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

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Abstract

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

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

1. Introduction

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

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

Local environmental effects such as changes in soil bulk density and vegetation can, in turn, cause regional problems. The introduction and subsequent spread of

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

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

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

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

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

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

2. Methods

2.1. Site description

The climate of the study area in west central Georgia is characterized by long, hot summers and mild winters, and precipitation is regular throughout the year

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

2.2. Approach for each scale

2.2.1. Local scale

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

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

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

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

2.2.2. Watershed scale

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

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

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

image (measured at 30-m resolution) was resampled to a 60-m resolution by means of nearest neighbor resampling.

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

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

2.2.3. Installation scale

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

2.2.4. Regional scale

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

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

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

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

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

3. Results

3.1. Local scale

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

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

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

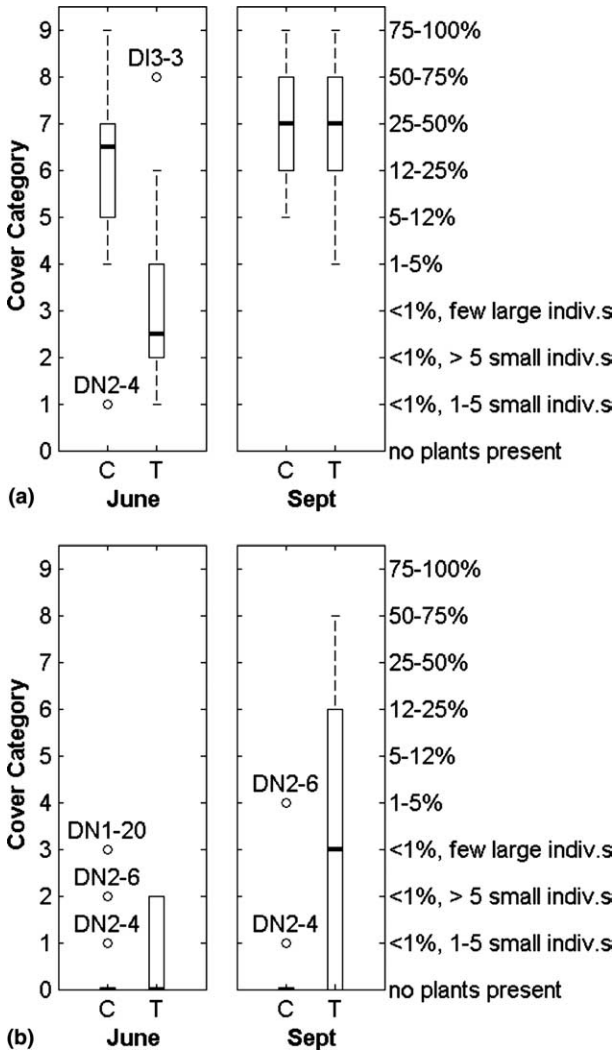

Fig. 1. Surveys within control, C, and treatment, T, transects in June and September of (a) total plant cover, and (b) cover of *Polypremum procumbens*. In these box plots, the median is represented by a solid line; the 25th and 75th percentiles, by the upper and lower edges of the box; and the minimum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

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

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

Each mean is based on seven measurements.
[a] NS = not significant.

matter. Surface (0–10 cm) soil density under the treatment transect was significantly greater than that under the control transect ($F_{1,12} = 6.48$; $P < 0.05$) (Table 2). The mean (±SE) densities of surface soil samples from the treatment and control transects were 1.43 ± 0.03 and 1.28 ± 0.06, respectively. Although soil densities for increments deeper than 10 cm tended to be greater under the treatment transect, the differences were not significantly different from the controls. Soil compaction from the bulldozer track at K11 was primarily limited to the surface mineral soil layer and produced an increase of approximately 12% in surface soil density.

3.2. Watershed scale

Road effects within the watershed over the period from 1974 to 1991 were quantified by examining conversion of cover types from forest to nonforest within buffered distances from roads. Visual comparison of the orthophotographs determined that the roads in the study watershed had been there since before the 1960s. This result made it possible to analyze the effect of roads within the watershed in the given time period. The 7.2 km of unpaved roads and trails was used to create buffers and to identify changes in forest cover over the 25-year period from 1974 to 1999 (Fig. 2). In general, land-cover conversion tends to decrease as the distances from the roads increase. The land closest to the roads (0–60 m) showed a 35% conversion from forest to nonforests, and as the distance increased, the percentage of conversion was reduced. At 120–180 m from the roads, 21% of the land was subject

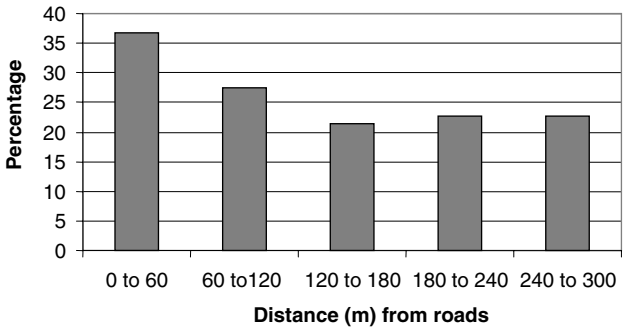

Fig. 2. Percent change in the conversion from forest to nonforest from 1974 to 1999 at different distances from unpaved roads and tank trails for the study watershed in training compartment K11.

to conversion, which is close to 21.9%, the overall percentage of conversion of forest to nonforest in the watershed. However, when the distances increased further, edge effects started to show up and the influence of roads in adjacent watersheds played a role. A visual analysis of the nearby roads on the map clarified this effect. To prevent such effects, the buffer distance for analysis was restricted to 300 m.

3.3. Installation scale

Change detection performed over the installation provided percentages of change from forest to nonforest categories over different time periods (Fig. 3). The first time period, from 1974 through 1983/86, showed a slight decline, but there was an overall increase by 1991. Part of this difference may be attributed to the differing lengths of the two time frames. In the first case a longer span, 10–13 years, was considered, and in the second case a shorter span, 6–9 years, was considered. Most of the change occurred in the third period, from 1991 to 1999. This last period is only 9 years, so it does not fit the observation that the comparative length of the first two periods affected the amount of change.

It is not known how the roads for the entire installation changed over the years of the analysis; however it is assumed that no major changes occurred. Therefore, the data layer of roads present in 1995 was used to create buffers and to identify changes over the years. The buffer analysis carried out for the watershed scale differs from that carried out for the installation scale in that many more types of roads exist at the installation scale. The 316 km of major roads consists of interstate and two- and four-lane highways, which cut across the installation. The largest effect of these major roads was the 18.3% change from forest to nonforest for the 0–60-m buffer, with the effect being stable for distances greater than 60 m (Fig. 4(a)). The 148 km of minor paved roads had a smaller (13.6%) effect on forest conversion at the 0–60-m distance. Observations of the maps suggest that, at a buffer distance of

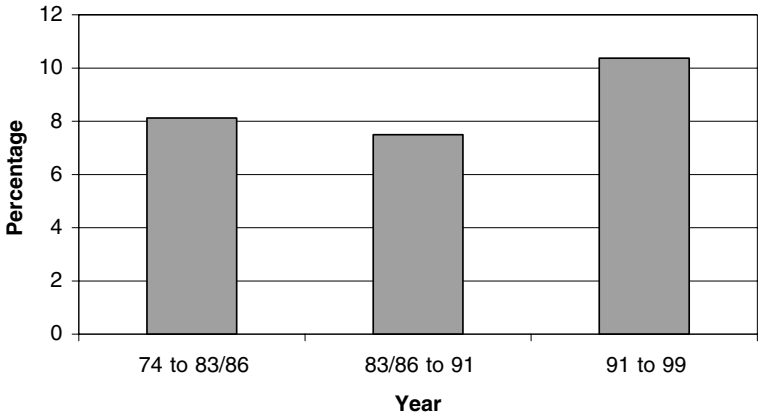

Fig. 3. Results of the change detection performed on the land-cover maps of Fort Benning. The percentages indicate conversion from forest to nonforest land-cover categories for different time periods.

120–180 m, forest conversion near minor paved roads was influenced by the major roads (Fig. 4(b)). Thus the 1568 km of unpaved roads and trails had a large effect on forest conversion, with the percentage of forest conversion declining from 19% to 9% as the distance from the road increased from 0–60 to 240–300 m (Fig. 4(c)).

3.4. Regional scale

Urban growth predictions generated by the RSim model results in an increase of 6.8% of pixels that are in an urban land-cover category under conditions expected to prevail in the coming decades (Fig. 5). Most of these new urban areas are near Columbus. Where Columbus is close to the northern boundary of Fort Benning, the projected growth is directly adjacent to military lands.

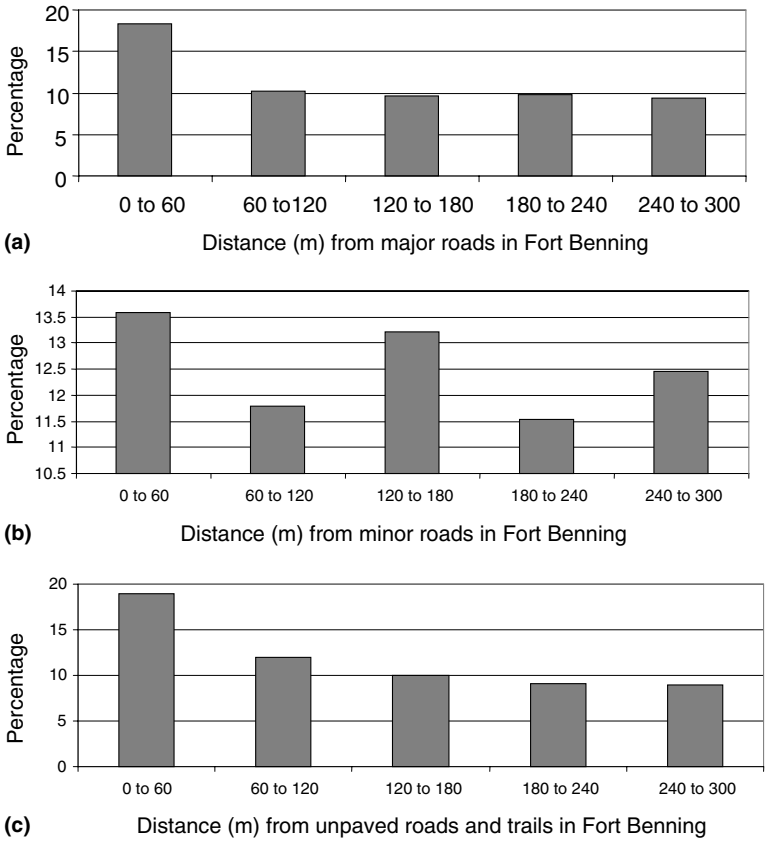

Fig. 4. Results of the change detection from 1974 to 1999 performed for the land cover of buffered roads at Fort Benning for distances from (a) major roads (interstates, two- and four-lane highways), (b) minor paved roads, and (c) unpaved roads and tank trails. The percent conversion from forest to nonforest land-cover categories at different distances from the roads is plotted for the time period 1974–1991. The percentage indicates new changes for each buffer distance in comparison with smaller buffer areas.

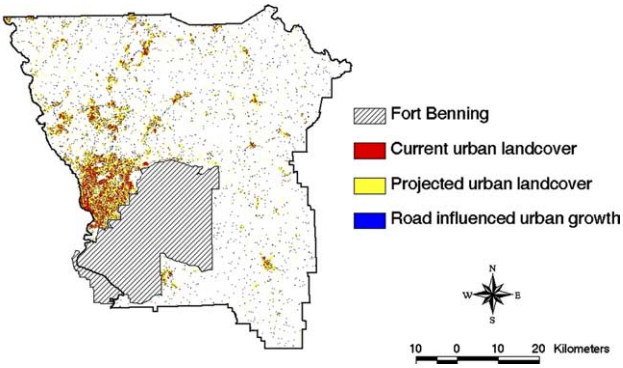

Fig. 5. Map of the current and projected urban areas in the five-county area around Fort Benning and the small area of projected growth due solely to roads.

The regional simulation model projected few urban growth differences between maps produced with the influence of new roads and maps produced without the influence of new roads even though a road-instigated urbanization algorithm was a part of the model. Most of the change to urban land cover resulted from the spread of the urban areas, and less than 0.2% of the total change in 30 simulation steps for the five-county region could be attributed to the influence of roads.

4. Discussion

4.1. Local catchment

The response of total plant cover to mechanized disturbance shows a remarkable recovery by 4 months after the disturbance to an equivalent value of the control transects. The rapid recovery occurred over the growing season and during an abnormally wet summer [38], even though soil compaction was certainly of longer duration. Despite the renewed cover, however, vegetation composition became significantly different from that in the control transects. The September survey showed a significant increase in juniper leaf (*Polypremum procumbens*). This species-specific increase agrees with the species ecology described by Radford et al. [27], who notes that *P. procumbens* is found within habitats showing recent disturbance, including roadsides.

Two plots (DN2-4 and DN2-6) frequently appear as outliers in Fig. 1. These plots were not directly impacted by the blade of the bulldozer but were located between the path of its tracks as it moved between transects. As a result, their composition reflected partial disturbance. The other outliers most likely were a result of environmental heterogeneity created either during the disturbance (DI1-20) or preceding it (DI3-3).

Rapid recovery from soil compaction is not expected. Studies of military training on dry sandy soils indicate that surface soil compaction caused by heavy tracked vehicles can persist for decades [39]. Soil compaction can change the properties of soil pores affecting infiltration capacity [39], the accessibility of organic matter to soil microorganisms, organic matter decomposition rates, and soil N availability [40]. Soil compaction by heavy machinery is also detrimental to root development and plant growth [41–43]. Soil compaction is a potential long-term effect of heavy vehicle use, and it can have an overall adverse impact on soil and vegetation properties.

Previous studies along disturbance gradients at Fort Benning [44] indicate a persistence of soil compaction for several years following site disturbance. The persistence of soil compaction depends on both soil clay content and moisture status at the time of disturbance. Fine-textured or wet soils are more prone to compaction by heavy vehicle traffic than coarse-textured or dry soils [41,45–47], but shrink/swell cycles in soils with significant clay content [46] or repeated cycles of soil wetting and drying [48] or ecological succession [49] can act singularly or together to reduce soil compaction over long time periods.

4.2. Watershed scale

Forest conversion was highest near unpaved roads and tank trails in the K11 watershed. Since the roads have width of about 3.7 m per lane, the 0–60-m buffer includes the roads themselves. The remote-sensing evidence suggests that at the watershed scale, vehicles on the unpaved roads and the roads themselves affected the areas closest to them. In this context, closeness can be defined as a buffer distance of approximately 120 m. Within that zone, clearing of trees and road-bed erosion likely caused many observed changes over the 25-year period.

4.3. Installation scale

Major roads and unpaved roads and trails were associated with most of the conversion from forest to nonforest cover at the scale of the installation. Within Fort Benning, these types of roads cover a larger area than the minor paved roads. In addition, the forest conversion in the buffered area near the major roads and unpaved roads and trails declined as distance increased. Along some major roads, considerable clearing (especially along the western edge of Fort Benning) had taken place. Because this western area makes up the cantonment where soldiers live and work, most of this conversion was likely associated with urban growth and expansion.

The minor paved roads graph is bimodal, with a peak at the 0- to 60-m buffer and a peak at the 120- to 180-m buffer (Fig. 4(b)). This second peak could result from the paucity of paved roads and their proximity to major roads. The large forest conversions near major roads (Fig. 4(a)) could have affected the minor paved roads, for the two are often close to each other at Fort Benning.

4.4. Regional scale

Most of the urban growth is projected to result from urban spread rather than road impacts (Fig. 5). Columbus is a rapidly developing municipality, and its high urban growth trend is simulated in the RSim model. Furthermore, by 2004 the Governor's Road Improvement Program (GRIP) planned for the next 25 years will have completed its major activity in the five-country region of this study. Yet roads uniquely produce linear features, which can act to dissect a connected landscape. Effects of roads on ecological pattern and connectivity, as well as effects on nonurban land-cover types, have yet to be examined in the five-county region, but RSim can facilitate such analyses.

4.5. Scale of vehicle and road impacts on the environment

Table 3 illustrates our hypothesis that road impacts differ by scale and have unique effects on the environment at each resolution. At the resolution of a road segment, there are pressures for establishment and use of roads, which can result in vegetation removal and soil compaction. At the larger watershed scale, the need for military training within the installation calls for roads that can be used for maneuvers with the result of local conversion of forest to nonforest land. Similar pressures and effects occur at the installation scale, but the restrictions of the Endangered Species Act influence management decisions. As a federal facility, habitats for federally listed species must be protected, which limits the extent and places where military training can occur. At the resolution of the five-county area, the pressure for urban development appears to have a more pronounced impact on conversion of forest to nonforest land than the roads themselves. Of course, road development and improvement are a part of urban expansion, but it appears that change in land use is the prevailing influence on forest conversion for the region. As a largely local phenomenon, road establishment and use may have greater impacts at local and subregional scales, and effects at regional scales may be overridden by other pressures and processes. The concept is supported by the "road effect zone" that is based on observational evidence that environmental effects can extend as far as 1 km from a road [50]. At a national perspective, this road-zone effect translates into about one fifth the area of the United States being affected by roads [51]. Even so, there are large areas where roads are not the primary influence on environmental conditions as well as locales where road effects are pervasive. Our analysis from west central Georgia suggests that road effects should be considered at local and subregional resolutions.

In summary, the results of these combined studies for Fort Benning suggest that effects at all scales are important to consider. Even at the broadest scale of the five-county region, it is the relative relationship between urban growth and the influence of roads that helps to determine the importance of road impacts. The mid-scale remote-sensing analysis suggested that forest conversion was greatest nearest the roads. A local tracked vehicle impact study demonstrated that vegetation cover might not be indicative of the full recovery of mature vegetation or of soil

Table 3
Four spatial resolutions and their pressures on roads with corresponding effects on roads and the environment

Road resolution	Area (ha)	Pressures	Effect on roads	Effects on the environment
Road segment in second order catchment	4	Establishment and use of roads	New roads	Vegetation removal and soil compaction
Road network in third order watershed	244	Military training	Roads for training	Local conversion of forest to nonforest
Road network within Fort Benning	73,503	Military training	Roads for training	Conversion of forest to nonforest over entire installation
		Endangered Species Act	Must retain habitat for listed species when using federal funds	Protection of habitat for listed species
Road network in five-county area	442,357	Changes in land use	Land cover change	Regional conversion of forest to nonforest
			Pressure for new and improved roads	

compaction. Hence field studies, remote-sensing analyses, and modeling all have their place in understanding environmental impacts of vehicle and roads.

5. Management questions

Roads on military lands are unique because of the high number of unpaved roads and trails that are heavily used by tracked vehicles [52]. Even so, military lands support a high number of rare species and their habitats [53]. It is partly for this reason that roads on military lands have received special attention. Yet, many questions still remain about appropriate ways to manage for ecological impacts of roads on and near military lands. For example, it would be useful to catalogue the road features that are unique to military lands and those that are common to other types of land ownership or use.

A key question resulting from this multifaceted study is: what metrics should be used to assess road impacts on ecological systems? In this study, we used different techniques for determining potential impact at each scale of analysis. At the local scale, we examined the total percentage of plant cover, cover by species, and soil density of different depths. At the watershed and installation scales, past forest conversion in relation to distance from roads was used as a metric. Simulated urbanization was examined at the regional scale.

Instead of these techniques and metrics, we could have used other alternatives. For example, groups of species may respond similarly to roads and traffic at the local scale [54]. In addition, historical orthophotography can be used to create a time sequence of data layers of road for the entire installation, and the developing road network can be used to estimate how much forest conversion is influenced by distance from roads at each time period. In addition, the simulation approach can be refined to explore not only the causes but also the impacts of road-induced urbanization. For example, models can be used to determine how road infrastructure can affect changes in noise, air, and water quality as well as habitat alteration.

Features of roads themselves can be used as metrics of environmental impacts. Such metrics as the number of passes of a tracked vehicle, length of paved road, number of times a stream is crossed per unit of road length, or road width (e.g., two or four lane) all contain information on how roads and vehicles can impact the environment.

Further studies are needed to attribute causes to effects on land cover. Experimental studies to attribute causality could most easily be carried out at the local scale. At that scale, for example, the relationship between vegetation diversity and cover, on one hand, and soil compaction, on the other, can be explored. The mechanistic relationships between soil compaction and growth and yield of woody plants are reviewed by Kozlowski [55]. Unfortunately, causes of forest conversion near roads at larger spatial scales are difficult to identify through retrospective assessment. As stated in Section 1, the clearing of trees and roadbed erosion are both likely contributors to vegetation impacts; however, the direct crushing of vegetation by tracked vehicles and compaction of soils along roads surely occurred regularly in the past.

Records of military activities in road corridors and experiments at the local scale would prove useful for determining causes (or at least reasonable hypotheses) for forest conversion; however such records are not available.

Addressing measurement needs and attributing causation to land-cover change would help determine how environmental impacts might be avoided or mitigated. Considering the metrics in terms of spatial resolution will help assess conditions under which spatial scale might make a difference to management options. In any case, a suite of approaches and metrics likely will best reveal how vehicles and roads affect their environment.

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