Dale, V. H., F. Akhtar, M. Aldridge, L. Baskaran, M. Berry, M. Browne, M. Chang, R. Efroymson, C. Garten, Jr., E. Lingerfelt, and C. Stewart. 2008. Modeling the effects of land use on the quality of water, air, noise, and habitat for a five-county region in Georgia. *Ecology and Society* **13**(1): 10. [online] URL: http://www.ecologyandsociety.org/vol13/iss1/art10/

Research, part of a Special Feature on Crossing Scales and Disciplines to Achieve Forest Sustainability

Modeling the Effects of Land Use on the Quality of Water, Air, Noise, and Habitat for a Five-County Region in Georgia

Virginia H. Dale, Farhan Akhtar [1], Matthrew Aldridge [2], Latha Baskaran [3], Michael Berry [2], Murray Browne [2], Michael Chang [1], Rebecca Efroymson [3], Charles Garten, Jr. [3], Eric Lingerfelt [2], and Catherine Stewart [4]

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 was designed to simulate these environmental impacts for five counties in Georgia that surround and include Fort Benning. The model combines existing data and modeling approaches to simulate the effects of land-cover changes on: nutrient export by hydrological unit; peak 8-h average ozone concentrations; noise 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 urbanization influenced by existing roads, nonurban land cover transitions, and a new military training area under development at Fort Benning. The model was run under scenarios of business as usual (BAU) and greatly increased urban growth for the region. The projections show that the effects of high urban growth will likely differ from those of BAU for noise and nitrogen and phosphorus loadings to surface water, but not for peak airborne ozone concentrations, at least in the absence of associated increases in industry and transportation use or technology changes. In both scenarios, no effects of urban growth are anticipated for existing populations of the federally endangered Red-cockaded Woodpecker. In contrast, habitat for gopher tortoise in the five-county region is projected to decline by 5 and 40% in the BAU and high urban growth scenarios, respectively. RSim is designed to assess the relative environmental impacts of planned activities both inside and outside military installations and to address concerns related to encroachment and transboundary influences.

Key Words: *gopher tortoise; land use; landscape change; longleaf 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 that are affected by land-use change. Because these drivers and the factors that influence these processes change over space because of variation in features such as topography, climate, and human activities, it is important to consider their influence in a spatial context to understand the full range and extent of the 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.

In addition, there is a need to examine how environmental impacts can change across several stressors, environmental media, and sectors, for example, water, air, noise, and habitats for species of special concern. Although environmental laws typically segregate these impacts in the ways in which they are both reported and managed, such an artificial division can lead to inadequate understanding and hence to 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 a focus on only one sector, rather than 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

[1]Georgia Institute of Technology, [2]University of Tennessee, [3]Oak Ridge National Laboratory, [4]Aberdeen Proving Ground

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 to use a spatial approach to environmental change. The undertaking of a regional and cross-sectoral approach to the study of environmental change requires the determination of the appropriate spatial and temporal scales of resolution and the consideration of potential feedbacks across sectors. One of the goals in such a multisector approach is to provide a means to fully understand the key components of the system, including possible cumulative impacts.

Here, we propose a regional, cross-sectoral approach to examining land-use changes and their effects and present an example of its application to a five-county region in west central Georgia, USA. We focus on the region of Georgia around and inclusive of Fort Benning for three reasons: large quantities of data are available; the region will undergo dramatic changes in the future as the military training activities and the many people that support them at Fort Knox, Kentucky, are moved to Fort Benning; and military land, on which urban growth is restricted, serves as a control against which changes on private lands can be compared. The Regional Simulator (RSim) model has been developed for this five-county region and has the ability to project future changes in the quality of water, air, and habitat, and in noise (Dale et al. 2006). This 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 to apply 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 allowing the application of ecosystem management approaches to military lands and surrounding regions. We examined relative changes that resulted from two scenarios: “business as usual” 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.

We also address the issue of forest sustainability because the study region was originally dominated by longleaf pine (*Pinus palustris*) forest, and it is the continuance of the pine forest that allows the attainment of many other environmental goals for the region. Without the forest, some of the other environmental amenities such as wildlife habitat cannot be maintained. The 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).

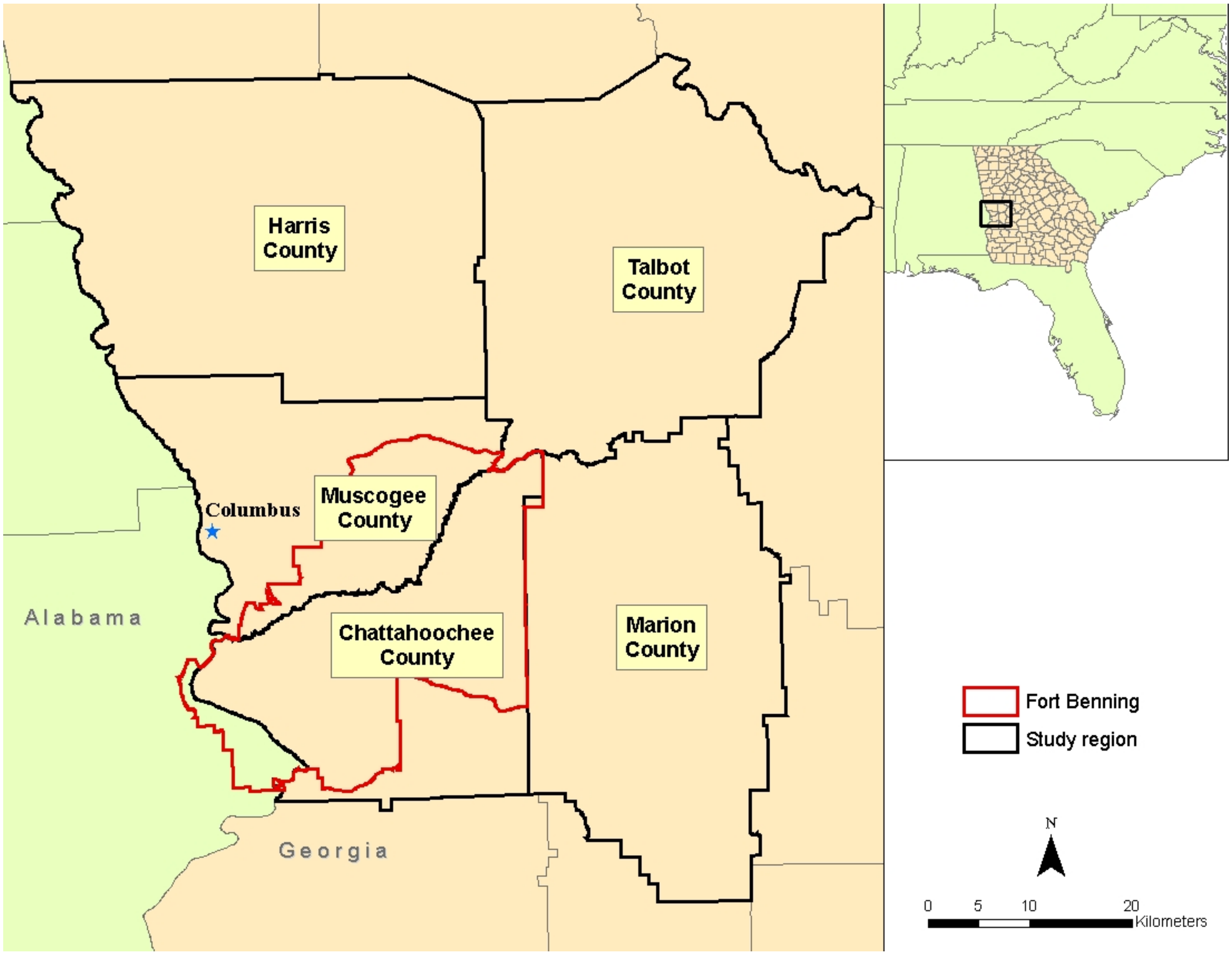
METHODS

Study area

The study area for model development and application was a five-county region in west central Georgia, USA (Fig. 1). This region surrounded and included most of the 73,503-ha Fort Benning military installation, which supports both a cantonment (area of extensive infrastructure) and undeveloped areas that are used for training and in which the forest structure supports various environmental amenities. Fort Benning military activities include the training of entry-level soldiers, Infantry, and Airborne and Ranger candidates. In addition to ranges for munitions training, the installation supports expansive pine forest that 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 currently support mature stands of longleaf pine and several rare species of plant and animal.

Because of land-use change and fire suppression throughout the southeastern United States, only approximately 4% of the original longleaf pine forest exists today; 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 longleaf 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 is protected from low-intensity fire by a lush bunch of needles. A subsequent bolt of

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



growth in the sapling moves the meristem to a height above that of ground fires, assuming that fires occur frequently enough that they are of low intensity. In the 1994 Guidelines for the Management of Red-cockaded Woodpecker on Army Lands (as cited by Beaty et al. 2003), the U.S. Army, in cooperation with the U.S. 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 longleaf pine trees. Controlled burning not only allows for the reestablishment of longleaf pine seedlings, it also reduces the ingrowth of hardwood trees in the forest.

The study region also included 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 was part of the study area. Major nonurban land uses of the five-county region are 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 had significant industrial development and intense use of fossil-fuel-based vehicles, both of which contribute to air pollution. Burning for the maintenance of longleaf pine habitat also affects air quality and soil conditions (Garten 2006). Training areas within the military installation produce loud noises as a result of small-arms activity, the firing of large-caliber arms, and military aircraft. Water quality in the region is affected by industrial activity and agricultural practices that induce runoff and required fertilizer use. In addition, the habitat of two key rare species, i.e., Red-cockaded Woodpecker and gopher tortoise (*Gopherus polyphemus*), can be affected by land-use practices and underlying conditions on the land (Boglioli et al. 2000, Hermann et al. 2002).

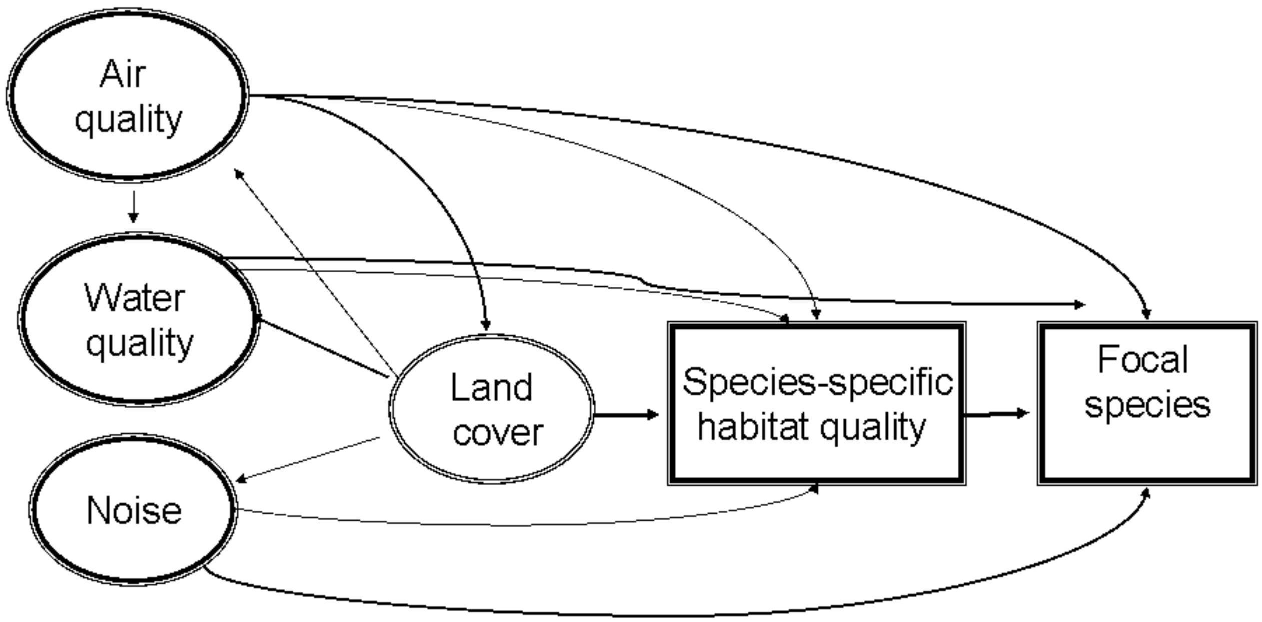
Simulating cross-sectoral environmental changes in the region

Because resource managers need to protect multiple aspects of the environmental quality of a region, the Regional Simulator (RSim) model was developed as a tool to integrate changes in a region for conditions relating to water, air, noise, and habitat (Fig. 2; Dale et al. 2006). The basic spatial unit of RSim is a 30-m pixel because most of the underlying data in the model are derived from satellite imagery reported at that scale of resolution. After much consideration, the basic time step of RSim was set to 1 yr because changes in land cover are typically reported at annual intervals. This choice means that all of the environmental changes projected by RSim are reported annually.

Where possible, RSim was built from existing models and data (Appendix 1). Urban growth in RSim is based on the SLEUTH model (Clarke et al. 1997, Clarke and Gaydos 1998, Candau 2002) supplemented by rules for low-intensity to high-intensity urbanization. Transitions for nonurban land cover are based on changes observed in the five-county region from 1990 to 1998 (Baskaran et al. 2006*b*). 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 nitrogen and phosphorus 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 as part of the Fort Benning Installation Environmental Noise Management Plan (Operational Noise Program 2007). RSim builds upon noise guideline levels that were developed by the military under the U.S. Army's Environmental Noise Program (U.S. Army 1997). RSim contains noise contour maps resulting from artillery, as projected by the Department of Defense noise simulation model BNOISE, because artillery is the greatest source of noise at Fort Benning. This approach produces noise contours that identify areas where noise levels are compatible or incompatible with noise-sensitive land uses outside of Fort Benning. The U.S. 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 estimates the effect of emissions changes on ozone air quality using sensitivity coefficients available from Chang et al. (2004). The measure of ozone air quality is based on the U.S. Environmental Protection Agency's Clean Air 8-h Ground-level Ozone rule, which designates areas in which 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 is healthy in a given area and is not designed to convey effects on plant physiology or productivity or at different temporal resolutions. The module to predict habitat for Red-cockaded Woodpecker was developed on the basis of spatial data for longleaf pine in the region (Appendix 2). The module to predict habitat for gopher tortoise was developed on the basis of an analysis of locations of gopher tortoise burrows at Fort Benning and was tested for the larger five-county region (Baskaran et al. 2006*a*).

Numerous future scenarios can be modeled using RSim, including both civilian and military land-cover changes. Our implementation of RSim included four specific types of scenario along with their effects on environmental conditions over the next decades: urbanization, i.e., the conversion of nonurban land cover to low-intensity urban land cover and the conversion of low-intensity urban land cover to high-intensity urban land cover; planned road expansion plus modeled urbanization; a new training area at Fort Benning; and hurricanes of various intensity. Low-intensity urban land cover included single-family-dwelling residential areas, schools, city parks, cemeteries, playing fields, and campus-like institutions. High-intensity urban land cover included paved areas with buildings and little vegetation, power substations, and occasionally grain storage buildings.

Fig. 2. Schematic diagram of the Regional Simulation model.



For the case considered here, RSim was run under conditions meant to simulate business-as-usual (BAU) urbanization for 40 yr into the future from 1998 compared to great increases in urban growth (see Appendix 2 for input conditions). The BAU case included 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 the development of four-lane highways in the region. The high-growth scenario was identical except for an increase in urban growth starting in 1998. This scenario was meant to simulate changes in urban growth in 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. 2006), no one has yet published an analysis of how these changes might affect land cover and other environmental conditions.

RESULTS

Land cover

Based on the conditions and scenarios selected, the Regional Simulation (RSim) model was used to project changes in land cover (Figs. 3–5). The business as usual (BAU) case resulted in a slight increase in the area of land under high-intensity urban cover (from 4329 to 4662 ha) and a great increase in land under low-intensity urban cover (from 7914 to 10,053 ha). Land on which timber had been cleared declined sharply from 44,735 to 20,317 ha, and row crops decreased from 11,101 to 4876 ha. Pasture lands increased from 22,886 to 27,147 ha.

The high urban growth and BAU scenarios resulted in different patterns of change in urban and agricultural lands (Fig. 4A, B). The high-growth case resulted in a great increase in the area of land under both high-intensity urban cover (from 4329 to 115,789 ha) and low-intensity urban cover (from 7914 to 135,247 ha). Clearcut land declined from 44,735 to 10,963 ha, and row crops decreased from 13,101 to 1837 ha. Contrary to the BAU case, pasture lands declined from 22,886 to 7779 ha.

Forest cover changed in the BAU scenario (Fig. 5A). Both mixed forest and forested wetlands declined from 32,145 to 12,775 ha and from 27,933 to 14,310 ha, respectively. Deciduous forest and evergreen forest both increased in area from 106,439 to 118,880 ha and from 144,905 to 191,419 ha, respectively. In comparison, forest cover had quite a different pattern of change over the next 40 yr for the high urban growth scenario (Fig. 5B). All of the common forest categories declined, with mixed forest changing from 32,145 to 10,765 ha, forested wetlands from 27,933 to 10,561 ha, deciduous forest from 106,439 to 42,488 ha, and evergreen forest from 144,905 to 70,911 ha.

Water quality

The water quality module projected large differences in the amount and location of major nitrogen (N) and phosphorus (P) export for the BAU scenario compared to the high urban growth scenario. In the BAU case, the greatest changes in N and P exports occurred in the watershed containing the city of Columbus (Hydrological Unit Code [HUC] 30104). In contrast, in the high urban growth scenario, the watershed northeast of Columbus (HUC 21206) had the greatest changes in these exports. The overall change in N export for the RSim region was 1.0×10^6 and 1.6×10^6 kg for the BAU and high urban growth scenarios, respectively. The overall change in P export was 1.6×10^5 and 3.7×10^5 kg for the BAU and high-growth scenarios, respectively.

Air quality

In both scenarios, the peak 8-h 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 the results of the two scenarios, the additional changes in the high urban growth scenario, which are over and above those in the BAU scenario, did not yield any additional changes to the estimated change in peak 8-h ozone concentration over the five-county region. It should be noted, however, that the peak 8-h ozone concentration is but one measure of air quality. Other metrics, for example, those that measure the dose or temporal or spatial distribution of ozone, might, in fact, show differences in air quality between the two scenarios. Regardless, over the 40 yr, the increase in the peak 8-h ozone concentration from 71 to 90 ppbv was caused by the projected growth in industrial, commercial, and transportation activity. Growth in both scenarios, though, was untempered by any future regulatory controls, technological innovations, or air quality management decisions. For context, the peak 8-h 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 projected 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 would be located in evergreen forest within the boundaries of Fort Benning; these forest stands mature to the stage at which they can support Red-cockaded Woodpecker by the end of the 40-yr model run. This quantity of new active breeding clusters would meet the U.S. Fish and Wildlife Service’s goal of 361 active clusters for Fort Benning (Beaty et al. 2003).

Fig. 3. Maps of land cover projected by the Regional Simulator (RSim) model at the end of the projection time period.

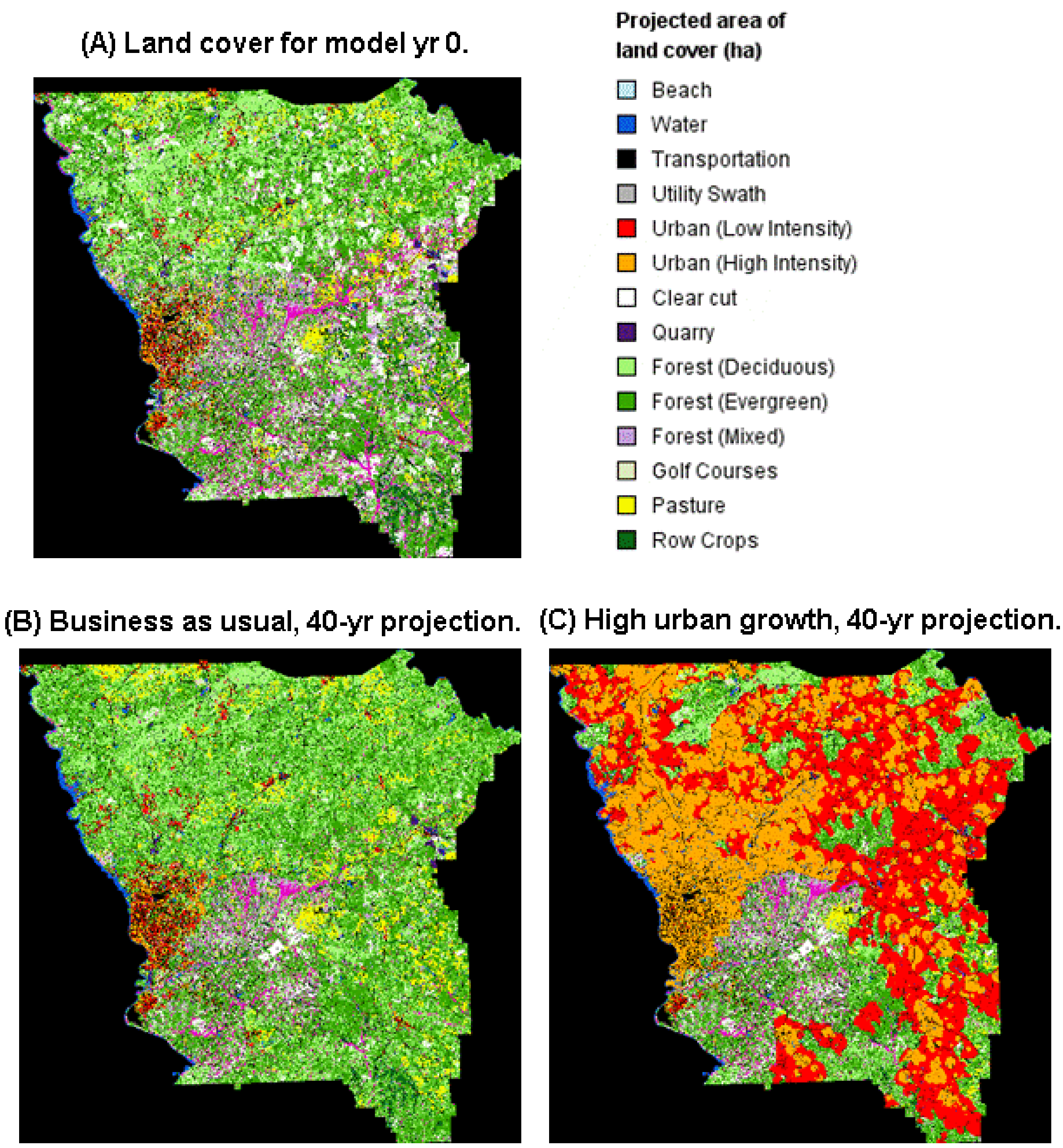


Fig. 4. Projected changes in urban land cover, pasture, and row crops over 40 yr for the (A) business as usual scenario and (B) high urban growth scenario.

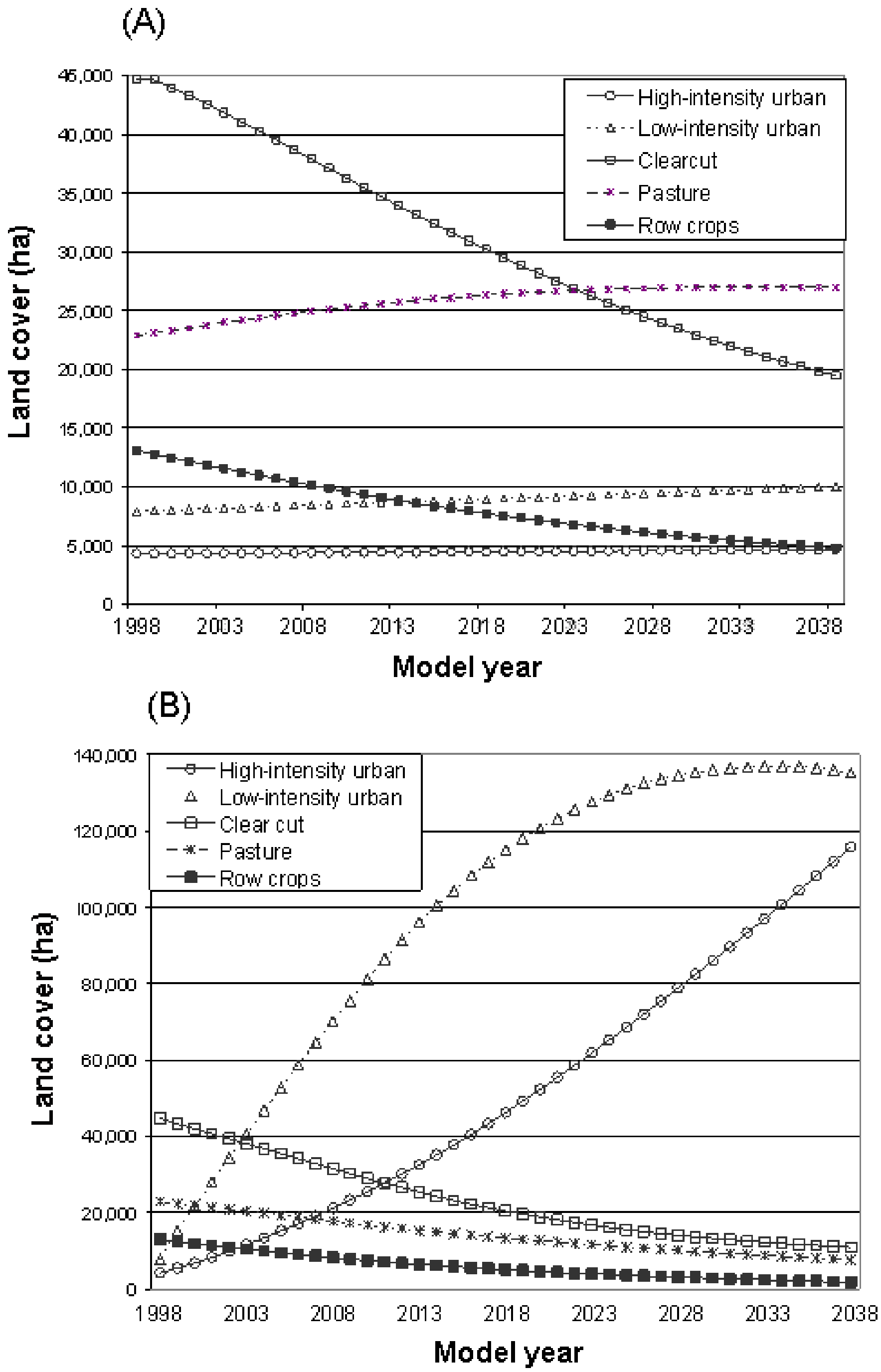
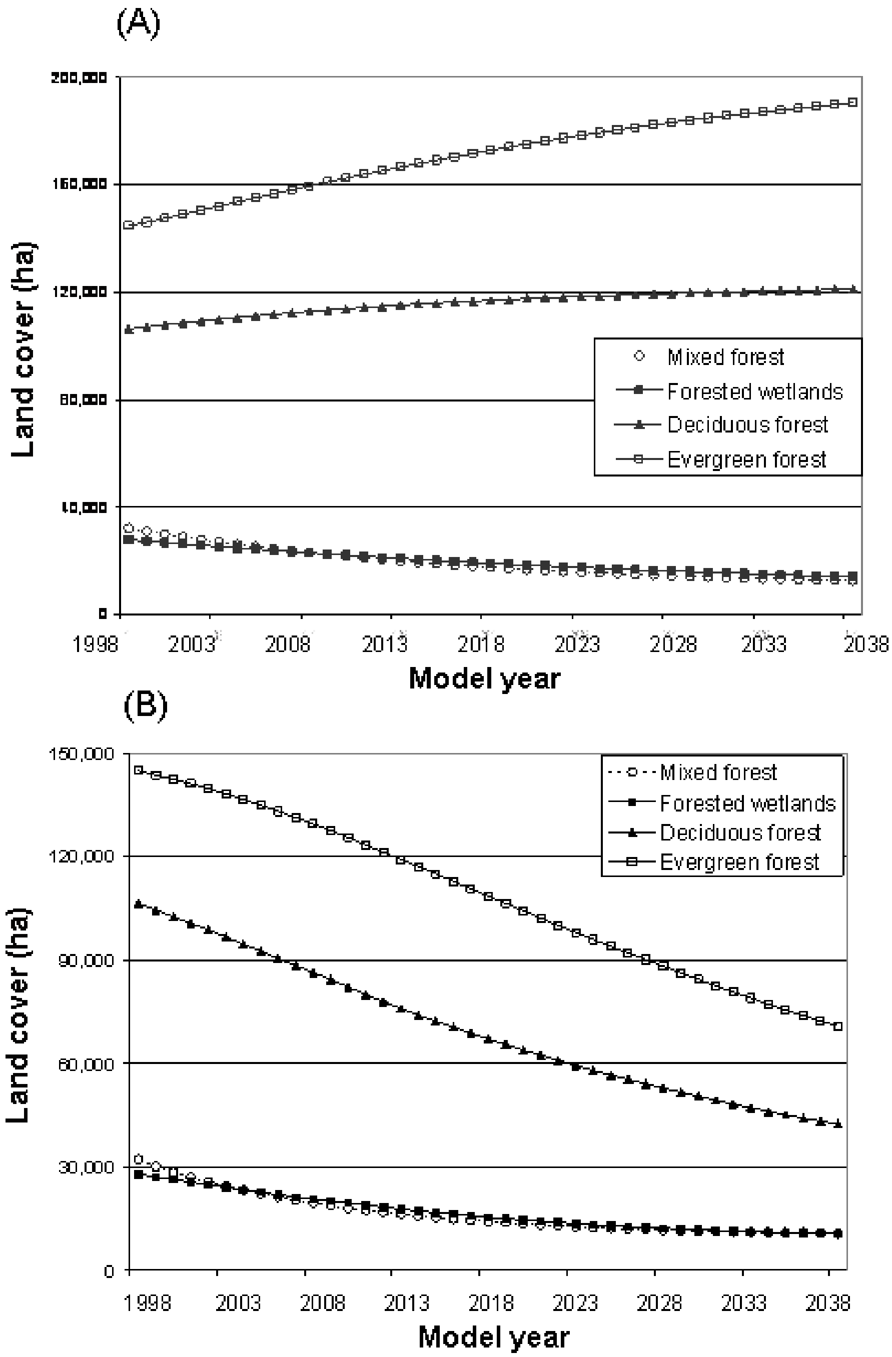


Fig. 5. Projected changes in forest cover over 40 yr for the (A) business as usual scenario and (B) high urban growth scenario.



Gopher tortoise

RSim projected that by model year 2038, there will be 181,288 and 113,639 ha of potential area of suitable gopher tortoise habitat for the BAU and high urban growth scenarios, respectively. In comparison, there was 190,918 ha of gopher tortoise habitat in the five-county region at the beginning of the simulation. The 5 and 40% reductions in potential area that can support gopher tortoise burrows reflect changes in land cover under the BAU and high urban growth scenarios, respectively. The probability of the presence of suitable gopher tortoise habitat increases when more land cover is used as pasture, clearcuts, forest, transportation corridors, row crops, or utility swaths.

Noise

For the two scenarios, the land-cover changes combined to produce different patterns of risk from noise (Fig. 6A, B). There was a moderate risk of noise complaints from areas of 6334 and 93,448 ha outside Fort Benning for the BAU and high urban growth scenarios, respectively. The areas that are likely to experience a high risk of noise complaints were relatively small in both scenarios, with 9 and 61 ha likely by 2038 for the BAU and high urban growth scenarios, respectively. RSim projected that by 2038 for the BAU and high urban growth scenarios, 8335 and 38,773 ha, respectively, of land outside of Fort Benning will be in land uses that are incompatible with noise produced from military activity.

DISCUSSION

The projected changes in land cover under the two scenarios are quite different (Figs. 4 and 5). The business as usual (BAU) case had only small changes in the urban land cover types. A sharp decline in clearcut land and a more gradual decline in row crops occurred as pasture and urban land cover increased in area. At the same time, evergreen and deciduous forest land increased in the region. In contrast, the sharp increase in high-intensity urban land cover under the high urban growth scenario is associated with a decline in all of the aforementioned land cover types. These alterations in land cover type set the stage for changes in some of the other environmental conditions.

Changes in nitrogen (N) and phosphorus (P) export to streams over the 40-yr 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 yr than does any other watershed in the region because it continues to be the center of high urban intensity. Columbus is currently the largest city in the five-county area, and in 1998, it had the greatest concentration of urban land cover in the region. The high proportion of urban land in Columbus is related to a high proportion of paved areas, which allow runoff and industrial inputs of N and P into the water system. Over the 40-yr projection, no land-cover changes in the rural or forested landscape were 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 urban growth scenario, intense urban development shifts to the northeast of Columbus (i.e., to Hydrological Unit Code 21206). This difference between 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.

Both scenarios resulted in similar air quality changes projected from land-cover changes in the five-county region. There are two principal ways in which forest cover can affect air quality, and both are represented in the Regional Simulator (RSim) model. 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. The removal of anthropogenic sources of hydrocarbons under any conceivable scenario (or the addition of more, for that matter) has no significant effect on ozone concentration. 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) from either burning activity in the forest or activities associated with logging or otherwise managing or using the forest (e.g., chainsaws, trucks, and all-terrain vehicles). Estimates of all of these contributions are included in the RSim current emissions inventory. However, forest-related emissions are only a small part of the total emissions inventory, and they have scant effects on the peak ozone concentration in the region, which is what RSim calculates and is the variable that is generally related to human health and vegetation growth. Further, unless the changes in forest emissions collocate with the place where the peak ozone concentration occurs, which is unlikely because the peak pollutant concentrations tend to occur near the urban areas where the more intense emissions sources are located, an effect on ozone concentration 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-h ozone concentrations produced by land-cover changes. Conversely, it is expected that air quality does affect land cover. Although this direct feedback loop has not yet been implemented in RSim, users should be aware that for both scenarios, the model projected that concentrations of ozone will exceed the secondary ozone standard that is protective of vegetation for 34 yr of the 40-yr projection period. Consequently, adverse effects on vegetation should be assumed.

The habitats for the two species that were included in the RSim model responded quite differently to projected changes in land cover under the two scenarios. The number of clusters of Red-cockaded Woodpecker had few differences between the two scenarios because almost all of the clusters are located in military lands that were not subject to urban expansion. In contrast, the habitat of gopher tortoise was strongly affected in the high urban growth scenario because that case instigates a change in several land cover types that are suitable for gopher tortoise. In the BAU case, clearcut lands undergo a steady decline from 44,735 to 20,317 ha; in contrast, in the high urban growth scenario, clearcut lands decline to approximately 10,963 ha. At the same time, pasture lands were projected to increase from approximately 22,890 to 27,150 ha in the BAU scenario, but to decline to 7800 ha in the high urban growth scenario. The decline in both clearcut and pasture lands that resulted from high urban growth reduced the amount of area suitable for gopher tortoise habitat.

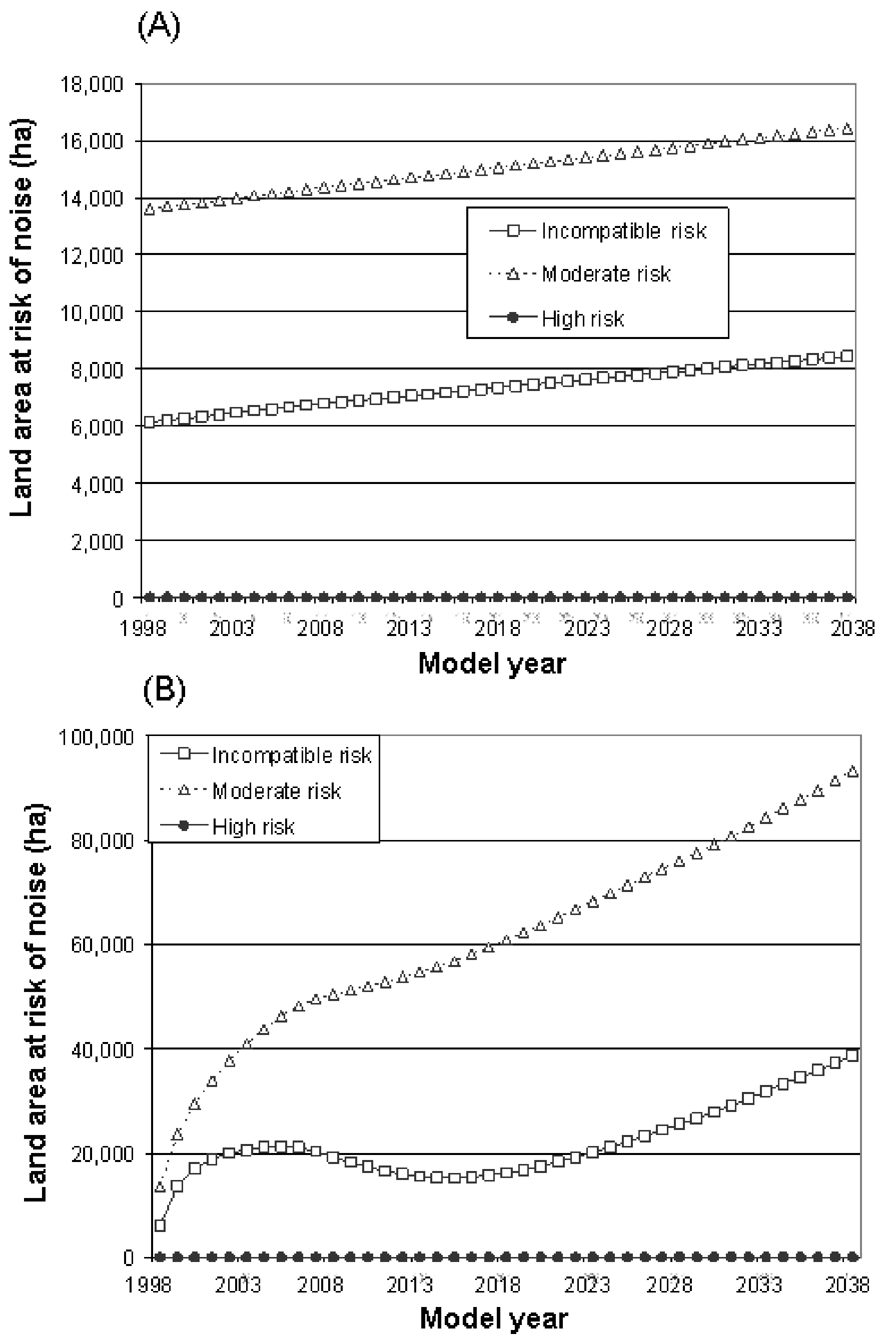
The projected risk from noise is very different under the two scenarios (Fig. 6). The BAU case was associated with a slight increase in lands with moderate risk from noise and incompatible land use. In contrast, the high urban growth scenario projected dramatic increases in the area of land with moderate 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 areas of land in high- and low-intensity urban categories approach similar values (Fig. 4). Before 2008, both urban land types contribute to noise risk, but the declining area of residential land after 2008 causes the noise risk to decline as well for a short period until the influence of the increasing high-intensity urban land causes another increase in the noise risk. The location of these new urban lands near the boundary of Fort Benning (Fig. 3) and within the range of noise effects is another factor that affects the sharp increase in risk from noise.

This regional, cross-sectoral analysis of the environmental effects of land-use change in west central Georgia illustrates some of the benefits of using such a holistic approach to land-use planning. A broad 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 promotes the discussion of and planning for on-the-ground repercussions of decision making. In addition, the simulation model identifies conditions under which cross-sectoral effects should be considered. For example, in the scenarios presented here, effects 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 uses or in technology changes, the effects of land-use changes on air quality are small. The use of the RSim model enhances the understanding of interactions between environmental effects (i.e., feedbacks and cumulative effects) and therefore allows for a greater understanding of the conditions necessary to sustain the various environmental amenities of the region.

CONCLUSIONS

The use of the Regional Simulator model to explore regional changes in west central Georgia, USA, projects that high urban growth can have dramatic effects on water and noise quality and on the habitat of one species of special concern, the gopher tortoise, but not another, the Red-cockaded Woodpecker. Hence, this example illustrates how management attention might be focused to promote

Fig. 6. Projected changes in land area at moderate or high risk of noise complaints and with incompatible land uses for the projected noise risk for the (A) business as usual scenario and (B) high urban growth scenario over the 40-yr projection period.



the 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 allow 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 the effects of land-use change in several sectors (i.e., air, water, noise, and habitat) requires that attention be paid to the spatial and temporal scales at which each sector operates and how the factors affecting the sectors interact.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol13/iss1/art10/responses/

Acknowledgments:

The assistance of Rusty Bufford with spatial data and Robert Addington, Thomas A. Greene, Wade Harrison, Robert Larimore, and Pete Swiderick with other information is appreciated. Hugh Westbury provided important logistic support. Discussions with Hal Balbach, John Brent, William Goran, Robert Holst, Don Imm, and Lee Mulkey were also quite helpful in implementing this project. The project was funded by a contract from the Strategic Environmental Research and Development Program (SERDP) project CS-1259 to Oak Ridge National Laboratory. Oak Ridge National Laboratory is managed by the UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

LITERATURE CITED

Baskaran, L. M., V. H. Dale, R. A. Efroymson, and W. Birkhead. 2006*a*. Habitat modeling within a regional context: an example using gopher tortoise. *American Midland Naturalist* **155** (2):335-351.

Baskaran, L., V. Dale, C. Garten, D. Vogt, C. Rizy, R. Efroymson, M. Aldridge, M. Berry, M. Browne, E. Lingerfelt, F. Akhtar, M. Chang, and C. Stewart. 2006*b*. Estimating land-cover change in RSim: problems and constraints. *Proceedings of the American Society for Photogrammetry and Remote Sensing 2006 Conference,* Reno, Nevada, May 1-5, 2006.

Beaty, T. A., A. E. Bivings, T. Reid, T. L. Myers, S. D. Parris, R. Costa, T. J. Hayden, T. E. Ayers, S. M. Farley, and W. W. Woodson. 2003. Success of the Army's 1996 red-cockaded management guidelines. *Federal Facilities Environmental Journal* **14**(1):43-53.

Beaulac, M. N., and K. H. Reckhow. 1982. An examination of land use–nutrient export relationships. *Journal of the American Water Resources Association* **18**(6):1013-1024.

Berry, M., J. Comiskey, and K. Minser. 1994. Parallel analysis of clusters in landscape ecology. IEEE Computational Science and Engineering **1** (2):24-38.

Boglioli, M. D., W. K. Michener, and C. Guyer. 2000. Habitat selection and modification by the gopher tortoise, *Gopherus polyphemus,* in Georgia longleaf pine forest. *Chelonian Conservation and Biology* **3**(4):699-705.

Candau, J. T. 2002. Temporal calibration sensitivity of the SLEUTH urban growth model. Thesis. University of California, Santa Barbara, California, USA.

Chang, M. E., A. Russell, and K. Baumann. 2004. *Fall line air quality study (FAQS) final report: an analysis of air quality and options for managing it in middle Georgia.* Georgia Institute of Technology, Atlanta, Georgia, USA. Available online at: http://cure.eas.gatech.edu/faqs/finalreport/.

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

Clarke, K. C., S. Hoppen, and L. Gaydos. 1997. A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B* **24**(2):247-261.

Constantin, J. M., M. W. Berry, and B. T. Vander Zanden. 1997. Parallelization of the Hoshen-Kopelman algorithm using a finite state machine. *International Journal of Supercomputer Applications* **11**(1):34-48.

Dale, V., M. Aldridge, T. Arthur, L. Baskaran, M. Berry, M. Chang, R. Efroymson, C. Garten, C. Stewart, and R. Washington-Allen. 2006. Bioregional planning in central Georgia, USA. *Futures* **38**(4):471-489.

Efroymson, R. A., V. H. Dale, L. M. Baskaran, M. Chang, M. Aldridge, and M. W. Berry. 2005. Planning transboundary ecological risk assessments at military installations. *Human and Ecological Risk Assessment* **11**(6):1193-1215.

Garten, Jr., C. T. 2006. Predicted effects of prescribed burning and harvesting on forest recovery and sustainability in southwest Georgia, USA. *Journal of Environmental Management* **81**(4):323-332.

Gilliam, F. S., and W. J. Platt. 1999. Effects of long-term fire exclusion on tree species composition and stand structure in an old-growth *Pinus palustris* (longleaf pine) forest. *Plant Ecology* **140**(1):15-26.

Hermann, S. M., C. Guyer, J. H. Waddle, and M. G. Nelms. 2002. Sampling on private property to evaluate population status and effects of land use practices on the gopher tortoise, *Gopherus polyphemus. Biological Conservation* **108**(3):289-298.

Johnes, P. J. 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. *Journal of Hydrology* **183**(3-4):323-349.

Johnes, P., B. Moss, and G. Phillips. 1996. The determination of total nitrogen and total phosphorus concentrations in freshwaters from land use, stock headage and population data: testing of a model for use in conservation and water quality management. *Freshwater Biology* **36**(2):451-473.

Mattikalli, N. M., and K. S. Richards. 1996. Estimation of surface water quality changes in response to land use change: application of the export coefficient model using remote sensing and geographical information system. *Journal of Environmental Management* **48**(3):263-282.

Munns, Jr., W. R. 2006. Assessing risks to wildlife populations from multiple stressors: overview of the problem and research needs. *Ecology and Society* **11**(1): 23. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art23/.

Operational Noise Program. 2007. *How is noise modeled?* U.S. Army Center for Health Promotion and Preventive Medicine, Aberdeen Proving Ground, Maryland, USA. Available online at: http://chppm-www.apgea.army.mil/dehe/morenoise/TriServiceNoise/document/model.pdf.

Turner, M. G., R. H. Garner, and R. V. O'Neill. 2001. *Landscape ecology in theory and practice: pattern and process.* Springer, New York, New York, USA.

U.S. Army. 1997. *Army regulation 200-1. Environmental protection and enhancement.* Department of the Army, Washington, D.C., USA. Available online at: http://usmilitary.about.com/gi/dynamic/offsite.htm?site=http://www.usapa.army.mil/pdffiles/r200%5F1.pdf.

U.S. Environmental Protection Agency. 2004. *EGAS version 5.0 beta.* U.S. Environmental Protection Agency, Washington, D.C., USA. Available online at: http://www.epa.gov/ttn/ecas/egas5.htm.

Appendix 1. Modules used in the Regional Simulatior.

A. Modeling land-cover change in the Regional Simulator

A.1 Modeling urbanization in the Regional Simulator

The Regional Simulator (RSim) simulates changes to urban pixels for land cover maps for the five-county region around Fort Benning, Georgia, USA. 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. 1997, 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-dwelling 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, new spreading center, and edge growth. First, an exclusion layer is referenced to determine the 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 pixels will be urbanized if they do not fall within 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 pixels according to different rules for two types of desired high-intensity urban pixels: (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 pixels; and (2) industrial facilities and commercial facilities (malls) that are created at the edge of the existing clumped areas of mostly low-intensity urban pixels 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): This parameter influences the number of randomly selected pixels for possible low-intensity urbanization. For dispersion (low) coefficient dL, a new DL value is computed as DL = (dL × 0.005) × sqrt($r^2 + c^2$), where r and c are the number of rows and columns in the land-cover map, respectively. During each time step, DL pixels are selected at random for attempted low-intensity urbanization. For this and all other rules defining the creation of new low-intensity urban pixels, only previously nonurban pixels lying outside urban exclusion zones may be changed to low-intensity urban;

- Dispersion (high): This parameter influences the number of randomly selected pixels for possible high-intensity urbanization. For dispersion (high) coefficient dH, a new DH value is computed as DH = (dH × 0.005) × sqrt($r^2 + c^2$), where r and c are 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 pixels, only previously low-intensity urban pixels lying outside urban exclusion zones may be changed to high-intensity urban;

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

- Spread (low): This parameter indicates the probability that a low-intensity urban pixel within a spreading center will spawn a new neighboring low-intensity urban pixel during any time step. Such growth is also termed edge growth;

- Spread (high): This parameter indicates the probability that a high-intensity urban pixel within a spreading center will spawn a new neighboring high-intensity urban pixel during any time step.

The SLEUTH model has been applied to more than 32 urban areas around the world. The parameters for these model runs are stored at the application's website (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 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 that 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 pixel, 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 pixels with a probability defined by a breed coefficient for each pixel. 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 pixel, the pixels adjacent to the discovered four-lane or wider road pixel are examined. If suitable, one adjacent pixel 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 pixels 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 transition growth rules were derived. Because forest management activities differ between 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 the whole 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 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:

$$\text{ozone}_t = \text{ozone}_{2000} + (\partial\text{ozone}/\partial\text{source})\ \Delta\text{Source}_{t-2000}$$

In the above equation, sources may change relative to how they were in the year 2000 ($\Delta\text{Source}_{t-2000}$), 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 that only one source changes during any given period. As implemented in RSim, the AQM really accounts for multiple changes in many sources throughout the emissions 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 ($\Delta\text{Source}_{t-2000}$) are estimated with growth factors from the U.S. Environmental Protection Agency’s Emissions Growth Analysis System (EGAS; U.S. Environmental Protection Agency 2004).

Ozone can cause foliar damage in trees, crops, and other vegetation, as well as other effects. RSim simulates the effects of ozone on vegetation by using the secondary standard for ozone to simulate the relative likelihood 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-h ozone concentration cannot exceed 0.08 ppm (parts per million).

B.2 Water quality and nitrogen and phosphorus export modules

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 hydrological 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 3200 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 positive correlation with size of the hydrological unit ($r = 0.80$ and $r = 0.48$, respectively, $P \leq 0.001$). However, the size of a watershed, the types of land cover within a watershed, and the export coefficients selected for different land covers all influence the predicted N and P exports.

B.3 Species of special concern module

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 changes in land cover. These clusters primarily occur in mature longleaf pine (*Pinus palustris*) 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's RCW management plan, Fort Benning's goal is 361 active RCW breeding clusters. RSim reports how this goal is affected by changes in land cover for every year of the projection.

The gopher tortoise habitat module in RSim computes the probability of suitable gopher tortoise habitat in a region according to a logistic regression model described by Baskaran et al. (2006*a*). 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 using a modification of the Hoshen-Kopelman algorithm (Berry et al. 1994, Constantin et al. 1997). The outputs from this module are:

- a map of the probability of occurrence of gopher tortoise habitat;
- a map of predicted burrow presence and absence;
- a table of the area of predicted burrows per year.

B.4 Noise module

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 effects 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 Arms Range Noise Assessment Model (SARNAM) projects noise effects 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 by 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. Residential development and other land uses associated with low-intensity urban land cover are not compatible with blast noise > 115 dBP (peak decibels).

APPENDIX 2. Summary of input conditions and parameters for the Regional Simulator model scenarios.

Table A. Select scenarios.

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

Table B. 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 C. Land-cover transitions matrix.

(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 D. Water quality module export coefficients.

	Kilograms of nitrogen per hectare per year	Kilograms of phosphorus per hectare per year
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 E. 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 F. Noise conditions.

Noise module selected?	YES

Table G. Species and habitats conditions.

Red-cockaded Woodpecker 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