that move across installation boundaries. Risk assessments at military installations should be conducted at the regional spatial scale if the management goals are regional. Components of the problem formulation stage of a transboundary risk assessment framework include (1) regional management goals such as developing installation Integrated Natural Resources Management Plans and acquiring land for conservation purposes, (2) identification of multiple stressors, (3) selection of assessment endpoint entities that are appropriate for a large spatial scale, and (4) description of linkages between stressors and assessment endpoint entities in conceptual models. The characterization of exposure of a transboundary risk assessment will have the following challenges: quantifying exposure to aggregate stressors such as urbanization, describing land cover and rates of land-cover transition in sufficient detail and consistently across the assessment region, scaling point or local measurements to a region, and aggregating or isolating exposures from within the installation and in surrounding areas. The characterization of effects for a transboundary or regional ecological risk assessment at a military installation may include: thresholds for noise or distance from aircraft overflights, road-effect distances, species monitoring methodologies such as remote sensing, and habitat models. If transboundary ecological risk assessments are well planned, then the results will have a high likelihood of supporting natural resources management goals for military planners, highway developers, county and urban developers, and other interested parties.

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Table 1. Stressors causing habitat loss for 34 threatened or endangered and 1 delisted species residing on or near western arid military installations (Tazik and Martin 2002)

Stressor	Percentage of species affected[1]
Hydrologic alterations	49%
Urban/suburban development	46%
Livestock grazing	43%
Agricultural development	37%
Nonnative species invasions	29%
Mining/energy development	17%
Timber/woodcutting	9%

[1]As Tazik and Martin (2002) note, species can be included in more than one category, so the percentages do not add up to 100%.

Table 2. Stressors that cross military-civilian boundaries or that impact land areas across the border.

Activity	Stressor	Military	Civilian
Urban development	Loss and fragmentation of critical habitat, alteration of hydrology, alteration of nutrients, heat, light, nonnative vegetation, alteration of habitat structure (buildings, pavement)	X	X
Road development	Noise, loss of habitat, altered hydrology, visual stressor	X	X
Logging	Loss and fragmentation of habitat	X	X
Agriculture	Nutrients		X
Prescribed burns	Loss of and fragmentation of habitat, air pollutants	X	X
Wildfires	Loss and fragmentation of habitat, air pollutants	X	X
Troop training	Changes in vegetation from trampling, particulates in air, sedimentation	X	
Tracked vehicle movement	Soil erosion, sedimentation, altered hydrology, noise	X	
Aircraft overflight (training or testing)	Noise, visual stressor, air movement from takeoff/landing	X	X
Release of smokes, obscurants	Metals, chlorinated hydrocarbons, oils	X	
Explosions	Noise, erosion	X	

Table 3. Dominant vegetation communities of Army, Marine, and Army National Guard Lands (data from Demarais *et al.* 1999)

Vegetation community	Percentage of military land
Southern desert scrub	25.5%
Boreal forest	13.2%
Northern desert	12.4%
Southeast evergreen forest	11.8%
Montane woodland brush	10.7%
Eastern deciduous forest	10.4%
Grasslands	5.0%
Northern hardwood-conifer forest	4.5%
Pinyon-juniper-oak woodland	2.5%
Chaparral-oak woodlands	1.3%
Oak savanna	1.3%
Pacific rainforest	0.9%
Mesquite grasslands	0.3%
Tropical vegetation	0.2%

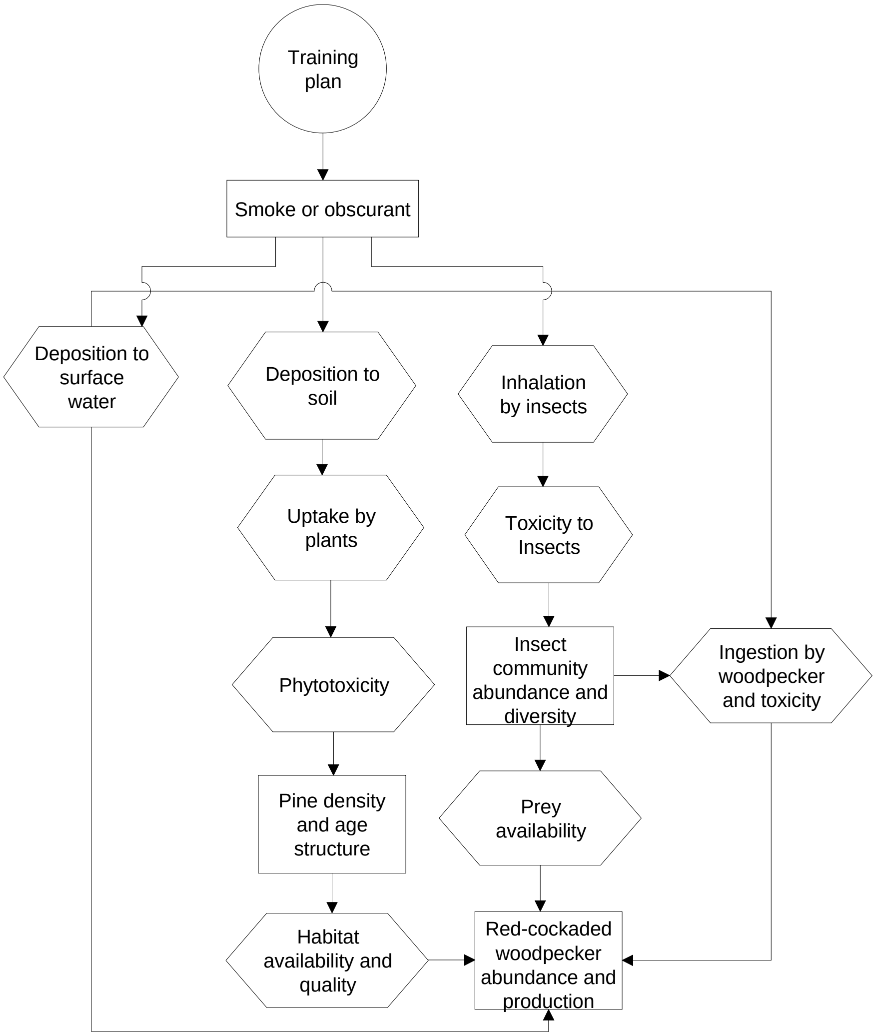
Table 4. Examples of assessment endpoint properties that increase susceptibility of terrestrial vertebrates to stressors. Properties lead to either increased sensitivity (s) or increased exposure (e)

Stressor	Endpoint property
noise	• lack of previous exposure to the sound (s) • high predisposition to auditory damage (s) • reliance on auditory cues to locate young, to locate a mate, to avoid predators, to emerge from hibernation, or to detect prey (s) • seasonal tendency toward energy limitation (s) • sensitivity to sound while raising young (s) • flocking or herding behavior (s)
Habitat loss or fragmentation	• territoriality (s) • dispersal and foraging at scale of fragmentation (e) • edge sensitivity (s) • social breeding (e.g., lekking behavior) (s) • habitat specificity (s) • seasonal tendency toward energy limitation (s)
Air pollutants	• low threshold for toxic effects from ozone, particulates, metals, chlorinated hydrocarbons, oils, etc. (s) • high rate of metabolism (e)
Erosion	• requirement for high vegetation cover (s) • (also, see entries under habitat loss or fragmentation)

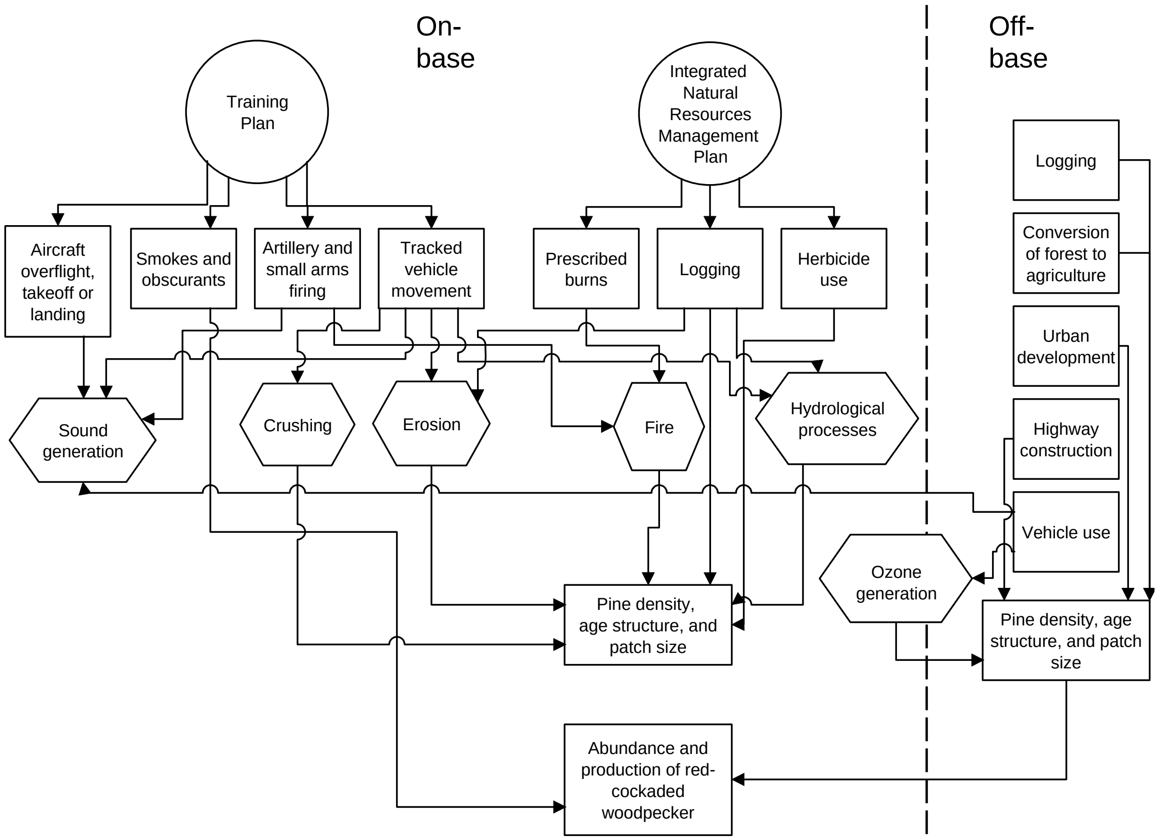
FIGURE CAPTIONS

Figure 1. Conceptual model for effect of smoke or obscurant on red-cockaded woodpecker, modified from Sample *et al.* (1997). Rectangles are states, hexagons are processes, and circles are management plans.

Figure 2. Conceptual model for effects of on-base and off-base stressors on a population of red-cockaded woodpecker at a military installation in the southeastern U.S. Rectangles are states, hexagons are processes, and circles are management plans.


Training plan
Smoke or obscurant
Deposition to surface water
Deposition to soil
Inhalation by insects
Uptake by plants
Toxicity to Insects
Phytotoxicity
Insect community abundance and diversity
Ingestion by woodpecker and toxicity
Pine density and age structure
Prey availability
Habitat availability and quality
Red-cockaded woodpecker abundance and production

1



On-
base
Off-
base
Training
Plan
Integrated
Natural
Resources
Management
Plan
Logging
Conversion
of forest to
agriculture
Urban
development
Highway
construction
Vehicle use
Aircraft
overflight,
takeoff or
landing
Smokes and
obscurants
Artillery and
small arms
firing
Tracked
vehicle
movement
Prescribed
burns
Logging
Herbicide
use
Sound
generation
Crushing
Erosion
Fire
Hydrological
processes
Ozone
generation
Pine density,
age structure, and
patch size
Pine density, age
structure, and patch
size
Abundance and
production of red-
cockaded
woodpecker

1

SECTION 11

HABITAT DISTURBANCE AT EXPLOSIVES-CONTAMINATED RANGES

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11.1 INTRODUCTION

The sustainability of wildlife populations at explosives-contaminated ranges depends on the presence of adequate habitat as well as the absence of bioavailable concentrations of energetic chemicals in soil that would adversely affect these populations. The extent and importance of habitat disturbance is rarely investigated on ranges where explosives are used. Risk assessments for wildlife at contaminated sites occasionally consider habitat preferences in models of trophic uptake of chemicals [1, 2], but almost never the potential habitat loss associated with those contaminants or physical disturbance [3]. Ecological risk assessments for explosives-contaminated ranges should consider physical habitat disturbance in addition to exposure to explosives contaminants in order to distinguish habitat-based effects from putative toxicity observed in the field. Additionally, ecological risk assessments that are intended to include all ecological stressors from live-fire training, (e.g., those that may support installation Integrated Natural Resources Management Plans) [4], should incorporate the effects of habitat loss, even if these are small in scale, compared to the often large areas of military installations characterized by relatively intact vegetation communities. Therefore, a discussion of habitat disturbance on explosives-contaminated ranges is included in this volume on ecotoxicology of explosives.

Little research has been performed to investigate ecological effects of munitions use within impact areas, including the possible spatial scales of these effects [5]. The phytotoxicity of explosives has been examined primarily in a laboratory context, which does not consider additional potential sources of habitat disturbance that are present on ranges. Habitat disturbance can result from construction of ranges; range management practices (e.g., clearing of woody vegetation); phytotoxicity of explosives, cratering and associated, localized disturbance of soil; unintentional wildfire from explosives detonation; and removal of ordnance scrap and associated chemicals. Those plant communities and wildlife populations that require a minimum contiguous area of soil having specific bulk densities or vegetation cover are potentially at risk from large-scale activities at explosives ranges. In contrast, impact areas and surrounding buffer zones sometimes provide beneficial habitats for species that thrive in disturbed areas and those that prefer open or edge habitats.

Few studies have summarized the scale and magnitude of potential habitat loss and species sensitivities due to detonations, contamination from explosives, and range construction and management practices. This chapter describes munitions ranges (mission, design and construction practices), the spatial distribution of contamination and phytotoxicity, and the spatial scale of physical effects (e.g., detonation craters, fire, clearing of vegetation). Principles of habitat suitability and connectivity are summarized, as well as ways to quantify habitat change, responses of species to disturbance, resiliency and recovery, and confounding effects of multiple stressors, such as foot traffic, vehicle maneuvers, noise, fire, and invasive vegetation. Together, these topics form the basis for understanding the nature and scale of habitat disturbances at explosive-contaminated ranges. This discussion is not meant to imply that poor wildlife habitat is ubiquitous at military installations; many of these installations and surrounding buffer areas have large vegetation communities that serve as reservoirs for protected species [6]. This chapter is meant to argue that in ecological risk assessments and environmental management decisions, ecotoxicity should be considered in the context of habitat quality, which may be poor in isolated locations for particular species. Although issues of habitat quality are equally important in aquatic and terrestrial environments, this chapter has a terrestrial emphasis. For information on the toxicity of explosives and related contaminants to specific groups of ecological receptors, the reader is referred to for soil; for surface water; for sediment; and for wildlife.

11.2 MUNITIONS RANGES

U.S. Forces must practice live-fire training and thoroughly test weapons and munitions that will be relied upon in battle. The military manages its land, air and water assets in ranges to assure that its arsenal has high quality and reliable weapons. The size, construction practices, uses, duration and intensity of uses, target maintenance, and contamination of military ranges affect wildlife habitat suitability.

Ranges have multiple definitions in the military context. A recent U.S. Department of Defense Directive [7] attempts to clarify the definitions of Range and Operating Area as: “specifically bounded geographic areas that may encompass a landmass, body of water (above or below the surface), and/or airspace used to conduct operations, training, research and development, and test and evaluation of military hardware, personnel, tactics, munitions, explosives, or electronic combat systems. Those areas shall be under strict control of the Armed Forces or may be shared by multiple Agencies." Terrestrial ranges within the U.S. Air Force, Navy, and military testing community typically are large expanses of land, sea or air, and the term "range" sometimes denotes the entire installation, as with the White Sands Missile Range. In contrast, Army and some Marine trainers often view ranges as a specialized configuration of land features conducive to or designed to safely and effectively train specific skills and missions. Examples of these are rifle, artillery and tank gunnery ranges. Because this chapter emphasizes habitat issues, including the spatial distribution of habitat, we adopt the latter, more specific definition of range, because it refers to physically disturbed areas.

As defined above, different types of ranges may be designed and used for varied purposes, such as flight training, vehicle maneuvering, and urban warfare. This discussion includes only those ranges intended for weapons firing, which are more narrowly defined in the Military Munitions Rule as "designated land or water area set aside, managed, and used to conduct research on, develop, test, and evaluate military munitions and explosives, other ordnance, or weapon systems, or to train military personnel in their use and handling… " [8]. In this chapter, these ranges are designated "explosives ranges," which is not a military term and is not limited to Explosives Ordnance Demolition Ranges.

The design, construction and mission of firing ranges are highly variable, although efforts have been made to standardize these elements [9]. For example, a small arms range for soldier training, especially a hand grenade range, may be a considerably altered environment. The clearing of vegetation, grading of surfaces, earth moving to construct containment berms, and construction of support facilities, such as firing lanes, targets, observation towers and staging areas, are often involved. However, for some uses, such as scattered artillery firing points, the range alterations may be limited to markers designating the firing points, and the impact area, which is often out of sight several kilometers away, may have no intentional alterations other than the posting of warning signs or fencing. Often, single impact areas serve multiple weapons systems. Clearly, air-to-air combat training and ground-to-air training, such as antiaircraft firing, require little more than secure land (or open water) for spent rounds to land. Air-to-ground combat training ranges typically require ground target placement and surface improvements, such as service roads, to maintain them.

Recent range design trends include investment in highly instrumented ranges capable of creating multiple scenarios of targets, obstacles and objectives. Many of the existing landscape features and vegetation are often retained for tactical concealment [10]. On the other hand, such ranges are often heavily used and require intensive maintenance and support facilities, such as access roads, observation towers and instrumented targets. These training ranges are similar to weapons testing ranges in their investment in instrumentation.

Test ranges conduct firing tests to certify that weapons and munitions meet performance specifications and to report failure analyses back to program managers. Often the test article is an experimental prototype or a limited lot tested against performance criteria under controlled conditions, in contrast to the synergistic approach of soldiers, weapons, tactical equipment and systems common to training doctrine. Support services at test events add assets, such as sensitive optic, acoustic and other sensors; observation bunkers and towers; meteorological stations and other monitors; or high-speed networking and communication systems. Fired rounds or their explosion fragments may be recovered from impact areas for further analysis.

These activities nominally involve off-road vehicle operations and excavation to retrieve buried rounds. A further complication of munitions testing is the risk that prototype items in different stages of development may not perform as planned (which is why testing is important in the first place). In response, heightened safety precautions and conservatively estimated surface danger zones are in place to counter the elevated risk of misfire or malfunction. Additionally, developmental munitions testing is not typically located in permanent firing positions and impact areas, because each test is driven by the proponent's requirements and specifications.

Production or Lot Acceptance Testing (PAT), whereby samples are routinely taken and fired from current munitions inventories for quality assurance, can generate a tremendous amount of expended ordnance down-range. Such a mission at the now closed Jefferson Proving Ground in Indiana generated an estimated 23,000,000 rounds fired (and an estimated > 1,000,000 duds, i.e., rounds that did not explode on impact) during its more than 40 years of operation [11]. In most instances, recovery of spent rounds is not a requirement of PAT.

In short, troop weapons training needs fixed, standardized ranges for use on a frequent and intense basis. PAT requires the same, but at an even higher, routine rate of use, depending on the current munitions inventory. Developmental testing requires highly variable, custom range configurations for short term, low intensity use, with increased ancillary services and support areas. In the future, the differences between training and testing will be less apparent as the National Defense Strategy mandates large sophisticated ranges on multiple installations functioning synergistically in order to conduct exercises combining missions of both testing and training [12].

An additional factor that determines potential exposure to habitat disturbance is the spatial extent of munitions ranges. Ranges at Army training installations where energetic compounds are used vary in size from hand grenade ranges (400-500 m^2) and demolition ranges (a couple of hectares), to antitank rocket ranges (a hundred hectares), to mortar and artillery ranges (hundreds of km^2). It is important to note that range size is increasing dramatically as operational speed, range and fire-power increase. For example, the typical large range requirement for World War II era tactics was 10 km^2. That required area has tripled recently and is soon anticipated to expand to over 3000 km^2 to meet needs of future forces [12]. Additionally, the use of joint forces in complex, networked exercises implies more frequent training objective scenarios that cross multiple installations.

11.3 SPATIAL DISTRIBUTION OF CONTAMINATION AND PHYTOTOXICITY

Among other factors, an investigation of habitat loss requires consideration of the spatial extent of contamination from a field perspective. Potential habitat loss can be quantified if the sizes and shapes of contaminated areas and chemical concentrations available to plants are known, as well as the area of physical disturbance. Shapes of contaminated areas help to determine the connectivity of species-specific habitat (see discussion below). Chemical concentrations determine the likelihood and spatial extent of phytotoxicity and the time to recovery of vegetation. In addition, the depth of contamination, relative to that of plant roots, is a factor that determines the potential for plant uptake of explosives.

Activities that potentially contaminate portions of explosives ranges include small arms and artillery firing (training and testing), blow-in-place operations by ordnance recovery teams, the use of Depleted Uranium (DU) tank penetrator rounds, and the use of smokes and obscurants. Munitions-related energetic compounds may be deposited at detectable levels near firing points and impact areas. The spatial distribution of these compounds is related to the munition and targetry type. Artillery ranges increasingly use “shoot and scoot” procedures of rapid deployment and withdrawal, rather than fixed firing points, and this practice leads to dispersed contamination. At firing points, the major potential contaminants are related to the propellants. For artillery, mortars, and shoulder-fired rockets, these propellants are nitrocellulose-based. For single-base propellant, 2,4-dinitrotoluene (2,4-DNT) is added; for double-base propellant, nitroglycerin is added; and for triple-base propellant, nitroglycerin and nitroguanidine are added. Many larger rocket and missile systems use ammonium perchlorate as the oxidant.

The major energetic compounds deposited at the impact areas are high explosives. These include trinitrotoluene (TNT), Composition B (60% Royal Demolition Explosive (RDX), 39% TNT, 1% wax), octol (60-70% High Melting Explosive (HMX), 30-40% TNT), tritonol (TNT and aluminum), and Composition A5 (98.5% RDX). When duds are destroyed within active impact areas, the donor charge is generally C-4, which is 91% RDX and 9% oil. The military also fires smoke rounds downrange, and one of the major smoke-producing chemicals is white phosphorus (P_4), although restrictions on where these may be used have reduced their numbers somewhat, especially in situations where the impact area consists of marshes or wetlands.

The potential for phytotoxicity from explosives is discussed at length elsewhere in this volume (see Chapter 4). Few studies of the phytotoxicity of these chemicals have been undertaken, and most of these, which are reviewed in Rocheleau *et al.* [13], were tests of TNT. Concentrations of TNT that reduce shoot or root biomass in crop test plants in the laboratory range from about 0.1 mg kg^{-1} to >1600 mg kg^{-1} dry soil [14-17]. Phytotoxicity tests with amended soils produced LOEC values for TNT ranging from 0.1 to 64 mg kg^{-1} depending on plant species and exposure type used [15] (see Chapter 4). Plant growth was not affected by HMX at concentrations up to approximately 1900 mg kg^{-1} dry forest soil [16], and additional studies suggest that nitro-heterocyclic compounds are not as toxic as nitroaromatic compounds

[13-14]. Notably, concentrations of TNT below 50 mg kg^{-1} have sometimes been observed to stimulate seedling growth in the laboratory [15, 17]. Clearly, more studies of phytotoxicity of these chemicals are needed, especially field investigations and laboratory studies using native species. In general, the concentrations of explosives in soil are not sufficiently high to denude the area of all vegetation [18].

The nature of constituent residues observed in surface soils on training ranges is determined by the characteristics of the munitions fired. The following discussion describes residues associated with hand grenade, anti-tank and artillery/mortar ranges. Hand grenade ranges are relatively small, sparsely vegetated, and heavily cratered, and the soils contain high concentrations of metallic fragments. The energetic compounds detected at the highest concentrations at these ranges include RDX, TNT, HMX, and two environmental transformation products of TNT, 2-amino-4,6-dinitrotoluene and 4-amino-2,6-dinitrotoluene [19-20]. The energetic compounds are largely in the top 15 cm of soil with concentrations of RDX and TNT ranging from the high ppb (µg kg^{-1}) to low ppm (mg kg^{-1}) levels. The bulk of the residue appears to be due to low-order (partial) detonations and destruction (blow-in-place) of duds, which results in deposition of particles of the undetonated explosive [21].

The spatial distribution of contamination at several antitank rocket ranges has also been studied [19, 22-27]. These relatively small ranges (e.g., 5 ha)generally consist of grasslands, because most current weapons systems require a line-of-sight from the firing point to the target. The weapon fired with the greatest frequency at these ranges has been the M72 66-mm LAW Rocket. The propellant used with this weapon is double base, and concentrations of nitroglycerine as high as a few percent have been detected behind the firing line where deposition occurs from the back blast [24-25]. The high explosive used in the warhead of this rocket is octol, and the major residue detected at the impact areas is HMX. Concentrations of HMX are inversely related to the distance from the target with concentrations as high as hundreds of ppm adjacent to targets. Even though octol is 70/30 HMX/TNT, the concentration ratios of these compounds in surface soils are about 100/1 HMX/TNT due to the much lower solubility of HMX and its much greater half-life in the soil compared to TNT [24, 28]. The major source of the deposition of octol at these ranges appears to be the rupture of these thin-skinned rockets when they do not directly impact a target, and the fuse fails to function normally. Such an occurrence can spread relatively high concentrations of explosive compounds at target locations.

Research on energetic compounds has also been conducted at artillery/mortar ranges at several installations [19-20, 27, 29-35]. These ranges are very large, and the terrain varies significantly, encompassing grasslands, forests, wetlands, and dry, sparsely vegetated areas of the desert southwest. Typical shoot-and-scoot exercises do not utilize fixed positions, so the deposition that occurs near the firing point is widely dispersed at low concentrations. The energetic compounds that can sometimes be detected at firing points are 2,4-DNT from single-base propellants and nitroglycerin from double- and triple-base propellants. These chemicals are found at ppb to low ppm concentrations in the top few centimeters of soil.

Only a small portion of the large tracts of land designated as impact areas have artillery targets; thus, the majority of the surface of these ranges is largely uncontaminated [19, 27, 29, 30, 32, 34]. Live-fire testing has indicated that when artillery and mortar rounds detonate as designed, only microgram to milligram quantities of high explosives are deposited. The major contamination at artillery and mortar ranges results from low-order detonations of TNT and Composition B-containing munitions. Using the data presented by [21], we estimate that it can take as many as 100,000 normal detonations to deposit as much residue of RDX and TNT as would one low-order detonation in which half of the explosive fill remains undetonated. These "hot spots" of contamination are often (but not always) located in the general vicinity of targets, and they result in an extremely heterogeneous distribution of residues in surface soils at these ranges. A recent study indicated that concentrations of RDX varied over five orders of magnitude within a 10-m x 10-m area whose primary contamination came from a single Composition B-filled mortar round that had undergone a low-order detonation [36].

Distributional heterogeneity of residues of energetic compounds is observed at the impact (detonation) area of all ranges, but especially at artillery/mortar ranges. Compositional heterogeneity is also present, as residues of energetic compounds are often deposited as particles of energetic compounds of various sizes [35]. It is very difficult to collect truly representative soil samples under these conditions, and studies indicate that characterization based on discrete samples would result in huge uncertainties [37, 35]. Multi-increment composite samples using 30 increments or more have been used to reduce sampling error [20, 24, 33, 35], but uncertainties can still be significant.

Very little research has been conducted on residue deposition at Air Force or Naval terrestrial ranges. One study conducted at a Canadian Air Force range found that most training activities do not use high explosive-filled bombs and rockets [38]. Typically, no detonators are present and spotters rely on visual observation of impact, or there is a small smoke marker. Only one relatively small grassland range (a few hundred acres) was used for training with high explosives-filled bombs and rockets. The soil was tilled to reduce the potential for forest fires at this largely forested range, and TNT was found in concentrations up to several hundred ppm in surface soils near the target. RDX was not present; Air Force bombs are often filled with tritonol (TNT and aluminum).

White phosphorus-based smoke rounds are also used frequently at artillery/mortar training ranges. White phosphorus is a form of elemental phosphorus that is pyrophoric, spontaneously igniting in the presence of air. At one Army artillery range where the impact area was in a salt marsh, particles of white phosphorus present in shallow sediments resulted in mortality of a variety of waterfowl through ingestion of these particles while feeding [39]. As with other energetic contaminants, the deposited white phosphorus particles are spatially heterogeneous, complicating the characterization of these areas. White phosphorus is less of a problem in terrestrial environments because of its pyrophoric behavior, although it can sometimes crust over, protecting chunks of white phosphorus from oxidation and resulting in issues of safety when these particles are broken open at a later date.

Based on the limited field sampling that has been performed, only small fractions of the area of explosives ranges are contaminated with explosives, and often these are at concentrations that may not be bioavailable or phytotoxic. However, concentrations of TNT in hot spots of soil in most impact areas exceed the lowest levels that have been observed to be toxic to some test plant species as discussed above (7 mg kg^{-1}) [14-15].

The uncertainty associated with spatial predictions of contamination (and therefore phytotoxicity) is typically higher on testing grounds, where new ordnance items are tested, than on training installations. Targeting error may be unknown, including propulsion, ballistic, and detonation reliability; however, technological advances may allow impact locations to be calculated more precisely.

11.4 SPATIAL SCALE OF PHYSICAL EFFECTS

The exposure of wildlife to physical disturbance on explosives ranges may be as important (or unimportant) as their exposure to chemical explosives. Habitat disturbance from range construction may occur at the scale of the entire range. This type and scale of disturbance may be intense and large enough to fragment habitat (see discussion of fragmentation below). However, other sources of physical disturbance generally occur at much smaller spatial scales. A single firing point may be used (and therefore disturbed) repeatedly by rotational training units in free-maneuvering combat vehicles that establish a hasty firing position and fire into a distant impact area. Detonation craters are a source of local disturbance in topography, soil organic matter, and vegetation. Although these craters are dense on hand grenade ranges [18], they may represent no more than ten percent of typical impact areas [40]. If line-of-sight is required (e.g., for small arms and many tank gunnery and anti-tank weapons, but not digital ranges), then range management practices may include clearing of all woody vegetation between the firing points and targets, sometimes with mowing and herbicide use. The area cleared of vegetation around individual firing points of artillery and mortar ranges is typically no more than 0.2 ha, unless groupings of firing points occur in close proximity [40]. Vegetation at U.S. Air Force bombing ranges is often cleared of vegetation at the larger scale of one km^2 or more. The spatial scales of fires, including wildfires from detonations and tracer rounds, depend on meteorology, as well as the presence of adequate fuel. Range management practices often include controlled burns or disking (turning over vegetation attached to soil clods with a harrow) to control potential wildfires. The spatial scales of controlled burns used to protect against wildfires from detonations and those conducted for habitat management (e.g., for red-cockaded woodpecker at Fort Benning) are prescribed at each installation. Blow-in-place of unexploded ordnance (UXO) on ranges and excavation to remove explosives at closed ranges (e.g., for open burning/open detonation treatment) are intense but small-scale disturbances. Safety buffer areas, often more than a thousand hectares around major ordnance impact areas, tend to be almost undisturbed habitat, and human safety restrictions within ranges can increase wildlife habitat quality in areas where firing points and targets are not located.

11.5 HABITAT SUITABILITY AND CONNECTIVITY

Habitat for a wildlife species is the sum of the locations from which it derives food, water and cover, as well as locations where reproductive activities occur. Particular environments may be well suited, partially suited or not suited to specific species. Winter and summer habitats differ for migrating species, and breeding habitats may differ in spatial extent and other characteristics from non-breeding habitats. Some of the variables that determine wildlife habitat include: soil characteristics (particle size, moisture content, pH, nutrient content, etc.), topography (slope, aspect), temperature, precipitation, vegetation characteristics (type, height, basal area, cover), distance to a specified land feature, and edge length per unit area [41]. In addition, the connectivity of habitat is important. The exact nature as well as the relative importance of each of these factors depends on the species of concern. For example, soil particle size would be expected to be important to burrowing wildlife species and to species that require plant cover or forage vegetation that is associated with soil of a particular particle size, but not for other species. Moreover, some species have specific habitat requirements for breeding territories, such as grassland birds that form leks (male group displays) in open areas. These habitat suitability factors are incorporated into U.S. Fish and Wildlife Service habitat models: numerical indices of habitat suitability are derived on a scale of 0.0 to 1.0 based on the assumption that key environmental variables are related to habitat carrying capacity [42].

Habitat suitability factors may be affected by the use of explosives, at least on the small scale (Table 11.1). Areas may be cleared by blading (removing surface soil) and removing vegetation [43], particularly during construction and excavation of UXO. Detonations remove surface soil (including organic matter), alter soil particle size, induce down-slope erosion, decrease plant cover, and may kill or alter the spatial distribution of key invertebrate foods. Indirect changes to plant cover or food availability can also occur as a result of fires initiated by munitions. Detonation craters may locally alter slope and aspect, as well as surface soil characteristics, thus altering soil moisture. Contamination might be present at phytotoxic concentrations. The relative extents of disturbance and uncertainty of spatial disturbance pattern of many of these stressors is depicted in Figure 11.1. In this example, the spatial extent of range maintenance activities (e.g., vegetation clearing) is greater than the area affected by detonation craters, explosives contamination or excavation. The locations of disturbance associated with excavation and range maintenance activities are planned with exact boundaries, unlike areas of contamination or fire, where affected locations are not entirely predictable (Figure 11.1). In addition, large-scale disturbances at explosives ranges can lead to the fragmentation of wildlife habitat and increases in disturbed and edge habitats (e.g., transitions from forest to grassland), which are not depicted on Figure 11.1.

TABLE 11.1 HERE

FIGURE 11.1 HERE

Habitat Suitability Index models provide habitat suitabilities for specific locations [42] but do not consider the importance of landscape pattern. The connectivity of habitat is often just as important as soil or vegetation type in determining if habitat for a particular species is adequate [44]. Habitat fragmentation is the process of dividing an area into unassociated pieces that affect an organism's use of the area for all or part of its life cycle. Fragmentation can have three components: loss of area of the original habitat, reduction in habitat patch size, and increasing isolation of habitat patches. The major effect of fragmentation is change in biodiversity, including genetic, species and landscape diversity [45]. Typically, fragmentation results in a decline of those species that have restricted habitat requirements. However, species that thrive in ecotones become more abundant [46]. Other effects include changes in predation, competition, pollination, seed dispersal and mating behavior [47]. Fragmentation concepts have spawned the field of metapopulation dynamics (the idea that the regional persistence of a species depends on the maintenance, colonization, and extinction of subpopulations).

Fragmentation effects are most intensely observed for species that require large areas of habitat or those that avoid or will not move across unsuitable habitats. Fragmentation is of greatest concern in relatively large ecosystems that have a history of minor human disturbances but are now subjected to major human disturbances, as well as those where wildlife movement corridors (e.g., to water sources or breeding sites) are interrupted [48]. The intensity and frequency of disturbances are important predictors of effects. Several models that predict population response to habitat fragmentation on military installations have previously been developed. For example, a model that projects how the spatial distribution of nesting habitat affects the reproductive success of territorial migrant bird species breeding in fragmented, patchy landscapes was implemented for Henslow's sparrow (*Ammodramus henslowii*) at Fort Riley, Kansas, and at Fort Knox, Kentucky [49]. Results indicated that persistence of the sparrow at Fort Knox appears to require recruitment of individuals from other parts of the species' range, which in turn may reflect the marginal habitat at Fort Knox, for it is on the southern edge of the species' summer range.

Patches of habitat may sometimes be lost from a landscape without the isolation of patches that denotes fragmentation, producing holes in the landscape (Figure 11.2). The relative importance of habitat loss and fragmentation on military installations is likely to depend on the habitats and sensitivities of particular species. The areas of patches of suitable habitat may be compared to what Carlsen *et al.* [50] term "critical patch size," (i.e., the contiguous habitat area needed to maintain a population). Estimates of critical patch sizes are available for 249 species [50]. If these critical thresholds in patch size are not met because of range construction or clearing practices, cratering, or phytotoxicity due to explosives, a population may not persist. The effect of detonation craters on populations depends on the cumulative number and distribution of craters and rates of natural recovery. As stated above, phytotoxicity is observed in the field if soil concentrations exceed phytotoxic concentrations at rooting depths [51]. (see Chapter 4).

FIGURE 11.2 HERE

Studies of habitat alteration on military installations have not focused on explosives ranges. Investigations of the responses of soil and vegetation communities to disturbance by tracked vehicles call attention to some of the habitat factors that could also be studied on explosives ranges. Tracked vehicles can cause direct plant mortality by crushing and can indirectly affect plant communities through the compaction of soil and species competition [52]. Prose [53] measured the extent of soil compaction laterally from and below track locations. Several researchers studied vegetation cover and succession patterns [52, 54-56]. Ayers [57] related tracked vehicle operations such as turning radius and pad-load ratio to soil and vegetation disturbance.

11.6 QUANTIFYING HABITAT CHANGE

Numerous methods are available to measure or model the impact of explosives contamination and detonation craters or other physical stressors on vegetation. U.S. Army installations may collect data on the distribution of vegetation and soils to describe plant communities and the distribution of small mammals, birds, reptiles, and amphibians to characterize species-specific habitat as part of the *Land Condition - Trend Analysis* (LCTA) Program [58-59]. Permanent inventory plots are located in a stratified random manner based on soil data and satellite imagery, but less frequently within demarked impact zones because of the dangers of sampling there. Because military testing and training typically result in intense, local, and broadly spaced impacts, the LCTA plots typically do not capture the full spatial distribution of the effects. For example, at Yuma Proving Ground (YPG), Arizona, 60 to 70% of the plots showed no use during 1991 to 1993 and again in 1998 and 2003 [60-61]. Thus, the LCTA approach should be supplemented by a method designed to focus on discerning impacts of use and integrating over broader spatial scales. Studies evaluating LCTA data at the Kansas Army National Guard Training Facility compared LCTA results with a modified methodology designed to place sampling transects in field-identified rather than satellite-identified land-cover types. The studies found that LCTA sampling was too limited in the ecologically important riparian woodland habitat, with the result that bird species were not adequately sampled [62]. In 2004, the LCTA program was restructured into the Range and Training Land Assessment program [63] with the understanding that modifications of LCTA's standardized approach are needed in order to address the issues above, and to reflect local landscapes and land uses.

Remote sensing is useful to detect large-scale (and increasingly, small-scale) changes in vegetation cover and type where field sampling is impractical because of safety issues or cost. General methods are described by Lillesand *et al.* [64]. Underwood *et al.* [65] describe hyperspectral methods for detecting invasive plants, and that research group is currently mapping nonnative species at military installations. Moreover, the U.S. Army Corps of Engineers Engineer Research and Development Center is attempting to develop remote sensing methods for detecting explosives contamination [66].

Maps of potential habitat distribution can be produced when information from ground surveys is not available, such as occurs in impact areas. Mann *et al.* [67] developed a geographic information system (GIS) model that predicts potential location and successional status of threatened calcareous habitat at the Fort Knox Military Reservation, including heavily impacted ordnance and tank training areas that are unsafe for public access. Their model uses ecosystem information contained in the U.S. Department of Agriculture Natural Resources Conservation Service State Soil Geographic Database, as well as satellite imagery. These threatened calcareous habitats support several rare plant species. The combined soil/geology/slope GIS approach is useful in conservation management and restoration, especially where intensive ground surveys are impractical [67].

Models are also available to predict vegetation or soil changes in the future. A random optimization procedure (neural network model) has been used to estimate vegetation cover probabilities based on past disturbance pattern and vegetation coverage data collected according to LCTA methods at Fort Sill, OK [68]. Transition models can also be used to project potential vegetation and habitats [69]. Ecological Dynamics Simulation Modeling (EDYS) is an ecosystem model that has been used in a wide range of applications, including the assessment of potential impacts of different training regimes on vegetation and endangered species habitats at the U.S. Air Force Academy, CO; Fort Bliss, NM; and Fort Hood, TX [70]. EDYS models soil water and nutrient dynamics, species-specific plant uptake and growth, herbivory, fire, contaminant dynamics, physical disturbance and management actions. The Army Training and Testing Carrying Capacity model measures training load in terms of maneuver impact miles (MIM) of an M1A2 tank driving one mile in an Armor battalion field training exercise [71]. Impacts from firing and bombing ranges could be quantified in a similar manner.

11.7 RESPONSES OF SPECIES TO DISTURBANCE

Numerous threatened, endangered and other valued wildlife species are present on U.S. Department of Defense (DoD) installations in greater abundance on a per area basis than on most other federal lands [72,6]. These and other federal lands often form refuges for species from land-use changes and activities on adjacent, privately held lands [73]. For example, habitat complexity in the prairie-forest ecotone of southwestern Oklahoma is reduced by agricultural development and enhanced by protection afforded by the Fort Sill Military Reservation [74]. Large tracts of intact habitat on military lands are important for the sustainability of these species; therefore, the potential habitat loss associated with explosives use is worthy of examination.

We are aware of no studies that attribute any species declines to the presence of explosives contamination or firing ranges. However, most vegetation and wildlife (other than disturbance-adapted species) are often removed by the initial construction or clearing to create an impact area. In addition, the cumulative habitat loss and fragmentation associated with explosives ranges and other military training and testing activities (see discussion of multiple stressors below) could adversely affect particular wildlife populations. The loss of shrub cover during training in the Mojave Desert was previously determined to lower the relative abundance of the little pocket mouse (*Perognathus longimembris*) and southern grasshopper mouse (*Onychomys torridus*) [75-76].

Several examples exist of species that have benefited from disturbance at explosives-contaminated ranges or similar sites. At Jefferson Proving Ground in Indiana, artillery impact craters were posited as the habitat enhancement factor supporting increased vegetation diversity [77]. In the Chocolate Mountain Aerial Gunnery Range in southeastern California, 250-lb bombs create detonation craters that break through and expose the sandy soil beneath the desert pavement. Kangaroo rats (*Dipodomys merriami*) colonize the soft walls of the crater, resulting in an apparent population increase [78]. Anecdotal evidence suggests that Sonoran pronghorns (*Antilocapra americana sonoriensis*) prefer the watering holes and young vegetation found in craters of bombing ranges, areas that also have fewer creosote bushes that impede the pronghorns' view of predators [79]. Tadpoles have been observed in water-filled impact craters at Eglin Air Force Base [80], and it is likely that these ephemeral pools serve as beneficial habitat for amphibians at other military installations. At Fort Hood, the black-capped vireo (*Vireo atricapillus*) is an example of an endangered species that colonizes early successional scrub arising within several years after range fires caused by explosives, flares or other military activities. Another endangered species, the Karner blue butterfly (*Lycaecides melissa samuelis*) is on a precipitous decline, probably due to habitat fragmentation, yet it occurs in a habitat that persists only with regular light fires or some other similar disturbance, such as military training

[81]. At Fort McCoy, Wisconsin, populations of the Karner blue butterfly are found in oak and pine barren communities, which are habitat for wild lupine, a disturbance-dependent forb required by Karner blue butterfly larvae. The butterfly is more abundant in some impact zones, although obtaining data on these butterflies has proven perilous to biologists [82]. Severe disturbances may cause the demise of these butterfly habitats. At YPG and similar arid installations, impact craters collect surface runoff allowing plants to colonize otherwise barren desert pavement (Figure 11.3). Although individual plants benefit, the impediment to surface runoff may adversely affect plant communities downstream [83].

FIGURE 11.3 HERE

In general, ranges where explosives are used (and their boundaries) may provide valuable habitats for endangered species highly specialized to open or edge landscapes. For example, disturbance by tracked vehicles promoted the lupine (*Lupinus perennis*) vegetation required by the federally endangered Karner blue butterfly [84]. Imbeau *et al.* [85] argue that species that prefer edge habitats at agriculture-forest junctures are actually species that prefer early-successional habitats wherever they are available. Early-successional habitats are common and are regularly created on explosives ranges.

11.8 RESILIENCY AND RECOVERY

The habitat disturbance associated with explosives and explosives-contaminated ranges is temporary. The duration of the disturbance depends on the life expectancy of the range and the time periods during which: 1) explosives reside in surface soil; 2) plant communities that are adapted to the contamination or physical disturbance become dominant; 3) surface soil in detonation craters is replaced; and 4) the ecosystem recovers from unintentional wildfire from the detonation of explosives.

A detailed review of environmental fate of energetic materials is provided in Chapter 2. Houston *et al.* [5] provided metrics for assessing the resiliency of generic environmental settings to explosive residue contamination. These environmental characteristics influence the fate and transport of explosives. Resilient impact areas are characterized by: 1) low moisture values from Thornwaite Moisture Regions that indicate low dissolution of chemicals; 2) high cation exchange capacity of soils that indicates limited desorption; 3) long effective growing seasons that indicate high potential for biodegradation and biological uptake; and 4) high soil organic carbon that suggests high potential for chemical transformation. Houston *et al.* [5] also ranked the resilience of 11 installations based on these criteria, but other important predictors of resiliency were not included, such as plant regeneration, fragmentation or sensitive populations.

Recovery typically refers to the colonization, growth or succession of ecological entities, following the effective removal of the direct pressure of a stressor. The stressors that are most relevant here include those listed in Table 11.1: clearing of vegetation, explosives contamination, detonation craters, and remediation. Factors that influence the recovery of ecosystems from disturbance include current state, disturbance severity and frequency, successional history, history of disturbance, preferred state, management of the disturbance, and random factors such as weather [86]. Recolonization time is dependent on the size of the site and proximity to a recolonization source. Species that are characteristic of early successional communities recover relatively rapidly from disturbance to colonize disturbed areas, due to their high reproductive rates and rapid dispersal mechanisms [87]. Diersing *et al.* [88] defined recovery by estimating the average number of years for tracked vehicle-affected areas to regrow vegetation cover equivalent in C-value (for the universal soil loss equation) to untracked areas.

Steiger and Webb [43] studied the recovery of desert vegetation in military target sites in the Mohave and Cerbat Mountains of northwestern Arizona. The sites were cleared between 1942 and 1944 with up to 0.2 m of the surface material displaced by blading. The sites were used for strafing runs and did not use impact explosives. Steiger and Webb [43] found greater variability in the extent of recovery for sites on older geomorphic surfaces than on younger surfaces and a weak inverse relationship between the degree of recovery and geomorphic age. Vegetation parameters in desert washes had generally recovered since the 1940s. In some cases, the survival of root crowns (e.g., of *Larrea* and *Ambrosia* species) facilitated revegetation of study sites. The recovery of vegetation in detonation craters might be expected to display similar dynamics to the recovery in blading locations. Steiger and Webb [43] note that blading could enhance the moisture and perennial vegetation in disturbed sites on desert pavement, which is consistent with the effects observed in detonation craters at YPG, as described above. Recovery times in deserts likely represent a worst-case scenario for terrestrial ecosystems. Similarly, low moisture (ice-bound water, low precipitation) and low temperature conditions result in slow ecological recovery in subarctic training areas.

The time periods that are required for recovery from possible phytotoxicity and physical disturbance are uncertain [89]. In general, recovery of vegetation from physical disturbance in arid ecosystems can take hundreds of years [90]. An estimate of the minimum time to recovery could be provided by the average age of the lost vegetation [90]. It should be noted that the recovery of one ecological property can be impeded by restoration or reclamation of another. For example, the maintenance of impervious soil caps over a waste disposal site involves the removal (and therefore prevention of recovery) of deeply rooted vegetation and burrowing mammals [91].

The potential for a habitat to recover following fragmentation depends on the degree of fragmentation and rates of recovery of the vegetation. For example, the demise and fragmentation of longleaf pine (*Pinus palustris*) forest from timber harvesting, fire suppression, and land-use change [92, 93] resulted in the decline of red cockaded woodpeckers (RCW) (*Picoides borealis*) in the southeastern United States, but active management for longleaf pine (as well as the continued presence of other pines) on military installations, has contributed to the stabilization of remaining RCW populations [94].

11.9 CONFOUNDING EFFECTS OF MULTIPLE STRESSORS

Multiple stressors that are associated with explosives ranges and range operation and management include, but are not limited to: foot traffic from soldiers, maneuvering of tracked vehicles, maintenance of targets, noise, fire, heat, water- and wind-eroded soils, flooding, forest management, grazing, installation infrastructure development, petroleum spills and other contaminants such as metals, and encroachment of invasive vegetation associated with surface disturbance. Together, these stressors can result in changes to soil or vegetation components of wildlife habitat. For example, military training in longleaf pine ecosystems and in grasslands was associated with increased bare soil, reduced total plant cover, and compositional shifts in plant communities [95-96]. Military training resulted in reductions in both soil carbon and soil nitrogen levels, and greater surface soil bulk density at the Fort Benning Military Reservation [97]. Furthermore, soil microbial biomass and community composition were significantly altered by military training at Fort Benning [98]. In general, training has been shown to increase the abundance of early successional species that replace less common climax and other native species [76].

Range construction practices can involve the use of bulldozers, excavators and other earth moving equipment for potentially extensive clearing and grubbing of large areas of the landscape to meet design requirements for long-range firing of both small and large arms. These practices can temporarily strip most existing vegetation and topsoil, with potentially significant impacts to wildlife habitats. Invasions by non-native vegetation may reduce habitat quality. The potential interruption of site hydrology may impact wetland ecosystems and increase flooding of ranges.

Tracked vehicles, including tanks and Bradley armored fighting vehicles, may be maneuvered across range areas to established firing positions, leading to erosion along unpaved roads and trails. Aerial maneuvers using helicopters can disperse significant fugitive dust. Foot traffic by soldiers can also promote erosion and slow vegetation recovery in areas of exposed sub-soils, though these impacts can be minimized if soldiers are directed to different areas on a rotational basis. Frequent foot traffic through long-leaf pine ecosystems at Fort Benning resulted in more trees in the understory, probably because small woody vegetation was better able to withstand the mechanical stressor than herbaceous species [95].

A common practice of planting or hydro-seeding of fescue and other non-native “turf” grasses to hold soils and to promote line-of-sight or to stabilize disturbed ground may not reestablish adequate habitat for many species. Native, fire-climax, mixed grassland communities provide superior wildlife food and shelter, as well as better soil holding capabilities, to those of the “turf” grass monocultures, but may be very costly to establish following construction of ranges.

A major source of habitat loss on closed explosives ranges can be remedial activities such as excavation. Remedial goals for explosives ranges are typically defined on the basis of human health and safety, but remedial technologies for contaminated sites are chosen based primarily on two engineering criteria, the ability to achieve those goals and cost-effectiveness, rather than ecological criteria [99]. Even deep UXO that poses little risk is sometimes removed along with the associated soil ecosystem and vegetation community. Whicker *et al.* [100] describe putatively unrealistic land-use assumptions that result in highly conservative risk assessments and habitat removal during contaminant remediations at U.S. Department of Energy sites. Similar conclusions may apply to explosives ranges at closed DoD installations. A net environmental benefit analysis is recommended prior to the remediation of explosives-contaminated soil, especially in arid or semi-arid regions, where recovery from disturbance can take centuries [99].

Effects due to multiple stressors are observed if stressors overlap in space or if wide-ranging wildlife are exposed to stressors in different locations. The stressors discussed here may be found in close proximity to or at a distance from chemical contamination in soil. Noise is one of the stressors that always overlaps spatially with contamination from explosives and clearing of range vegetation. Noise affects habitat suitability of many species, such as the endangered Sonoran pronghorn. At the Barry M. Goldwater Range in southwestern Arizona, habitat areas with noise levels greater than or equal to 55 dB are used less by the Sonoran pronghorn than quieter, equally suitable areas [101]. In the Snake River Birds of Prey National Conservation Area in Idaho, firing of artillery, small arms, and main turret guns or machine guns on tanks reduced counts of raptors on ranges, whereas tank preparation (i.e., assembling and loading ammunition), driving, laser training, and convoy traffic had no effect [102]. To our knowledge, noise has never been included in habitat suitability indices, but future knowledge about the impacts of blast noise could be incorporated into habitat models.

In addition to on-base stressors, urban development encroaches near the boundaries of many military installations. Development may increase species abundance in relatively undisturbed areas of installations and buffers, but it decreases the available habitat for populations or metapopulations that extend beyond installation boundaries [103].

The combined effects of particular groups of stressors at specific ranges may be evaluated through field studies of wildlife populations if adequate control sites or pre-disturbance data are available, if natural variation in population abundance is not too high, and if sample sizes are adequate. A simulation model has been developed that can integrate effects from multiple stressors if adequate exposure and effects data are available from military installations. The Regional Simulator (RSim) is designed to simulate: 1) land cover changes caused by urban development, road development and changes in military training activities; 2) resulting changes in air quality, water quality, soil nutrients, and noise; and 3) changes in vertebrate populations and their habitats [92]. For example, RSim could be employed to assess the ecological benefits of establishing native grasslands on ranges, as discussed above. A framework that addresses a process for determining the additivity of effects or exposures associated with various stressors can be found in [104]. This framework was developed in the context of military activities, and it addresses the importance of spatial and temporal overlap of multiple stressors.

An even greater challenge than integrating the effects of multiple stressors is determining the cause of observed effects (e.g., distinguishing the ecotoxicity of explosives from other effects of detonation craters, range clearing, or noise). A risk assessment for a single stressor is easy if multiple stressors are present that together produce no effect (e.g., the absence of effects of firing of small arms and artillery on red-cockaded woodpecker at Fort Benning Georgia) [105]. Principles for determining causation in streams were developed by Suter *et al.* [106] and are applicable here. For example, they recommend an evaluation of the association of measurements of exposure and effects, including spatial co-occurrence, spatial gradients, temporal relationships and temporal gradients, as well as the association of effects with mitigation or manipulation of causes. Thus, the effects of contamination by explosives could be distinguished from those of noise if a range is inactive or closed.

11.10 CONCLUSION

Changes in species-specific habitat suitability may arise from localized chemical contamination and physical stressors present on explosives ranges. However, existing studies do not attribute any species declines on or around military installations to the presence of explosives contamination or firing ranges. The relative and cumulative contributions of chemical contaminants, detonation craters, range clearing practices, and environmental management to the loss, gain, or fragmentation of habitats of various species have not been investigated. The characterization of munitions range variables, such as ordnance type, amount and delivery and clearance rules, is a necessary precursor to studies of habitat change. Studies are in progress to describe the spatial distribution of contamination, and these will support investigations of potential phytotoxicity of nitroaromatic and other chemicals on explosives ranges. Preliminary data suggest that major contamination and detonation craters are typically limited to small areas of explosives ranges, i.e., firing points (contamination) and targets (contamination and craters). The RSim model is able to integrate risks to wildlife populations from multiple chemical and physical stressors if sufficient supporting data are available. Results from models of habitat loss should be verified by field studies on all military installations. Although ecotoxicity of explosives is important, an understanding of ecological effects of explosives and firing and bombing ranges is not complete without a thorough understanding of the potential and actual removal and fragmentation of wildlife habitat, as well as the beneficial effects of open and edge habitats and undisturbed range buffer areas. Demarais *et al.* [76] assert, "physical modification of habitat [from all training exercises] resulting in changed levels of available resources is the primary disturbance affecting vertebrate populations on military installations."

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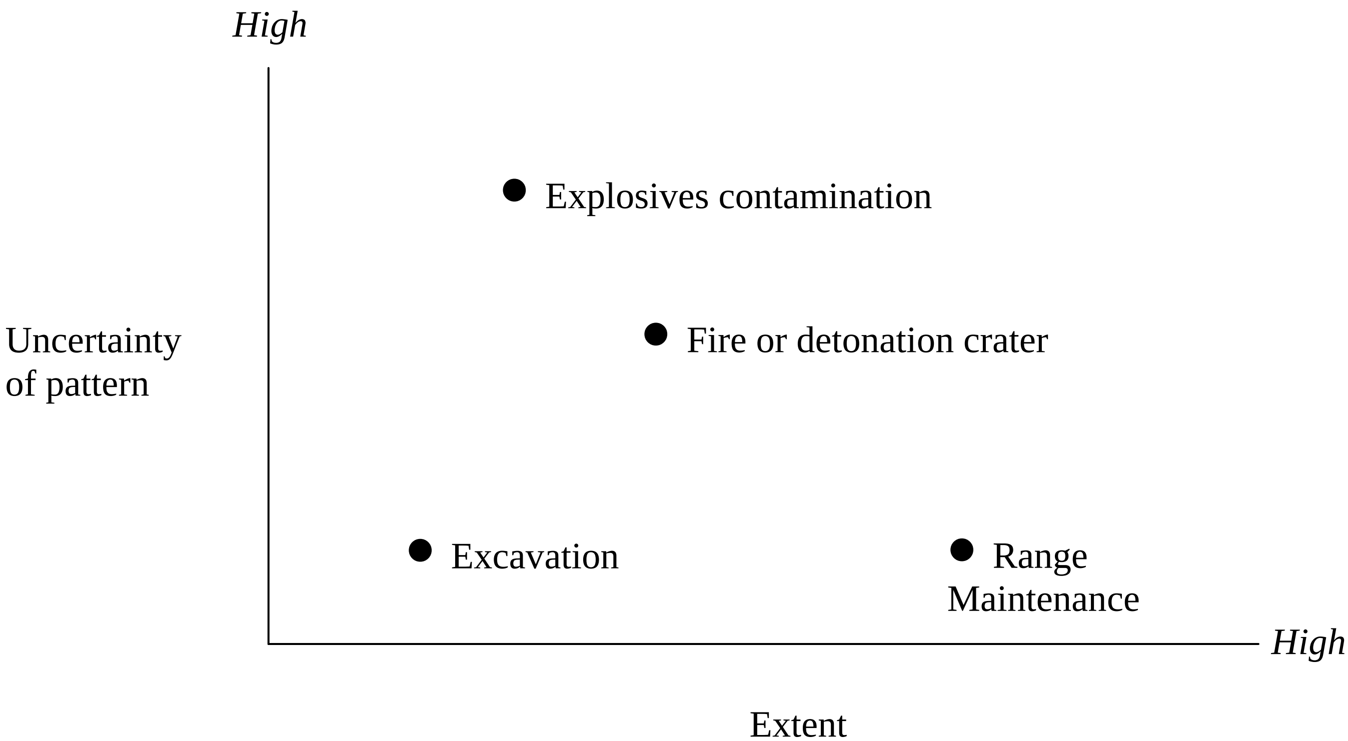

High
Explosives contamination
Uncertainty
of pattern
Fire or detonation crater
Excavation
Range
Maintenance
High
Extent

Figure 1.

Figure 2.

Figure 3.

Section 12: User interface

Work was completed on transitioning the user interface to one that is suitable for expected end-users. This involved creating an easily navigable interface for selecting appropriate scenarios and optionally setting custom model parameters along with simulation output options. While model outputs can be saved to disk for future reference and analysis by advanced users, the user interface design work also includes a mechanism for some high-level exploration of the results of each RSim model, which allows the user to save customized model parameters for future use (Figure 1). The interface is now a part of the RSim CD.

In order to gauge how resource managers might use RSim, a meeting was held on February 23, 2005 at the Columbus Chamber of Commerce with resource mangers from the five county area (see attached Appendix). The purpose of this meeting was to inform local resource managers of the development of RSim and to get their input on design of RSim and its interface.

Appendix A: Summary of February 23, 2005 meeting:

Using a Simulation Model to Understand Environmental Impacts in the Five County Region *(Chattahoochee, Harris, Marion, Muscogee, and Talbot)*

RSim is a Regional Simulation to explore impacts of resource use and constraints, that is funded by the Strategic Environmental Research and Development Program (SERDP: http://www.serdp.org/). RSim is being designed to integrate environmental effects of on-base training and testing and off-base development. Effects considered include air and water quality, noise, and habitats for endangered and game species. A risk assessment approach is being used to determine impacts of single and integrated risks. The plan is to make the simulation environment available via web interface. The model is being used in a gaming mode so that users can explore repercussions of military and land-use decisions. A summary of the RSim project is available at: http://www.esd.ornl.gov/programs/SERDP/RSim/ .

The RSim interface will therefore allow managers and planners from both within the Installation and its regional partners to interact with the model and learn more about the interdependence of resource use. The building of the model will identify these relationships and provide a shared format for the consideration of mutually beneficial development.

It is necessary that regional managers and planners participate in the development of the model interface and identify the components of the model that will be most useful for their needs. On Wednesday, February 23rd, a two hour meeting was held by the RSim team (Dr. Virginia Dale and Murray Browne) to introduce the project to the Installation managers and community planners. This meeting also served to establish contacts between the RSim team and the end users of the product.

The list of attendees follows:

Last Name	First Name	Business Affilitation	E-Mail	Telephone
Dale	Virginia	Oak Ridge National Laboratory	dalevh@ornl.gov	865-576-8043
Browne	Murray	University of Tennessee	mbrowne@cs.utk.edu	865-974-3510
Hadden	Biff	Greater Columbus Chamber of Commerce	bhadden@columbusgachamber.com	706-327-1566, x17
Lusk	Rita	Greater Columbus Chamber of Commerce	rlusk@columbusgachamber.com	706-327-1566, x34
Clark	Ken	Marion County Development Authority	thepines@sowega.net	229-649-6303
Cullen	Patti	Lower Chattahoochee RDC	pcullen@jcrdc.org	706-256-2933
Davis	Steve	Columbus Water Works	sdavis@cwwga.org	706-649-3470
Garrard	Bob	Garrard Consulting	garv4665@bellsouth.net	706-323-4868
Harrison	Wade	The Nature Conservancy	wharrison@tnc.org	706-682-0104
Johnson	Slade	Talbot County Development Authority	jsladej39@hotmail.com	706-665-3598
Lynd	Jackie	Ft. Benning	jacqueline.lynd@us.army.mil	706-545-1296
McDaniel	Dorothy	Georgia Conservancy	dmcdaniel@gaconservancy.org	706-718-6856
Mote	Stacy	Consolidated Resources	stacymote@bellsouth.net	706-317-5942
Parris	Steve	USFWS	steve_parris@fws.gov	706-544-6999
Slay	Brant	The Nature Conservancy	bslay@tnc.org	706-682-0217
Steverson	Kathy	Greater Columbus Chamber of Commerce	ksteverson@columbusgachamber.com	706-327-1566, 37
Tant	Bob	Columbus Water Works	btant@cwwga.org	706-649-3432
Turner	Billy G.	Columbus Water Works	bturner@cwwga.org	706-649-3430
Veenstra	Linda	OSJA, Ft. Benning, GA	linda.veenstra@us.army.mil	706-545-8072
Westbury	Hugh	ERDC CERL	hugh.westbury@benning.army.mil	706-545-7882

Flow Chart of User's Interaction with RSIM

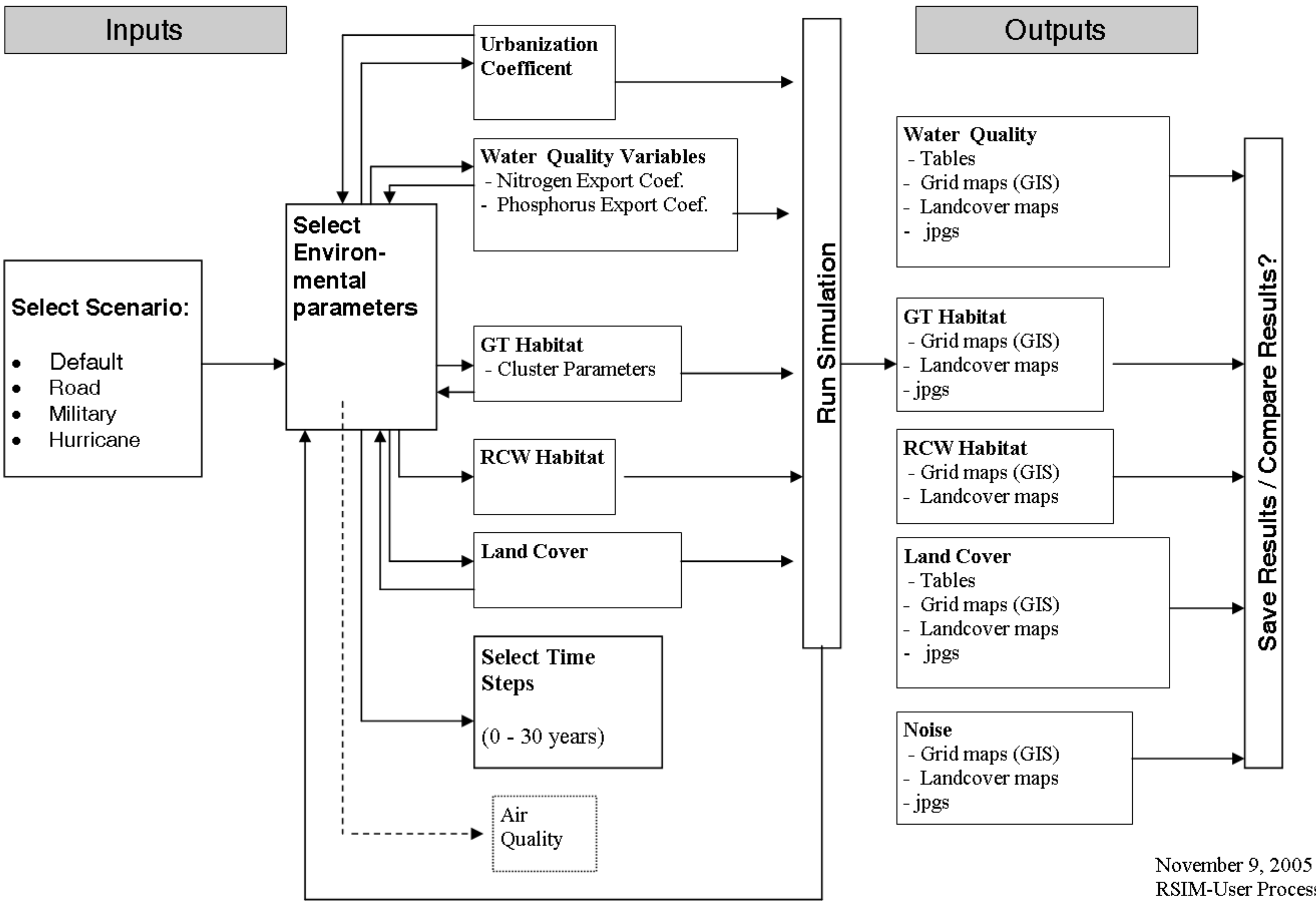


Figure 1

Section 12: Appendix B - Programming Product Specification for RSim Version 1.3

General Description & Business Rules

RSim: A Regional Simulation to Explore the Impacts of Resource Use and Constraints. It is an environmental decision support system for the five-county region surrounding Fort Benning, Georgia. RSIM looks at several scenarios with respect to certain environmental aspects.

RSIM scenarios

1. The Current Scenario

   The "Current" conditions – the default values are "set at the factory" so to speak for the Ft. Benning area. This is the baseline for comparisons to other scenarios and time frames. The user can always reset the current conditions to factory specs.

2. The Urbanization Scenario

   Population growth in the Ft. Benning area based on an urban growth model (Gigalopolis/Sleuth) and constrained by U.S. Census population data.

3. The Road Scenario

   New proposed roads based on the Governor Road Improvement Program (GRIP).

4. Military Expansion (DMPRC) scenario

   Proposed construction of a new Digital Multipurpose Range Complex.

Note: Currently elements of the Urbanization and the Road scenario are rolled into the Current scenario. One of the questions is whether new variations of these scenarios would be created.

Modifying Scenarios

In each scenario, users will be permitted to "stop" scenarios and change pixels to reflect changes in Land Cover. This feature will allow users to modify the scenarios and create situations that reflect new developments in the Ft. Benning region.

RSIM Time Intervals

User will be allowed select time interval of one year increments between 0 and 20 years.

RSIM Environmental Aspects

Within each scenario and time frame, RSIM users can look at different environmental aspect. These include:

1. **Air Quality > Effects on Vegetation**
2. **Water Quality > Nitrogen > Phosphorus**
3. **Habitats > RCW > Gopher Tortoise**
4. **Noise > Effects on RCW, Gopher Tortoise**

General Input

In the opening screen there is a general description of RSIM and the user would then select which scenario (current, urbanization, road, military) they would like to investigate first.

The user is then prompted as to whether they would like to make land cover changes to the simulation. (See: Changing the Land Cover Pixels Specification for more details.) If the user wants to change pixels s/he will be given a map to select pixels to change their land cover values. If not, the user will be asked to select the Time Interval s/he wishes to run for the simulation.

After selecting the time interval, the user selects one of the four major environmental categories to investigate (Air quality, water quality, habitat and noise). A brief description of the four categories and what information the user can find in each category is available on this screen. After the user makes their selection, then s/he would proceed to a one of the environmental categories to view the results of the simulation. Each environmental category "page" would have:

- A high level summary or abstract
- Links to relevant supporting documentation/websites
- Atlas-like data sheets of relevant information

General Output:

In general, the user is presented with a spatial representation of the area with relevant facts and data on the layer for examination.

The user can specify what how the spatial information would be outputted as either an ARC map or as a jpg. The accompanying data can be output as text or put into a spreadsheet. User selects what legends – boundaries they want displayed.

The various outputs are able to be saved, so different outputs could be compared. *Outputs like a map and tabular data can be set up to be displayed on the same screen, HOWEVER, they cannot be saved in the same file.*

With respect to movie output, the user will be pointed to utilities and documentation such that they can use the jpgs (time steps of 1 year) to make their own movie. This process is similar to creating a "flipbook."

Also, the user will be permitted to save results at different junctures throughout RSIM.

Specific Examples

Example of Water Quality Nitrogen Scenario 1 [*]:

1. User selects which scenario they want to look at: (Current, Urbanization, Road, Military Expansion)
2. User either goes with current land cover or changes land cover.
3. User selects: time span (0-20 years).
4. User navigates to Water Quality module
5. User selects which value (low, medium, high) of export coefficient of nitrogen s/he wants to run.

Medium is the default. High is a 25 % increase in nitrogen. Low is a 25 decrease in nitrogen. The default nitrogen values are currently calibrated to 8 land cover types: Wetland, Forest, Pasture, Idle, Industrial, Residential, Business, Row Crops and possibly a 9th -- Animal Agriculture.

3. Simulation runs on Medium setting
4. User receives output of scenario and "saves" it.
5. Repeats steps 3-4-5 using same land cover values as first run, except the value is set to high.
6. User is able to compare final (high) output with initial (medium) output. The outputs include a map and a table.
7. User also receives a histogram of initial value compared with last value that they can view and then output.
8. User is provided with a link that offers a general explanation of results.
9. User is allowed to "save" both results. By saving image of map and by being allowed to export the data used in tabular form.

Example: Gopher Tortoise Burrows

Using RSIM, users can see where gopher tortoises burrows are, possible nearby locations where gopher tortoises could be, and where gopher tortoises can be fruitful and multiply. Conversely, this simulation would also show where the gopher tortoises would eventually die out because of insufficient habitat.

How this might look to the user:

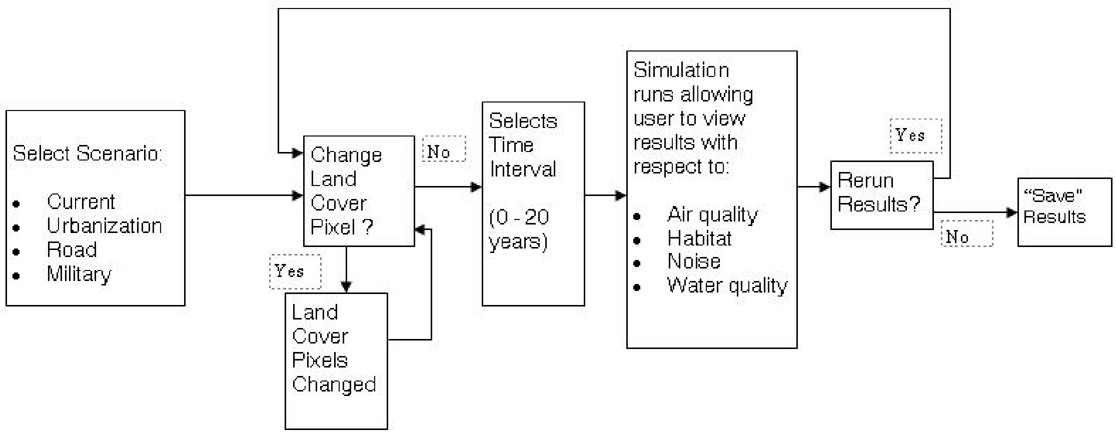
1. User selects applicable scenario (Current, Road, Urbanization, Military expansion).
2. User makes changes to Land Cover, if desirable
3. User selects time span (1-20 years).
4. Simulation runs User selects the Environmental Gopher Tortoise Habitat to view.
5. Results are based on the composite value of four factors: land cover, clay content of soil, distance to roads and distance to streams for each pixel. Once a map of the presence of burrows is computed, Matthew's cluster algorithm would be used to determine which of those "presence" pixels occur in patches that are smaller than two hectares. This would be used to determine which habitats are not suitable for g.t. reproduction.
6. User receives ARC or jpg. map of scenario.
7. From the map the user can press various buttons to see:
    - Actual location of gopher tortoise burrows in Ft. Benning
    - Likely locations of gopher tortoises burrows in region
    - Likely "cells" of old tortoises that will die out because they won't reproduce well.
    - Areas where the gopher tortoises would likely to reproduce
8. User has option of outputting respective maps as jpgs or ARC map.

9. A link to documentation explaining the results would be accessible for the user.

Summary

The flow chart represents a Users perspective of how to use RSIM.

Flow Chart of User's Interaction with RSIM



Section 13. The Potential Role of RSim in BioRegional Planning

The way in which RSim fits into bioregional planning for central Georgia is described in depth in our paper: A component of that regional activities is county-level planning, which became a requirement in Georgia as a result of the 1989 Georgia Planning Act. The planning process is managed by the Georgia Department of Community Affairs. It should be noted, however, that counties are not required to implement the plans that they create, and therefore it is important to communicate with county planners about the validity of these plans. Also, plans do not include map coordinates.

We obtained Comprehensive Zoning Plans for Harris, Chattahoochee, and Talbot counties from Patty Cullen, executive director of the Lower Chattahoochee Regional Development Center. We obtained the zoning plan for the Columbus-Muscogee County unified government from the world-wide web at http://www.georgiaplanning.com/planspub1/. Additional information is available from the Valley Partnership Joint Development Authority, which is a potential stakeholder in our modeling effort. The Valley Partnership Joint Development Authority (VPJDA) is a multi-governmental entity created by local governments from the City of Manchester, City of West Point and the counties of Chattahoochee, Harris, Marion, Muscogee, Talbot and Taylor, Georgia.

With additional coordinates, land use maps from these plans could be used to digitize particular, future land cover types, as an alternative to implementing the urbanization algorithms in RSim. RSim already has an option for digitizing future roads, for example, highways in the Governor's Road Improvement Program. Thus, particular future land uses would have to be translated to one of the 44 land cover types available in the Georgia Gap Program. However, the land cover types that are depicted in the county zoning plans may not be accurate for one of several reasons: 1) as noted above, counties are not required to implement their plans; 2) plans are continually changing; and 3) land use designations in the plans do not typically consider topography, so land that is marked as residential land on the plans will not all be low-intensity urban land cover; and 4) many of the land use types can translate into one or more land cover types (e.g., "agriculture/open space" can refer to "pasture, hay," "rowcrop," "clearcut-sparse vegetation," or "parks, recreation"). Therefore, the use of these plans is not necessarily more accurate than the use of the RSim urbanization algorithms. Also, the urbanization algorithms of RSim are needed for counties where no plan maps are available (e.g., Marion County). The best use of these plans might be to locate future and current industrial parks and recreational parks and to digitize these to add as a layer to RSim.

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Bioregional planning in central Georgia, USA

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Available online 2 November 2005

Abstract

Human influences in the five-county region around Fort Benning, Georgia, USA, have been long and intense. Only 4% of the native longleaf pine (*Pinus palustris*) forest remains intact. Besides the loss of species, habitats, and ecosystem services associated with longleaf pine forests, the environmental concerns of the region include air, water, and noise pollution. The mix of federal and private ownership in this region leads to complicated land-management issues that will likely become even more difficult as the city of Columbus continues its projected growth along the northern border of Fort Benning. To understand how anthropogenic developments affect the environment, we are developing a Regional Simulator (RSim) to project future developments and their impacts on environmental conditions. Using RSim, we can identify the potential effects of growth on noise and air pollution, water-borne nutrients, and habitats for focal species. Noise impacts are already large in the areas of current and projected urban growth for the region. This knowledge of potential futures allows options for environmental protection to be considered. A key lesson from this analysis is that regional simulation models are a cost-effective way to assess the long-term environmental implications of anthropogenic growth and development.
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1. Description of five-county study region

The region for this study is the five-county area around Fort Benning, Georgia, in the southeastern United States (Fig. 1). These counties occur along the fall line that bisects Fort Benning and differentiates between the coastal plain and the Piedmont. The fall line occurs where the Piedmont transitions into the Southeastern Plains (following the ecoregion definitions set forth by Omernik) [40,41]. This area is characterized by strong gradients in topography and soils ranging from rolling sandy–clay hills to sandy plains. The fall line extends from central Alabama northeasterly to North Carolina and was once dominated by longleaf pine (*Pinus palustris*), but only 4% of the original longleaf pine forest remains [47]. Loss of the longleaf pine forests is primarily due to land-use change, timber harvesting, and fire suppression [28,30]. Longleaf pine is a fire-adapted species; small trees can withstand the light, frequent fires typical of these systems. Fires can also reduce growth of hardwood trees into the overstory. The longleaf pine is considered a keystone species, for it supports many other organisms, including the federally endangered red-cockaded woodpecker (*Picoides borealis*). The woodpeckers are unique in that they create cavities in living trees that provide homes for at least 23 other species [12]. Hence, protection of and habitat management for the red-cockaded woodpecker and longleaf pine forest is a top priority for federal land managers. Although an understanding of the effects of human modifications and alterations on longleaf pine systems is developing [22,34, 42,43], much still remains to be learned about how human impacts on the longleaf pine system will affect future forest conditions.

About 75% of the current longleaf forest is in private ownership and caters to a variety of services, including recreation and timber extraction. The remaining forest occurs on public land. Large patches of intact longleaf pine forest best represent typical ecological conditions and hence support the highest number of native species [38]. Most of the larger patches of longleaf pine forest are in federal ownership, managed primarily by the Department of Defense (DoD) or the Forest Service [58]. An effective form of habitat management of longleaf pine forest is prescribed ground fires about every 3 years, which kill hardwoods and other conifer species.

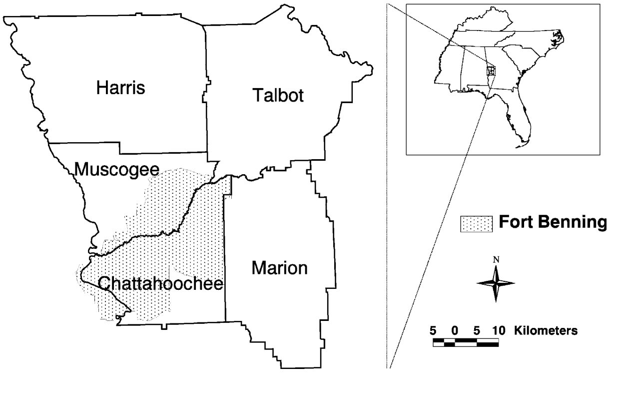

Fig. 1. The five-county study area around Fort Benning, Ga, shown in relation to the southeastern United States.

Fort Benning has been the 'home of the infantry' since 1918, when the land was first acquired for military use, and it is now the site of much infantry- and tank-training activity. Before that time, European settlers practiced intensive agriculture on the land beginning in the 1800s, and earlier still, Native Americans occupied settlements along the rivers and hunted and grew crops for centuries [31]. The Fort Benning Army Installation occupies 73,503 ha in Chattahoochee, Muscogee, and Marion counties of Georgia and Russell County of Alabama. Military training occurs on much of the installation, although there are also large areas of relatively untouched forests. In 1827, pine forests occupied about 75% of the area that became Fort Benning [11]. By 1974, only 25% of the installation was in pine, though this area had gradually increased to 35% by 1999 under management activities designed to facilitate pine establishment (e.g. regularly prescribed fires and planting longleaf pine) [10]. Probably, because much of the installation was protected from land development, it now supports ecosystems and species that were once common in the southeastern United States but are now quite rare (such as occurs on lands managed by the Department of Energy [33]).

The lands in the five-county region outside Fort Benning are largely under private ownership and have a mix of land-cover types. The city of Columbus, GA, is directly to the north of Fort Benning, and its growth has already constrained some activities on the installation. The rest of the five-county region is a mix of urban, bare-ground, nonforested vegetation (largely agriculture), and forested land (Fig. 2). Over the past 30 years, the human population of Chattahoochee County has declined, and that of Talbot County has remained constant, but the populations of the other counties have increased [48]. The study region lies between Atlanta, one of the fastest-growing cities in the United States, and Florida, one of the fastest-growing states [56], and as their populations increase, so will their influence on the study region.

The climate of the region is humid and mild, with rainfall occurring regularly throughout the year. Average annual precipitation is 105 cm, with October being the driest month. The warmest months are July and August, which have daily maximum and minimum temperatures averaging 37 and 15 °C, respectively. The coldest months, January and February, have average daily maximum and minimum temperatures of 15.5 and −1 °C, respectively.

2. Current planning efforts

With stakeholders including several different levels of government (federal, state, five counties, several cities, and the Columbus-Muscogee consolidated government), the Army at Fort Benning, countless nonprofit advocacy groups, private landowners, and many others, current land-use planning efforts in the region reflect complex and frequently competing demands for economic development, environmental conservation, and military expedience. Nevertheless, as the current array of land-management efforts demonstrates, there are wide windows of opportunity for cooperation, largely because even those stakeholders who are not interested in conservation as a primary goal have incentives for pursuing sustainable development. Furthermore, most planning efforts focus on

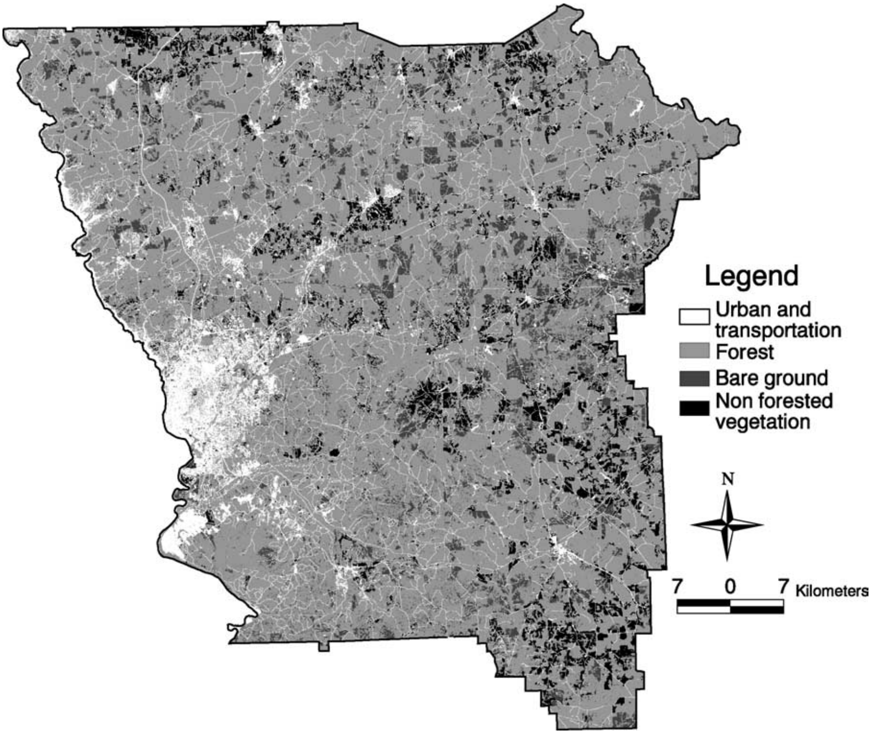

Fig. 2. Land cover uses in 1998 in the five-county region.

the decadal time scale or less; yet changes over a longer period of time also need to be considered.

2.1. Economic planning

In general, future economic development in the area will lead to a push to further develop land in the area. Both the state and local governments in the study area have taken steps to attract businesses over the next 15 years. The state of Georgia encourages new and expanding businesses by offering a variety of tax and other incentives, including a permit process that does not require a formal environmental impact statement [23]. The five counties in the study—Chattahoochee, Harris, Marion, Muscogee, and Talbot—have joined with Taylor County and the cities of Manchester in Meriwether County and West Point in Troup County to form the Valley Partnership Joint Development Authority to combine their resources and incentives [54]. Economic development without tighter controls on real estate planning, however, could add to future land-management conflicts by contributing to the sprawl for which Georgia's metropolitan areas have already become notorious.

Economic development has received further state support in the form of the Georgia Department of Transportation's (DOT) Governor's Road Improvement Program (GRIP).

GRIP aims to improve transportation infrastructure over a 10-year period in order to foster economic growth, particularly in rural areas, by widening existing interstates, highways, and state roads [3]. Within the five counties of this study, one interstate, (I-185), and three US highways (27, 80, and 280) were earmarked for improvement under GRIP. As of January 2004, all work had been completed except for the stretch of US 27 south of the junction with US 280 in Chattahoochee County and a stretch of US 80 located in eastern Talbot County [25]. Increased transportation infrastructure will logically lead to increased urbanization, as development springs up alongside roadways.

Economic development and ecological conservation are not necessarily wholly incompatible, however. Current landowners tend to find that the presence of green space increases the value of their property, and thus they often have an incentive to block further development, or at least to concentrate it within a smaller area. For example, in Fulton County, to the northeast of this study's region, landowners have established the Chattahoochee Hill Country Alliance, which won approval from the County Commission for a 10-year plan to establish a 'model village' with large areas of green on their property [62]. Moreover, economic growth does not necessarily have to equal sprawl. Atlanta is currently experimenting with 'smart growth' development [45], which builds high-density commercial and residential complexes, often centered on transit systems. Zoning codes and public ambivalence about the smart growth concept currently hamper the effort [21], but future success in Atlanta could provide a model for the region.

2.2. Environmental planning

Ecological conservation programs that affect the five-county region of this study have been undertaken by a wide variety of public and private actors, frequently operating in cooperation with one another. A collaboration of the Environmental Protection Agency (EPA) Region 4 and the University of Florida produced the Southeastern Ecological Framework (SEF) [5], which acts as a guidebook for many land-use planning programs throughout an eight-state region (Florida, Georgia, South Carolina, North Carolina, Alabama, Mississippi, Tennessee, and Kentucky). The SEF used a GIS model to identify a network of ecologically significant 'hubs' and the 'corridors' connecting them. The EPA has used the study to prioritize programs in its own decision making and has made the data and results available to federal, state, and local government agencies, as well as to nonprofit organizations [5]. In addition to the static SEF, other publicly available EPA initiatives designed to help communities comply with federal environmental standards include the Economic Growth Analysis System (EGAS). EGAS uses a model to predict growth and the corresponding emissions over 25 years, to help communities satisfy their obligations under the Clean Air Act and the National Ambient Air Quality Standards [18].

Between 1990 and 2000, Georgia was the sixth fastest-growing state in the country, according to the US Census [56]. In an effort to restrain development, in 2000 the state implemented the Georgia Community Greenspace Program. The program provided funding for land acquisition to counties with a population of at least 60,000 or an average annual growth rate of 800 people. Eligible counties could receive funds by submitting a plan to preserve at least 20% of their land as greenspace. Of the five counties in this study, only Muscogee received program funding—a total of over $1.12M in FY 2001–2002 [24].

The Greenspace Program was discontinued in 2003 when funding was cut by incoming governor Sonny Perdue. As a replacement, the governor has proposed the Georgia Land Conservation Partnership, which would redistribute the financial burden of acquiring land for greenspace, either by issuing bonds or soliciting funds from local governments, nonprofit organizations, and individual philanthropists [50].

One model for a broad-participation approach is the Chattahoochee River Land Protection Campaign, which has brought together a broad coalition of governmental and nongovernmental actors, spearheaded by the Trust for Public Land, The Nature Conservancy, and the Georgia Conservancy. The coalition aims to create a buffer zone along a 290-km stretch of the Chattahoochee River, from the mountains of North Georgia to the city of Columbus. Through a combination of acquisitions, donations, and easements, as of November 2003 the initiative had managed to protect 4046 ha of land along 100 km of the river [44,53].

The quality of the water in the Chattahoochee has been subject to much scrutiny over the past few years, as an EPA project to assess water pollution shifted its attention to the Chattahoochee River Basin in 2002. A handful of water bodies in the study region were found to be contaminated, in most cases with the pathogen fecal coliform and/or polychlorinated biphenyl chemical compounds. The state of Georgia has therefore been obligated under the Clean Water Act to issue total maximum daily loads (TMDLs) for these pollutants [26]. According to the EPA definition, a TMDL assesses the maximum amount of a pollutant that a water body can receive and yet still comply with water quality standards, and then divides that amount among the pollutant's sources [57]. This information is relevant to many players on the middle Chattahoochee watershed, including Columbus Water Works (CWW), which has been responsible for providing drinking water and collecting wastewater for the Greater Columbus region since 1902. CWW has made national news with its innovative initiatives, most recently for implementing a program to use municipal waste as fertilizer [36]. Currently, CWW is working on a plan to establish a permanent monitoring and data-management system, and ongoing projects are carried out with the cooperation of a number of stakeholders, including Georgia Institute of Technology, the Georgia Conservancy, and other nonprofit organizations [8].

The future of water quantity in the region will be affected by the results of ongoing water-rights litigation. Georgia, Alabama, and Florida spent 5 years trying to negotiate an agreement on use of water from the Apalachicola–Chattahoochee–Flint river system. The process culminated in a tentative agreement in July 2003, but a few months later Florida refused to accept the terms, preferring to appeal to the Supreme Court. The final agreement will probably take years to settle, but it seems certain that water shortages will have profound environmental and economic impacts, with possibilities ranging from restricted irrigation, higher rates, and stricter dumping laws, since there is less water to dilute any pollution [49].

Longleaf pine, a prominent species at Fort Benning, has also attracted conservationists' attention. The Longleaf Alliance, based at the Solon Dixon Forestry Education Center and Auburn University's School of Forestry and Wildlife Services, works with conservationists and land managers to increase awareness and provide guidance on maintaining and restoring longleaf forests, particularly on privately held lands [32].

Often, conservation is practiced by private landowners who agree to establish easements on their land. Agreements on the duration and the conditions of the easement are negotiated on a case-by-case basis, and the holder of the easement can be either a government entity—frequently city and county governments, the Georgia Department of Natural Resources, or the US Fish and Wildlife Service—or a private, nonprofit land trust [2]. The Department of Agriculture's Natural Resources Conservation Service (NRCS) also sponsors several initiatives in Georgia. NRCS offers financial and technical assistance in a number of areas to landowners who are willing to practice conservation on their property, e.g. by establishing an easement and/or restoring a wetland [37].

2.3. Military planning

Conservation advocates frequently find an ally in the military through a combination of mutual interests and the military's obligations as a publicly supported institution. The Sikes Act of 1960 laid the groundwork for cooperation among government agencies for environmental conservation on military property. Over the following decades, the law was modified multiple times [51], and was joined by legislation, such as the Endangered Species Act, the Clean Air Act, the Safe Drinking Water Act, and other acts that were binding on the military as well as on the general population. To cope with its increasing environmental obligations, in 1989 DoD issued a directive for all DoD land managers to establish a natural resources management program [14], and in 1997 amendments to the Sikes Act, Congress mandated such programs. In the late 1990s, the Army's response to these obligations coalesced into two separate but closely related programs for land management at its installations: the Integrated Training Area Management (ITAM) program and the Integrated Natural Resources Management Plan (INRMP). The Integrated Training Area Management program is made up of four subprograms: (1) Land Condition Trend Analysis (LCTA), which is responsible for managing environmental data, primarily in the form of GIS mapping; (2) Training Requirements Integration (TRI), which is responsible for synthesizing training demands with natural resource preservation; (3) Land Rehabilitation and Maintenance (LRAM), which is responsible for preventing damage to training areas and repairing damage that is incurred; and (4) Environmental Awareness (EA), which is responsible for public relations and education [13]. The program has met with both success [35] and skepticism—the latter primarily focused on the Land Condition Trend Analysis component of the program. For example, Prosser and others [46] noted that the LCTA technique was developed in the ecosystems of Colorado and Texas and that, consequently, a base in a different ecosystem should consider sampling methods that are potentially more relevant. They further added that collecting LCTA data is labor-intensive and time-consuming [46].

One of the duties of the Training Requirements Integration component of ITAM is to provide input for an Integrated Natural Resources Management Plan. Each installation's INRMP outlines its goals for integrating military needs with effective management of natural resources and indicates how those objectives will be achieved. The responsibility for preparing and implementing the INRMP falls on the installation commander, who in turn solicits input from other government agencies, scientific experts, conservation groups, neighboring landowners, and others with a stake in the environmental future of the installation. The plans must be kept current and reapproved every 5 years [15].

The INRMP for Fort Benning, the installation in this study, was prepared with the help from The Nature Conservancy (TNC). The plan contains a list of 21 goals, which are to be accomplished by means of 150 tasks, ranging from prescribed burns for the promotion of longleaf pines to measures to encourage the proliferation of the red-cockaded woodpecker [29]. The latter task is rendered more difficult by the uncertainty surrounding the degree of impact that military training has on the woodpecker. TNC researchers were unable to establish that nearby firing ranges had an impact on the birds' reproductive behavior. Nevertheless, they advise avoiding any changes in the current scale and areas of range training [17].

In addition to its conservation duties, however, Fort Benning has an obligation to train soldiers. For this purpose, Fort Benning currently is constructing a new digital multipurpose range complex (DMPRC). The proposed DMPRC would cover approximately 730 ha and would provide facilities for training with the Bradley Fighting Vehicle and the Abrams M1A1 tank. The project's environmental impact statement predicts that construction will negatively impact air and water quality in the short-term as a result of the clearing of trees and removal of soil and that the project will have a long-term negative impact on wetlands and federally protected species, including the red-cockaded woodpecker. The findings of the Final Environmental Impact Statement (FEIS) suggest that the No Action alternative (i.e. no construction) has the fewest potential impacts; however, noise concerns would continue, and needed improvement in range facilities would not occur [16]. Alternatives II and III in the EIS would have negative effects on several resources; however, mitigations are identified in the FEIS that would reduce those impacts, and both alternatives would result in less noise disturbance from the Bradley fighting vehicle and tank weaponry firing than currently occurs. Fort Benning has asked the Strategic Environmental Research and Development Program (SERDP) Ecosystems Management Project, of which our research team is a part, to analyze the issue further [59].

A major issue where military and conservation stances coincide is that of encroachment onto undeveloped areas around installations. From the military's perspective, the primary concerns are twofold: (1) a reduction in natural habitat outside the base will put pressure on military personnel to step even more delicately with regard to the environment on the base, since a decrease in natural habitat could drive endangered species onto the base's property or could make the populations on the installation be even more rare; (2) the proximity of civilians to the borders of the installation will lead to problems ranging from noise complaints to electromagnetic interference [19]. Noise ordinances are set locally, and although they are not applicable to installation property itself, they can become an issue when the sound emanates into the surrounding community. Therefore, military bases prefer to acquire buffer zones around their property, which can be accomplished by acquiring land, coming to an agreement with neighboring landowners, or, on occasion, condemning the land. Some bases have entered into cooperative, cost-sharing agreements with advocacy groups in order to gain possession of land on their borders. For example, through DoD's Private Lands Initiative, TNC is jointly purchasing off-post land with Fort Bragg in North Carolina [61], and TNC and the Trust for Public Land's Greenprint Program are working to help buffer Fort Stewart, Georgia [52]. Fort Benning could elect to do the same in a future project. Meanwhile, our research team and others are working to determine the scope of the future encroachment problem (as described later in this paper).

State and local authorities are also striving to address the encroachment problem, largely as a result of the jolt they have received from DoD in the form of the Base Realignment and Closure (BRAC) program. Under BRAC, DoD is currently evaluating the missions of all military installations to determine where cuts and reshuffling can be carried out [39], and encroachment will likely be a factor in the decisions on which bases will be closed in 2005. In an effort to protect Georgia's numerous military facilities and the benefits that they bring to local economies, in June 2003 Governor Perdue signed into law a bill that requires local governments to consult with military bases on zoning decisions for land within 3000 ft of the base [9]. Fort Benning itself is unlikely to be closed; in fact, Columbus city officials have seized on the opportunity to try to expand Fort Benning by acquiring for their local base some of the missions currently carried out by bases slated for closure, even hiring a consulting firm to help strategize [60]. In short, local authorities are currently primed to be very receptive to Fort Benning's land-use preferences in the buffer zone around the installation.

3. Treatment of the future

The need for applying ecosystem management approaches to military lands and the regions that contain them is critical because of unique resources on these lands and the fact that inappropriate management of conservation issues may jeopardize military missions. We are building a computer simulation model, the Regional Simulator (RSim), to integrate land-cover changes with effects on noise, water and air quality, and species of special concern and their habitats. The RSim model is being developed for the region around Fort Benning because of the large amount of data available for the installation and surrounding region and the cooperation offered by the base in developing and testing the model. However, this spatially explicit model is being designed so that its basic framework can be applied to other military installations and their regions, thus ensuring broad applicability to DoD environmental management concerns.

Numerous future scenarios can be modeled using RSim. These include both civilian and military land-cover changes. We have modeled two specific scenarios, along with their impacts on environmental conditions over the next 300 years: (1) modeled urbanization (conversion of nonurban land cover to low-intensity urban and conversion of low-intensity to high-intensity urban), and (2) planned road expansion plus modeled urbanization. One intended use of RSim is to create scenarios of new developments resulting from changes in policy for federal, state, or private lands in order to explore their environmental impacts. For example, management policy for the longleaf pine forest may be revised when the Fish and Wildlife Service updates its recovery plan for the federally threatened species that inhabits these forests (red-cockaded woodpecker). Closure of some military installations and ongoing military engagement around the world will put pressure on Fort Benning to train more infantry troops. RSim should allow the environmental implications of these changing conditions to be explored.

3.1. Modeling urbanization

Our methods for simulating population growth generated new urban pixels in land-cover maps for the five-county region around Fort Benning. Urban growth rules are applied at each iteration of RSim to create new urban land cover. The subsequent RSim modeling step then operates off a new map of land cover for the five-county region. The computer code (written in Java) has been built from the spontaneous, spread center, and edge growth rules of the urban-growth model from Sleuth [4,6,7,27].

The urban-growth submodel in RSim includes both spontaneous growth of new urban areas and patch growth (growth of preexisting urban patches). We have focused first on generating low-intensity urban areas (e.g. single-family residential areas, schools, city parks, cemeteries, playing fields, and campus-like institutions). Three sources of growth of low-intensity urban pixels are modeled: spontaneous growth, new spreading center growth, and edge growth. First, an exclusion layer is referenced to determine those pixels not suitable for urbanization. The exclusion layer includes transportation routes, open water, the Fort Benning base itself, state parks, and a large private recreational resort (Callaway Gardens). Spontaneous growth is initiated by the selection of n pixels at random, where n is a predetermined coefficient. These cells will be urbanized if they do not fall within any areas defined by the exclusion layer. New spreading-center growth occurs by selecting a random number of the pixels chosen by spontaneous growth and urbanizing any two neighboring pixels. Edge-growth pixels arise from a random number of nonurban pixels with at least three urbanized neighboring pixels.

Low-intensity urban pixels become high-intensity urban cells according to different rules for two types of desired high-intensity urban cells:

- central business districts, commercial facilities, high impervious surface areas (e.g. parking lots) of institutional facilities that are created within existing areas with a concentration of low-intensity urban cells;
- industrial facilities and commercial facilities (malls) that are created at the edge of the existing clumped areas of mostly low-intensity urban cells or along four-lane roads.

For the first high-intensity category, land-cover changes occur in a manner similar to changes in low-intensity growth, as described above: a spontaneous-growth algorithm converts random low-intensity pixels to high-intensity pixels, and an edge-growth algorithm converts random low-intensity urban pixels with high-intensity urban neighbors to high-intensity pixels. The second type of conversion, from low-intensity to high-intensity urban land use, is road-influenced growth and is described in Section 3.2.

3.2. Modeling the effects of roads on urban growth

The road-influenced urbanization submodel of RSim consists of growth in areas near existing and new roads by considering the proximity of major roads to newly urbanized areas. The new-road scenario makes use of the Governor's Road Improvement Program

(GRIP) data layers (as described above) for new roads in the region. Upon each iteration (time step) of RSim, some number of nonurban pixels in a land-use land-cover map are tested for suitability for urbanization according to spontaneous and patch growth constraints. For each pixel that is converted to urban land cover, an additional test is performed to determine whether a primary road is within a predefined distance from the newly urbanized pixel. This step is accomplished by searching successive concentric rings around the urbanized pixel until either a primary road pixel is found or the coefficient for a road search distance is exceeded. If a road is not encountered, the attempt is aborted.

Assuming the search produces a candidate road, a search is performed to seek out other potential pixels for urbanization. Beginning from the candidate road pixel, the search algorithm attempts to move a 'walker' along the road in a randomly selected direction. If the chosen direction does not lead to another road pixel, the algorithm continues searching around the current pixel until another road pixel is found, aborting upon failure. Once a suitable direction has been chosen, the walker is advanced one pixel, and the direction selection process is repeated.

In an effort to reduce the possibility of producing a road trip that doubles back in the opposite direction, the algorithm attempts at each step of the trip to continue moving the walker in the same direction in which it arrived. In the event that such a direction leads to a nonroad pixel, the algorithm's search pattern fans out clockwise and counterclockwise until a suitable direction has been found, aborting upon failure. Additionally, a list of road pixels already visited on the current trip is maintained, and the walker is not allowed to revisit these pixels.

The road-trip process continues until it must be aborted due to the lack of a suitable direction or the distance traveled exceeds a predefined travel limit coefficient. The latter case is considered a successful road trip. To simulate the different costs of traveling along smaller two-lane roads and larger four-lane roads, each single-pixel advancement on a two-lane road contributes more toward the travel limit, allowing for longer trips to be taken along four-lane roads such as the GRIP highways.

Upon the successful completion of a road trip, the algorithm tests the immediate neighbors of the final road pixel visited for potential urbanization. If a nonurban candidate pixel for urbanization is found, it is changed to a low-intensity urban type, and its immediate neighbors are also tested to find two more urban candidates. If successful, this process will create a new urban center that may result in spreading growth as determined by the edge-growth constraint.

As noted in Section 3.1, roads also influence the conversion of low-intensity urban land cover to high-intensity urban land cover. For the second high-intensity urban subcategory (industry and malls), the RSim code selects new potential high-intensity-urbanized cells with a probability defined by a breed coefficient for each cell. Then, if a four-lane or wider road is found within a given maximal radius (5 km, which determines the road_gravity_coefficient) of the selected cell, the cells adjacent to the discovered four-lane or wider road cell are examined. If suitable, one adjacent cell is chosen for high-intensity urbanization. Hence, the new industry or mall can be located on the highway, within 5 km of an already high-intensity urbanized pixel.

3.3. Modeling noise impacts

Noise from military installations may affect populations outside of base boundaries and wildlife within the fence. RSim uses GIS data layers of military noise exposure developed by the US Army Center for Health Promotion and Preventive Medicine (CHPPM) as part of the Fort Benning Installation Environmental Noise Management Plan (IENMP). RSim builds upon noise guideline levels developed by the military under the Army's Environmental Noise Program [ENP] [55]. ENP guidelines define zones of high noise and accident potential and recommend uses compatible in these zones. Local planning agencies are encouraged to adopt these guidelines. IENMP contains noise contour maps developed from three DoD noise simulation models: NOISEMAP, BNOISE, and SARNAM.

- The Army, Navy, and Air Force use NOISEMAP (Version 6.5), a widely accepted model that projects noise impacts around military airfields. NOISEMAP calculates contours resulting from aircraft operations using such variables as power settings, aircraft model and type, maximum sound levels and durations, and flight profiles for a given airfield.
- The Army and the Marines use BNOISE to project noise impacts around ranges where 20-mm or larger caliber weapons are fired. BNOISE takes into account both the

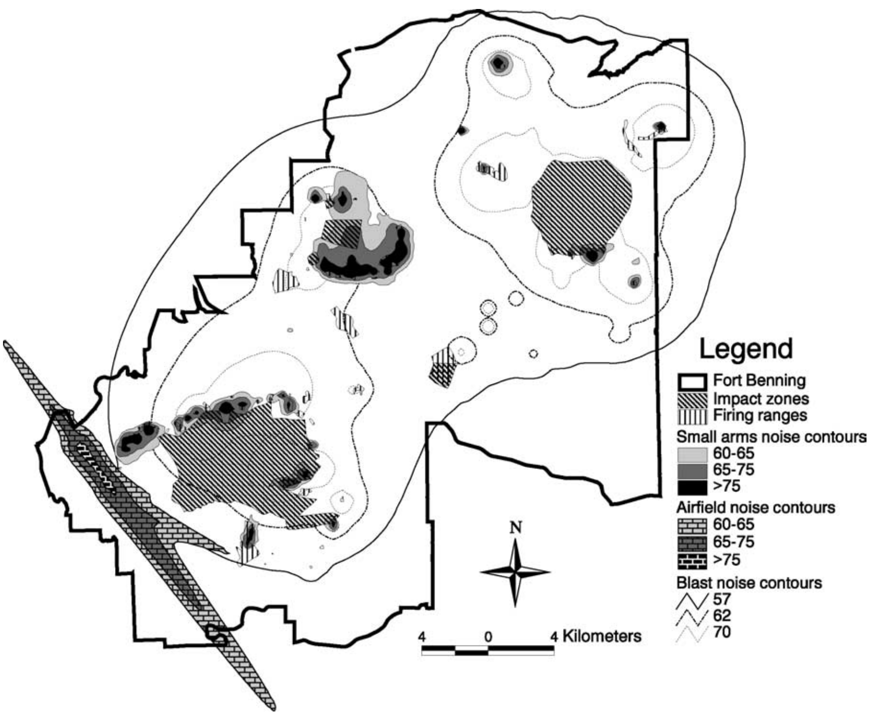

Fig. 3. Noise impact contours (in decibels) for the Fort Benning area.

annoyances caused by hearing the impulsive noise of weapons and by experiencing house vibration caused by the low frequency sound of large explosions. BNOISE uses operational data on the number of rounds of each type fired from each weapon broken down by day and night firing. Contours show the cumulative noise exposure from both firing point and target noise.

- All the military services use the Small Arms Range Noise Assessment Model (SARNAM) to project noise impacts around small arms ranges. SARNAM is designed to account for noise attenuated by different combinations of berms, baffles, and range structures.

Each model produces noise contours that identify areas where noise levels are compatible or incompatible with noise-sensitive land covers. The output could also be used to determine the effects of noise on wildlife if species audiograms and spectra for noise sources are available. The common output of all three noise models (Fig. 3) allows RSim projections to be overlain on the GIS data layer from the noise models.

4. Assessment of the future of the five-county region

RSim projections of urban growth show that the city of Columbus is expected to grow and hence to exert even more pressure on the northern boundary of Fort Benning (Fig. 4). With no zoning or other restrictions, the model projects that both low-intensity and high-intensity urban land covers will occur along the northern boundary of the installation. Urban growth in Harris County (farther north of Fort Benning) is also expected to be high. This growth is likely to come from preexisting communities, but such development would

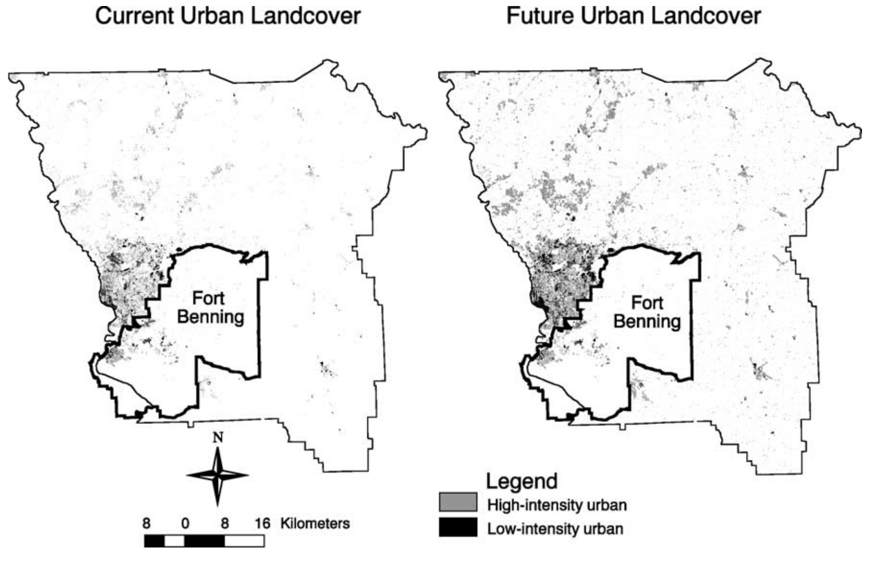

Fig. 4. Current and projected urban land cover for five-county region.

Table 1
Land cover for the study region in 1998 and projected with and without new roads

Class	Area (ha)			% Cover		
	1998	Projected with new roads	Projected without new roads	1998	Projected with new roads	Projected without new roads
Urban and transportation	41,874	60,354	59,636	9	14	14
Bare ground	45,532	43,125	43,222	10	10	10
Forest	311,424	297,522	298,048	72	68	68
Nonforest vegetation	36,550	34,381	34,475	8	8	8
All classes	435,380	435,383	435,382	100	100	100

also make sense in view of the proximity of Atlanta, which grew by 38.9% between 1990 and 2000 and continues to grow at a rapid rate [56]. Harris County is within commuting distance for people working in Atlanta. Over the five-county region the RSim model projects a small increase in urban areas with most of the land cover coming from forested areas (Table 1).

With the expansion of roads, RSim predicts very little change in urban growth compared to the projection without the influence of new roads (Table 1). With new roads included in the model, less than 0.2% more area is converted to urban sites as a direct result of the roads [10]. Hence, new roads are not anticipated to have many new direct impacts on land-cover change in this region, in contrast to the great effect of new roads in rural areas of developing countries [20]. In the United States, few new roads are being created, and most environmental effects arise from existing or renovated roads [20].

We are most interested in using the RSim model to project ways in which land-cover changes will have direct and indirect impacts on noise, water, and air quality and rare species. Here, we focus on the effects of noise. By overlaying the noise contours from military activities on current and projected urban growth, we can determine what land-cover classes are or will be exposed to high noise levels. Projections from the noise models for Fort Benning show that noise levels are high in areas to the northwest of the installation, where urban growth is projected to occur, and to the east, where a mix of forested and nonforested lands occurs (Fig. 2). The noise levels are reported according to C-weighting [1], which are impulsive sounds such as sonic booms and are perceived by more than just the ear. These vibrations are flat over the range of human hearing (about 20–20,000 Hz). Quantities of interest for human annoyance include: (1) the C-weighted day-night sound levels (CDNL) between 62 and 70 dB, termed 'Noise Zone II', in which the location of residences is not recommended and (2) CDNLs between 57 and 62 dB, termed the 'Land Use Planning Zone', in which noise complaints may arise. Urban areas with sound levels of 57–62-dB CDNL (Table 2) and 62–70-dB CDNL (Table 3) are potentially affected by noise both now and in the future, in particular in areas where noise reduction features have not been incorporated into buildings (Tables 2 and 3). Both with and without the new road scenario, about 20% of the land in the 57–62-dB CDNL contour is projected to be in urban cover. The mission at Fort Benning would be protected if urban

Table 2
Land cover between the 57- and 62- dB noise contours in 1998 and projected with and without new roads

Class	Area (ha)			Percentage		
	1998	Projected with new roads	Projected without new roads	1998	Projected with new roads	Projected without new roads
Urban and transportation	5253	6594	6603	16	20	20
Bare ground	2720	2448	2448	8	7	7
Forest	23,615	22,680	22,678	72	69	69
Nonforest vegetation	1300	1166	1160	4	4	4
Total	32,888	32,888	32,888	100	100	100

land use could be discouraged in that area. Thus, this modeling example is being used to alert local planners of this impending conflict. We are building subcomponents for RSim to examine air and water quality and habitat effects in a similar manner.

5. Concluding thoughts

Planners in the five-county region of Georgia are extremely interested in future developments of the state, counties and municipalities. Their efforts focus on meeting economic needs and providing clean water and air over the next 5–20 years. The military planners are most concerned with addressing training requirements while obeying environmental laws and regulations and maintaining good relations with their neighbors. Fort Benning tends to be assigned a new garrison commander about every 5 years. Hence the installation tends to focus on the 5-year time scale or less, for it is within the planning budgets and community experience. Yet, some environmental repercussions of land management practices may not be apparent for several decades. Therefore, bioregional planning should include the long term.

Table 3
Land cover between the 62- and 70-dB noise contours and projected with and without new roads

Class	Area (ha)			Percentage		
	1998	Projected with new roads	Projected without new roads	1998	Projected with new roads	Projected without new roads
Urban and transportation	2181	2207	2208	11	11	11
Bare ground	1451	1448	1445	7	7	7
Forest	14,598	14,582	14,584	74	74	74
Nonforest vegetation	1483	1476	1476	8	8	8
All classes	19,713	19,713	19,713	100	100	100

The RSim model offers several benefits to the research community and resource managers. The model design and building effort is intended to contribute to workable management and monitoring plans. RSim is being designed so that it can be incorporated into existing management systems for an installation and also to relate to the needs of private resource managers and developers for the area. RSim provides a tool for planners to consider environmental impacts up to and beyond the 5-year time frame, which is the typical focal period. The model provides new ways to consider the influence of different spatial scales and types of feedback and to minimize environmental impacts. We are developing an approach that integrates processes that operate on very different temporal and spatial scales. For example, the air-quality model is an instantaneous projection for a large area, while the water-quality model operates seasonally and has spatial units of 30-m resolution. The plan is to have RSim incorporate feedback between different aspects of the environment that operate at different spatial scales and to focus on projections over a decade or more. Accommodating such feedback relationships is one of the biggest challenges of interdisciplinary research.

There is a need for an integrated perspective in addressing environmental concerns. Current environmental laws and regulations address such concerns by sector but may impact other sectors and often occur without consideration for how solving one problem may create another (e.g. actions designed to meet local noise standards may jeopardize water or air quality). There are few attempts to design approaches that allow resource managers to consider ways in which environmental management or restoration affect the variety of environmental concerns. RSim is designed to be such a tool. Hence, the model should improve the ability to manage for multiple concerns. Such an integrative approach may lead to steps to simultaneously and proactively address environmental laws and regulations. Optimization is a key issue for environmental research, as advancements have been constrained by efforts to meet a single criterion. Acceptable land covers are those that maintain standards within all environmental categories—air and water quality, noise control, and species protection.

Maybe the greatest contribution and challenge of this approach is in its long-term and regional perspective. Historically, many environmental efforts have focused on addressing impacts over a few years and within a single land ownership or within similar land uses. Using RSim, we examine long-term impacts within a region that includes many different owners and land uses.

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Vehicle impacts on the environment at different spatial scales: Observations in west central Georgia, USA ☆

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Abstract

Roads and vehicles change the environmental conditions in which they occur. One way to categorize these effects is by the spatial scale of the cause and the impacts. Roads may be viewed from the perspective of road segments, the road network, or roads within land ownership or political boundaries such as counties. This paper examines the hypothesis that the observable impacts of roads on the environment depend on spatial resolution. To examine this hypothesis, the environmental impacts of vehicles and roads were considered at four scales in west central Georgia in and around Fort Benning: a second-order catchment, a third-order watershed, the entire military installation, and the five-county region including Fort Benning. Impacts from an experimental path made by a tracked vehicle were examined in the catchment. Land-cover changes discerned through remote sensing data over the past three decades were considered at the watershed and installation scales. A regional simulation model was

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used to project changes in land cover for the five-county region. Together these analyses provide a picture of the how environmental impacts of roads and vehicles can occur at different spatial scales. Following tracked vehicle impact with a D7 bulldozer, total vegetation cover responded quickly, but the plant species recovered differently. Soils were compacted in the top 10 cm and are likely to remain so for some time. Examining the watershed from 1974 to 1999 revealed that conversion from forest to nonforest was highest near unpaved roads and trails. At the installation scale, major roads as well as unpaved roads and trails were associated with most of the conversion from forest to nonforest. For the five-county region, most of the conversion from forest to nonforest is projected to be due to urban spread rather than direct road impacts. The study illustrates the value of examining the effects of roads at several scales of resolution and shows that road impacts in west central Georgia are most important at local to subregional scales. The insights from these analyses led to several questions about resource management at different spatial scales.
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Keywords: Bulk density; Disturbance; Fort Benning; Land cover; Landscape; Management; Scale; Simulation; Soil compaction; Vegetation

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1. Introduction

Environmental impacts of human activities vary by spatial scale. In terms of vehicle impacts on the environment, the vehicles themselves and the creation of roads cause the most impact at the fine scale, but broad scale effects can include noise, water or air pollution, and disruption of habitat. Furthermore, ecological systems can be viewed as spatially and temporally hierarchical [1,2]. In other words, ecological processes observed at one level of organization arise from lower level behaviors and are constrained by higher level processes. As an example, the avoidance of roads by gray wolves (*Canis lupus*) is a fine-scale response that affects broad-scale patterns in wolf density: that is, wolf density is low in areas that have a relatively high density of roads (more than 0.45 km of road per km^2 area) [3]. Thus environmental effects at one scale can, in turn, affect the ecological system at other scales. In this paper, we examine the ways in which road effects on the environment can vary by spatial resolution.

Fine-scale environmental impacts that are associated with off-road vehicle movement include soil compaction and changes in vegetation properties such as species, cover, and diversity in association with crushing and later plant colonization and competition. Studies of tracked vehicle impacts on vegetation at military installations in semiarid and arid environments have demonstrated changes in soil compaction [4], herbaceous plant composition [5,6], density, and cover [7]. Increased soil compaction would lead to longer recovery periods for the affected plant properties. The level of effect on vegetation is determined by the exact path of the vehicle: sharp turns by tracked vehicles disturb a larger width of soil and cause deeper track ruts than smooth turns or straight operation [8].

Local environmental effects such as changes in soil bulk density and vegetation can, in turn, cause regional problems. The introduction and subsequent spread of introduced species can lead to broad-scale land-cover changes. For example, Scotch broom (*Cytisus scoparius*) was planted along selected highways in western Washington state for beautification but has now become a regional pest that competes with native species, widely disseminates pollen to which many people are allergic, disrupts fire regimes, and provides habitat for feral animals [9]. Kudzu (*Pueraria lobata* Ohwi) is another example of a deliberately introduced plant that has become a regional pest along roads. Kudzu was established in the southern United States for erosion control, as fodder for cattle and sheep, and as a porch vine. This liana native of China has overgrown and killed trees in many locations in the American Southeast [10]. In addition to quickening the spread of such invasive species, road development can alter surface water bodies by changing wetland drainage, forcing streams into channels, and increasing inputs of sediment, road salt, and heavy metal to streams [11]. Thus, the cumulative effects of local events can lead to regional changes.

Land use and land management are basically local phenomena: farmers clear land for crops; state governments construct roads between cities; businesses are developed in industrial parks. Nevertheless, across the globe most land transformations now have large-scale effects although they originate from local changes. As an example of cumulative effects, timber harvesting and clearing occur at local scales but, when aggregated, can result in large-scale deforestation [12]. Moreover, Shaw and Diersing [5] speculate that the impacts of tracked vehicles on the density and cover of woody plants at the local scale at a military installation in Colorado could exceed a threshold for sustainability of larger scale juniper (*Juniper monosperma*) woodlands. If the trend of reductions in density and cover of woody plants continues, the density of juniper, which dominates the woodlands, would be reduced to a critical level, for regrowth of this species is very slow. Local versus broad-scale perspectives on the benefits and costs of land management provide different views of the implications of land actions. Recognition that human impacts occur on a broad scale as well as a local scale is changing the way that natural resources are managed.

A multi-scale perspective is needed to address today's land management problems [13] for several reasons. It is now recognized that the spatial scale of environmental problems is complex and can be multifaceted. Furthermore, all ecological processes (and management actions) occur in a spatial context and are constrained by spatial location. A broad-scale perspective is necessary for the management of wide-ranging animals [e.g., the Florida panther (*Puma concolor coryi*) [14] or the marbled murrelet (*Brachyramphus marmoratus*) [15]]. Understanding and managing disturbance also requires a broad-scale perspective because land-cover patterns can retard or incite the spread of natural or anthropogenic disturbances (e.g., connected forests may lead to larger fires). Therefore, solutions for contemporary environmental problems need to be provided within a spatial context. For example, natural areas that provide essential ecological services (e.g., cleansing of water) are limited in extent, and their contributions must be interpreted within the landscape matrix in which they occur and with the understanding that environmental conditions may change spatially or across an area as well as over time (as with global warming). Thus, spatially optimal solutions to land management problems should be considered.

Military installations are an ideal setting in which to examine the environmental impacts of vehicles and roads at multiple scales. Military training involves the use of tracked and wheeled vehicles in off-road locations, as well as on unpaved and paved roads, and new roads are periodically constructed to provide access to new training areas. The military installations themselves can be situated near highway development and urbanization. Road densities commonly are high around military bases because civilian traffic is not permitted through much of the installation area, which forces that traffic to occur near the perimeter or in specified corridors.

As with any area where off-road vehicles operate their operation on military installations impact soil, vegetation, and streams in the immediate area of vehicle operation; whereas erosion and noise may cause impacts at a distance; and land-use change along roads can result in still other cumulative environmental effects. Effects of vehicles or roads on vegetation or wildlife at military installations are often environmentally significant because these installations serve as reservoirs for vegetation diversity and for threatened and endangered species [16].

The question considered in this paper is how the environmental impacts of roads vary by spatial resolution. We hypothesized that impacts of road segments at fine scales would largely be to local soil and vegetation conditions and that impacts of road networks would be observable at the broad scale, i.e., conversion from the native forest cover types to nonforest conditions. We anticipated that as the scale of resolution became more broad, the effects of roads would be more pronounced at a distance. To examine this concept, environmental impacts of vehicles and roads were considered at four scales in west central Georgia in and around Fort Benning. Field experiments, comparison of land cover over time (as determined through remote sensing analysis), and a simulation model were used to determine potential environmental effects. The finest scale was a single second-order catchment (4 ha) within a training compartment in the northeast corner of Fort Benning, referred to by the installation's land managers as compartment K-11. An experimental disturbance was created in the catchment with a D7 bulldozer. This catchment was also thinned and burned as part of routine management prior to the tracked-vehicle disturbance. The second scale was a third-order 244 ha watershed also in training compartment K-11 of Fort Benning. The third scale was the entire 73,503-ha Fort Benning installation. The fourth, or broadest, scale was a five-county region in west central Georgia (Harris, Talbot, Muscogee, Marion and Chattachoochee counties) of 442,347 ha containing Fort Benning, the city of Columbus, and extensive farm and forest land primarily in private ownership. The insights from these analyses led to several questions about resource management at different spatial scales.

2. Methods

2.1. Site description

The climate of the study area in west central Georgia is characterized by long, hot summers and mild winters, and precipitation is regular throughout the year but with most occurring in the spring and summer [17]. Soils are composed of clay beds, weathered Coastal Plain material, and alluvial deposits from the Piedmont [17]. Before the military base was established in 1918, both Native Americans and European settlers farmed the region largely growing corn and cotton, respectively [18]. Fort Benning is currently used extensively for US military infantry and tank training exercises, yet it retains large areas within the installation in semi-natural vegetation. Fort Benning constitutes part of the Southeastern Mixed Forest Province of the Subtropical Division [19], which is now characterized by second-growth pine forests of longleaf (*Pinus palustris*), loblolly (*P. taeda*), and slash pines (*P. elliotii*) mixed with many species of oaks and other deciduous trees. Frequent, low-intensity fires are thought to have been an integral component of the pine forest ecosystem [20] and have been a component of the management plan at Fort Benning since the 1970s. Before European settlement began, pine forests covered much of the landscape, but since then they have been lost or degraded [21,22] mainly as a result of land-use change, timber harvest, and fire suppression [23,24].

2.2. Approach for each scale

2.2.1. Local scale

Because tracked vehicles can cause environmental damage to plants and soil [8], attributes of both these features were measured after a disturbance. In May 2003, a disturbance treatment was created within an experimental catchment in training compartment K11 at Fort Benning. Several passes of a D7 bulldozer with the blade lowered were used to remove both extant vegetation cover and surface soil organic matter. Vegetation surveys were conducted shortly after the disturbance treatment in June and in September to capture the temporal response in plant cover. Three sets of 50-m transects were established to monitor response and recovery from the disturbance. Control transects were established parallel to the disturbance treatments at a distance of 5 m. Ten points were chosen at random along each treatment and control transect, for a total of 60 survey points, and plant cover was assessed using 0.568-m radial plots at each point. Total and individual species plant cover was ranked according to a modified form of the Braun-Blanquet [25] cover-abundance system [26] (Table 1). Species identification followed Radford et al. [27]. Matlab® [28] was utilized for data analysis.

Replicate soil samples were collected at the randomly chosen sampling points along both treatment and control transects to a depth of 30 cm by means of a soil probe (2.54-cm diameter) with hammer attachment (AMS, American Falls, ID) in June 2003. The O-horizon, when present, was removed from a known area (214 cm^2) prior to sampling the mineral soil. The mineral soil samples at each sampling point were cut into 10-cm increments and composited by depth. Soil density was calculated on the basis of air-dry mass (<2 mm) and the known volume of the sample. O-horizon mass was determined after oven-drying (75 °C).

Table 1
Key of the cover-abundance class modified from the Braun-Blanquet [25] system

Cover-abundance class	Species cover and distribution characteristics
0	No plants present
1	Less than 1% cover; 1–5 small individuals
2	Less than 1% cover; many small individuals
3	Less than 1% cover; few large individuals
4	1–5% cover
5	5–12% cover
6	12–25% cover
7	25–50% cover
8	50–75% cover
9	75–100% cover

2.2.2. *Watershed scale*

The third-order watershed in training compartment K11 was selected for analysis at an intermediate scale. This watershed has not experienced major tracked vehicle traffic, but it does have several unpaved roads and trails. Orthophotographs and current roads maps were used to determine how the roads within the watershed had changed since the 1950s.

Changes in land cover over time from the 1970s to the 1990s were assessed through the use of satellite imagery [29]. A combination of ARC INFO 7.2.1™, GRID™, ArcView 3.2™, and ERDAS IMAGINE 8.2™ software was used to derive land cover from satellite imagery. The North American Landscape Characterization (NALC) data that are largely derived from Landsat Multispectral Scanner (MSS) imagery were used in this analysis. The NALC data have a sample resolution of 60 m. The NALC data set covering the Fort Benning area is composed of triplicates dated 1974, 1983/86, and 1991 for two scenes (i.e., path 019/row 037 and path 019/row 038). The two scenes for each time period had to be connected in a mosaic in IMAGINE™ before the classification process could begin. The two scenes comprising the mosaic for the 1980s were made in different years; however, given the nature of the landscape and method of comparison used, this time interval was considered acceptable, and the date of mosaic is referred to as "1983". Two Landsat-7 Enhanced Thematic Mapper (ETM) images dated July 24, 1999 were used to create a current land-cover map of Fort Benning.

Unsupervised classification, which identifies a user-defined number of classes based upon spectral response, was used to create 45 spectral classes from the imagery. These 45 classes were then combined into six land-cover classes with the use of a 0.5-m resolution digital color orthophoto from 1999 and Land Condition Trend Analysis (LCTA) [30] point data of 1991 as reference data. The six classes are water, barren or developed land, pine forest, deciduous forest, mixed forest (deciduous and pine, areas of sparse forest cover, or areas of transition between forest and nonforest), and cleared lands (areas cleared of forest vegetation but with some ground cover that may be grass or transitional areas). For comparison with data derived from other imagery sources for other years, the unsupervised classification of the 1999 image (measured at 30-m resolution) was resampled to a 60-m resolution by means of nearest neighbor resampling.

Post-classification change detection was conducted for the land-cover maps derived from the NALC data. Two operations were carried out to identify the influence of roads on the land cover. First, the changes from forest categories to nonforest categories for the watershed as a whole were identified. The forest categories include deciduous, evergreen, and mixed forests, whereas the nonforest category includes cleared and barren land. Through map queries in ArcView 3.2™, locations of regions belonging to a forest category in an earlier year but to a nonforest category in a later year were identified. By this approach, the percentage of change from forest to nonforest was calculated for the time period 1974 to 1991.

The second process to evaluate road and vehicle influence involved quantifying the forest-to-nonforest conversion at various distances from the roads. Only unpaved roads and tank trails occur in the watershed. Buffers were created on the land-cover maps at distances of 60, 120, 180, 240, and 300 m from the roads within the watershed. Multiples of 60 were chosen because the pixel resolution of the land-cover map was 60 m. The buffers were used to extract regions of forest-to-nonforest change within the specified distances. Based on the number of pixels that changed from forest to nonforest between 1974 and 1991, percentages of change were calculated. This process was carried out for each of the buffer distances.

2.2.3. Installation scale

Land cover for all of Fort Benning was derived as described for the watershed (Section 2.2.2). Change detection for the entire installation was performed by identifying the percentage change from forest to nonforest for three time periods: 1974 to 1983/86, 1983/86 to 1991, and 1991 to 1999. Land-cover maps generated from the NALC data set and the Landsat ETM images were used for this purpose. Six classes, as described for the watershed scale, were used. The change detection process for the installation scale was similar to that for the watershed-scale (i.e., by means of map queries in Arc View 3.2™). For the entire installation, the road buffers were created for three types of roads: major roads (two- and four-lane highways, including interstates), minor paved roads, and unpaved roads and trails. The forest-to-nonforest conversion buffer analyses were carried out separately for each road type.

2.2.4. Regional scale

The analysis of road impacts for the region was based on a computer simulation model, the Regional Simulator (RSim), which is described in detail elsewhere [31,32]. As with the watershed and installation scales, land cover was the subject of analysis, but more specifically the effect of roads on urbanization within the region was assessed. The region for the simulation consisted of five counties in west central Georgia: Harris, Talbot, Muscogee, Chattahoochee, and Marion. This area encompasses the middle reach of the Chattahoochee River basin; the Columbus, Georgia, municipality and smaller communities; agricultural, forest, industrial and residential lands; and most of Fort Benning. The output of RSim includes projected maps of land cover for different time steps. The RSim model was developed for the region around

Fort Benning, Georgia, because of the large amount of data available for the installation and surrounding region and because of the cooperation offered by the installation in developing and testing the model. However, the model is being designed so that it is broadly applicable to environmental management concerns for other areas as well.

The urban growth submodel in RSim consists of spontaneous growth of new urban areas, patch growth (growth of preexisting urban patches), and road-influenced urbanization constraints that are applied at each iteration of the model to create new urban land cover [31,32]. This approach builds upon the concepts set forth by a regional planning model called SLEUTH [33–36]. Spontaneous urban growth in RSim allows for randomized urbanization, and the patch growth in RSim is influenced by the proximity of existing urban centers. Road-influenced urban growth considers the proximity of major roads to newly urbanized areas. Upon each iteration of the urban growth model, a set number of nonurban pixels in a land-cover map are tested for suitability for urbanization according to the spontaneous and patch growth constraints. For each pixel that is converted to urban land use, an additional test is performed to determine whether a major road is within a predefined distance from the newly urbanized pixel. The proposed road changes were primarily derived from the Georgia Department of Transportation's (DOT's) Governor's Road Improvement Program (GRIP) [37], which began in 1989 and plans to widen two-lane roads to four-lane roads and to attract economic development by improving the state's highway network.

In order to identify a candidate road for growth, a search procedure is performed in RSim to seek out potential pixels for urbanization [31]. The search process continues either until it must be aborted because a suitable direction is lacking or until the distance traveled exceeds a predefined travel limit coefficient. To simulate the higher costs of traveling along smaller two-lane roads than along larger four-lane roads, each single-pixel advancement on a two-lane road contributes more toward the travel limit than a single-pixel advancement on a four-lane road; this accounting in effect allows longer searches along four-lane roads.

Upon the successful completion of a search, the immediate neighbors of the final road pixel visited are tested for potential urbanization. If a candidate pixel for urbanization is found, it is changed to an urban type and its immediate neighbors are also tested to find two more urban candidates. If successful, this process creates a new urban center that may result in spreading growth as determined by the patch growth constraint.

3. Results

3.1. Local scale

Total plant cover was substantially lower in the treatment transects following the bulldozer disturbance in June; however, this difference was no longer apparent by September, when both control and treatment transects had the same median cover values (Fig. 1(a)). Yet, not all plant species responded in the same way as did total vegetation cover. The median cover category for juniper leaf (*Polypremum procum-*

bens) in June for both the control and treatment transects was 0, but in September the treatment transects displayed greater cover than the control transects (Fig. 1(b)).

As expected, O-horizon mass was significantly reduced along the treatment transect (257 g m^{-2}) in comparison with the control transect (640 g m^{-2}) ($F_{1,26} = 9.41$, $P < 0.01$). Thus, the treatment caused a substantial reduction in forest floor organic

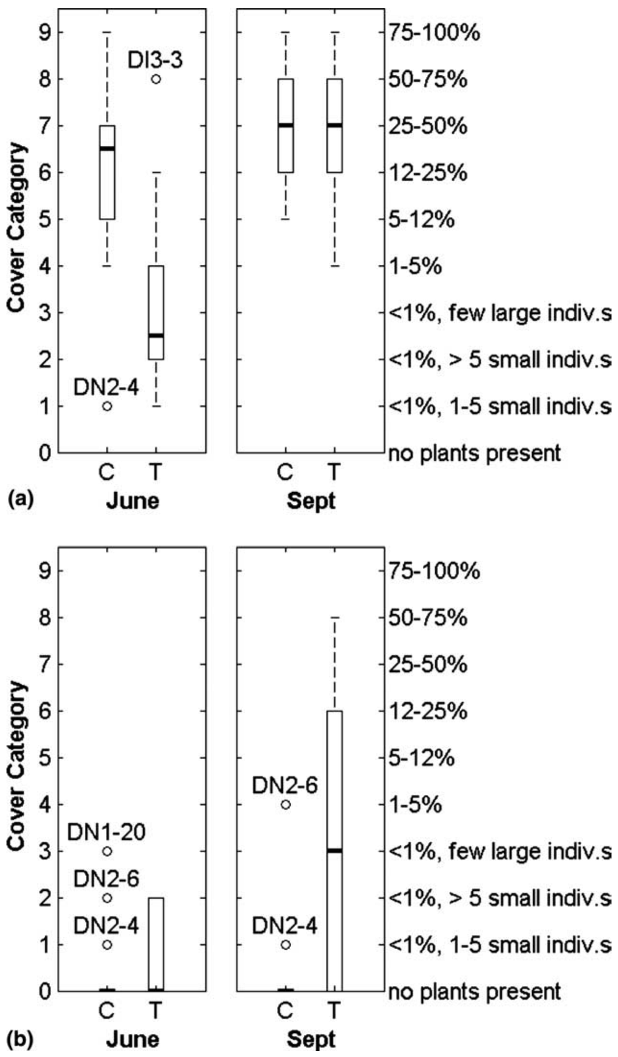

Fig. 1. Surveys within control, C, and treatment, T, transects in June and September of (a) total plant cover, and (b) cover of *Polypremum procumbens*. In these box plots, the median is represented by a solid line; the 25th and 75th percentiles, by the upper and lower edges of the box; and the minimum and maximum values of the data, by the dashed lines. Outliers, values more than 1.5 times the box extent, are shown with a circle.

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Table 2
Mean (±SE) soil densities (g/cm[3]) with depth under treatment and control transects

Soil depth (cm)	Treatment	Control	Probability[a]
0–10	1.44 ± 0.026	1.28 ± 0.058	<0.05
10–20	1.63 ± 0.030	1.56 ± 0.042	NS
20–30	1.68 ± 0.027	1.61 ± 0.048	NS

Each mean is based on seven measurements.
[a] NS = not significant.

matter. Surface (0–10 cm) soil density under the treatment transect was significantly greater than that under the control transect ($F_{1,12} = 6.48$; $P < 0.05$) (Table 2). The mean (±SE) densities of surface soil samples from the treatment and control transects were 1.43 ± 0.03 and 1.28 ± 0.06, respectively. Although soil densities for increments deeper than 10 cm tended to be greater under the treatment transect, the differences were not significantly different from the controls. Soil compaction from the bulldozer track at K11 was primarily limited to the surface mineral soil layer and produced an increase of approximately 12% in surface soil density.

3.2. Watershed scale

Road effects within the watershed over the period from 1974 to 1991 were quantified by examining conversion of cover types from forest to nonforest within buffered distances from roads. Visual comparison of the orthophotographs determined that the roads in the study watershed had been there since before the 1960s. This result made it possible to analyze the effect of roads within the watershed in the given time period. The 7.2 km of unpaved roads and trails was used to create buffers and to identify changes in forest cover over the 25-year period from 1974 to 1999 (Fig. 2). In general, land-cover conversion tends to decrease as the distances from the roads increase. The land closest to the roads (0–60 m) showed a 35% conversion from forest to nonforests, and as the distance increased, the percentage of conversion was reduced. At 120–180 m from the roads, 21% of the land was subject

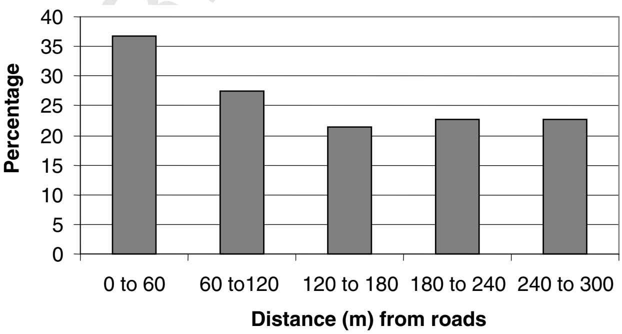

Fig. 2. Percent change in the conversion from forest to nonforest from 1974 to 1999 at different distances from unpaved roads and tank trails for the study watershed in training compartment K11.

to conversion, which is close to 21.9%, the overall percentage of conversion of forest to nonforest in the watershed. However, when the distances increased further, edge effects started to show up and the influence of roads in adjacent watersheds played a role. A visual analysis of the nearby roads on the map clarified this effect. To prevent such effects, the buffer distance for analysis was restricted to 300 m.

3.3. Installation scale

Change detection performed over the installation provided percentages of change from forest to nonforest categories over different time periods (Fig. 3). The first time period, from 1974 through 1983/86, showed a slight decline, but there was an overall increase by 1991. Part of this difference may be attributed to the differing lengths of the two time frames. In the first case a longer span, 10–13 years, was considered, and in the second case a shorter span, 6–9 years, was considered. Most of the change occurred in the third period, from 1991 to 1999. This last period is only 9 years, so it does not fit the observation that the comparative length of the first two periods affected the amount of change.

It is not known how the roads for the entire installation changed over the years of the analysis; however it is assumed that no major changes occurred. Therefore, the data layer of roads present in 1995 was used to create buffers and to identify changes over the years. The buffer analysis carried out for the watershed scale differs from that carried out for the installation scale in that many more types of roads exist at the installation scale. The 316 km of major roads consists of interstate and two- and four-lane highways, which cut across the installation. The largest effect of these major roads was the 18.3% change from forest to nonforest for the 0–60-m buffer, with the effect being stable for distances greater than 60 m (Fig. 4(a)). The 148 km of minor paved roads had a smaller (13.6%) effect on forest conversion at the 0–60-m distance. Observations of the maps suggest that, at a buffer distance of 120–

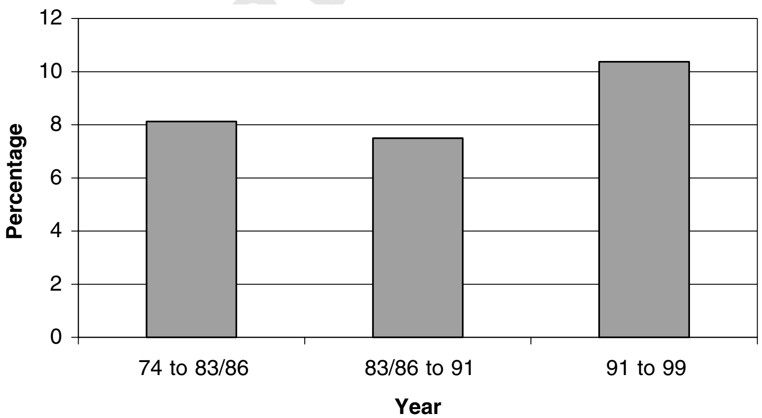

Fig. 3. Results of the change detection performed on the land-cover maps of Fort Benning. The percentages indicate conversion from forest to nonforest land-cover categories for different time periods.

180 m, forest conversion near minor paved roads was influenced by the major roads (Fig. 4(b)). Thus the 1568 km of unpaved roads and trails had a large effect on forest conversion, with the percentage of forest conversion declining from 19% to 9% as the distance from the road increased from 0–60 to 240–300 m (Fig. 4(c)).

3.4. Regional scale

Urban growth predictions generated by the RSim model results in an increase of 6.8% of pixels that are in an urban land-cover category under conditions expected to prevail in the coming decades (Fig. 5). Most of these new urban areas are near Columbus. Where Columbus is close to the northern boundary of Fort Benning, the projected growth is directly adjacent to military lands.

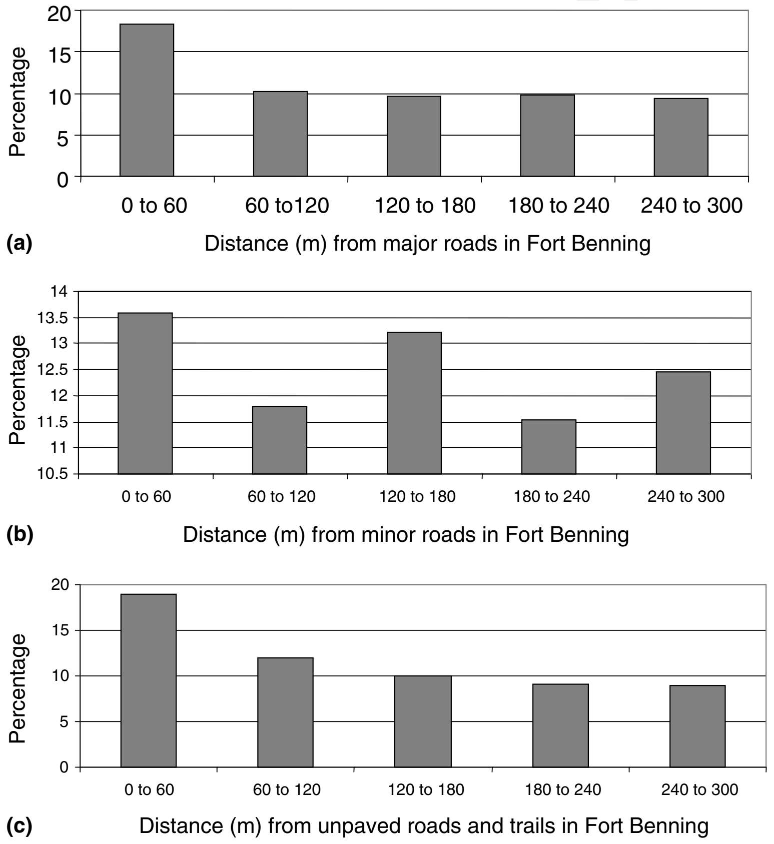

Fig. 4. Results of the change detection from 1974 to 1999 performed for the land cover of buffered roads at Fort Benning for distances from (a) major roads (interstates, two- and four-lane highways), (b) minor paved roads, and (c) unpaved roads and tank trails. The percent conversion from forest to nonforest land-cover categories at different distances from the roads is plotted for the time period 1974–1991. The percentage indicates new changes for each buffer distance in comparison with smaller buffer areas.

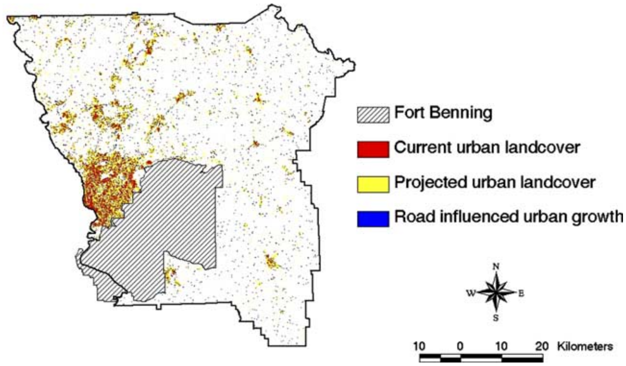

Fig. 5. Map of the current and projected urban areas in the five-county area around Fort Benning and the small area of projected growth due solely to roads.

The regional simulation model projected few urban growth differences between maps produced with the influence of new roads and maps produced without the influence of new roads even though a road-instigated urbanization algorithm was a part of the model. Most of the change to urban land cover resulted from the spread of the urban areas, and less than 0.2% of the total change in 30 simulation steps for the five-county region could be attributed to the influence of roads.

4. Discussion

4.1. Local catchment

The response of total plant cover to mechanized disturbance shows a remarkable recovery by 4 months after the disturbance to an equivalent value of the control transects. The rapid recovery occurred over the growing season and during an abnormally wet summer [38], even though soil compaction was certainly of longer duration. Despite the renewed cover, however, vegetation composition became significantly different from that in the control transects. The September survey showed a significant increase in juniper leaf (*Polypremum procumbens*). This species-specific increase agrees with the species ecology described by Radford et al. [27], who notes that *P. procumbens* is found within habitats showing recent disturbance, including roadsides.

Two plots (DN2-4 and DN2-6) frequently appear as outliers in Fig. 1. These plots were not directly impacted by the blade of the bulldozer but were located between the path of its tracks as it moved between transects. As a result, their composition reflected partial disturbance. The other outliers most likely were a result of environmental heterogeneity created either during the disturbance (DI1-20) or preceding it (DI3-3).

Rapid recovery from soil compaction is not expected. Studies of military training on dry sandy soils indicate that surface soil compaction caused by heavy tracked vehicles can persist for decades [39]. Soil compaction can change the properties of soil pores affecting infiltration capacity [39], the accessibility of organic matter to soil microorganisms, organic matter decomposition rates, and soil N availability [40]. Soil compaction by heavy machinery is also detrimental to root development and plant growth [41–43]. Soil compaction is a potential long-term effect of heavy vehicle use, and it can have an overall adverse impact on soil and vegetation properties.

Previous studies along disturbance gradients at Fort Benning [44] indicate a persistence of soil compaction for several years following site disturbance. The persistence of soil compaction depends on both soil clay content and moisture status at the time of disturbance. Fine-textured or wet soils are more prone to compaction by heavy vehicle traffic than coarse-textured or dry soils [41,45–47], but shrink/swell cycles in soils with significant clay content [46] or repeated cycles of soil wetting and drying [48] or ecological succession [49] can act singularly or together to reduce soil compaction over long time periods.

4.2. Watershed scale

Forest conversion was highest near unpaved roads and tank trails in the K11 watershed. Since the roads have width of about 3.7 m per lane, the 0–60-m buffer includes the roads themselves. The remote-sensing evidence suggests that at the watershed scale, vehicles on the unpaved roads and the roads themselves affected the areas closest to them. In this context, closeness can be defined as a buffer distance of approximately 120 m. Within that zone, clearing of trees and road-bed erosion likely caused many observed changes over the 25-year period.

4.3. Installation scale

Major roads and unpaved roads and trails were associated with most of the conversion from forest to nonforest cover at the scale of the installation. Within Fort Benning, these types of roads cover a larger area than the minor paved roads. In addition, the forest conversion in the buffered area near the major roads and unpaved roads and trails declined as distance increased. Along some major roads, considerable clearing (especially along the western edge of Fort Benning) had taken place. Because this western area makes up the cantonment where soldiers live and work, most of this conversion was likely associated with urban growth and expansion.

The minor paved roads graph is bimodal, with a peak at the 0- to 60-m buffer and a peak at the 120- to 180-m buffer (Fig. 4(b)). This second peak could result from the paucity of paved roads and their proximity to major roads. The large forest conversions near major roads (Fig. 4(a)) could have affected the minor paved roads, for the two are often close to each other at Fort Benning.

4.4. Regional scale

Most of the urban growth is projected to result from urban spread rather than road impacts (Fig. 5). Columbus is a rapidly developing municipality, and its high urban growth trend is simulated in the RSim model. Furthermore, by 2004 the Governor's Road Improvement Program (GRIP) planned for the next 25 years will have completed its major activity in the five-country region of this study. Yet roads uniquely produce linear features, which can act to dissect a connected landscape. Effects of roads on ecological pattern and connectivity, as well as effects on nonurban land-cover types, have yet to be examined in the five-county region, and RSim can facilitate such analyses.

4.5. Scale of vehicle and road impacts on the environment

Table 3 illustrates our hypothesis that road impacts differ by scale and have unique effects on the environment at each resolution. At the resolution of a road segment, there are pressures for establishment and use of roads, which can result in vegetation removal and soil compaction. At the larger watershed scale, the need for military training within the installation calls for roads that can be used for maneuvers with the result of local conversion of forest to nonforest land. Similar pressures and effects occur at the installation scale, but the restrictions of the Endangered Species Act influence management decisions. As a federal facility, habitats for federally listed species must be protected, which limits the extent and places where military training can occur. At the resolution of the five-county area, the pressure for urban development appears to have a more pronounced impact on conversion of forest to nonforest land than the roads themselves. Of course, road development and improvement are a part of urban expansion, but it appears that change in land use is the prevailing influence on forest conversion for the region. As a largely local phenomenon, road establishment and use may have greater impacts at local and subregional scales, and effects at regional scales may be overridden by other pressures and processes. The concept is supported by the "road effect zone" that is based on observational evidence that environmental effects can extend as far as 1 km from a road [50]. At a national perspective, this road-zone effect translates into about one fifth the area of the United States being affected by roads [51]. Even so, there are large areas where roads are not the primary influence on environmental conditions as well as locales where road effects are pervasive. Our analysis from west central Georgia suggests that road effects should be considered at local and subregional resolutions.

In summary, the results of these combined studies for Fort Benning suggest that effects at all scales are important to consider. Even at the broadest scale of the five-county region, it is the relative relationship between urban growth and the influence of roads that helps to determine the importance of road impacts. The mid-scale remote-sensing analysis suggested that forest conversion was greatest nearest the roads. A local tracked vehicle impact study demonstrated that vegetation cover might not be indicative of the full recovery of mature vegetation or of soil compac-

Table 3
Four spatial resolutions and their pressures on roads with corresponding effects on roads and the environment

Road resolution	Area (ha)	Pressures	Effect on roads	Effects on the environment
Road segment in second order catchment	4	Establishment and use of roads	New roads	Vegetation removal and soil compaction
Road network in third order watershed	244	Military training	Roads for training	Local conversion of forest to nonforest
Road network within Fort Benning	73,503	Military training	Roads for training	Conversion of forest to nonforest over entire installation
		Endangered Species Act	Must retain habitat for listed species when using federal funds	Protection of habitat for listed species
Road network in five-county area	442,357	Changes in land use	Land cover change	Regional conversion of forest to nonforest
			Pressure for new and improved roads	

tion. Hence field studies, remote-sensing analyses, and modeling all have their place in understanding environmental impacts of vehicle and roads.

5. Management questions

Roads on military lands are unique because of the high number of unpaved roads and trails that are heavily used by tracked vehicles [52]. Even so, military lands support a high number of rare species and their habitats [53]. It is partly for this reason that roads on military lands have received special attention. Yet, many questions still remain about appropriate ways to manage for ecological impacts of roads on and near military lands. For example, it would be useful to catalogue the road features that are unique to military lands and those that are common to other types of land ownership or use.

A key question resulting from this multifaceted study is: what metrics should be used to assess road impacts on ecological systems? In this study, we used different techniques for determining potential impact at each scale of analysis. At the local scale, we examined the total percentage of plant cover, cover by species, and soil density of different depths. At the watershed and installation scales, past forest conversion in relation to distance from roads was used as a metric. Simulated urbanization was examined at the regional scale.

Instead of these techniques and metrics, we could have used other alternatives. For example, groups of species may respond similarly to roads and traffic at the local scale [54]. In addition, historical orthophotography can be used to create a time sequence of data layers of road for the entire installation, and the developing road network can be used to estimate how much forest conversion is influenced by distance from roads at each time period. In addition, the simulation approach can be refined to explore not only the causes but also the impacts of road-induced urbanization. For example, models can be used to determine how road infrastructure can affect changes in noise, air, and water quality as well as habitat alteration.

Features of roads themselves can be used as metrics of environmental impacts. Such metrics as the number of passes of a tracked vehicle, length of paved road, number of times a stream is crossed per unit of road length, or road width (e.g., two or four lane) all contain information on how roads and vehicles can impact the environment.

Further studies are needed to attribute causes to effects on land cover. Experimental studies to attribute causality could most easily be carried out at the local scale. At that scale, for example, the relationship between vegetation diversity and cover, on one hand, and soil compaction, on the other, can be explored. The mechanistic relationships between soil compaction and growth and yield of woody plants are reviewed by Kozlowski [55]. Unfortunately, causes of forest conversion near roads at larger spatial scales are difficult to identify through retrospective assessment. As stated in Section 1, the clearing of trees and roadbed erosion are both likely contributors to vegetation impacts; however, the direct crushing of vegetation by tracked vehicles and compaction of soils along roads surely occurred regularly in the past.

Records of military activities in road corridors and experiments at the local scale would prove useful for determining causes (or at least reasonable hypotheses) for forest conversion; however such records are not available.

Addressing measurement needs and attributing causation to land-cover change would help determine how environmental impacts might be avoided or mitigated. Considering the metrics in terms of spatial resolution will help assess conditions under which spatial scale might make a difference to management options. In any case, a suite of approaches and metrics likely will best reveal how vehicles and roads affect their environment.

Acknowledgments

We appreciate the assistance of many people in this study. Troy Key and Phil Bennet from the Fort Benning land management staff operated the bulldozers. Hal Balbach and Hugh Westbury were persistent in their efforts to make the experiment occur. Rusty Bufford located and scanned the orthrophotographs used in the study. James Cantu and Kelly Maloney provided photo records of the experimental site. Jennifer Ayers, James Cantu, John Dilustro, Sharon Hermann, and Keiran O'Hara helped with the field sampling. Karmen Smith and Jordon Smith entered some of the field data. Paul Ayers provided the equipment to record the path of the bulldozer and translated the results into a GIS file. Gay Marie Logsdon edited the manuscript. Comments of two anonymous reviewers greatly improved the manuscript. The project was funded by a contract from the Strategic Environmental Research and Development Program (SERDP) projects CS-1114C and CS-1259 to Oak Ridge National Laboratory (ORNL). Oak Ridge National Laboratory is managed by the UT-Battelle, LLC, for the US Department of Energy under contract DE-AC05-00OR22725.

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NREL / ORNL

00-02

BIOENERGY CENTER

Weekly Update
January 14, 2000

First meeting of new council

The Biobased Products and Bioenergy Council, comprised of agency heads or their designees, will hold its first meeting January 21, 2000.

Inventory and gap analysis

In response to the Executive Order and the legislative request

DOE has accepted the proposal from NREL to undertake a gap analysis of federally funded bioenergy R&D, and to create a "boxology" for bioenergy. ORNL will be directly involved. Funds to undertake a similar analysis of biobased products and boxology were not yet made available.

Outreach and communications group

In response to the Executive Order

NREL's participants are Sally Neufeld, Anne Jones, and Kristi Theis from communications, Cynthia Riley from biofuels, and Helena Chum from the power and chemicals areas. The ORNL representatives are Lynn Wright, Ann Ehrenshaft, and Jonathan Scurlock. The Argonne representative is Tom Snyder, from the ANL Washington, D.C. office. The DOE outreach group is led by Valerie Sarisky-Reed and members of the team are Paul Grabowski, from Office of Power Technologies (OPT), and Merrill Smith and Tom King of the Office of Industrial Technologies. The DOE and lab group met to discuss the strategic outreach plan and next steps.

Updates

Comments on the new solicitation. Please pay attention to the solicitation's details and intent. The solicitation seeks to initiate any emerging technology that can provide integrated production of fuel, power, or biobased products. A goal is to have biomass usage make an impact on the President's goal of tripling biomass use by 2010. There is a strong hint of a technology demonstration to make the desired impact by 2005 so that it would be in commercial use by 2010. In addition, there is the need to show integration among one or more of the three areas: biobased products, fuels, and heat and/or power. For example, food or feed products probably would not count as "desired" co-products from fuel or power generation unless there was some significant energy or waste impact savings.

Remember that the DOE laboratories cannot compete with the private sector by responding to the solicitation. Industry can respond and indicate in their proposals that they need unique capabilities of DOE laboratories. Industry can form teaming arrangements that involve multiple parties, including universities.

Lynn Wright has completed a near final draft of a feedstock research plan for the biomass power program. Oak Ridge and NREL personnel will receive it soon for review.

Lynn Wright will be speaking at the Electric Power Research Institute (EPRI) Biomass Working Group in the near future.

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ECOHEALTH

Commentary

Systems Approach to Environmental Security

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Introduction

Currently, a systems approach is not being applied in the allocation of efforts to fight terrorism. In fiscal year 2003, nearly $38 billion were requested by the U.S. Department of Homeland Security to be distributed among 28 federal agencies. A dramatic shift in funding has occurred from counterintelligence and nonproliferation to buying equipment for first responders. No analysis has identified the best actions for investing in prevention versus response. Instead, the current budget allocations are driven by the events of 9/11, with emphasis on protecting large buildings and airports. A more careful evaluation is needed that considers the benefits of investing in new counterterrorism strategies as compared to the risk of natural disturbances, disease spread, and environmental impacts caused by ongoing human activities (e.g., pollution and land-cover change). In any disaster, the healthcare community is often more prepared than the emergency-response community to deal with the situation, yet the medical aspects of a disaster typically account for less than 10% of resource and personnel expenditures (Mattox, 2001). Lessons from systems theory can be used to help prepare emergency-response teams by making them aware of the potential for feedbacks, delays in response, secondary impacts, chaotic reactions, etc. Thus, systems knowledge should be a part of the training for those involved in emergency leadership, civil defense, security, evacuation, and public welfare. Here we focus on arguments for the importance of taking a systems approach to environmental security, describing the application of the systems approach to environmental systems, reviewing key contributions of environmental systems analysis, and providing examples where its application could improve security.

Defining Environmental Security

We collect threats to peace and security associated with environmental issues under the term *environmental security*. The term also refers to approaches adopted to maintain environmental security, including protecting the supply of food, water, energy, and other natural resources; ensuring the continued availability of renewable resources (e.g., forests and fisheries); maintaining access to essential resources; and avoiding the spread of diseases associated with environmental change. Environmental security also addresses management strategies to maintain life-support characteristics, production capacity, and the evolutionary potential of ecological systems (e.g., Holling, 1986; Holling et al., 2002). Predictable and reliable availability of natural resources also is a part of security. Environmental security provides a means to respond effectively to changing environmental conditions that may reduce peace or stability in the world and, thus, affect a country's political, economic, social, or environmental stability (King, 2000). Preserving environmental security requires planning and execution of programs to prevent or mitigate adverse anthropogenic

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changes in the environment and to minimize impacts of environmental disaster or terrorism (King, 2000).

Systems Approach

The systems approach is a way of grappling with a complex problem for which a Newtonian reductionist approach is too limited (Checkland, 1993; Prigogine and Stengers, 1984). A *system* can be defined as a collection of interacting or interdependent entities that produces a unified functional whole, whose properties or behavior cannot be predicted from a separate understanding of each individual component. Systems of interest in relation to environmental security include purely ecological systems (e.g., wilderness areas and parks); highly managed systems (e.g., intensive, industrialized agriculture); and intricate combinations of societal, political, economic, and ecological systems (e.g., watersheds characterized by urban areas, other land uses, and multiple jurisdictions). Scales of systems of concern range from sites to localized ecological resources to larger-scale regional, national, and global environmental issues (e.g., global climate change).

The systems approach is commonly applied in the form of "systems analysis" as a means of identifying the components of the system, defining the functional relationships between them, determining the positive and negative interactions, and delineating the possible constraints on the interactions. It is used to identify efficient ways to perform tasks and possible consequences of poor performance, including threats and risks to the survival of the systems or their components. Thus, it has particular relevance to assessing existing and designing new environmental security systems.

Systems analysis in this sense normally is applied to "human-built" systems, which can be a group of machines, electrical circuits, people, agencies, or other elements that work together to perform a certain job related to fulfilling a particular function or producing a good or service. Environmental security requires application of systems thinking and analysis to both the human-built security systems and the ecological system being protected.

Systems Ecology As a Key Knowledge Base

Systems thinking applied to ecological systems emerged several decades ago with the first applications of mathematics to ecological questions (e.g., Lotka, 1925). Odum (1964) formally introduced the term *systems ecology*, and the application of systems concepts to ecology has produced useful ways to explore ecological interactions (e.g., Van Dyne, 1966; Watt, 1966; Shugart and O'Neill, 1979; Müller, 1997). Tansley's (1935) introduction of the term *ecosystem* emphasizes the system resulting from the integration of living and nonliving environmental factors, as well as the hierarchical-character natural systems (Van Dyne, 1966). By focusing on the interrelations between organisms and their environment, ecosystem science calls for a holistic view of the ecological system, which is a hallmark of system theory.

Several properties of ecological systems' interaction have been derived from theoretical perspectives of open systems (Müller, 1997). These properties include *order, hierarchical structure, irreproducibility, self-regulation*, and *self-organization*, which all have implications for environmental security (Table 1). *Order* implies that the arrangement of elements in an ecological system is not random but reflects the outcome of interrelationships among all component parts. In relation to environmental security, order implies that changes to any interactions can affect the entire system. *Hierarchy* refers to the organization of ecological systems according to a series of biological groups (individuals, populations, species, communities, ecosystems, landscapes, and biomes), such that interactions most often occur between adjacent levels. For environmental security, this hierarchical organization implies that impacts at any one level of a system most intensively affect the levels immediately above and below it. Being *irreproducible* means that ecological systems are unique, implying that each system has distinct features and may respond to impacts in individual ways. Thus, after a disruption, the "new" system will likely have a novel and distinct set of state variables and interactions between them. Because *self-regulating* ecological systems become stable in the absence of disturbances, perturbations to the system may result in a new level or type of stability (e.g., a point of no change as compared to a limit cycle). Yet, anthropogenic stresses may alter the structure, function, or organization of dissipated systems and thus compromise the self-regulatory mechanisms in an ecosystem (Downs and Ambrose, 2001). *Self-organization* implies that inputs (or removals) to one part of an ecological system maintain (or impede) processes elsewhere in the system. As an example, succession is the self-organizing process by which systems of organisms develop structure and function (Prigogine, 1978; Odum, 1983). As a result of

Table 1. Key Attributes of Ecological Systems and Their implications for Environmental Security

Attribute	Application to ecological systems	Implications for environmental security
Order	The arrangement of elements in an ecological system is not haphazard but reflects interactions amongall of the components	Changes to the interactions between the elements can impact the entire system
Hierarchy	Ecological systems are organized according to series of groups (individuals, populations, species, communities, ecosystems, landscapes, and biomes), and interactions most often occur between adjacent levels	Effects at one level of a system are, likely to impact the levels immediately above and below it
Irreproducibility	Ecological systems cannot reproduce and are unique	Each system has unique features and may respond to threats in different ways. After a disturbance, the new system will likely have a new set of characteristics and interrelations
Self-regulation	Ecological systems seek stability in the absence of perturbations	Changes to the system may result in a new type of stability
Self-organization	Inputs (removals) to one part of an ecological system subsidize (deter) processes elsewhere in the system. Succession is the self-organizing process by which systems develop structure and function	Changes to one part of a system will affect other parts and their interactions

self-organization, changes to one part of a system will likely affect other parts and their interrelationships.

Ecologists have to deal explicitly with the issues of scale because ecological interactions occur along the biological hierarchy (e.g., species interact at the community level and landscapes interact within biomes) (e.g., Roswell et al., 1988; Campbell, 2000; Holling, 2001; Patil et al., 2001). Spatial pattern on the landscape can be an important aspect of ecosystem health that affects susceptibility to terrorism. Patterns of land cover clearly affect the spread of disease organisms (Kitron, 1998). For example, Lyme disease is more common in areas with humans in close proximity to woods, the common habitat for the black-legged ticks (*Ixodes scapularis*) which host the disease organism (Frank et al., 1998). Habitat-related variation in tick density can be maintained even with moderate dispersal, and dispersal can produce nonlinear or threshold responses as a result of positive and negative feedbacks, which are a common feature of ecological systems (Van Buskirk and Ostfeld, 1998). These feedbacks suggest that dynamics in heterogeneous systems are often unpredictable from an understanding of isolated components.

Costs and Benefits of Preventative and Mitigative Strategies

One of the greatest benefits of putting environmental security in a systems context is that it provides a framework for considering costs and benefits of preventative and mitigative strategies. An example comes from the nation's historical approach to managing natural hazards. In *Disaster bv Design* (Mileti, 1999), researchers argue that human choice that focuses on economic gain is a main reason that disasters occur. Not using a systems approach that includes both economic and ecological costs and benefits; the lack of long-term time horizons; and the failure to anticipate complexity, change, and surprise have led to increasing losses from disasters. As Kates (1985) pointed out, we will continually face new surprises in the arena of hazard management—some caused by new technologies, others by increasing complexities, and still others by social change and tensions. A root problem is that sustainability has not been a key concept of built environments.

Management of coastal zones has been subject to systems analysis. As a result, insurance programs discourage development in flood plains. Furthermore, building in coastal areas subject to hurricanes now requires elevation of structures and advanced-warning systems. This approach likely will reduce short-term losses but may shift losses to the future and increase the potential for catastrophic disturbance when a large-scale hurricane occurs. Using systems analysis to identify optimal long-term management strategies and to determine where to invest resources to help avoid loss is necessary to achieve disaster-resilient communities.

Another area in which the application of a systems framework would be beneficial is industrial agriculture. Intensively managed agro-ecosystems are vital components of the environmental infrastructure and contribute to a high standard of living (i.e., plentiful, inexpensive, and readily accessible food). Fundamental to the high productivity of these agrosystems is the use of a small number of strains or cultivars that are planted over very large areas in order to reap the high yields that are characteristic of such specially bred plants. The unfortunate by-product of this strategy is the potential increase in susceptibility of these plants to disease, which might spread more rapidly than the implementation of control measures and devastate extensive areas. The purposeful infection of livestock or genetically homogeneous crops with a virulent pathogen might prove inexpensive and effective for a terrorist, and could cause damage sufficient to threaten economy and environment at levels ranging from local to international, especially given foreign dependence on U.S. agricultural exports.

Conclusions

The benefits of applying a systems approach, drawing in particular on systems ecology, to environmental security are many. The systems perspective requires explicitly defining causes, potential impacts, consequences, interactions, and feedbacks. It allows different components of the system to be interpreted in the context of the whole. A systems approach also affords a way to compare impacts of natural versus anthropogenic risks to environmental security. It provides a means for addressing the considerable uncertainties associated with anticipating threats (natural or anthropogenic, including terrorism). The systems perspective also contains a framework to consider effectiveness, costs, and benefits of preventative and mitigation strategies. Emergency preparedness cannot be guided solely by reactions to security breaches, as occurred after the sarin release in the Tokyo subway and the mailing of anthrax spores in the U.S. We support the use of systems analyses in the formulation of policy related to environmental security. The process of developing and applying the systems approach typically yields short-term actions and long-term strategies that are both cost-effective and critical. The greatest risk to ecological systems may be diverting limited resources from protection of the environment to mitigation against ecoterrorism. A systematic analysis of the costs, benefits, and risks to ecosystems may show that increasing regulations and other means for environmental preservation may be the most effective and reliable way to improve environmental security in the near term. Furthermore, reaction to the threat of terrorism may put ecological systems in jeopardy because of unanticipated delays in response or feedback effects. We hope that the tools of systems ecology will be used to assess the most appropriate application of resources and protective measures in the face of an uncertain future.

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ECOLOGICAL IMPACTS AND MITIGATION STRATEGIES FOR RURAL LAND MANAGEMENT

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Abstract. Land-use change and land-management practices affect a variety of ecological processes. Land-use impacts on ecological processes include local extirpations, introductions of new species, changes in land-cover extent, changes in juxtaposition of land-cover types, changes to disturbance regimes, changes in vegetation structure and composition, and effects on air, water, and light quality, and noise pollution. Effects of land-use changes on ecological processes are discussed with special reference to changes in rural environments. Our premise is that better understanding of ecological processes improves land management. Mitigation strategies are presented with respect to management of initial ecological conditions, of the changes themselves, and of the altered system. The paper focuses on proactive environmental management efforts and identifies key research issues as (1) quantifying land-use legacies, (2) determining conditions under which land use modifies impacts of other stressors, (3) identifying conditions under which deleterious impacts can be avoided, (4) understanding cumulative impacts of land-use change, (5) improving our understanding of how land use alters resistance or susceptibility to invasion and impacts of pollutants, (6) crafting socioeconomically reasonable incentives for restoring or reducing effects of land-use practices, and (7) accelerating the integration of social and ecological sciences

Key words: aggressive species; biomass; carbon sequestration; cumulative impacts; disturbance; invasion; land cover; land use; legacy; pollution.

INTRODUCTION

Land use and land management are prevailing forces on the Earth (Meyer and Turner 1992, 1994, Dale et al. 2000, Watson et al. 2000). Humans alter ecological processes directly and indirectly through land use, management, and policy decisions regarding natural resources (Brookfield 2001). In the United States, food production uses about 50% of the total land area, 80% of the fresh water, and 17% of the fossil energy used in the country (Pimentel and Pimentel 2003). Land degradation via removal of vegetation, soil erosion, salinization, and soil compaction is also severe, but it is difficult to estimate its extent or cost (Dregne 2002). About 60% of the historical wetland area in the Upper Midwestern region of the United States has been drained, largely for agriculture, causing a decline in flood abatement, water quality improvement, and biodiversity (Zedler 2003). Human activities on the land are pervasive in all types of ecological systems on Earth, even those typically thought of as ''pristine'' and not inhabited by *Homo sapiens* (e.g., Chase 1987, Wilkening 2001). Furthermore, rural land use and management affect all ecological processes, often in several ways that together induce changes to ecological composition, structure, and function.

Changes in rural land use in the conterminous United States over the past 50 years (1950–2000) are pronounced. The general trends are increases in human population density, large exurban growth, and conversion and abandonment of agricultural lands (Brown et al. 2005). Implications for biodiversity of these trends are discussed by Huston (2005) and Hansen et al. (2005). Theobald et al. (2005) set forth how ecological science perspectives can improve land-use planning and policy. The goal of this paper is to examine how improved understanding of ecological processes can facilitate progressive and more enlightened rural land management so as to avoid or mitigate undesirable consequences. We begin with a brief review of environmental issues related to land use and management. We then discuss mitigation strategies and end by articulating research questions that need to be addressed to advance the ecological science forming the foundation

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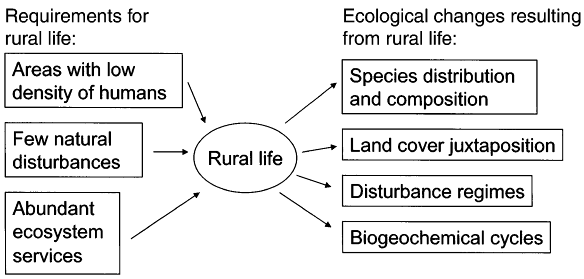

FIG. 1. Requirements for rural life and the ecological impacts.

upon which effective land management is built. In addressing these scientific questions, ecologists can more effectively contribute to the development of proactive and broad-scale land-use and land-management policies.

Terms basic to this discussion are defined (building upon definitions in Dale et al. 2000) as follows. Land cover refers to the ecological state and physical appearance of the land surface. Examples include closed forest, open forest, grassland, and cropland. Change in land cover converts land from one type of dominant vegetation or built environment to another. Land use refers to the land-management practices of humans. Examples are protected areas, timber harvest, row-crop agriculture, grazing, and human settlements. Change in land use may or may not cause a significant change in land cover. Land management is the administration of a given land use by humans. Land management can affect ecological processes without changing the basic land use. For example, management of livestock grazing can be minimal or intensive and regulated or unregulated. Rural living relates to the land uses of agriculture, ranching, and forestry that support country life. Rural life is supported by areas with low density of humans (see Fig. 1a of Brown et al. 2005), few natural disturbances, and an abundance of ecosystem services (e.g., clean water, clean air, etc.) yet induces ecological impacts (Fig. 1).

ECOLOGICAL IMPACTS OF RURAL LAND USE AND MANAGEMENT

Because environmental concerns related to rural land use and management are diverse and occur on a variety of scales, our discussion of impacts is organized around the means by which they affect ecological structure or process. Four major pathways are identified by which land use and management practices can affect ecological processes—changes to species demography and diversity, land cover juxtaposition, disturbance regimes, and biogeochemical cycles. These pathways can occur simultaneously and interact with each other against a backdrop of other stressors that, collectively, can induce dramatic, nonlinear, and self-reinforcing changes. Hence, discerning the means of impact is not always direct, and management based on knowledge of a single pathway may not be adequate when forces interact. Predictions as to the effects of land-management practices are, therefore, likely to be context dependent (Archer and Bowman 2002).

Species changes

Species changes resulting from rural land use and management include changes in demography that may lead to local and selective extirpation or proliferation, introduction of new species, and changes in distribution. Elimination of local populations of a species can occur when land-use practices cause extensive mortality and/or prevent recruitment by altering habitat. For example, replacing forest with suburban homes or farmlands has eliminated populations of lady slipper (*Paphiopedilum villosum* (Lindl) Stein) (V. Dale, *personal observation*), and heavy grazing of rangelands by livestock or wildlife can shift the relative abundance of grasses, forbs, and woody plants, causing the local extinction of some species and a dramatic increase in others (Archer and Smeins 1991, Vavra et al. 1994). Reduction in native earthworm (*Heteroporodrilus mediterreus*) populations as a result of farming can adversely affect soil aeration and other soil processes (Friend and Chan 1995). The spread of agriculture alone has been responsible for the selection of a few crop species that now dominate the Earth's surface. Selection for varieties of plants that resist pests and are easy to grow and harvest has drastically reduced the genetic variation over much of the Earth. For example, 90% of the world's food is provided by 15 crop plant species (Brookfield 2001).

Management actions directed at one species or set of organisms may also lead to unexpected changes in the abundance of other organisms and cause dramatic changes in ecological structure and function. For example, the widespread eradication of prairie dogs, traditionally viewed as competitors with livestock for range forage, may enable the proliferation of undesirable woody plants and, thus, create a whole new set of management challenges and ecological impacts (Weltzin et al. 1997). In another example, xeric habitats associated with urban land uses supported less spider diversity than agricultural fields or residential yards, indicating the importance of incorporating natural habitats into planning of human environments (Shochat et al. 2004).

The widespread use of pesticides associated with farming and other land-management activities has impacted both target and nontargeted organisms. Pesticides include many products, such as insect repellants, weed killers, disinfectants, and swimming pool chemicals, designed to prevent, destroy, repel, or reduce pests of any sort. In the United States, the Environmental Protection Agency (EPA) must evaluate pesticides before they can be marketed to ensure that they protect human health and the environment (especially rare and threatened species). Even so, nontarget species can be killed or adversely affected when these chemicals are used correctly or incorrectly.

Demographic changes can also occur with changes in the size and shapes of habitat. Land uses may bisect populations so that interactions are no longer possible. For example, linear features such as roads can interrupt movements of terrestrial animals (Forman et al. 2002). The long-term consequences of land-use induced disruption on gene flow and population structure are not known. Offerman et al. (1995) suggested a scheme of classifying species according to ''gap-crossing ability'' and using home range size as a means to identify species that are most susceptible to habitat fragmentation.

Another way land use can affect species is via purposeful introduction or unintended spread of aggressive species, which are brought into an area as part of a land-management practice. Examples include the introduction of exotic pasture grasses (e.g., smooth brome (*Bromus inermis*), kleingrass (*Panicum coloratum* L.), and buffelgrass (*Pennisetum cillare* L.)), which are spreading into and displacing native species in rangelands (e.g., D'Antonio and Vitousek 1992, McClaran and Anable 1992). Sometimes particular land-use or management practices foster the spread of certain species. Highways, roads, and right-of-ways along power lines and pipelines can serve as corridors facilitating the spread of exotic plants and animals (Forman et al. 2002). Domestic livestock may promote the spread and establishment of invasive forbs and shrubs in grasslands via seed dispersal and disruption of fire regimes (Archer 1995).

Nonnative species introductions, whether accidental or intentional, have potentially long-lasting ecological and economic impacts (Mooney and Drake 1986, Mack et al. 2000, McNeely 2001) associated with modification of disturbance regimes (Mack and D'Antonio 1998), alteration of biogeochemical cycles (Vitousek and Walker 1989, Le Maitre et al. 1996), reductions in overall species richness (Bock et al. 1986), and, ultimately, species extinctions (Pimm et al. 1995). Biological invasions are internationally regarded as a major threat to biological diversity, second only to habitat loss (Coblentz 1990, Vitousek et al. 1997*a*, Wilcove et al. 1998). Though many papers have cited the impacts of nonnative species on native biodiversity and ecosystem processes, studies quantifying these effects are few (Parker et al. 1999) and largely descriptive or observational in nature (Cronk and Fuller 1995).

These examples illustrate the importance of ecosystem rather than organismic approaches to land use and management. Such a systems approach considers all plant and animals and the physical conditions of their environment, as well as socioeconomic conditions (Holling 2001). Recognition of how land-use practices might foster or impede the spread of organisms is a first step toward developing strategies for containing deleterious organisms and altering barriers affecting the movement of species. For instance, knowing that the fungus killing Port Orford cedar (*Chamaecyparis lawsoniana*) in southern Oregon and northern California is spread by logging trucks, the washing of logging trucks was initiated (Strittholt and DellaSala 2001, Jules et al. 2002). This simple and inexpensive action has proven to be an effective deterrent to the spread of the fungal spores. Control of the spread of deleterious species may require local sacrifices and drastic land-use changes to avert escalation to regional scales. For example, when the Asian long-horned beetle (*Anoplophora glabripennis*) was first introduced into Halifax, Nova Scotia, Canada, there were calls to cut all spruce (*Picea mariana*) trees in a broad swath around the point of infestation as means to prevent their spread (Haack et al. 1977). However, local homeowners did not want to compromise their landscaping and refused to implement this action. The insect eventually killed the trees around those homes anyway, and its spread now threatens the logging industry in northeastern North America.

Changes in land-cover juxtaposition

Changes in land cover that result from land use can alter habitat and the juxtaposition of cover types. Habitat alterations (such as occur with cropland conversions, urban expansion, logging, grazing, construction of dams, water course alterations, etc.) can make a site unsuitable for species that once occupied an area. Local site disturbance can make a place available for new species or ecosystems. Linear features, such as roadside vegetation and fencerows, may enhance the spread of select organisms (Camp and Best 1994). For example, the spread of the gypsy moth (*Lymantria dispar*) is so tightly linked to road networks in the eastern United States that maps of gypsy moth distribution over time delineate roads (Sharov and Liebhold 1998); and coyote (*Canis latrans*) emigrate along highways, taking advantage of road kills for food and culverts for shelter (Clevenger et al. 2001). Conversely, some land uses may constitute barriers to the spread of other organisms. The presence of wolves (*Canis lupus*) is inversely related to road density (Mladenoff et al. 1995).

Changes in the juxtaposition of land-cover types can also impact ecological processes. For example, the expansion of suburban areas and loss of forests in the eastern United States has drastically increased the area of forest edge. As a result, those species that occur in forest edges (such as the native Cowbird [*Molothrus ater*]) are becoming more prolific (Chalfoun et al. 2002). Simultaneously, the erosion of soil from disturbed areas into more pristine areas is more common now (Pimentel and Skidmore 1999, Pimentel 2000). Agricultural land typical erodes soil at rates ranging from 13 $tons \cdot ha^{-1} \cdot yr^{-1}$ to 40 $tons \cdot ha^{-1} \cdot yr^{-1}$ worldwide

(Pimentel and Kounang 1998). Other papers in this issue discuss examples of how patterns of land cover affect biodiversity (e.g., Hansen et al. 2005).

Changes to disturbance regimes

Land-use and management practices alter disturbance regimes (e.g., fire, pest outbreaks, floods, blowdowns) by disrupting the frequency, extent, and intensity of disturbance as well as by instigating new disturbances. Fire severity and time since fire can affect the richness and dominance of nonnative species (Keeley et al. 2003). Curtailment of surface fires exemplifies how disruption of disturbance frequencies can alter fundamental ecosystem properties. Elimination of fire in systems that evolved with frequent surface fires has caused dramatic changes in structure and function (e.g., oak savannas of the Midwest [Peterson and Reich 2001], ponderosa pine [*Pinus ponderosa*] forests of the western United States [Covington and Moore 1994], and longleaf pine [*Pinus palustris*] forests of the southeastern United States [Gilliam and Platt 1999, McCay 2000]). Ironically, increases in disturbance intensity often result from land-management practices designed to control frequent, small, low intensity disturbances. Such controls may create the very conditions that make large, catastrophic disturbances possible. Examples include the recent massive crown wildfires in southwestern U.S. forests (Covington 2000) and outbreaks of the native southern pine bark beetle (*Dendroctonus frontalis*) (Perkins and Matlack 2002).

Land-management practices are often aimed at altering the frequency and intensity of disturbances such as fires (e.g., Keeley 2002) and floods (e.g., Persoons et al. 2002). But reductions in seasonal flooding (Johnson 1994, Friedman and Lee 2002) and in the frequency of low-intensity surface fires (Covington and Moore 1994, Brawn et al. 2001) have altered communities that once depended on these events. Changes in the frequency or intensity of one type of disturbance may be linked to alterations in the frequency or intensity of other disturbances. For example, livestock overgrazing can reduce the amount and continuity of fine fuels to the extent that surface fires are not possible (Madany and West 1983, Baisan and Swetnam 1990, Savage and Swetnam 1990). In recognition of the importance of disturbance in maintaining certain ecological structures and preventing changes to undesirable states, land-management practices may seek to mimic historical conditions to which species in a region are accustomed (Parsons et al. 1999). Examples include the reintroduction of flooding in the Grand Canyon (Powell 2002) and prescribed burning in grasslands, savannas, and certain forests (e.g., Scifres and Hamilton 1993, Arno et al. 1995, Andersen et al. 1998, Agee 2003, Fuhlendorf and Engle 2001, 2004).

Land use and management practices can also increase the susceptibility of ecological systems to other disturbances (e.g., landslides can result from building roads on steep slopes [Swanson and Dyrness 1975] and from land-use modifications [Glade 2003]; heavy grazing can exacerbate wind and water erosion and hence ecological degradation [Tongway and Ludwig 1997]). Knowing the conditions that foster disturbances and when to control them is a challenge facing both the ecological research and environmental management communities.

Changes to biogeochemical cycles

Changes in the cycling of water, nutrients, and energy inevitably occur from land use and management via many pathways. For example, air and water pollution often accompany use of land for industry, transportation, and urban growth. Current emissions of carbon dioxide, nitrous oxide, and methane have increased dramatically due to changes in land management, especially with industrialization and intensification of agricultural practices. Changes in vegetation structure that occur with land use and management alter pathways of energy flow and nutrient cycling. Changes in the extent of forest and impervious land covers can dramatically alter watershed hydrology (e.g., Wissmar et al. 2004). Climate and atmospheric chemistry are directly and indirectly influenced by land cover, via biophysical and biogeochemical aspects of land-surface–atmosphere interactions (Hoffman and Jackson 2000, Aber et al. 2001, Bonan 2002). Even when a land-use practice is no longer in place, its legacies remain (e.g., plow furrows or livestock wastes can have long-term effects on the environment; Bellemare et al. 2002, Foster et al. 2003). We focus on three examples of land-use impacts to biogeochemical cycles (air pollution, greenhouse gas emissions, and changes in vegetation structure and composition) as a way of illustrating the diversity of interacting factors.

Air pollution

Air pollution is the accumulation of solid, liquid, and gaseous compounds in the atmosphere at concentrations that are greater than would naturally occur at a particular location under given meteorological, biological, and geological conditions. Ozone, particulate matter, lead, carbon monoxide, mercury, and sulfur dioxide are just a few examples of air pollutants. These and other pollutants can alter physical and chemical atmospheric cycles and affect human and ecological health. Changes in land use and cover can affect these pollutants through two direct mechanisms (emissions and deposition) and three indirect mechanisms (atmospheric chemistry, physical meteorology, and radiation transfer). These same mechanisms can feed back and affect land cover, and possibly even land use.

Even in an unperturbed natural ecological system, volatile organic compounds (VOCs) emitted by vegetation (Rasmussen and Went 1965, Hewitt 1999) can

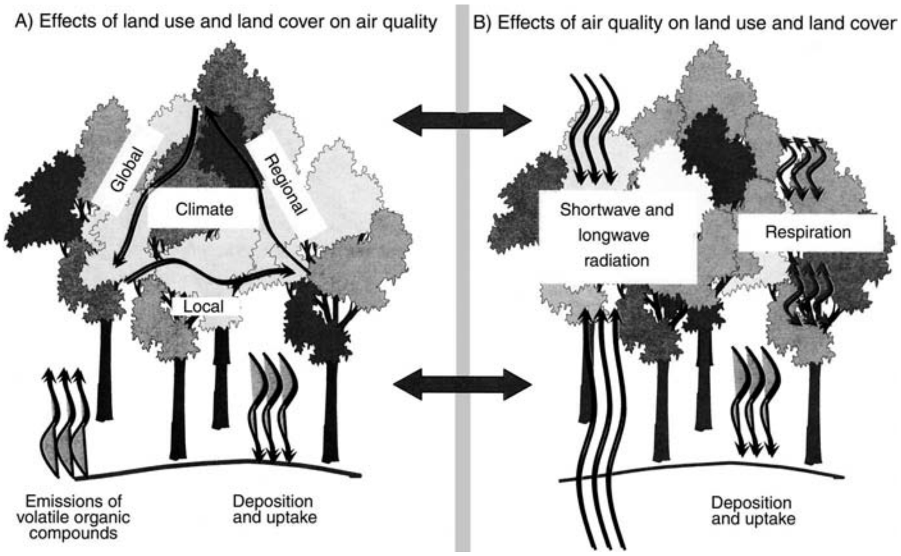

FIG. 2. Depiction of mechanisms by which (A) land use and land cover affect air quality and (B) air quality affects land use and land cover. These feedback mechanisms differ depending on the prevailing vegetation type, soil moisture, temperature, pH, nutrients, and surface permeability.

contribute to the secondary formation of organic aerosols (Hatakeyama et al. 1989, Mazurek et al. 1991, Hoffman et al. 1997). In a polluted, highly oxidizing atmosphere, these gas-to-particle conversions may be accelerated. Regardless, all VOCs are not equal, and different plant species emit different types of VOCs. For example, many deciduous trees are high emitters of isoprene, a compound that can be important in the formation of ozone (Chameides et al. 1988) but is less significant to the secondary formation of organic aerosols. In contrast, many evergreen species are prolific emitters of α- and β-pinene and can contribute significantly to the formation of organic aerosols (Hoffman et al. 1997) but are less important to ozone formation. Thus, for any parcel of land, wholly different emission profiles may be expected within the broad spectrum of potential biotic land covers (Fig. 2) (Lamb et al. 1993, Simpson et al. 1995, Isebrands et al. 1999). Similarly, different land covers have surfaces that differ in two and three dimensions (e.g., size, shape, and orientation) that can affect the rate of aerosol deposition (Wesely and Hicks 2000). In turn, deposition of particles onto foliage can influence rates of photosynthesis and nutrient and contaminant loads (Chameides et al. 1999, Bergin et al. 2001).

Other feedbacks associated with particulate matter include local, regional, and global impacts on longwave and shortwave radiation budgets, which, in turn, influence temperature, precipitation, and photosynthetic active radiation (Cerveny and Balling 1998, Rosenfeld 2000, Chameides and Bergin 2002, Kaufman et al. 2002, Menon et al. 2002). Proliferation or intensification of industrial, commercial, transportation, or residential land uses can further (and sometimes drastically) alter emissions and deposition profiles. The more intensified land uses can open new pathways to primary and secondary particulate matter production and removal, with corresponding climate effects (e.g., some anthropogenic sources may inject large quantities of diesel soot directly into the atmosphere, whereas others may contribute to the secondary formation of sulfate aerosols from the oxidation of directly emitted sulfur dioxide). Thus, cumulative effects on air pollution arising from land use and management depend on initial conditions and actions on the land, but these impacts can be difficult to predict because of the many feedbacks and indirect interactions.

Greenhouse gas emissions

Land-management practices, such as grazing, forestry, and conversion to arable lands, affect trace gas emissions due to alterations in the cycling of nutrients and distribution of organic matter. These changes in land management have substantially contributed to decreased CH_4 oxidation and increased CO_2 emissions as well as N_2O production from soils. CO_2 emissions resulting from land-use change since 1850 are approximately 50% of the contributions due to fossil fuel burning and cement production (Watson et al. 2000). Extensive use of N fertilizers and increased atmospheric loading of N into many regions of the world have probably contributed to the observed increases in atmospheric CH_4 and N_2O (Ojima et al. 1993, Mosier et al. 1997). Increased use of nitrogen has simultaneously contributed to changes in primary production, decomposition, and carbon storage; eutrophication of lakes, estuaries, and coastal areas; acidification of soils, streams, and lakes; and changes in species composition and biodiversity (Galloway et al. 1995, Holland et al. 1997, Vitousek et al. 1997*b*, Smil 1999).

Rural land-use practices associated with land clearing, cultivation, and drainage of wetlands affect the cycling of carbon and nitrogen and enhance the mobilization of nitrogen from soil organic matter. Fertilizer consumption in a number of developing countries has accelerated at a much faster pace than the global average in recent years (United Nations Food and Agricultural Organization 2002). These changes portend large increases in N trace gas emissions, since N volatilization losses can be much higher from tropical and subtropical agricultural soils than from temperate soils (Keller and Matson 1994, Matson et al. 1996). Agricultural practices associated with livestock and poultry production directly and indirectly affect emissions and hydrological efflux of nutrients. The livestock industry produces large amounts of waste material (Nevison and Holland 1997), which are used as organic fertilizer. However, much of the nitrogen associated with animal manure is lost through volatilization to NH_3, accounting for over one-third of global NH_3 emissions to the atmosphere (Bouwman et al. 1997).

Rural land clearing in many developing countries is associated with biomass burning. Biomass burning releases large amounts of carbon dioxide and reactive nitrogen to the atmosphere. These emissions contribute to recent changes in greenhouse gas fluxes from agricultural lands around the world (Crutzen and Andreae 1990, Crutzen and Goldammer 1993, Lindesay et al. 1996). Fluxes of N_2O in some cases remain elevated following biomass burning due to increased nitrate levels in soil and reduction of plant uptake of nitrogen.

Changes in vegetation structure

Another example of the effects of rural land use and management on biogeochemical cycles is via changes in physiognomy. In the process of using natural resources, humans often induce changes in vegetation structure. The most well-known examples are deforestation and desertification. Desertification results from extraction of water in excess of what a region can afford to lose and can lead to long-term change in water availability (Dregne 1983, Verstraete 1986, Schlesinger et al. 1990, Moat and Hutchinson 1995, de Soyza et al. 1998). The process of increasing woody plant density is less well known and, thus, is the focus of our discussion here (Fig. 3).

The proliferation of shrubs and trees in grasslands and savannas has been widely reported in arid, semiarid, and montane regions of North and South America, Australia, and Africa over the past century (Archer et al. 2001, Archer 2003). The causes of woody encroachment are actively debated, but likely reflect changes in climate (amount and seasonality of rainfall), herbivory (increased grazing or decreased browsing), fire regimes (decline in frequency and/or intensity), atmospheric

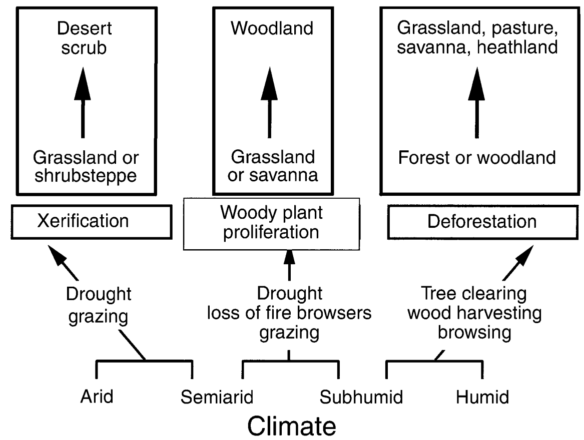

FIG. 3. Diagrammatic representation of processes of biomass change: woody proliferation in relation to desertification and deforestation (adapted from Archer and Stokes [2000]).

CO_2 enrichment, and N deposition (Archer 1994, Archer et al. 1995, van Auken 2000, Kochy and Wilson 2001). It is difficult to assign primacy to these factors, which have likely interacted strongly through time. In drylands, woody plant encroachment occurs when mesophytic grasses are replaced by unpalatable shrubs and trees (e.g., *Larrea*, *Artemesia*, *Prosopis*, *Juniperus*, *Pinus*). There are many ramifications for such vegetation change. Because woody plant proliferation adversely affects grass production and, hence, livestock production (Scholes and Archer 1997), it threatens the sustainability and profitability of commercial ranching and pastoral land uses. In addition, shifts from grass to woody plant domination alters wildlife habitat; and proliferation of deep-rooted woody plants is often assumed to cause ground water depletion and reduce flows of springs and streams. As a result, ''brush management'' in drylands is often a key element of wildlife (Ben-Shaher 1992), livestock (Scifres 1980, Valentine 1997, Bovey 2001), and watershed management.

Early approaches to brush management for livestock grazing typically had the goal of widespread, indiscriminant woody plant eradication; however, the rising cost of fossil fuels coupled with short-lived treatment effects have made large-scale mechanical and chemical treatments of woody plants economically tenuous or unrealistic. In addition, the recognition that herbicides can have deleterious environmental effects and that woody plants provide habitat for wildlife has lead to the advent of more progressive and selective approaches (e.g., Scifres et al. 1985, 1988).

Numerous studies have challenged traditional perspectives on the effects of woody plants on the hydrological cycle in drylands, but this topic remains highly controversial (Belsky 1996, Wilcox 2002). Effects of woody plant encroachment on biodiversity have not been studied but likely vary with species, growth form, and stand development. Field observations indicate that woody plants such as *Juniperus*, *Tamarix,* and *Pinus* can form virtual monocultures. Furthermore, increases in woody plant abundance in drylands can lead to significant changes in ecosystem carbon stocks (e.g., Archer et al. 2001, Jackson et al. 2002, Houghton 2003, Wessman et al. 2004), which may support new land-use drivers as industries seek opportunities to acquire and accumulate carbon credits to offset their CO_2 emissions. Woody plant proliferation in grasslands and savannas may, therefore, shift from being an economic liability to a source of income. However, perverse incentives may result, as land management may shift to promote rather than deter woody plant encroachment. Thus, potential benefits associated with carbon sequestration should be carefully weighed against costs in the form of increases in nitrogen and non-methane hydrocarbon emissions (Guenther et al. 1999, Martin et al. 2003), potentially adverse effects on livestock production, stream flow and ground water recharge, the extirpation of plants and animals characteristic of grasslands/savannas, and, indeed, the local or regional extinction of grassland and savanna ecosystems.

Mitigation Strategies

Clearly, major challenges are associated with understanding and mitigating the negative impacts of rural land use on ecological processes. The complexity of meeting these challenges can be simplified by considering potential impacts before, during, and after land-use change occurs. We first consider the situation where ecological functions are relatively intact. Second, we focus on the land use and management activity itself. The last analysis deals with the ecological system after it has been altered by land use and management practices. This approach to coping strategies reflects the need to envision the land both before and after the transformation, as well as the changes themselves. Because changes to the land typically are intense and cumulative and leave persistent legacies, recovery to initial conditions is often not plausible or requires a long time or high investments. A proactive and broad-scale perspective on land use and management is the most effective approach (Robertson et al. 2004).

Managing ecological conditions

In situations where ecological systems are still relatively intact and the effects of surrounding land-use changes have not had a great impact, land management and policy decisions can be designed to enhance resilience (i.e., the ability to bounce back after a change) or resistance (ability to endure). Sometimes, protecting key areas can reduce ecological vulnerability. Preserved areas should be large enough to protect habitats, species, and the environmental conditions required to support them. Typically, the optimal size of protected areas depends on the home range of species that inhabit the area, topographic conditions, and use of neighboring lands (e.g., Hansen and Rotella 2001). Spatial features of the landscape often need to be considered, and boundaries should be selected based on the configuration of ecological conditions (e.g., catchment boundaries) rather than political or social features (e.g., land owner county or country borders). For example, watershed protection should include the headwaters of streams, and distance to other preserved areas can be important if animals are anticipated to move between them. In his analysis of land planning, Forman (1995) argued that initial land-management decisions should be based on location of water and biodiversity concerns, for these are the most susceptible features.

A second way to enhance resilience and resistance in the face of impending change is by maintaining or establishing species able to tolerate stressful conditions. Via their persistence, such species may reduce ecological impacts. For instance, Freeway Park in downtown Seattle is placed high above the interstate highway and planted with trees and shrubs able to tolerate air pollution and shallow soils. More often, the selection of species for landscaping is based on appearance and cost rather than resistance and resilience. For example, rural and suburban lawns are typically planted with nonnative grasses, which are relatively inexpensive to establish and thrive under moderate traffic and repeated cutting. But other plant species can be more effective at maintaining a diversity of ecosystem services while reducing the need for high volumes of water, pesticides, and fertilizers that ultimately impact groundwater, streams, and atmospheric chemistry (Baron et al. 2002).

Maintaining ecological conditions is the most cost-effective way to protect environmental conditions, for reclamation or restoring dysfunctional ecological systems is costly and often has a low probability of success. However, it is sometimes unrealistic to maintain ecological conditions. Proactive strategies to reduce environmental impacts may be most effective. For example, field tests of pesticide free production (PFP) demonstrate that reduced use of pesticides is becoming a reasonable alternative for farming (Nazarko et al. 2003). Similarly, Integrated Pest Management (IPM) is a proactive practice that reduces pesticide use by a four-step approach that (1) sets action thresholds, (2) monitors and identifies pests, (3) prevents pests from becoming a threat, and (4) controls pests by use of pesticides (only when necessary, and then using less risky chemicals first).

Influencing land use and management practices so they are less harmful to the environment

There are several ways that changes to the land can be managed so that they are less deleterious to ecological services. By organizing the location of land uses within a landscape context, land-use choices, which take advantage of natural features, can be developed to reduce harmful impacts on the ability of the system to provide ecosystem services. Zoning regulations restrict the location of land uses but typically focus only on making adjacent land uses compatible with socioeconomic goals. The extent to which industrial and other intensive activities that cause severe environmental harm are confined to the more resistant or resilient locations varies greatly. Such locations may include areas that support few rare species, have soils and bedrock through which water does not readily percolate, or are not directly connected to groundwater. Salt caverns are examples of such resistant locations.

Another way to reduce impacts of land use is to create sacrifice areas where concentrated and intense land uses occur and can be contained, so that other areas can be spared. This strategy is implemented on many military installations in the United States and is likely one of the reasons these lands support so many endangered species (Leslie et al. 1996). Focusing high human impacts on resistant or resilient locations can diminish the potential for spread of the impact. For example, dense residential development can translate to more natural areas left undisturbed and to placing forest plantations on sites resilient to the repercussions of intense tree management so that sensitive sites can be protected.

An additional strategy is to adopt strategies and regulations that diminish environmental impacts such as water runoff, atmospheric emissions, and loud noises that result from land-use activities. For example, rotation grazing during droughts can decrease the area of bare ground (Teague et al. 2004), which often leads to erosion. Mulching and composting reduce evapotranspiration and enhance soil quality. More broadly, the traditional default approach of ‘‘dilution as the solution to pollution’’ is appropriate only for point sources and where unpolluted areas are large. Now that pollution sources are almost ubiquitous, the dilution approach exacerbates pollution intensity and may induce cumulative effects. Building higher smoke stacks simply causes regional rather than local air quality changes. Furthermore, most environmental regulations only address the rate of emissions and not the effects. For example, air quality management is largely driven by direct regulation of technology: cleaner cars, cleaner fuels, cleaner industry, etc.; but cumulative impacts of many sources of pollution are not addressed.

Even so, coping strategies aimed at technology are a major opportunity for improving environmental effects of land use. For example, resource extraction activities can be designed to reduce sources of environmental problems. The use of whole-tree harvesters (e.g., feller-bunchers) to cut trees results in more beneficial debris left in the forest, less soil disturbance, and more wood sent to market. Technological options on agricultural lands include conservation tillage, integrated nutrient management (which uses manure and compost), precision farming, organic farming, conversion of monoculture to complex diverse cropping systems, meadow-based rotations and winter cover crops, and establishing perennial vegetation along contours of steep slopes (Leopold 1948, Lal 2003). No-till farming can significantly reduce erosion from agricultural lands where erosion occurs largely as a result of rain and wind action on plowed ground (Pimentel and Kounang 1998). Of course technology changes also impact land use itself. With the advent of chain saws, bulldozers, and other large machinery, rates of land-cover change have dramatically accelerated worldwide (e.g., Leopold 1948, Klink et al. 1993).

Furthermore, land use can be managed so that deleterious effects are reduced in size, impacts are less likely to occur, or the size or longevity of their legacies are diminished. For example, breaks in vegetation can reduce the spread of wild fires or insect outbreaks and reduce the size of the impacted area. As another example, pollution resulting from transportation can be diminished by placement of industrial, residential, and commercial uses to reduce transit distance and by embracing mass-transportation systems. The emerging trend seems now to concentrate sources of pollution (e.g., build more dense core cities and maintain outlying green space) and to make those sources cleaner.

Given that land use and management actions that change ecological conditions are sometimes necessary, one benefit of an ecological perspective is that the potential for environmental losses is recognized. Thus, plans can be set in place to reduce negative impacts of land changes to the environment (e.g., by protecting vulnerable resources during construction). Alternatively, losses at one location can be used to bargain for environmental gains at another place (e.g., wetland mitigation).

Managing the land and ecological processes after the land changes

In situations where land use and management have degraded ecological composition, structure, and function, it is necessary to develop coping strategies that promote ecological restoration and mitigate against further harmful impacts. However, restoration to the original ecological state is costly, takes time, may have a low probability of success, and sometimes is not even possible or useful. Land-management practices benefit from recognizing that ‘‘an ounce of prevention is worth a pound of cure.’’ Yet current activities on the land typically do not have a strong ecological perspective. Mitigation and coping strategies for impacted ecological systems need the joint effort of the scientific and decision-making communities to provide restoration of the impacted ecological system or amelioration of the deleterious effects on natural resources. Being able to modify an ecological system requires a high level of cooperation and agreement among landowners and managers. There are a few examples of such cooperation (e.g., the Applegate Partnership in Oregon; the Malpai Borderlands Group in southern Arizona [McDonald 1995]), and ways to develop collaboration have been set forth (Wondolleck and Yaffee 2000). Ecological understanding has provided sound principles for decisions about land use and management (Dale et al. 2000).

Coping with changes to the land requires recognizing that human activities are a part of the rural landscape. Dealing with natural variability requires a perspective that builds on the history as well as social values for of an area (Hunter 1993, Hessburg et al. 1999, Landres et al. 1999). There is a growing literature on desired future conditions, which is often a more achievable goal than trying to reestablish historical conditions (e.g., Gonzalez 1996, Liu et al. 2000). The concept of desired future condition is most meaningful at the scale of a region because it explicitly considers the mix of habitats (type and seral stage) generated by processes that are only observable at the broader scale. To sustain ecological systems and preserve ecological integrity, management must allow for the dynamic processes that accompany disturbance–recovery cycles and protect essential energy and material transfers that take place during changes to the land. When these ecological processes are operative over a broad area, a mosaic of habitat patches exist in various stages of postdisturbance recovery (e.g., Fuhlendorf and Engle 2001, 2004). Given the nonequilibrium nature of ecological systems, the distribution of terrestrial and aquatic habitats is dynamic. As a consequence, desired future conditions include variability as an integral and essential component of habitat and population objectives.

Attainment of desired future conditions can be assessed by a suite of ecological metrics that collectively represent key features of the environment (Dale and Beyeler 2001). For example, one metric might compare the distribution of terrestrial and aquatic habitats following management to that expected under natural disturbance regimes (e.g., Hunter 1993, Landres et al. 1999). A critical management challenge is to ensure that human activities do not increase the frequency or severity of disturbances to such an extent that they surpass the capacity of the ecological systems to recover. To ensure resilience, management practices must not disrupt those energy and material transfers that promote habitat recovery. An appropriate goal for management activities would be to mimic, to the extent possible, natural disturbance events in terms of their severity (i.e., spatial extent and character) and recurrence interval.

Structural changes to ecological systems can sometimes enhance function and artificially speed up the rate of succession or even change the recovery path to an alternative stable state (Leopold 1948, Ludwig et al. 1997, Whisenant 1999). Early stages of succession are most affected by substrate characteristics (soil texture, moisture, and nutrient condition), distance to seed sources, and seed morphology, whereas later stages are largely determined by environmental changes caused by earlier immigrants. Thus, the rate of succession can be enhanced by such actions as establishing plants that promote autogenic recovery and providing nesting sites that attract birds that disperse seed of native plants and hence foster succession. Placing wood and debris in recovering systems can quickly create habitats that allow the reintroduction of a variety of species (Bouget and Duelli 2004). Physical enhancement to soil texture and establishment of berms and retention ponds can dramatically reduce water runoffs, which is often detrimental to aquatic organisms. Restoration of wetlands can provide the services of flood abatement, water quality improvement, and enhancement of biodiversity (Zedler 2003).

Incentives are often needed to implement management practices that are in tune with the environment. Satisfying environmental laws and regulations is the typical goal. With the globalization of the world's economy and the recognition of the relationship between the carbon stored in vegetation and soils and climate change (e.g., Shukla et al. 1990, Dale 1997, Malhi et al. 2002, Antle et al. 2003), carbon credits are emerging as a measure of land-use impacts on the carbon cycle. In this situation, industry provides funding for carbon sequestration efforts associated with improved cropping systems, afforestation, land improvements, and rehabilitation of degraded lands. These efforts have additional positive spin-offs, including decreased erosion, increased soil fertility, and water-holding capacity, and enhanced biodiversity and wildlife habitat. Thus, the use of carbon credits is promoted as a strategy that has both environmental and social benefits, which allows industry to meet emissions standards while providing land managers the funds needed to implement progressive management and restoration practices (Cairns and Lasserre 2004).

Research Needs

Exploring ''causes, mechanisms, and consequences of land use and land-cover change'' is one of the top 10 research topics in landscape ecology (Wu and Hobbs 2002) and has been an ongoing research theme in NASAs Land-Cover Land-Use Change program (more information *available online*)[6] and the Strategic Environmental Research and Development Program's Ecosystems Management Project (more information *available online*).[7] Under this broad topic, we identify seven major areas for research focus:

1) Quantify land-use legacies. This quantification involves characterizing changes in structure, function,

[6] ⟨http://lcluc.gsfc.nasa.gov/⟩
[7] ⟨http://www.cecer.army.mil/KD/SEMP⟩

and composition and determining persistence and spatial extent. It also requires knowing what conditions may influence the type, duration, and extent of land-use legacies.

2) Determine conditions under which land-use change modifies (exacerbates or ameliorates) impacts of other stressors. For example, during droughts the impacts of land-management practices can be more severe. It will be useful to determine conditions under which severe impacts of ''compounded perturbations'' (Paine et al. 1998) are common. The effect of land-use changes on natural disturbances is also an area that needs further investigation.

3) Identify conditions under which increased impacts can be avoided. For example, what properties of ecological systems confer resistance to change or an ability to recover from change (resilience)? What types of farming practices enhance soil water retention?

4) Understand cumulative impacts of land-use change. This understanding requires knowing how and when different land-use changes interact with other stresses to affect the environment. Because cumulative and synergistic effects are so pervasive, defining when such conditions do *not* occur might be the easier task.

5) Improve understanding of how land use alters resistance or susceptibility to invasion and impacts of pollution. Quantitative and experimental studies are needed if we are to develop a robust understanding of the drivers and functional consequences of the spread of nonnative species and environmental pollutants.

6) Craft socioeconomically reasonable incentives for restoring or reducing effects of land practices. Setting environmental goals within their socioeconomic context highlights research needs and the potential for establishing incentives that have global as well as local significance. A key challenge in implementing viable strategies and incentives is the political instability in developing countries. Ways to quantify both realized and potential benefits over large and spatially heterogeneous areas need to be developed, along with methods of monitoring and tracking how well incentives are met.

7) Accelerate the integration of social and ecological sciences. Long-lasting plausible ecological solutions will not be effectively implemented unless multiple goals of society are reasonably met. It is, therefore, necessary for ecologists to work with social scientists a priori to determine how goals for land management are developed and when and how political, economical, or social conditions may constrain management options. Ultimately, ecologists need to achieve a better understanding of political, economic, and social drivers of change in land use if they are to effectively assess and influence present and future land-use options.

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Ecological Applications, 15(6), 2005, pp. 1906–1914

ECOLOGICAL SUPPORT FOR RURAL LAND-USE PLANNING

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Abstract. How can ecologists be more effective in supporting ecologically informed rural land-use planning and policy? Improved decision making about rural lands requires careful consideration of how ecological information and analyses can inform specific planning and policy needs. We provide a brief overview of rural land-use planning, including recently developed approaches to conservation. Effective participation in land-use planning requires ecologists to understand trade-offs—for example, the need to balance a land owner's desire for a fair and predictable process with the ''learn as you go'' approach of adaptive management—and the importance of integrating local knowledge with landscape-level information.

Four primary challenges require attention from ecologists to improve rural land-use planning. First is the mismatch between the spatial and temporal scales in which ecological processes occur and the scales and tempos of land-use planning. Second, ecologists must engage in interdisciplinary research to critically evaluate and determine how, if, and when ecological information influences rural land-use outcomes. Third, a comprehensive land-use framework is needed to better place ecological studies within a broader landscape context. Finally, ecologists have a key role in developing environmental indicators that directly inform local, rural land-use planning efforts.

Key words: environmental indicators; exurban development; rural land-use planning.

Introduction

Biotic resources throughout North American are threatened by rapid development of landscapes by people, particularly development of private land in rural areas (Theobald and Hobbs 1998, Dale et al. 2000, Hansen et al. 2002, Travis et al. 2002). In the United States, four trajectories of land-use change dominate dynamics in rural landscapes. The first is urbanization. Commercial, industrial, and residential development resulting from regional population and economic growth are extending relentlessly from existing urban centers. Urbanization includes the expansion of suburbs, increased road density, and upgrading of roads and other related infrastructure. The second trajectory is conversion of natural areas to agricultural or intensive forestry. Although the maximum extent of agricultural land peaked in the United States in the 1950s (Theobald 2001), some conversion to agricultural land use continues. In addition, abandonment of agriculture exposes cropland to forces of natural succession (Bürgii and Turner 2002, Hall et al. 2002). Finally, exurban or rural residential development, including construction of resorts, second-homes, vacation cabins, ranchettes, and farmettes, are perforating landscapes beyond the urban fringe. Exurban development is increasingly stimulated by environmental and recreational amenities (e.g., Ullman 1954, McGranahan 1999) and occurs throughout the United States, particularly on barrier islands in the southeastern United States; around lakes in Michigan, Minnesota, and Wisconsin (Christensen et al. 1996, Schnaiberg et al. 2002); or where private land borders public lands, such as in the Rocky Mountain West (Maestas et al. 2001, Theobald 2001, Hansen et al. 2002) or Southern Appalachians (Wear and Bolstad 1998).

These trajectories form the context of rural land-use decision making in the United States, yet the ecological consequences of land-use changes are rarely considered. Improving access to scientific information could help decision makers anticipate potential consequences of rural land-use change and in so doing, avoid unin-

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tended ecological effects. For example, in response to concerns over forest and farmland loss to development, the State of Oregon enacted the Land Conservation and Development Act in 1973 requiring cities and counties to prepare land-use plans to meet statewide goals (Abbott et al. 1994). Yet, only recently have spatially explicit studies examined how these plans and policies might affect biodiversity or natural ecological processes over time (e.g., Hulse et al. 2004). Given this context, ecologists presume that more information will better inform land-use decision makers regarding the potential ecological consequences of particular land-use plans or actions.

How can ecologists be more effective in supporting rural land-use planning and policy? Our goal in this paper is to offer guidelines about how ecological science can be more effectively applied to support rural land-use planning and policymaking. Rather than attempting a comprehensive review of a nascent field, we summarize typical rural land-use issues, describe a generalized land-use planning framework that forms the context for incorporating ecological information, and identify gaps in ecological research and the practical application of ecological knowledge to rural land-use planning.

Ecological questions associated with rural land-use planning

Land-use planners and policymakers face a broad range of issues, including provision of affordable housing, schools, water and sewer infrastructure, and emergency services. Ecological questions may also be raised during the planning process, and typical questions ordered roughly from fine to broad scale include:

1) How close can houses (or a road) be built near a lake or riparian area without adverse effects?
2) If we change land use at a given location, will populations of species *X* decline, and should we be concerned about that decline?
3) Where is habitat for Federal/State Threatened and Endangered listed species? Under what land use in the region is the habitat likely to be compromised?
4) Given that landowners have different goals for their lands, what opportunities exist to match landowner goals with biodiversity goals?
5) Where are high-priority areas of habitat, where are locations that would be suitable for restoration or improvement as part of mitigation?
6) What areas are most ecologically unique within our jurisdiction (e.g., county, city, state, etc.)?
7) What habitat types are rare regionally and therefore need protection?
8) Are there particular places and land cover types that are important to maintain landscape connectivity?
9) What are the long-term effects of modification of natural ecological processes (e.g., fire suppression in southwestern US ponderosa pine forests, health of riparian ecosystems due to alteration of hydrologic flow regime, increased proportion of impervious land cover)?
10) Do particular land-use changes increase the risk of loss to human settlements and natural resources as a result of natural disturbances or climate change (e.g., flooding and fire)?

Ecologists are particularly concerned over loss and fragmentation of rare species habitat and subsequent declines in populations from land-use changes (e.g., Dale et al. 2000). Less recognized, but perhaps of equal importance in rural areas, are potential conflicts caused by overabundant species. For example, in the West, exurban development often creates ‘‘private reserves’’ where deer and elk congregate safely without being exposed to hunting. Exurban development has been linked with increased prevalence of chronic wasting disease in mule deer (Farnsworth et al. 2005). As a result, spatial concentrations and increased population sizes of wildlife can exacerbate conflict between wildlife and agriculture, complicating management in rural areas experiencing significant exurban development (National Academy of Science, National Research Council 2002). A third concern, gaining resonance with the public, focuses on the consequences of modifying ecological processes such as wildfire and invasive species. Understanding is particularly problematic because it may take decades to centuries to clearly demonstrate the ill or unintended consequences of seemingly successful natural resource policies. Moreover, sometimes management actions that may be outside of the range of natural variability are required to direct a system back into a healthy ecosystem (Allen et al. 2002).

Land-use planning context

Ecologists must understand the land-use planning context in which ecological information might be used (Clark 1992: Fig. 1). A complex set of laws and policies at federal, state, and local scales regulate natural resources throughout the United States, yet consideration of ecological effects of land-use change does not fit neatly within the traditional federal/state/local government hierarchy (U.S. Government Accountability Office 2004). Although the ecological implications of land-use changes can often be most effectively evaluated at the regional scale, applying this knowledge on the ground presents challenges. In rural areas there is no counterpart to the 377 metropolitan planning organizations (MPOs) that have formed since 1994. These MPOs operate at a regional level as a requirement for spending federal highway funds in urbanized areas (at least 50 000 residents) and have primarily led the development and operation of an integrated, intermodal transportation system to facilitate the efficient,

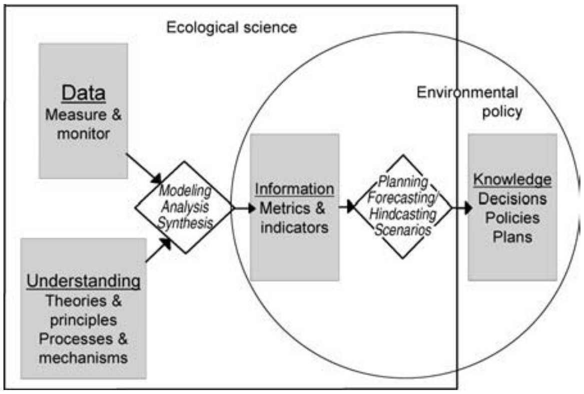

FIG. 1. A framework showing how ecological science develops information used in environmental policy. Ecologists generate data through measurement and monitoring, and use their understanding to convert data to information through process modeling, analysis, and synthesis. Ecological information applied to a study area comes in a variety of forms, often as general landscape metrics and metrics that have been found to be useful by decision makers for a particular purpose—an indicator. Ecologists also participate in the policy realm by developing forecasts from present to future conditions based on policy-relevant assumptions (and hindcasts that simulate past to present). This information is then used by stakeholders, decision makers, and managers to develop policies and plans.

economic movement of people and goods. However, the MPOs do not explicitly address healthy ecosystems in rural areas.

Planners and policymakers often lack high quality, regional-scale information about existing ecological conditions or the potential ecological implications of land-use changes. ''In recent years, a general consensus has developed on the need to judge the success of the nation's environmental policies against environmental quality outcomes. . . The adoption of such a performance-based environmental policy, however, has been hampered by the lack of reliable scientific information on environmental conditions and trends'' (U.S. Government Accountability Office 2004:1–2). For example, data were insufficient to support periodic national-level reporting for nearly half (44%) of the 103 indicators developed by the 2002 Hienz Center's State of the Nation's Ecosystems (Heinz Center 2002).

Land-use planning can involve diverse assemblages of public and private landowners, managers, and stakeholders, who must be identified, involved, and empowered if land-use planning processes are to be effective (Wondelleck and Yaffee 2000, Theobald and Hobbs 2002*a*). Given a potentially large number of stakeholders possessing different views of land use, regional planning necessarily must incorporate diverse land-use goals. This problem is exacerbated as the planning region is enlarged. As a result, ecoregional planning efforts have emerged in the United States and worldwide by nongovernmental organizations such as The Nature Conservancy and World Wildlife Fund (Groves et al. 2002). Well-focused issues in relatively well-defined geographic areas have a better chance of being addressed in planning and policymaking processes. Yet an institutional gap in planning at the regional level remains—no institution is assigned to conduct ecoregional or cross-ownership planning (Spies et al. 2002).

Despite a longstanding tradition that extends authority for land-use control to local governments (Porter 1997), decisions about land use, both public and private, are often constrained by a potpourri of policies and regulations created by a variety of federal, state, regional, county, and municipal jurisdictions. Land-use planning becomes particularly challenging in situations where intermingled public/private land ownership patterns are included because of the number of agencies, laws, and disparate interest groups involved, but also because relevant planning processes often are uncoordinated. Also, regional social and cultural differences can greatly impact planning outcomes. Different traditions and values span the spectrum from extreme property rights to common property traditions. These differences vary throughout the United States, resulting in a patchwork of federal and state laws, regulations, and policies that influence landscape patterns.

Although all levels of government may possess authority to restrict land use on private lands, ultimately land-use laws and regulations most often are applied at local levels. Each state determines through enabling legislation the extent of planning authority in counties and municipalities. The typical land-use planning structure of local governments involves two distinct processes, both of which can benefit from ecological information (Duerkson et al. 1996). First is the master planning process, which provides a vision for the types of preferred development and directs future land-use changes toward that vision using zoning and other land-use ordinances. Second, the process of development review evaluates individual projects for conformity to existing land-use regulations. Local development plans commonly are reviewed by other branches of government that have greater expertise in evaluating the ecological implications of development projects. However, this ad hoc input is usually advisory to local governments unless public monies are involved invoking federal oversight (e.g., the National Environmental Policy Act, the Endangered Species Act, etc.).

The mismatch of spatial and temporal scale (Fig. 2) underlies perhaps the toughest conundrum ecologists face when informing local land-use decision making: should the future land use of a single property be restricted because of the cumulative effects of past land-use changes on neighboring lands? The aggregate effect of land-use change is the result of many, relatively small individual decisions that are diffuse in space and time, made by a diverse array of planners and policymakers—an ecological form of ''the tyranny of small

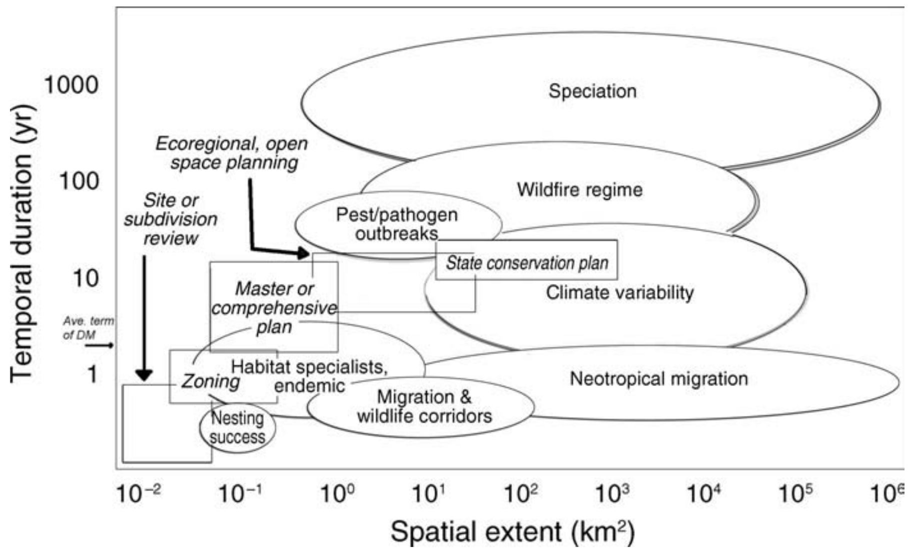

FIG. 2. There is a general mismatch between spatial extent and tempo of ecological processes, shown by ellipses, and local land-use planning activities, shown by rectangles. In particular, note that many ecological processes (such as wildfire regime, migration, disease epidemics, etc.) occur at longer and broader scales. Note that the average term of a local decision maker is approximately two years. The figure is based on Delcourt et al. (1983).

decisions'' (Kahn 1966, Odum 1982). It is often difficult to demonstrate that an individual land-use change (~100 ha) may have significant impacts on the long-term viability of a declining species or that would alter broad-scale ecological processes (~10 000 000 ha).

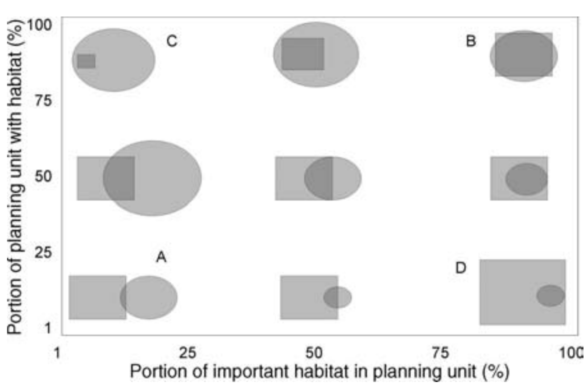

FIG. 3. The relationship of the spatial intersection between the planning unit (e.g., a county, represented by rectangles) and the extent of the important habitat for a given species (represented by ellipses) is critical. In situations where there is little overlap (A), it is difficult to show that land-use actions within the planning unit will likely have an effect (though tyranny of small decisions). As the intersection becomes a larger proportion of both the planning unit and habitat (B), there is a clearer and more direct linkage between land-use actions and the fate of habitat. In the situation where the proportion of the unit is large but is only a small part of the habitat (C), land-use actions will be important but not sufficient—coordination with adjacent and nearby jurisdictions will be required. Conversely, as the habitat becomes fully contained but remains a small proportion within the planning unit, it is easier to carefully plan on setting aside habitat to protect a species.

Yet, the cumulative effects of many land-use changes exert demonstrable impacts. For example, consider a hypothetical valley that contains 100 individual properties, each containing critical habitat. It is difficult to demonstrate that the loss of habitat on a single property is significant when a parcel is a small (e.g., 1%) portion of the total habitat, however, it is more likely that the cumulative changes of 50% or 75% of parcels is significant. Ideally ecological science would differentiate the effects of alternative approaches and identify where and when an individual land-use change will cause demonstrable impacts. Currently, ecological science can only identify relative risks of different courses of action or provide expert opinion from scientists based on first principles.

The precautionary principle (Cooney 2004) is occasionally invoked as well, but is unlikely to withstand immediate demands for economic development. An additional concern often expressed as the aphorism ''death by a thousand cuts'' is raised when only a small proportion of critical habitat is located within any single jurisdictional boundaries (Fig. 3). Differences in the frequency of decisions between agencies that plan land use on publicly vs. privately owned land (e.g., decadal cycle of the National Forests vs. monthly to yearly in counties and municipalities) also can make coordination among multiple planning jurisdictions difficult (G. Wallace, *personal communication*).

Currently, much rural land-use planning is regulatory based (e.g., zoning) and restricts certain land-use activities. However, a number of other incentive-based land-use tools, such as conservation easements, purchasable or transferable development rights, fee-simple purchase, and cluster developments, are receiving renewed attention because they encourage desirable land uses by offering positive incentives to landowners (Theobald and Hobbs 2002*b*, Hilty and Merenlender 2003). For example, in 2001, over 2.6 million hectares have been protected by local and regional land trusts (Land Trust Alliance 2001). The information needs for strategic protection by land trusts may be different from those of the more standard policy tools, for example development of a certification system for ''green development'' that awards points based on meeting ecological criteria. Ecologists should be involved in evaluating the efficacy of a full range of policy options. Doing so will require collaboration with economists, political scientists, landscape architects, planners, and other social scientists.

Data integration and communication

What are the most effective ways to integrate ecological information into rural land-use planning processes? One of the most important ways is through collaboration among stakeholders from federal, state, and local government, and private organizations, groups, and individuals (Theobald and Hobbs 2002*a*, Cohn and Lerner 2003). As with other forms of collaboration (Likens 1998), significant investment in the process itself is needed to establish credibility and trust among project members. Collaborative planning efforts could be facilitated by expanding traditional roles of regional planning agencies, watershed councils, and extension agents beyond their important educational and integrative roles to empower these groups, perhaps by extending some limited decision making authority to them. Also, it is important to support actively engaged field ecologists with consistent, timely, and pertinent information that complements their local, ''in-the-field'' experience and knowledge.

A common challenge in efforts to inform land-use planning is to integrate data from a variety of agencies and administrative units into a cohesive, consistent database. Although there are some notable recent efforts to better standardize geographical data, such as the National Spatial Data Infrastructure and the U.S. Geological Survey's Gap Analysis Program, it remains a formidable task to develop and make these data accessible and usable. Further, regional databases are suitable for identifying critical habitat and biodiversity hotspots within a large area (i.e., $>$1000 ha), but they usually are unsuitable to identify whether a particular landowner's property (i.e., 10 ha) has critical habitat or not. The credibility of projects can be jeopardized without careful consideration of whether the scale of data is sufficient to meet certain stakeholders' expectations.

The ability to customize regional models using ''local knowledge'' is needed as well. Although ecologists usually come to a land-use decision process as invited experts, the knowledge of local stakeholders must also play a role that is valued by ecologists. Ranchers, farmers, and public land agency personnel often have tremendous knowledge of the flora, fauna, and traditional use of the natural resources of local areas. This knowledge is often richer than the information provided in typical comprehensive land cover maps. Integrating this knowledge into spatial data and simulation models is critical, both to improve the quality of information produced and to honor the contribution of all stakeholders. Ecological support for rural land-use decisions should be conceived as collaborations that ensure mutual sharing and learning among all parties, rather than the simple transfer of knowledge or technology from experts to decision makers (i.e., yet another ''outreach'' effort). Ecological support should come from an exchange rather than an export of information.

A number of technological advances provide unparalleled opportunities for using ecological information to inform rural land-use planning. Geospatial technologies such as geographic information systems (GIS) allow spatial data to be collected, integrated, analyzed, and visualized in relation to other environmental and land-use factors. Simulations based on spatially explicit data can be used to examine the consequences of various assumptions on the landscape. The Internet can provide ready access of ecological information to rural land-use decision makers. For example, the Colorado Natural Diversity Information Source (*available online*)[8] was developed to support planning by local communities by providing readily accessible information on the consequences of development for wildlife. It allows planners, decisions makers, and citizens to foresee how cumulative changes in land use over time are likely to affect the extent and distribution of habitat for wildlife (Theobald et al. 2000). Additional opportunities exist through public-participatory research to formalize modes of public interaction with spatial data. For example, visual modeling languages help to explain the logic of models. Interactive ''white-board'' interfaces to computers offer the potential stakeholders to examine, in real-time, the effect of various assumptions that will more fully engage participants (Nyerges et al. 2002).

Models are particularly useful tools to integrate ecological information and communicate assumptions, potential uncertainties, and the complexity of feedbacks to decision makers (Dale 2003). Throughout the United States, efforts to map alternative future land-use patterns and examine the implications of those changes have been particularly useful and an increasingly common way to integrate ecological information with other socio-economic concerns in long-term, comprehensive planning processes (e.g., White et al. 1997, Wear et al. 1998, Theobald and Hobbs 2002*b*, Hulse et al. 2004).

[8] ⟨www.ndis.nrel.colostate.edu⟩

Most efforts to date have yet to fully incorporate ecological mechanisms to these assessments, however.

Research and application gaps

A number of research and application gaps need to be bridged to better inform rural land-use planning. Traditionally, ecologists are inclined to vigorously pursue filling gaps in ecological knowledge. For instance, a principle goal is to understand functional properties of organisms and their relationship to spatial heterogeneity of resources to predict population viability (often related to Endangered Species Act requirements). Synthesis of spatial databases into simulation models is important as well. The foundation of information supporting rural land-use decisions is a high-quality spatial database. To improve these data, we need better mapping of fine-scale landscape features (e.g., tree snags, nests, riparian areas, etc.). Promising new mapping approaches integrate satellite imagery, GIS, and ground plots to estimate fine-scale habitat elements (e.g., Ohmann and Gregory 2002). Although techniques to map land cover using either aerial photos or satellite imagery are improving, mapping land use remains challenging, particularly when mapping rural residential development, where a land-use change often causes only a small footprint which is often invisible (Theobald 2001). Land use can be inferred from landowner parcel data that are becoming available through local governments, yet even current basic datasets on land ownership (e.g., USFS, BLM, private, easements, etc.) are generally not available. Moreover, detailed information about human activities on public lands (especially recreation) generally is unavailable, and so identifying potential conflicts between biological resources and human activities are difficult.

Progress has been made in developing empirical models and simulation approaches to examine land-use change using broad-scale spatial databases (e.g., Landis 1995, Theobald and Hobbs 1998, Brown et al. 2000, Maxwell et al. 2000, Theobald 2001, Aspinall 2002, Kline et al. 2003); and in examining the ecological effects of these changes (White et al. 1997, Hansen et al. 2002, Theobald 2003). Consideration of the variety of model approaches is needed to understand their utility in different decision making contexts. Most spatial landscape-level models focus on ecological change in forests and ignore climate change, catastrophic events, and vegetation dynamics in non-forested land-use areas. Thus, extant models may apply poorly to many areas of the nation undergoing rapid changes in land use and land cover. Routine integration of socio-economic factors, which largely are responsible for motivating land-use changes, is usually absent from landscape models developed by ecologists. This absence limits the realism of ecological evaluations of alternative policy actions, such as protection of biodiversity (Polasky et al. 2001, Musacchio and Grant 2002). Also, landscape-level models need to better account for the combined influences of uncertainty and error associated with individual modeling components, in resulting landscape simulations and predictions.

A final gap, one in which ecologists typically have little experience, is in the effective application of ecological knowledge. That is, it is not enough to simply produce useful ecological information in a timely manner, rather it must be carefully incorporated into rural land-use planning through effective communication in the proper decision making processes. This step often requires staff and institutional support to create and run models, help users interpret output, and describe uncertainty and appropriate uses of models to decision makers. Because of the critical need to develop consistent, comprehensive, and credible ecological databases and information delivery tools, a new and important opportunity exists to expand the role of ecologists and existing institutions, or to create new natural resource science institutes that are unaffiliated with advocacy groups.

Ecologists have a timely and important role to assist in the development of environmental indicators that provide decision makers and the public with information to set priorities and assess the efficacies of land-use policies. To ensure the success of indicators, a sound process must be followed to develop indicators, sufficient data must be collected to report status and trends, and changes in indicators must be linked to specific management actions and land-use policies (U.S. Government Accountability Office 2004). A logical next step is to build on the progress of national-level efforts (e.g., Heinz Report) to develop targeted indicators for local planning processes. In particular, there is a need to develop a set of standardized indicators for rural landscapes that have received scientific review, are based on detailed spatial data that resolves fine-scale features (e.g., houses, small wetlands and riparian zones, etc.), and that respond directly to changes in land use (J. Bennett, *personal communication*).

Ecologists who develop integrated models face difficult problems when incorporating data from multiple sources that are characterized by varying degrees of accuracy. To maximize confidence in model output, assumptions and data manipulation for models must be transparent, and where models are used to predict, output should be called forecasting (Clark et al. 2001), projections (Dale and Van Winkle 1998), or scenarios (Schoonenboom 1995). Where possible, models should include the measured variation in data or some assumption about variation (particularly associated with local knowledge) and process outputs as probabilities rather than deterministic responses. Models must clearly portray uncertainty in forecasted outcomes and portray results as best estimates of experts rather than as calculated facts. Evaluation of the effects of alternative land-use scenarios is a useful way to do this (e.g., Steinitz 1996, White et al. 1997, Theobald and Hobbs 2002*b*, Hulse et al. 2004).

Future studies should identify successful situations to determine the ways in which ecological information was helpful and to critically examine failures as well. Colleagues from other disciplines, especially political science and sociologists, could assist ecologists in the use and application of ecological information and tools in the rural land-use process. For example, interdisciplinary teams should critically examine whether and when ecological information changed a land-use decision, how it was used by decision makers during deliberation, and what information was missing or how information that was provided could be improved.

Conclusions

We believe that ecologists can be more effective in supporting wise decisions on rural land use. To that end, we have offered a brief review of recent ecological work, sketched the typical rural land-use planning framework, and identified some emerging useful approaches to incorporating ecological knowledge in established decision making processes. We are encouraged by an increasing level of awareness and enthusiasm from ecologists for the critical need to improve ecological support for rural land-use planning (e.g., Perlman and Milder 2005). Unfortunately, we have been challenged to find useful examples of truly outstanding or successful projects that have informed rural land-use planning. We do not mean to imply, however, that ecologists are having no influence on rural land-use planning. Rather, we conclude there is a paucity of organized and systematic efforts to evaluate and learn from applied projects.

We believe that four fundamental challenges remain that require additional attention from ecologists. First, there is a mismatch in spatial and temporal scales where ecologists have the greatest understanding and those where land-use decisions occur (Fig. 2). In addition, critical and systematic evaluations of how, if, and when ecological information has influenced land-use outcomes are needed. Ideally, these should be conducted by social scientists to better understand how ecological information is used, how it can be improved, and what different information is needed.

For instance, although NDIS is arguably successful in informing land-use planning with readily available biological information, it remains difficult to provide objective measures of its success. How many land-use decisions have been influenced by NDIS? How many times have NDIS maps been considered during land-use hearings? How many county supervisors, planning and zoning commissioners, or interested citizens have visited the NDIS website? How many students have used NDIS as a source of information for their research projects? Regrettably, we do not have good answers to these questions. Ecologists excel at producing data and insight, but improving the relevancy and practical application of ecological science requires that ecologists critically evaluate its use and efficacy.

Moreover, standard land-use frameworks used to classify the type of land use (i.e., urban, suburban, agricultural) or the level of stewardship and protection require significant refinement. Negative ecological effects are typically inferred from classes of land use such as high-density residential, commercial, or dryland agriculture, but more detailed examination and analysis are needed to identify specific, measurable factors of these effects. For instance, are impermeable surfaces, maintenance of exotic species (lawn), modification of vegetation structure (trimming, thinning), etc. the main land cover modifications of high-density residential land use that cause impacts? What activities associated with high-density residential have impacts (e.g., Lepczyk et al. 2004)? Are the major activities that impact ecological systems free-roaming cats and dogs, increased automobile traffic and associated noise, presence of humans? Coarse classes or levels of stewardship (e.g., U.S. Geological Survey's Gap Analysis Project Status I-IV and IUCN's I-VII; Davey 1998) also need to be refined to explicitly examine allowed activities (e.g., active vs. passive recreation) and possible modification of disturbances such as fire suppression or unintended introduction of disturbances from activities such as mechanical thinning.

Finally, a critical component of adaptive management is missing in land-use planning—monitoring and evaluation. For example, a monthly or yearly summary of environmental performance should be assessed using ecological indicators that directly measure land-use decisions. These indicators could include the decrease of critical habitat (or increase through restoration), increase or decline of protected lands, change in air quality due to vehicle miles traveled, etc. Yet, effective participation in land-use planning requires ecologists to understand trade-offs, for example the need to balance a land owner's desire for a fair and predictable process with the ''learn as you go'' approach of adaptive management. Perhaps most importantly, ecologists must challenge the assumption that simply providing better ecological information and knowledge leads to better land-use planning. Broberg (2003) emphasized the direct roles that ecologists may play (rather than in generating information per se) in the planning process, from less to more direct: generate recommendations while participating in citizen review panels, testify at public hearings, educate staff and planning boards, and become planning board members. Ecologists have a significant and important role in generating and sharing scientific information to decision makers to help anticipate possible unintended ecological effects of rural land-use change.

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In review with *Ecology and Society*

Research, part of a Special Feature on Crossing scales and disciplines to achieve forest sustainability: A framework for effective integrated modeling

Modeling Effects of Land Use on Quality of Water, Air, Noise, and Habitat for a Five-County Region in Georgia.

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ABSTRACT. A computer simulation model, the Regional Simulator (RSim), was constructed to project how land-use changes affect the quality of water, air, noise, and habitat of species of special concern. RSim is designed to simulate these environmental impacts for the five counties in Georgia surrounding and including Fort Benning. The model combines existing data and modeling approaches to simulate effects of land-cover changes on nutrient export by hydrologic unit; peak 8-hour average ozone concentrations; noise impacts due to small arms and blasts, and habitat changes for the rare red-cockaded woodpecker (*Picoides borealis*) and gopher tortoise (*Gopherus polyphemus*). The model also includes submodules for urban growth, new road-influenced urbanization, non-urban land-cover transitions, and a new military training area under development at Fort Benning. In this paper, the model was run under scenarios of business as usual (BAU) and greatly increased urban growth for the region. The projections show that high urban growth will likely impact nitrogen and phosphorus loadings to surface water as well as noise, but not ozone levels in air (at least in the absence of associated increases in industry and transportation use or technology changes). Effects of urban growth on existing populations of the federally endangered red-cockaded woodpecker are not anticipated. In contrast, under the simulation conditions, habitat for gopher tortoise in the five-county region declines by 5% and 40% in the BAU and high urban growth scenarios, respectively. RSim is designed to assess environmental impacts of planning activities both inside and outside the installation and to address concerns related to encroachment and transboundary influences.

Key Words: *gopher tortoise, landscape change, long leaf pine, nutrient export, red-cockaded woodpecker, simulation*

INTRODUCTION

A regional approach to environmental impacts (Munns 2006) provides the opportunity to examine the extent and spatial interactions of key drivers and processes affected by land-use change. Because these drivers and the factors influencing these processes change over space due to variations in such features as topography, climate, and human activities,

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it is important to consider their influence in a spatial context in order to understand the full range and extent of causes and implications of environmental change. Such analyses can be of assistance to regional planning and hence foster sustainability by allowing potential environmental repercussions to be a part of planning.

Furthermore, there is a need to examine how environmental impacts can change across several stressors, environmental media, and sectors (e.g., water, air, noise, and habitats for species of special concern). Although environmental laws typically segregate these impacts both in the ways they are reported and managed, such an artificial division can lead to inadequate understanding and, hence, management problems. For example, contrary incentives can arise if one sector gains at the expense of another. In other situations, inappropriate management actions can result from the focus on only one sector and not the consideration of all aspects of the environment that might be affected.

As a major driver of environmental change, it is critical to understand how land-use activities affect the landscape. For example, human use can degrade or ameliorate soil properties, enhance or reduce runoff, and aggravate or alleviate drought. In turn, land use can be constrained by environmental conditions such as topography, slope, exposure, soil conditions, and climate.

With the recent advent of geographic information systems and the field of landscape ecology (Turner et al. 2001), it has been possible for such a spatial approach to environmental change to be conducted. Undertaking a regional and cross-sectorial approach to the study of environmental change requires determination of the appropriate spatial and temporal scales of resolution and consideration of potential feedbacks across sectors. One of the goals in such a multi-sector approach is to provide a way to fully understand the key components of the system including possible cumulative impacts.

This paper proposes a regional, cross-sectorial approach to examining land-use change and its effects and presents an example of its application to a five-county region in west, central Georgia. We focus on the region in Georgia around and inclusive of Fort Benning for three reasons: (1) large quantities of data are available; (2) the region will be undergoing dramatic changes in the future as the military training activities and the many people supporting them now at Fort Knox, Kentucky, are moved to Fort Benning; and (3) the military land (on which urban growth is restricted) serves as a control against which changes on private lands can be compared. The Regional Simulator model (RSim) has been developed for this five-county region and includes the ability to project future changes in the quality of water, air, noise, and habitat (Dale et al. 2005). The spatially-explicit simulation model is structured so that the basic framework can be applied to other resource management needs and other regions. Hence, the model is designed so that it is broadly applicable to environmental management concerns. The need for applying ecosystem management approaches to military lands and regions that contain them is critical because of unique resources on these public lands and the fact that conservation issues for the entire region may jeopardize military missions if not appropriately managed. The RSim model addresses this critical need by enabling application of ecosystem management approaches to military lands and surrounding regions. This paper examines changes that result from two scenarios: a "business as usual" (BAU) case and a dramatic increase in urban growth. The analysis illustrates how a simulation model can be used as a cost-effective means to explore potential environmental ramifications of land-use changes.

This paper fits into a special issue on forest sustainability because the study region was originally dominated by long-leaf pine (*Pinus palustris*) forest, and it is the continuance of the pine forest that allows many other environmental goals for the region to be attained. Without the forest, some of the other environmental amenities such as wildlife habitat are not possible. Environmental impacts of planning activities both inside and outside military installations need to address concerns related to encroachment and transboundary influences (Efroymson et al. 2005).

METHODS

Study area

The study area for model development and application is a five-county region in west, central Georgia (Figure 1). This region encompasses and includes most of the 73,503 ha Fort Benning military installation, which supports both a cantonment, where infrastructure is extensive and also undeveloped areas where training occurs and where forest structure supports several environmental amenities. Fort Benning military activities include training entry-level soldiers, training the Infantry, and conducting Airborne and Ranger candidates' training. In addition to the ranges for munitions training, the installation supports expansive pine forests, which receive low-intensity military use. Because these forests have been protected from urban development and because there has been a focused program of controlled burning since the 1960's, these lands now support mature stands of long leaf pine forests and several rare species of plants and animals.

Because of land-use change and fire suppression throughout the southern eastern United States, only about 4% of the original long leaf pine forest exists today, and thus the remaining forest and the species that it supports has great ecological value (Gilliam and Platt 1999). Burning is a critical management practice for long leaf pine because the seedlings first grow in what is termed a "grass stage," in which the tree's meristem is located at the base of the stem and protected from low-intensity fire by a lush bunch of needles. A subsequent bolt of growth in saplings moves the meristem to a height above that of ground fires (assuming the fires occur frequently enough that they are of low intensity). In the 1994 Guidelines for the Management of Red-Cockaded Woodpeckers on Army Lands (as cited by Beaty et al. 2003), the Army in cooperation with the Fish and Wildlife Service selected Fort Benning as a site designated for the protection of the federally endangered red-cockaded woodpecker (*Picoides borealis*), which nest in living long leaf pine trees. Controlled burning not only allows for the reestablishment of long leaf pine seedlings, it also reduces hardwood ingrowth, which compromises the forest for support of red-cockaded woodpeckers.

The study region also includes private lands in the counties of Harris, Talbot, Muscogee, Chattahoochee, and Marion. The city of Columbus, which abuts Fort Benning on the north side, is the center of urban development in the region and is part of the study area. Major non-urban land uses of the five-county region include forestry, agriculture and pasture.

The region contains a complex mix of environmental pressures that can affect the quality of water, air, noise, and habitat. The urban areas have significant industrial development and intense use of fossil fuel-based vehicles, both of which contribute to air pollution. Burning for maintenance of habitat for long leaf pine also affects air quality and soil conditions (Garten, *in press*). Training areas within the installation produce loud noises as a result of small arms activity, firing of large caliber arms, and military aircraft. Water quality in the region is affected by industrial activities and agricultural practices, which induce runoff and require fertilizer use. In addition, habitat of two key rare species (red-cockaded woodpecker and gopher tortoise) can be affected by land-use practices and underlying conditions on the land (Bogliolo et al. 2000, Hermann et al. 2002).

Simulating cross-sectorial environmental changes in the region

Because resource managers need to protect multiple aspects of the environmental quality of region, the <u>R</u>egional <u>Sim</u>ulator model (RSim) was developed as a tool to integrate changes in the region for conditions relating to water, air, noise, and habitat (Figure 2) (Dale et al. 2005). The basic spatial unit of RSim is a 30-m pixel because much of the underlying data in the model are derived from satellite imagery, which is reported at that scale of resolution. After much consideration, the basic time step of RSim was set to a year because changes in land cover typically are reported at annual intervals. This choice means that all the environmental changes projected by RSim are reported annually.

Where possible, RSim was built from existing models and data. Urban growth in RSim is based upon the SLEUTH model (Clarke et al. 1998, Clarke and Gaydos 1998, Candos 2002) supplemented with rules for low intensity to high intensity urbanization, and transitions for the non-urban land cover are based on change detection observed for the five-county region from 1990 to 1998 (Baskaran et al. 2006A). The water quality module uses nutrient export coefficients (e.g., Johnes, 1996; Mattikalli and Richards, 1996) combined with information on the different land uses and land covers in the region to predict the annual flux of N and P from terrestrial watersheds. The noise module uses GIS data layers of military noise exposure developed by the U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM) as part of the Fort Benning Installation Environmental Noise Management Plan (IENMP). RSim builds upon noise guideline levels developed by the military under the Army's Environmental Noise Program [ENP] (U.S. Army. Army Regulation 200-1. 1997) and contains noise contour maps developed from three Department of Defense noise simulation models: NOISEMAP (aircraft), BNOISE (artillery), and SARNAM (small arms) but focuses on noise created by artillery, which have the greatest effect at Fort Benning. The approach produces noise contours that identify areas where noise levels are compatible or incompatible with noise-sensitive land covers outside of Fort Benning. The Army's Environmental Noise Program's guidelines define zones of high noise and accident potential and recommend uses compatible in these zones. Local planning agencies are encouraged to adopt these guidelines. The Air Quality module of RSim estimates the impact of emissions changes on ozone air quality using sensitivity coefficients available from the Fall Line Air Quality Study (http://cure.eas.gatech.edu/faqs/index.html). The module predicting habitat for red-cockaded woodpecker was developed based on spatial data of long leaf pine in the region. The module that predicts habitat for the gopher tortoise (*Gopherus polyphemus*) was developed based on analysis of locations of gopher tortoise burrows at Fort Benning and tested for the larger five-county region (Baskaran et al. 2006B).

Numerous future scenarios can be modeled using RSim. These include both civilian and military land-cover changes. The current implementation of RSim includes four specific types of scenarios, along with their impacts on environmental conditions over the next decades: (1) urbanization (conversion of non-urban land cover to low-intensity urban and conversion of low-intensity to high-intensity urban), (2) planned road expansion plus modeled urbanization, (3) a new training area at Fort Benning, and (4) hurricanes of various intensities. Low-intensity urban land cover includes single-family residential areas, schools, city parks, cemeteries, playing fields, and campus-like institutions. High-intensity urban land cover includes paved areas with buildings and little vegetation. When outside of urban areas, these high intensity urban low covers include power substations and grain storage buildings.

For the case considered in this study, RSim was run under conditions meant to simulate "business as usual" (BAU) urbanization for 40 years into the future from 1998, as compared to great increases in urban growth (see Appendix for input conditions). The BAU case includes typical urbanization for the region as based on regional growth patterns from 1990 to 1998, the new training area at Fort Benning (which is already under construction), and road expansion according to the Governor's plans for development of four-lane highways in the region. The high growth scenario is identical except for an increase in urban growth starting in 1998. This scenario is meant to simulate changes in urban growth of the region that may result from the transfer of training from Fort Knox, Kentucky, to Fort Benning. Although many changes in the region are anticipated (Dale et al. 2005), no one has yet published an analysis of how these changes might affect land cover and other environmental conditions. Such a study can be useful for planning in the region in such ways as to foster sustainability. This paper builds from the pending development in the five-county region of west, central Georgia to explore how a regional simulation model can be used to improve understanding of cross-sectorial regional environmental changes before those changes occur on the ground.

RESULTS

Land cover

Based on the conditions and scenarios selected, the projected changes in land cover are depicted in Figure 3. Graphs of the changes in land cover for the two scenarios are in Figures 4 and 5. The BAU case results in a slight increase in the area of land under high intensity urban (from 4,329 ha to 4,662 ha) and a greater increase in land under low intensity urban cover (from 7914 ha to 10053 ha). Clear-cut land declines sharply from 44,735 ha to 20,317 ha, and row crops decrease from 11,101 ha to 4,876 ha. Pasture lands increase from 22,886 ha to 27,147 ha.

The high urban growth scenario results in a different pattern of changes in urban lands and agricultural lands than in the BAU case (compare figures 4A and 4B). The high growth case results in a great increase in the area of land under both high intensity urban (from 4,329 ha to 115,789 ha) and low intensity urban cover (from 7,914 ha to 135,247 ha). Clear-cut land declines from 44,735 ha to 10,963 ha, and row crops decrease from 13,101 ha to 1,837 ha. Contrary to the BAU case, for the high urban growth scenario, pasture lands decline from 22,886 ha to 7,779 ha.

Forest cover also changes in the BAU scenario (Figure 5A). Both mixed forest and forested wetlands decline from 32,145 ha to 12,775 ha and from 27,933 ha to 14,310 ha, respectively. Deciduous forest and evergreen forests both increase in area from 106,439 ha to 118,880 ha and from 144,905 ha to 191,419 ha, respectively.

Compared to the BAU case, forest cover has a quite different pattern of change over the next 40 years for the high urban growth scenario (compare figures 5A and 5B). In the latter case all the common forest categories decline with mixed forest changing from 32,145 ha to 10,765 ha, forested wetlands from 27,933 ha to 10,561 ha, deciduous forest from 106,439 ha to 42,488 ha, and evergreen forests from 144,905 ha to 70,911 ha.

Water quality

For the BAU scenario, the water quality module predicts that the watershed containing the city of Columbus [Hydrological Unit Code (HUC) 30104] exhibits the greatest changes in N and P exports as compared to the high urban growth scenario, which predicts that the watershed northeast of Columbus (HUC 21206) has the greatest changes in these exports. The overall change in N export for the RSim region was 1,002,406 kg and 1,609,560 kg, respectively for the BAU and high urban growth scenarios. The overall change in P export was 164,703 kg and 374,600 kg, respectively for the BAU and high growth scenarios.

Air quality

For both the BAU and high urban-growth scenarios and meteorological episode selected, the air quality module predicts that area-wide peak 8-hour average ozone concentrations will change from 71 ppbv (parts per billion by volume) in 1998 to about 90 ppbv in 2038. For the 40-year simulation, the concentration of ozone exceeds the secondary standard for 34 years of the projection period. Thus, ozone exceeded the level protective of crops and other vegetation for 85% of the future time in both cases.

Habitats of key species in the region

Red-cockaded woodpecker

For both the BAU and high urban growth scenarios, RSim projects that by model year 2038, 150% of the original clusters of red-cockaded woodpecker will exist in the five-county region. Most of these clusters will be located in evergreen forest within the boundaries of Fort Benning that mature to the stage in which they can support red-cockaded woodpecker by the end of the 40-year model run. This quantity of new active breeding clusters would meet the U.S. Fish and Wildlife Service's (USFWS) goal of 361 active clusters for Fort Benning (Beaty et al. 2003)).

Gopher tortoise

RSim projects that by model year 2038 there will be 181,288 ha and 113,639 ha of potential area of suitable gopher tortoise habitat, respectively, for the BAU and growth scenarios. These projections compare to 190,918 ha of gopher tortoise habitat in the five-county region at the beginning of the simulation. The 5% and 40% reduction in potential area that can support gopher tortoise burrows reflects changes in land cover, respectively, for the BAU and high urban growth scenarios. The probability of having suitable gopher tortoise habitat increases when more land cover is in pasture, clear-cuts, forest, transportation corridors, row crop, or utility swaths.

Noise

For the two scenarios, the land-cover changes combine to produce different patterns of risk from noise (compare Figures 6A and 6B). There is a moderate risk of noise complaints from areas outside Fort Benning of 6,334 ha and 93,448 ha area, respectively, for the BAU and high urban growth scenarios. The areas likely to experience a high risk of noise complaints are relatively small in both scenarios, with 9 ha and 61 ha being likely by 2038 for the BAU and growth scenarios, respectively. RSim predicts that by 2038 that 8,335 ha and 38,773 ha, respectively, of land outside of Fort Benning will be in land uses that are incompatible with noise produced from military activities in the simulated scenarios.

DISCUSSION

Projected changes in land cover under the two scenarios are quite different (Figures 4 and 5). The BAU case has only small changes in the urban land cover types. A sharp decline in clear-cut land and a more gradual decline in row crops occur as pasture and urban land covers increase in area. At the same time, evergreen and deciduous forest land increases in the region. In contrast, the sharp increase in high intensity urban lands under the high urban growth scenario is associated with a decline in all of the other land cover types mentioned above. These alterations in land cover types set the stage for changes in some of the other environmental conditions discussed below.

Changes in N and P export to streams over the 40 year projection are dramatic for both scenarios. For the BAU case, the watershed containing the city of Columbus has more N and P export after 40 years than any other watershed in the region because it continues to be the center of high urban intensity. The city is currently the largest in the five-county area and in 1998 had the greatest concentration of urban land cover in the region. The high proportion of urban lands in Columbus increases the paved areas, which allow runoff as well as industrial inputs of N and P into the water system. Over the 40 year projection no land-cover changes in the rural or forested landscape are great enough to overcome the large influence of Columbus on the water quality of the region. These results suggest that current and future attention to the effects of N and P export should concentrate on the city of Columbus under the BAU case. However, under the high growth scenario, the intense urban development shifts to the northeast of Columbus, i.e., to HUC 21206. This difference in results for the two scenarios suggests that the region needs to be prepared to support infrastructure needs and increases in N and P export for a larger region than just the Columbus area.

Under both scenarios, air quality changes projected from land-cover changes in the five county region are similar. There are two principal ways that forest cover can affect air quality, and both are represented in RSim. First, forests emit reactive hydrocarbons that are involved in the chemistry that forms ground-level ozone. In the southeastern United States, biogenic hydrocarbons are ubiquitous, and stoichiometrically speaking, the region is saturated with hydrocarbons. Removing sources of hydrocarbons under any conceivable scenario (or adding more for that matter) has no significant effect on ozone concentrations. For this reason, projected changes in the forest cover have a negligible effect on hydrocarbon emissions and thus ozone concentrations. The second way that forests can affect ground-level ozone is via emissions of nitrous oxide (NOx) either due to burning activities in the forest or from activities associated with logging or otherwise managing or using the forest (e.g., chainsaws, trucks, and all terrain vehicles). Estimates of all these contributions are included in RSim's current emissions inventory. However, forest-related emissions are only a small part of the total emissions inventory, and they may or may not have any impact on the "peak" ozone concentration in the region (which is what RSim calculates and the variable that is generally related to human health and vegetation growth). Further, if the changes in the forest emissions are not co-located with the place where the peak ozone concentration occurs (which is likely since the peak pollutant concentrations tend to occur more near the urban areas where the more intense emissions sources are located), there is unlikely to be an effect on the NOx calculation from forest changes. Lastly, forest emissions are distributed over a large area so the effect is diluted at any one location. Even though all of these factors are included in the air quality module of RSim, there is little effect on regional air quality due to land-cover changes. This result was rather surprising for the region.

The habitats for the two species included in RSim respond in quite different ways to projected changes in land cover from the BAU and growth scenarios. The number of clusters of red-cockaded woodpecker has few differences in the two scenarios because the clusters are almost all located in military lands that are not subject to urban expansion. In contrast, the habitat of gopher tortoise is strongly affected by the increased urban growth scenario, for that case instigates a change in several land-cover types that are suitable for gopher tortoise. Under the BAU case, the clear-cut lands undergo a steady decline from 44,735 ha to 20,317 ha; whereas in the growth scenarios these clear-cut lands decline to about 10,963 ha. At the same time, pasture lands are projected to increase from about 22,890 ha to 27,150 ha in the BAU scenario and decline to 7,800 ha in the high growth scenario. The decline in both clear-cut and pasture lands that results from the high urban growth reduces the area suitable for gopher tortoise habitat.

The projected risk from noise under the two scenarios is very different (Figure 6). The BAU case is associated with a slight increase in the lands with moderate risk from noise and incompatible land use. In contrast, the high level of urban growth projects dramatic increases in the area of land with moderate risk from noise and incompatible land use. Both of these scenarios display a local peak in risk from noise that occurs just before model year 2008 [when the area of land in high and low intensity urban categories are approaching similar values (Figure 4)]. Before 2008, both urban types contribute to the noise risks, but the declining area of residential home lands after 2008 causes the noise risk to also decline for a short period until the influence of the rising high intensity urban land causes another rise in the noise risk. The location of these new urban lands near the boundary of Fort Benning (Figure 3) and within the range of noise impacts is another factor affecting the sharp rise in risk from noise.

This regional, cross-sectorial analysis of environmental influences of land-use change in west, central Georgia illustrates some of the benefits of using such an holistic approach to land-use planning. A broader understanding of potential effects of land-use changes can be achieved. This information can be used to streamline management activities by allowing potential effects to be considered before a decision is made and it promotes discussion and planning for on-the ground repercussions of decision making. In addition, the simulation model identifies conditions under which cross-sectorial effects should be considered (or not considered). For example, in the scenarios presented here, impacts on air quality are negligible. At least in the absence of large changes in dominant emissions factors such as might be associated with increases in industrial and transportation use or in technology changes, the effects of land-use change on air quality are small. Use of the RSim model enhances understanding of interactions between environmental effects (feedbacks and cumulative impacts) and therefore allows for greater understanding of the conditions necessary to sustain several environmental amenities of the region.

CONCLUSIONS

The use of RSim to explore regional changes in west, central Georgia projects that high urban growth can have dramatic impacts upon water and noise quality and upon the habitat of one species of special concern (gopher tortoise) but not another (red-cockaded woodpecker). Hence, this example illustrates where management attention might be focused in order to promote environmental sustainability of the region. However, only a limited set of conditions were considered in this example. The ongoing and regular use of this type of model in a planning environment is the most effective way to make use of the approach. Simulation models offer a cost-effective and efficient means to explore potential outcomes of resource management and land use. This analysis shows that modeling, understanding and managing for effects of land-use change on several sectors (air, water, noise, and habitat) requires attention to the spatial and temporal scale at which each sector operates and how the factors influencing the sectors interact.

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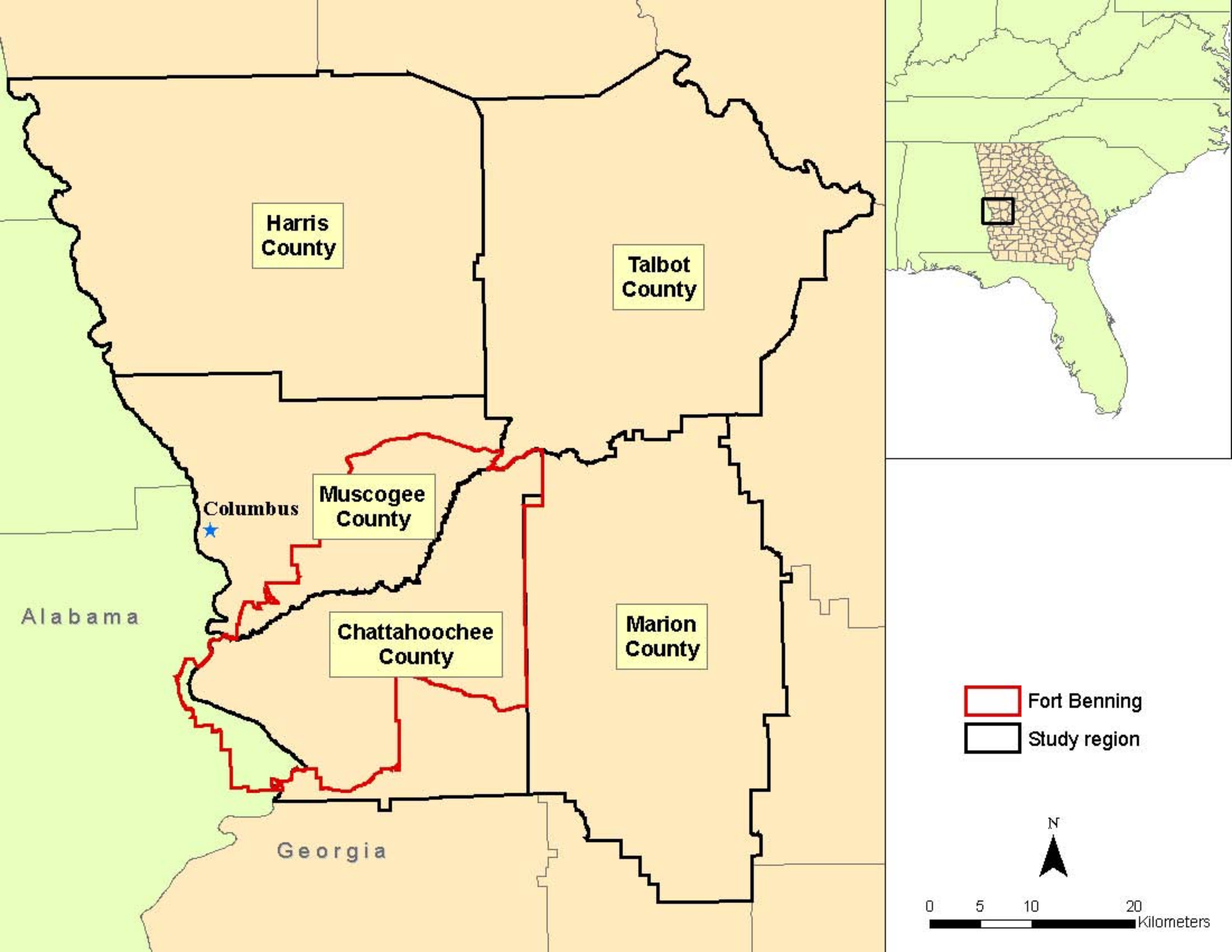
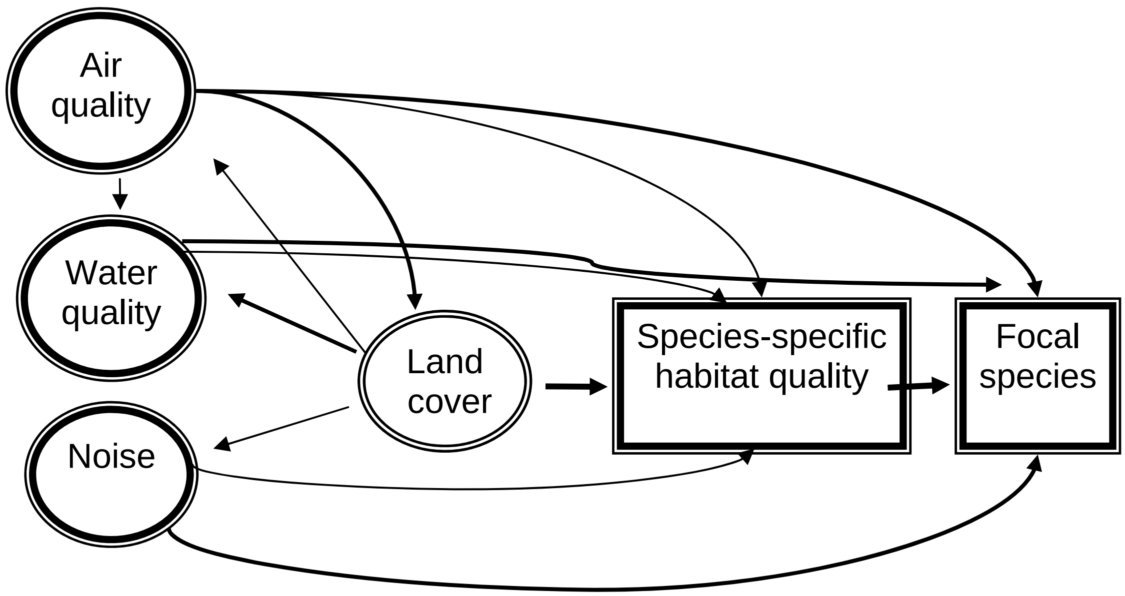
List of Figures



Harris County
Talbot County
Muscogee County
Columbus
Chattahoochee County
Marion County
Alabama
Georgia
Fort Benning
Study region
N
0
5
10
20
Kilometers

Figure 2. Diagram of RSim with the circles representing submodules of RSim.



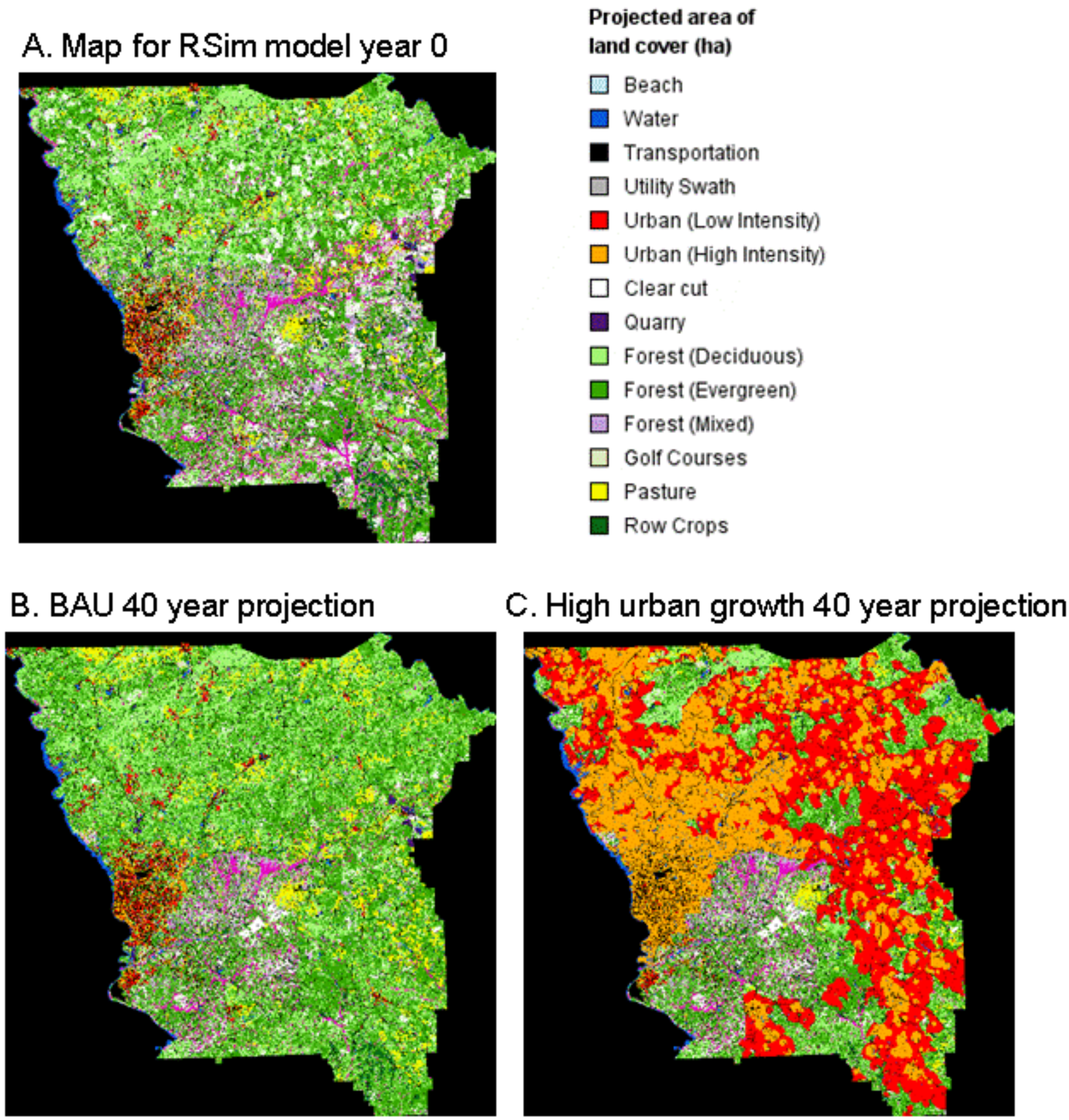
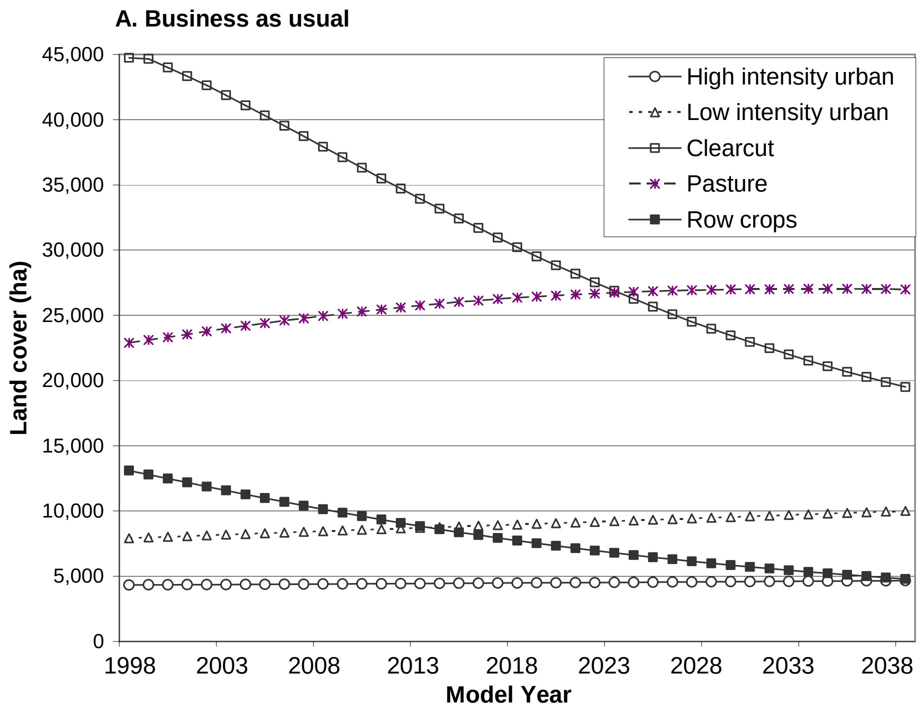
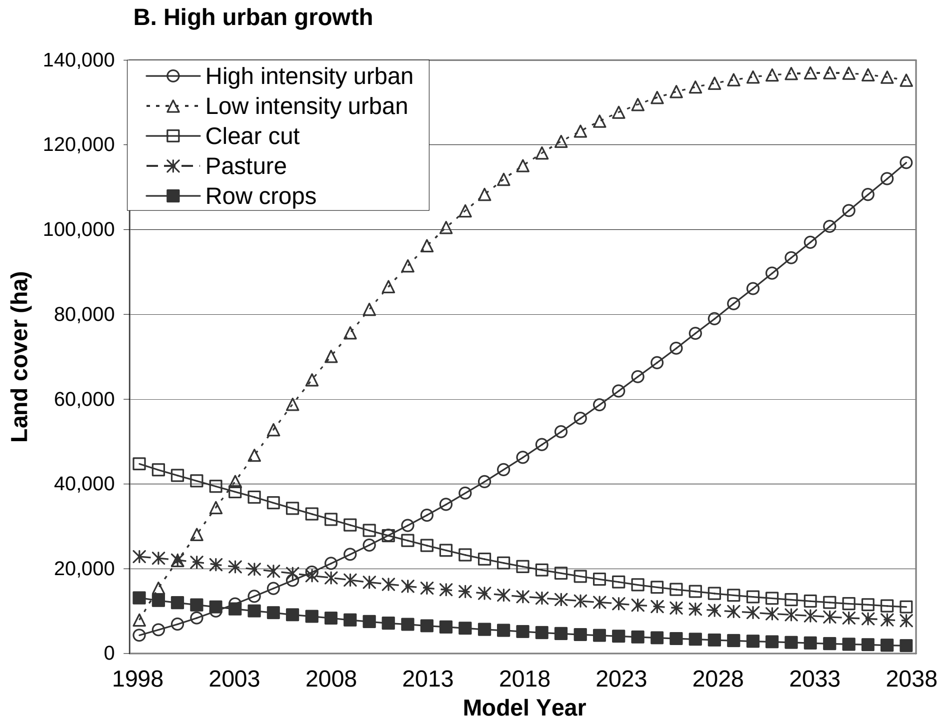
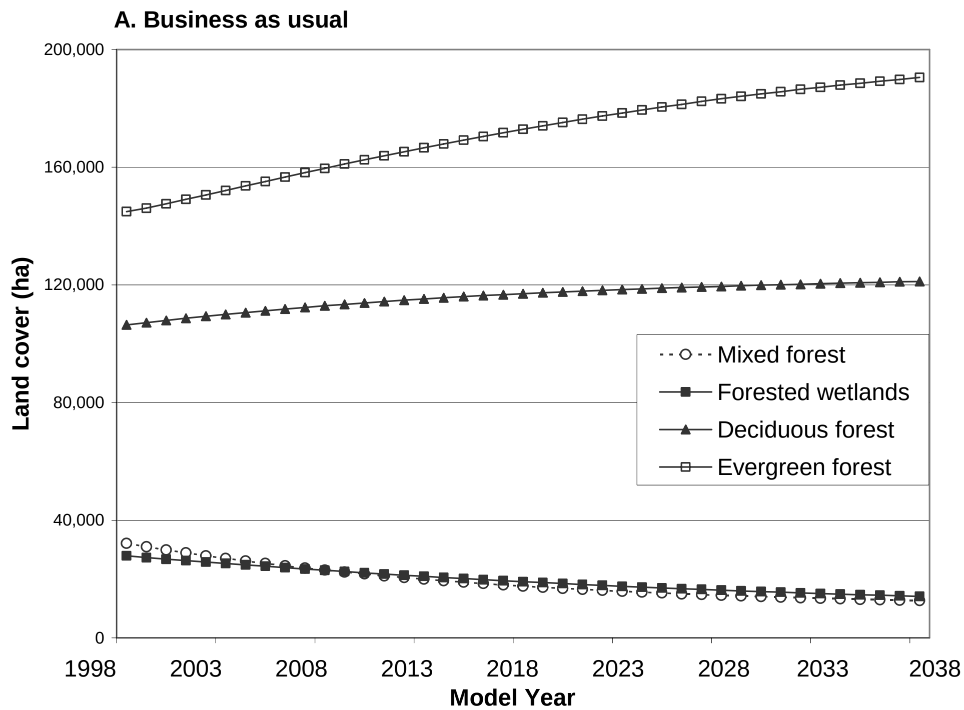

A. Map for RSim model year 0
Projected area of land cover (ha)
Beach
Water
Transportation
Utility Swath
Urban (Low Intensity)
Urban (High Intensity)
Clear cut
Quarry
Forest (Deciduous)
Forest (Evergreen)
Forest (Mixed)
Golf Courses
Pasture
Row Crops
B. BAU 40 year projection
C. High urban growth 40 year projection

Figure 4. Graph of changes in urban land cover, pasture and row crops over the 40 year RSim projection for the (A) business as usual (BAU) scenario and (B) the high urban growth scenario.





5. Graph of changes in forest cover over the 40 year RSim projection for the (A) business as usual (BAU) scenario and (B) the high urban growth scenario.



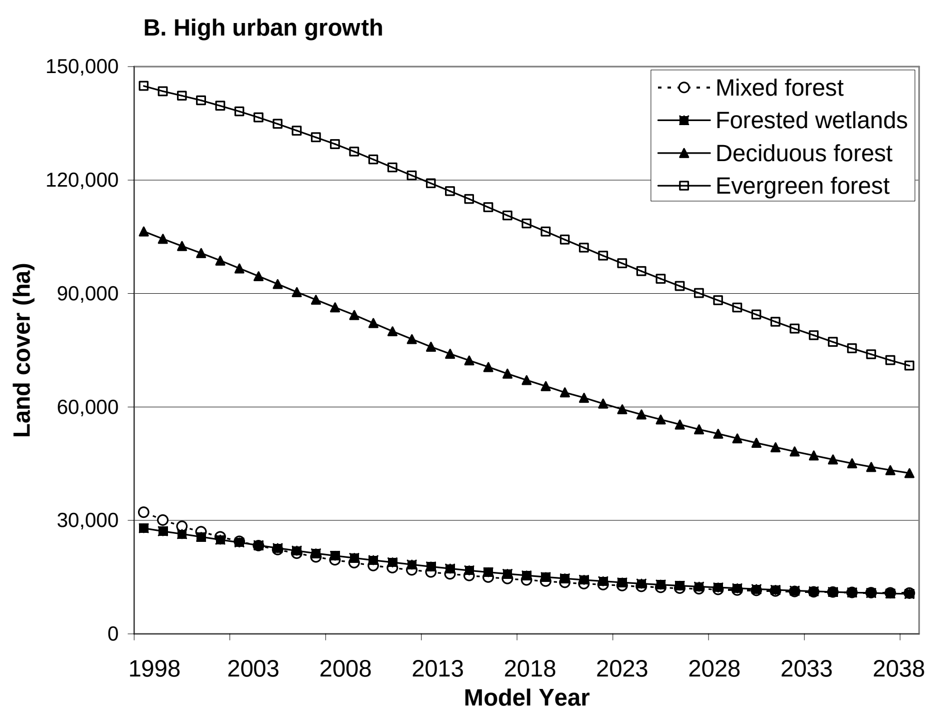


Figure 6. Land area at moderate or high risk to noise complaints and having incompatible land uses for projected noise risks for the (A) business as usual (BAU) scenario and (B) the high urban growth scenario over the 40 year RSim projection period.

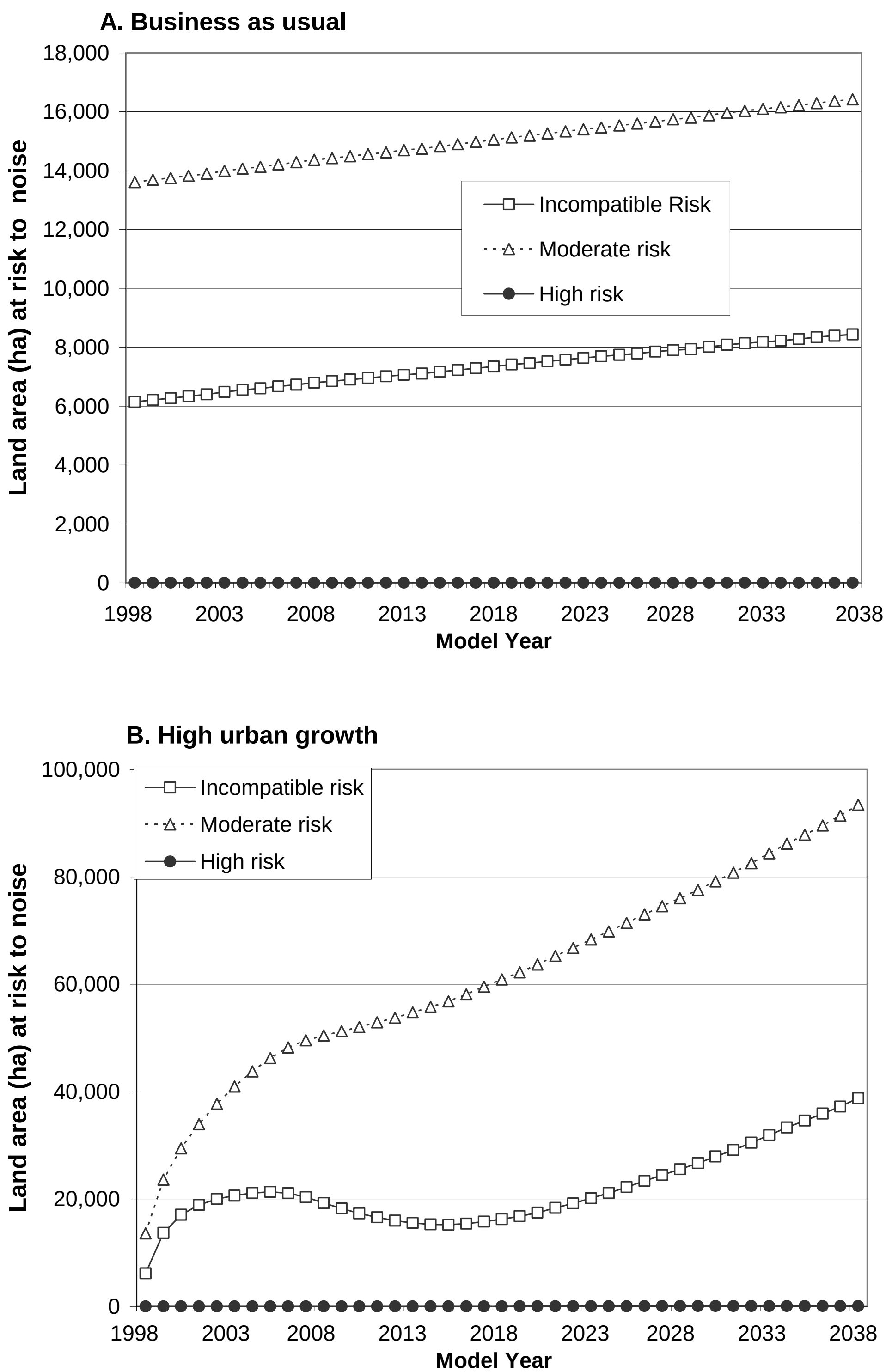


Table A1. Select Scenarios

Land cover transitions selected?	YES
Military expansion scenario selected?	YES
Hurricane scenario selected?	NO
Number of time steps (yrs)	40

Table A2. Urban Growth Model Parameters

Parameter	Business as usual	High urban growth
Dispersion (Low)	6.0	6.0
Dispersion (High)	5.0	5.0
Breed (spread)	4.0	4.0
Breed (roads)	15.0	15.0
Spread (Low)	0.9	90.0
Spread (High)	0.5	50.0
Road Search (High)	13.0	13.0
Road Search Distance (Low)	1000.0	1000.0
Road Search Distance (High)	5000.0	5000.0
Road Trip Energy	200	200

Table A3. Land Cover Transitions

	Deciduous	Evergreen	Mixed	Clearcut	Pasture	Row Crops	Forested Wetland
Deciduous		1.8	0.1	0.8	0.5	0.0	0.5
Evergreen	1.3		0.1	1.6	0.5	0.0	0.0
Mixed	4.1	4.2		1.0	0.5	0.0	0.2
Clearcut	1.3	7.8	0.1		0.7	0.0	0.1
Pasture	0.7	1.0	0.0	0.4		0.0	0.0
Row Crops	0.8	1.4	0.0	1.0	5.6		0.0
Forested Wetland	3.8	1.5	0.1	0.7	0.2	0.0	

Table A5. Water Quality Module Export Coefficients

	kg N/ha/yr	kg P/ha/yr
Wetland	5.5	0.25
Forest	1.8	0.11
Pasture	3.1	0.1
Idle	3.4	0.1
Industrial	4.4	3.8
Residential	7.5	1.2
Row Crops	6.3	2.3
Business	13.8	3.0

Table A6. Air Quality Conditions

Selected meteorological episode	Mild ozone episode
Mobile sources	1.0
Area sources	1.0
Non-road sources	1.0
Point sources	1.0

Table A7. Noise Conditions

Noise module selected?	YES

Table A7. Species and Habitats Conditions

RCW module selected?	YES
Gopher tortoise habitat module selected?	YES
Cutoff probability for burrow presence	0.8
Threshold habitat patch size (ha)	2.0
Minimum patch size applied?	NO