Section: Research

Modeling the 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 caused by 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, nonurban 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 impacts caused by high urban growth will likely differ from impacts caused by BAU for nitrogen and phosporus loadings to surface water as well as noise, but not for peak ozone concentrations in air (at least in the absence of associated increases in industry and transportation use or technology changes). In both scenarios, 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 relative environmental impacts of planned activities both inside and outside the installation and to address concerns related to encroachment and transboundary influences.

Key words: gopher tortoise; land use; landscape change; long leaf pine; nutrient export; red-cockaded woodpecker; simulation

INTRODUCTION

A regional approach to environmental impact assessments (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 because of variations in such features as topography, climate, and human activities, 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 multisector 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 relative 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) cannot be maintained. 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 (the area of a military installation 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 1960s, 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 southeastern 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 have 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 nests 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 nonurban 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, 2006). 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 the region, 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 (as is described in Appendix 1). 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. 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). RSim contains noise contour maps resulting from artillery, as projected by the DoD noise simulation model BNOISE, because artillery is the greatest source of noise at Fort Benning. The approach produces noise contours that identify areas where noise levels are compatible or incompatible with noise-sensitive land uses outside of Fort Benning. The Army's Environmental Noise Program's guidelines define zones of high noise and accident potential and recommend compatible uses in these zones. Local planning agencies are encouraged to adopt these noise 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 measure of ozone air quality is based on the U.S. Environmental Protection Agency (EPA) Clean Air 8-hour Ground-level Ozone rule, an EPA action designating areas whose air quality does not meet the health-based standards established in 1997 for ground-level ozone pollution (http://www.epa.gov/ozonedesignations/). This policy-based designation lets the public know whether air quality in a given area is healthy and is not designed to convey effects on plant physiology or productivity or at different temporal resolutions. The module predicting habitat for red-cockaded woodpecker was developed on the basis of spatial data of long leaf pine in the region (as described in Appendix 2). The module that predicts habitat for the gopher tortoise (*Gopherus polyphemus*) was developed on the basis of analysis of locations of gopher tortoise burrows at Fort Benning and was 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 nonurban 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, power substations, and (occasionally) 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 2 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.

RESULTS

Land cover

On the basis of 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 cover (from 4,329 ha to 4,662 ha) and a greater increase in land under low-intensity urban cover (from 7,914 ha to 10,053 ha). Land on which the timber has been cleared 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 cover (from 4,329 ha to 115,789 ha) and low-intensity urban cover (from 7,914 ha to 135,247 ha). Clearcut 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, 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

The water-quality module projects large differences in the amount and location of major nitrogen (N) and phosphorus (P) export for the BAU scenario as compared to the high urban growth scenario. The BAU case results in the watershed containing the city of Columbus [Hydrological Unit Code (HUC) 30104] exhibiting the greatest changes in N and P exports. In contrast, the high urban growth scenario projects 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

In both scenarios, the peak 8-hour ozone concentration over the five-county region increased from 71 ppbv (parts per billion by volume) in 1998 to about 90 ppbv in 2038. Thus, when comparing results of the two scenarios against one another, the additional changes in the high urban growth scenario, which are over and above the BAU scenario, did not yield any additional changes to the estimated change in peak 8-hour ozone concentration over the five-county region. It should be noted, however, that peak 8-hour ozone concentration is but one measure of air quality. Other metrics, for example those that measure dose or the temporal or spatial distribution of ozone, might, in fact, show differences in air quality between the two scenarios. As it is, the increase over 40 years of peak 8-hour ozone concentrations from 71 ppbv to 90 ppbv is caused by the projected growth in industrial, commercial, and transportation activities. Growth in both scenarios, though, is untempered by any future regulatory controls, technological innovations, or air-quality-management decisions. For context, peak 8-hour ozone concentrations actually observed in the five-county region in 1998 ranged up to 104 ppbv.

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 for the BAU and high urban growth scenarios, respectively. 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 for the BAU and high urban growth scenarios, respectively. 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, for the BAU and high urban growth scenarios, respectively. 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, 8,335 ha and 38,773 ha for the BAU and high-growth scenarios, respectively, of land outside of Fort Benning will be in land uses that are incompatible with noise produced from military activities.

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 clearcut 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 anthropogenic 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 local forest cover have a negligible effect on extant hydrocarbon emissions and thus ozone concentrations. The second way that forests can affect ground-level ozone is via emissions of nitrous oxide (NOx), either from 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 have scant 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, unless the changes in the forest emissions are collocated with the place where the peak ozone concentration occurs (which is likely because the peak pollutant concentrations tend to occur more near the urban areas where the more-intense emissions sources are located), an effect on ozone concentrations is unlikely. 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 as calculated in the form of peak 8-hour ozone concentrations produced by land-cover changes. Conversely, it is expected that air quality does affect land-cover. Though this direct feedback loop has not yet been implemented in RSim, users should be aware that, for both scenarios, the model projects that concentrations of ozone exceed the secondary-ozone standard that is protective of vegetation for 34 years of the 40-year projection period. Consequently, adverse vegetative impacts could be assumed.

The habitats for the two species included in RSim respond in quite different ways to projected changes in land cover from the BAU and high-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 high urban growth scenario because that case instigates a change in several land-cover types that are suitable for gopher tortoise. Under the BAU case, the clearcut lands undergo a steady decline from 44,735 ha to 20,317 ha; whereas in the high-growth scenario, these clearcut 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 clearcut 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 a 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. Both the counties and the military lands in Georgia require regular updates to their planning activities, and the use of a land-use planning model in such reporting would permit the model to include both the most recent data and scenarios relevant to recent activities. 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) require attention to the spatial and temporal scale at which each sector operates and how the factors influencing the sectors interact.

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Fig. 1. Study region in west, central Georgia.

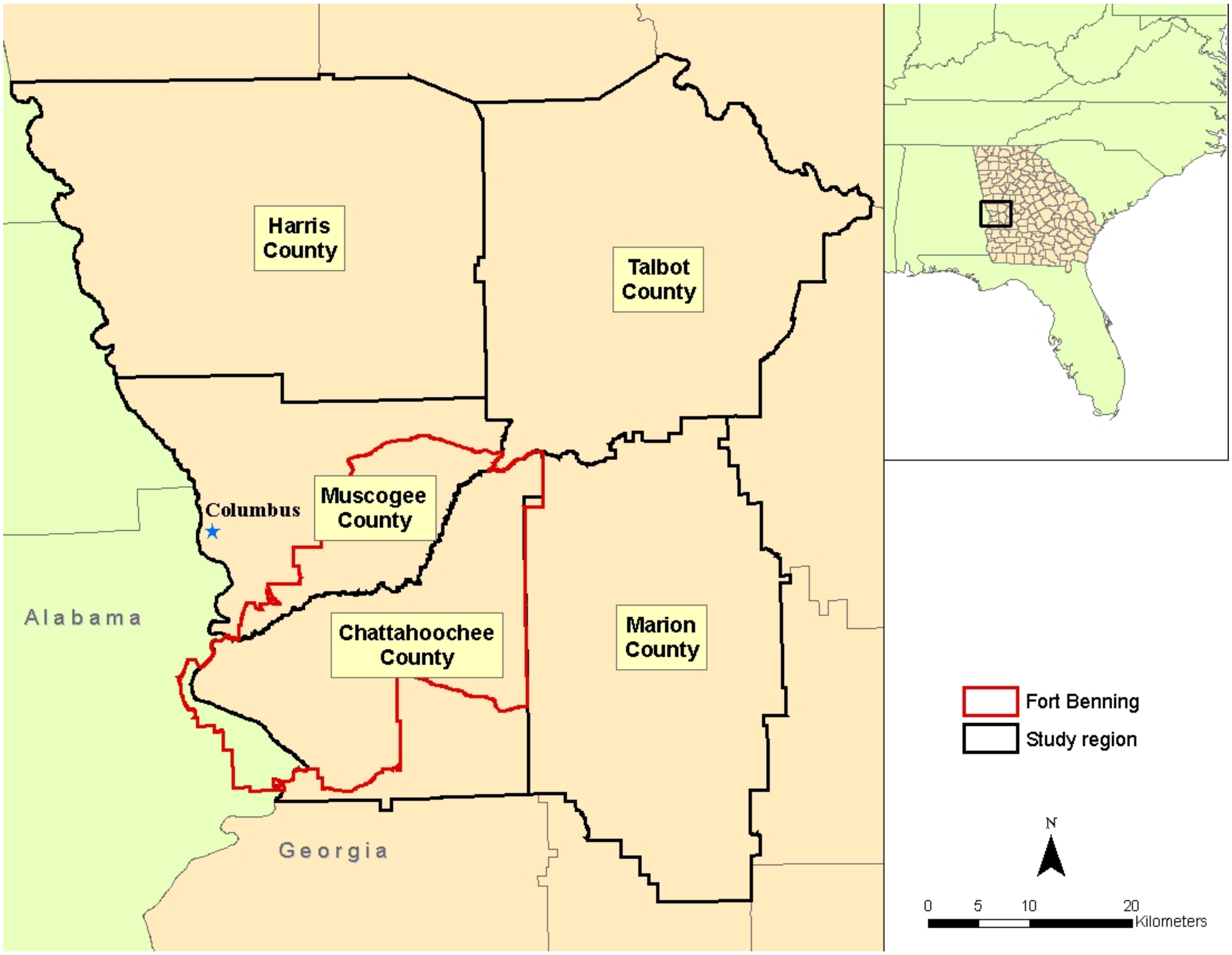


Fig. 2. Diagram of RSim

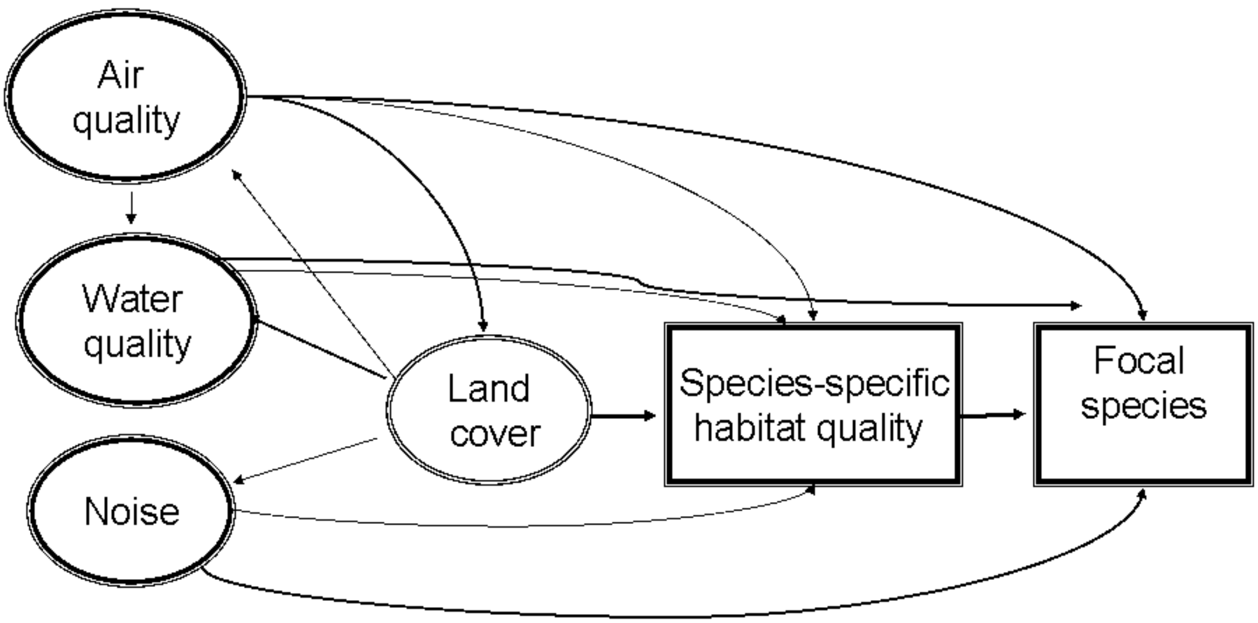


Fig. 3. Map of RSim projected land cover at end of RSim projection time period

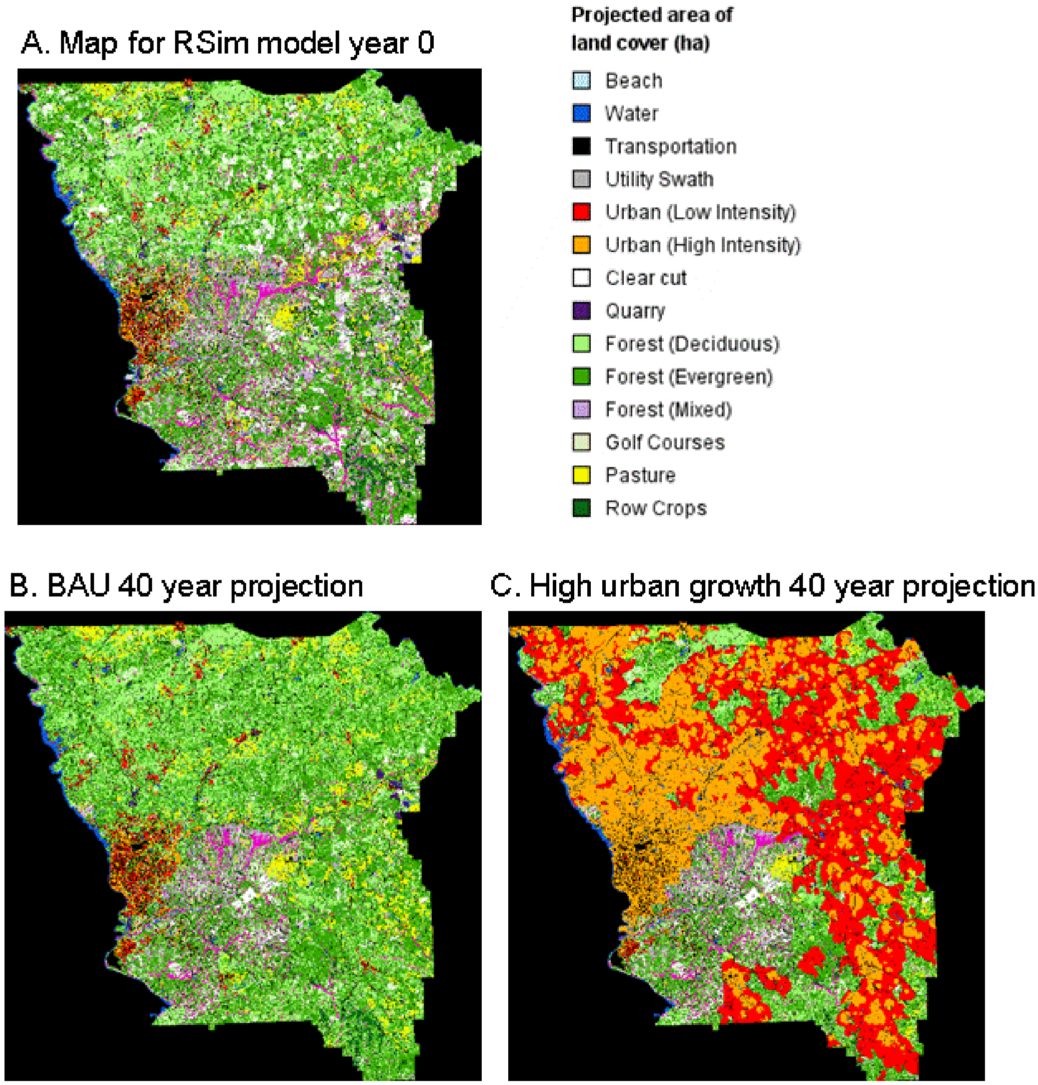


Fig. 4. Graph of changes in urban land cover, pasture and row crops over the 40 year RSim projection for the (A) business as usual (BAU) scenario and (B) the high urban growth scenario.

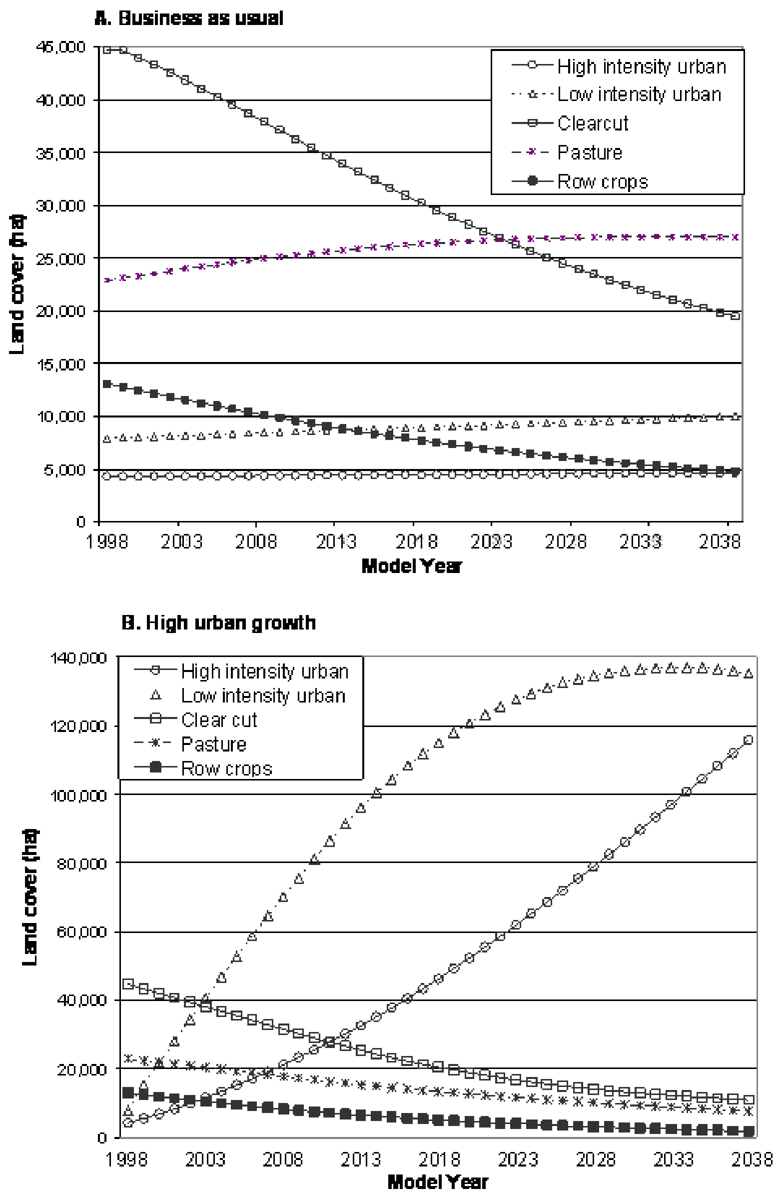


Fig. 5. Graph of changes in forest cover over the 40 year RSim projection for the (A) business as usual (BAU) scenario and (B) the high urban growth scenario.

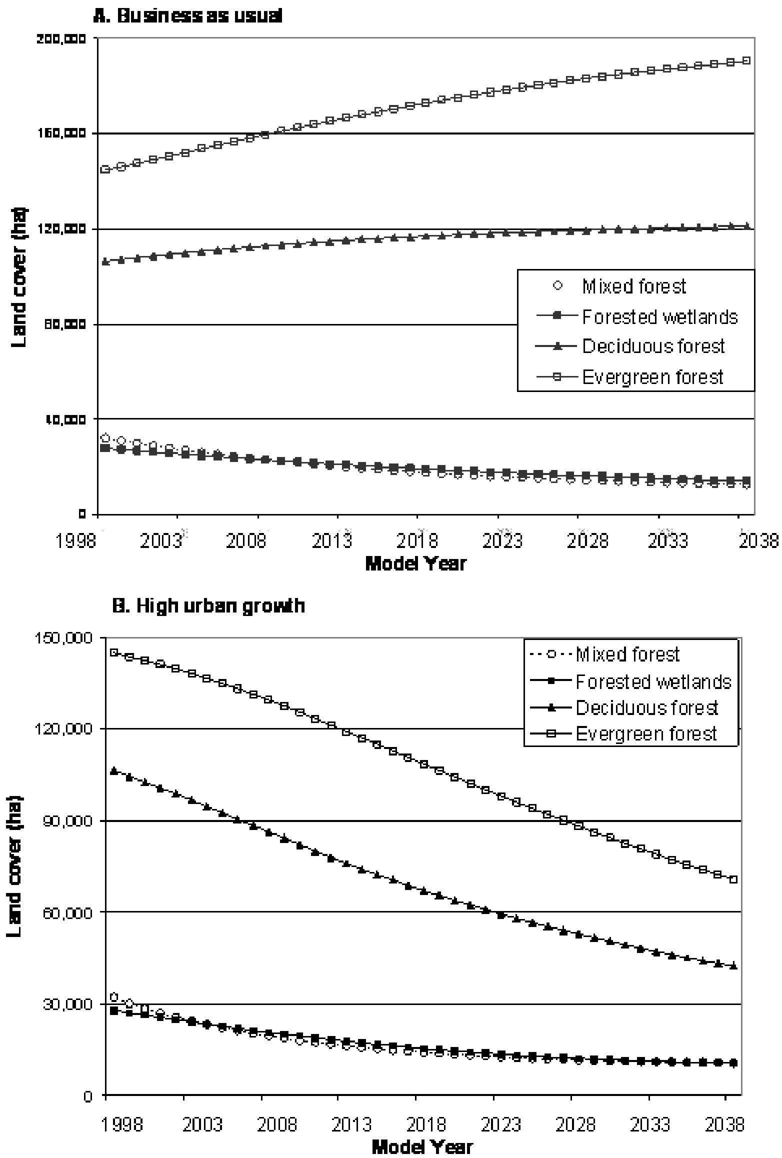
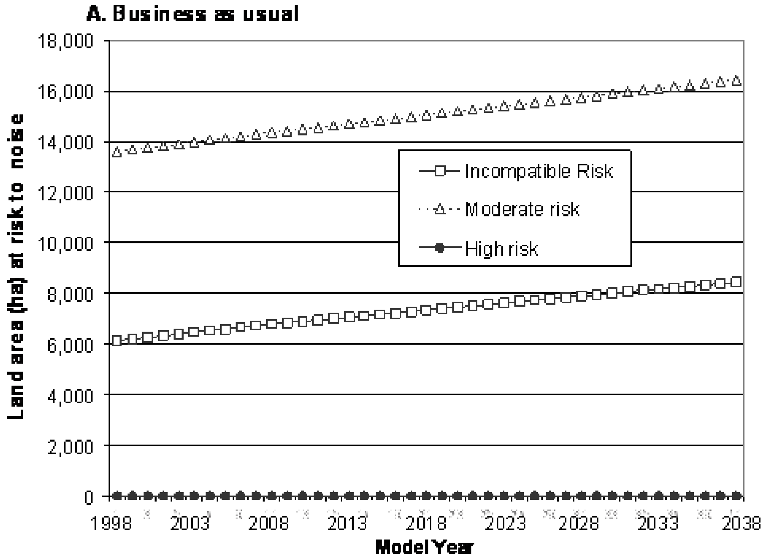
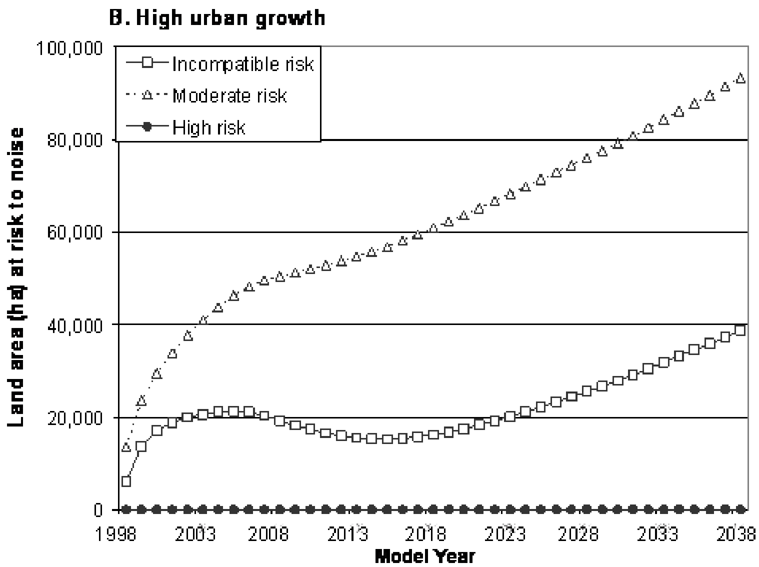


Fig. 6. Land area at moderate or high risk to noise complaints and having incompatible land uses for projected noise risks for the (A) business as usual (BAU) scenario and (B) the high urban growth scenario over the 40 year RSim projection period.





APPENDIX 1. Modules in RSim

A. Modeling land-cover change in RSim

A.1 Modeling urbanization in RSim

RSim simulates changes to urban pixels for 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 (Clarke et al. 1996, Clarke and Gaydos 1998, Candau 2002, http://www.ncgia.ucsb.edu/projects/gig/index.html).

The urban-growth submodel in RSim includes both spontaneous growth of new urban areas and patch growth (growth of preexisting urban patches). RSim generates low-intensity urban areas (e.g., single-family residential areas, schools, city parks, cemeteries, playing fields, and campus-like institutions) and high-intensity urban areas. 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: (1) central business districts, commercial facilities, and highly 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 (2) 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.

The user can influence the pattern and rate of urban growth via changes to several parameters:

- Dispersion (Low): Influences the number of randomly selected cells for possible low-intensity urbanization. For dispersion (low) coefficient dL, a new value DL is computed as DL = (dL * 0.005) * sqrt($r^2 + c^2$), where r and c refer to the number of rows and columns in the land-cover map, respectively. During each time step, DL pixels will be selected at random for attempted low-intensity urbanization. For this and all other rules defining the creation of new low-intensity urban cells, only previously nonurban cells lying outside of urban exclusion zones may be changed to low-intensity urban.

- Dispersion (High): Influences the number of randomly selected cells for possible high-intensity urbanization. For dispersion (high) coefficient dH, a new value DH is computed as DH = (dH * 0.005) * sqrt(r2 + c2), where r and c refer to the number of rows and columns in the land-cover map, respectively. During each time step, DH pixels will be selected at random for attempted high-intensity urbanization. For this and all other rules defining the creation of new high-intensity urban cells, only previously low-intensity urban cells lying outside of urban exclusion zones may be changed to high-intensity urban.

- Breed (Spread): The probability that a spontaneously created (by the above dispersion rule) low-intensity urban cell is chosen to become a potential new spreading center. For each such cell, two of its neighboring cells are randomly selected for new low-intensity urbanization, if possible. A patch of three or more urban cells is considered a spreading center, and is eligible for edge growth, as described below.

- Spread (Low): The probability that a low-intensity urban cell within a spreading center will spawn a new neighboring low-intensity urban cell during any time step. Such growth is also termed edge growth.

- Spread (High): The probability that a high-intensity urban cell within a spreading center will spawn a new neighboring high-intensity urban cell during any time step.

The Sleuth model has been applied to more than 32 urban areas around the world, and the parameters for these model runs are stored at the application web site (http://www.ncgia.ucsb.edu/projects/gig/v2/About/applications.htm). RSim was calibrated to the five-county region surrounding and including Fort Benning by running the model in a hind-cast mode and comparing projections to the U.S. census data.

A.2 Modeling the effects of roads on urban growth in RSim

The road-influenced urbanization module 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 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 because of the lack of a suitable direction or because 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.

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.

A.3 Modeling changes in land-cover types other than urban in RSim

Changes within land-cover types other than urban in the RSim region can affect the potential for cells to be urbanized. Therefore, a brief description of that change process is included here. The annual nonurban land-cover trend was determined by using change-detection procedures that identify changes from one land-cover type to another. Changes to and from urban classes were not considered in the results because 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 nonurban changes were incorporated in the form of a transition matrix from which the transition growth rules were derived. Because forest management activities are different within Fort Benning and the surrounding private lands, the transition rules were calculated separately for Fort Benning and for the area 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 of the five-county study region outside Fort Benning. Within Fort Benning, land-cover data sets from 2001 and 2003 were used to derive the annual transition rules for nonurban land-cover changes.

B. Modules for environmental effects in RSim

RSim was designed to focus explicitly on how changes in land cover affect and are affected by environmental conditions. As such, the following environmental interactions are an integral part of the RSim package.

B.1 The air-quality module

The air-quality module (AQM) of RSim estimates how demographic and economic growth, technology advances, activity change, and land-cover transformations affect ground-level ozone concentrations in the Columbus–Fort Benning area. The AQM is largely based on air-quality computer modeling completed during the Fall Line Air Quality Study (1999–2004) (Chang et al. 2004). Unlike the Fall Line Air Quality Study 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. The RSim AQM estimates the relative change in the concentration of ground-level ozone in the Columbus area caused by changes in transportation, business and industry, construction, military operations, and other human activities. In addition, the AQM simulates effects on vegetation.

RSim draws on the extensive, state-of-the-art, and thoroughly reviewed ozone air quality model simulations of the Fall Line Air Quality Study (FAQS). Therein, an air-quality model was created that accurately represents a historical ozone episode for the Columbus/Fort Benning area in the year 2000. In RSim, future-year changes in human activities (sources) are used together with the FAQS base case to estimate future-year changes in ozone air quality:

$$ozone_t = ozone_{2000} + (\partial ozone/\partial source)\ \Delta Source_{t-2000}$$

In the above equation, sources may change relative to how they were in the year 2000 ($\Delta Source_{t-2000}$), for example, from economic growth in the region or changes in transportation patterns, and these can be controlled by the RSim user. The term ∂ozone/∂source is a sensitivity coefficient that is unique to the source and quantifies how a change in the source, ∂source, affects changes in the concentrations of ozone, ∂ozone. These sensitivity coefficients were calculated outside of RSim and cannot be modified by the user. The description above assumes only one source changes during any given period. As implemented in RSim, the AQM really accounts for multiple changes in many sources throughout the e missions inventory, some of which may exasperate poor air quality and some of which may mitigate poor air quality. Selection of the Default RSim scenario creates a future in which relative changes in emissions sources ($\Delta Source_{t-2000}$) are estimated with growth factors from the U.S. EPA's Emissions Growth Analysis System (EGAS) (US EPA 2004a and2004b).

Ozone can cause foliar damage in trees, crops, and other vegetation as well as other effects. RSim simul ates effects of ozone on vegetation by using the secondary standard for ozone to simulate relative likelihoods of effects of ozone on vegetation. This standard is meant to protect crops and vegetation as well as other aspects of public welfare. The secondary standard for ozone is equivalent to the primary standard, which states that the fourth highest 8-hr ozone concentration cannot exceed 0.08 ppm (parts per million).

B.2 Water quality and nitrogen and phosphorus export

The water-quality module predicts changes in annual nitrogen (N) and phosphorus (P) exports from watersheds within the five-county (Harris, Muscogee, Marion, Chattahoochee, and Talbot) RSim region surrounding Fort Benning. It is widely established that land use and land cover are principal determinants of nutrient export from terrestrial ecosystems to surface receiving waters (Beaulac and Reckhow 1982). 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 by using export coefficients (Johnes 1996, Johnes et al. 1996, Mattikalli and Richards 1996).

Calculations of annual N and P export are performed for the 48 12-digit hydrologic units (HUC) that are included within the RSim region. 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. The area (ha) of each land-cover category is multiplied by its respective export coefficient, 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 3,200 to 12,000 ha.

RSim predictions of N and P exports (kg element yr^{-1}) over time 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.

B.3 Species of special concern

RSim considers effects on the two rare species in the vicinity of Fort Benning: red cockaded woodpecker (*Picoides borealis*) and gopher tortoise (*Gopherus polyphemus*). RSim simulates changes in red cockaded woodpecker (RCW) clusters based on land-cover changes. These clusters primarily occur in mature long leaf pine forest so as land changes from evergreen forest it becomes unsuitable for RCW. In the five-county region, most of the clusters are found within Fort Benning. In December 2005, there were 212 known active and 96 inactive RCW clusters at Fort Benning. According to the FWS biological opinion and the installation RCW management plan, Fort Benning's goal is set at 361 active breeding clusters. RSim reports how this goal is affected by land-cover changes for every year of the projection.

The gopher tortoise habitat module in RSim computes the probability of a suitable gopher tortoise habitat in a region according to a logistic regression model described by Baskaran et al. (2006). The gopher tortoise habitat module of RSim uses land-cover variables, distance to stream and road variables, and clay variables as inputs to derive the probability of finding a gopher tortoise. RSim gives the user the option to further define habitat suitability based on habitat patch size [identified within RSim by using a modification of the Hoshen-Kopelman algorithm (Berry et al. 1994, Constantin et al. 1997)]. Outputs from this module are

- Map of probability of gopher tortoise habitats
- Map of predicted burrow presence/absence
- Table of area of predicted burrows per year

B.4 Noise

Noise from military installations may cause human annoyance outside of installation boundaries. Noise can also affect wildlife. RSim uses estimates of exposure to noise from aspects of military training, namely aircraft overflights, large munitions, and small arms. Noise contour maps are developed from three noise simulation models external to RSim (Operational Noise Program, 2007):

- 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.
- BNOISE projects noise impacts around military ranges where 20-mm or larger weapons are fired and takes into account both the annoyances caused by both impulsive noise and vibration caused by the low-frequency sound of large explosions.
- The Small Arm Range Noise Assessment Model (SARNAM) projects noise impacts around small-arms ranges and accounts for noise attenuated by different combinations of berms, baffles, and range structures.

In the implementation of RSim in the region of Fort Benning, noise contour maps represent blast noise simulated with BNOISE, as well as the negligible noise from small arms, but not aircraft noise. RSim uses these contours to estimate human annoyance and to recommend compatible land uses [i.e., residential development and other land uses associated with low-intensity urban land cover are not compatible with blast noise above 115 dBP (peak decibels)].

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APPENDIX 2. Summary of input conditions and parameters for RSim scenarios reported in paper

Table 2A. Select Scenarios

Land-cover transitions selected?	YES
Military expansion scenario selected?	YES
Hurricane scenario selected?	NO
Number of time steps (yrs)	40

Table 2B. 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 2C. Land-Cover Transitions

(con'd)

	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 2D. Water-Quality-Module Export Coefficients

	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 2E. Air-Quality Conditions

Selected Meteorological Episode	Mild Ozone Episode
Mobile Sources	1.0
Area Sources	1.0
Nonroad Sources	1.0
Point Sources	1.0

Table 2F. Noise Conditions

Noise module selected?	YES

Table 2G. 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