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Road network development and landscape dynamics in the Santa Fe River watershed, north-central Florida, 1975 to 2005

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Road networks provide essential economic functions and are highly persistent landscape features with far-reaching ecological effects.

Most research about roads focuses on the effects of individual roads to native plant and animal populations. This research examined road network characteristics and road-related fragmentation of the landscape, and how these changed over time.

Specific questions included: How did the road network structure change? How did the dynamics of road network development and land cover affect patterns of landscape fragmentation? How did fragmentation vary across space/time as the road network changed?

Background

Studies examining the ecological effects of roads have established clearly that they are a cause of landscape fragmentation (e.g., *1*). The loss of biological diversity attributed to habitat loss and fragmentation (*2-3*), has highlighted the role of roads in this process. Roads have numerous ecological effects, with negative consequences for many species. For many animals, roads act as barriers in the landscape (*4*). In Florida, animal-vehicle collision is the leading cause of death for several large animal species (*5*).

Transportation geography theory posits that road networks become more extensive and interconnected with sustained human population growth and economic development. The capacity and accessibility of the network increases with these changes (*6*). The entire region becomes more accessible as roads are built or upgraded. Other studies have shown that as the road network expands space between roads decreases (*7*), the landscape is more easily accessed, and fragmentation increases (*8*).

This research used methods from transportation geography and landscape ecology to describe the structure and function of road networks and patterns of landscape fragmentation. The Santa Fe River watershed (SFRW), a 3584 km^2 semi-rural region of north central Florida (Figures 1-2), was chosen to analyze changes in road-related fragmentation that occurred from 1975 to 2005. The expectation was for the road network to become more extensive over time, and for its connectivity and accessibility to increase as it developed. At the same time, the SFRW landscape was expected to become more accessible and fragmented as the road network developed.

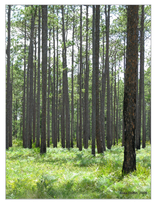

Figure 2. Longleaf pine woodland with hyper-diverse ground cover in Olustee Battlefield State Park in the northern reach of the watershed.

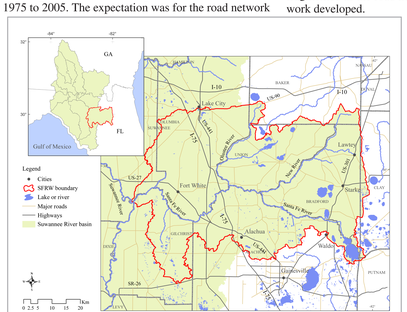

Figure 1. The Santa Fe River watershed study area.

Methods

Road network analysis

The structural and functional properties of the road network were observed using transportation network analysis and other commonly used road-related metrics (*7, 9-10*). Network analysis uses principles of graph theory (*11*) to abstract the road network as a graph, representing intersections as points (*v*) and road segments as lines (*e*). The structural and functional characteristics of the network are measured in terms that quantitatively describe its topological connectivity and accessibility. These methods provide an alternative to the most common approaches, which depend strongly on map accuracy.

The SFRW road network was studied for four dates (1975, 1985, 1995 and 2005). Road network data were digitized from Florida Department of Transportation (FDOT) county road maps into a GIS. These data were analyzed using ArcGIS® and *igraph*, a network analysis module of *R* (*12*). Twenty-three metrics of road network structure (Table 1) were measured, and their changes analyzed for each time period. The metrics were grouped and reported according to characteristics of extent, connectivity and accessibility.

Table 1. Indices of road network extent, connectivity and accessibility.

Class	Index	Description or equation (assuming planar graphs)	Index category for
Map-based indices	Total length (L)	Total length of the road network in distance units (meters, km, etc.)	Extent
	Total area (A)	Total area of the network in area units (m^2, km^2, etc.)	n/a
	Road density (L/A)	Density of roads per unit area or per capita.	Accessibility (landscape)
	Distance to road (DTR)	Euclidian distance to the nearest road. Value is usually calculated for a given point or a grid of points within the space of the network area (A).	Accessibility (landscape)
	Roadless Volume (RV)	A<DTR> (A is the area of the footprint area being analyzed, and <DTR> is the mean DTR of the study area)	Accessibility (landscape)
NA	Edges	e	Extent
	Vertices	v	Extent
	Vertex order	o	Extent
	Proportion of first-order vertices	$v_{o=1}/v_{o>1}$	Extent
TNA	Cyclomatic number (μ)	$\mu = e - v + p$	Connectivity
	Diameter (δ) and diameter distance (d)	$\delta = max(\ d(x,x)$	Extent
		$d(x,x)$ (*units*): topological length in distance units (meters, km, etc.)	Extent
	Connectivity or gamma (γ)	$\gamma = \frac{e}{3(v-2)}$	Connectivity
	Alpha (α)	$\alpha = \frac{\mu}{2v-5}$	Connectivity
	Beta (β)	$\beta = e/v$	Connectivity
	Shape index or Pi (π)	$\pi = L/d$	Extent
	Eta (η)	$\eta = L/e$ (in distance units)	Connectivity
	Weight (w)	$w = w_1 + w_2; w_1 = \sum v_{o=1} \cdot w_2 = \sum v_{o>1} * 2$	Extent
	Structure index or Iota (ι)	$\iota = L/v$ (in distance units)	Connectivity
	Shortest-path accessibility (A_i)	$A_i = \sum_{j \neq i} d(i,j)$	Accessibility (network)
SNA	Closeness	$C_c(n_i) = \left[\sum_{j=1}^{n} d(n_i,n_j)^{-1}\right]$	Accessibility (network)
	Betweenness	$C_B(n_i) = \sum_{j<k} g_{jk}(n_i)/g_{jk}$	Accessibility (network)

Note: These indices were derived from mapped characteristics and graph theoretic indices of basic network analysis (NA; *1*) transportation network analysis (TNA; *6, 9, 18, 19*) and social network analysis (SNA; *12, 20*). In this table g_{jk} is the length of the geodesic between vertices *j* and *k*, and *p* is the number of separated subgraphs (for this study $p = 1$).

Landscape fragmentation analysis

Landscape fragmentation was measured using effective mesh size (m_{eff}; *13, 14*). The m_{eff} metric describes the probability of connection between two randomly chosen points within a region (*15*). Values are calculated for areas of interest. Barrier elements prevent the connection of two locations within an area of interest. The arrangement of remaining landscape spaces is the "fragmentation geometry" (FG). Alternative geometries are used to compare the relative effects of different fragmenting elements (*15-16*). One way to interpret m_{eff} is in the case of animal movement. In this case, m_{eff} is the average space within an area that an animal can move without encountering a barrier.

In this study, the areas of interest were the entire watershed and each of its 118 sub-basins. Fragmenting elements included roads, large rivers, railroads, power lines and urban areas. There were two fragmenting geometries: FG1, which included wooded and agricultural/open land covers; and FG2, which included wooded land covers.

Land cover information was derived from the supervised classification of Landsat imagery from 1975, 1985, 1995 and 2005, referenced using field data and aerial photography (Figure 3). Thematic land cover maps were used to calculate land cover areas, basic patch size metrics, and meff for each date.

Changes in m_{eff} were calculated for both FGs: for the entire watershed, and for each sub-basin; for the entire study period, and from one decade to the next. A contingency table was created to summarize the dynamics of change in m_{eff} for FG1 ($FG1m_{eff}$) and FG2 ($FG2m_{eff}$). The gamma measure of association (*17*) was used to compare the proportion of concordant and discordant pairs in the contingency table and observe how they changed over time.

Aerial photograph of a dead-end road in the western reach of the Santa Fe River watershed.

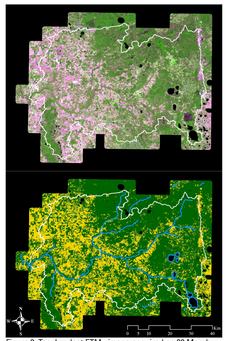

Figure 3. Top: Landsat ETM+ image acquired on 20 March 2005; Bottom: corresponding 2005 land cover classification in forested (green; including plantations) and non-forested (gold). The watershed boundary is shown in white, and the Santa Fe River is shown in blue on the classified image.

Results

Road network dynamics

Measures of overall network extent and circuitry all increased from 1975 to 2005; however, measures describing connectivity and accessibility of the road network generally decreased (Table 2). The greatest increase in extent was noted in the final decade of the study period (1995-2005). Mean vertex order decreased over time as the number of first-order vertices more than doubled. The greatest increase in the proportion of first-order vertices was during the second decade (1985-1995).

Although the number of circuits in the road network increased over time, the relative connectivity of the network declined over time, with the greatest decreases in connectivity measures occurring in 1985-1995. Road density increased over thirty years, while distance-to-road and roadless volume both decreased. Substantial changes in these metrics occurred in 1995-2005, coincident with the greatest increases in network extent.

Table 2. Measures of road network extent for 1975, 1985, 1995 and 2005. See Table 1 for metric definitions.

Category	Measure or index	1975	1985	1995	2005	increase + decrease –
Extent	L (km)	5887	6078	6431	7304	+
	v	5162	5765	6679	8705	+
	$v_{deg=0}$	227	226	230	283	+
	e	6734	7479	8480	10865	+
	δ	125	133	139	152	+
	APL	43.81	45.39	47.60	52.24	+
	d (km)	123.93	126.48	121.75	152.21	+
	π	47.50	48.05	52.82	47.98	+/–
	w	25,373	28,145	31,695	40,576	+
	$v_{o=1}/v_{o>1}$	0.223	0.238	0.263	0.275	+
	mean o	2.61	2.59	2.54	2.50	–
Connectivity	μ	1573	1715	1802	2161	+
	α	0.152	0.149	0.135	0.124	–
	β	1.304	1.297	1.270	1.248	–
	γ	0.435	0.433	0.423	0.416	–
	η (km)	0.87	0.81	0.76	0.67	–
	ι (km)	0.23	0.21	0.20	0.18	–
Accessibility (landscape)	L/A	1.18	1.22	1.29	1.47	+
	RV(km^2)	1724.16	1683.51	1592.28	1412.17	–
	DTR (m)					
	Mean	367	339	320	284	–
	Median	256	247	240	210	–
	Max	3118	3092	3090	2580	–
	SD	321.4	319.6	304.2	273.4	–
Accessibility (road network)	A_i					
	Mean	223,553	258,425	313,771	449,948	+
	Min	154,968	179,734	222,189	309,633	+
	Max	417,481	498,730	597,181	829,757	+
	SD	43,670	51,237	61,509	87,457	+

Table 3. Effective mesh size (ha) and patch number, size (ha) and area information reported by fragmentation geometry (FG) and year.

Fragmentation geometry	Year	m_{eff} (ha)	Number of patches (≥576 m^2)	Size of largest patch (ha)	Patches > 2000ha (total area/% area)	Patches > 1000 ha (total area/% area)
FG1	1975	1084.5	1547	6563	16 (538 km^2/15%)	58 (1101.7 km^2/30.7%)
	1985	1059.9	1668	6380	18 (602.3 km^2/16.8%)	59 (1149.4 km^2/32.1%)
	1995	1030.9	1769	6130	18 (602.2 km^2/16.8%)	54 (1091.8 km^2/30.5%)
	2005	775.0	1814	5480	12 (390 km^2/10.9%)	49 (874.7 km^2/24.4%)
FG2	1975	494.9	8138	4384	8 (253.2 km^2/7.1%)	27 (516.8 km^2/14.4%)
	1985	464.2	12103	4510	7 (236.4 km^2/6.6%)	25 (494.8 km^2/13.8%)
	1995	435.5	21808	4512	8 (252.8 km^2/7.1%)	23 (466.4 km^2/13%)
	2005	342.8	21788	4093	4 (129 km^2/3.6%)	20 (359.4 km^2/10%)

Note: FG1 includes wooded land covers combined with agricultural/open land covers. FG2 includes wooded land covers. Values reported for patches whose centroids fall within the boundaries of the study area.

Table 4. Contingency table summarizing relative changes in FG1 and FG2 in sub-basins of the SFRW, categorized by percent change in effective mesh size.

Percent change in effective mesh size for FG1 (% $FG1m_{eff}$)	Percent change in effective mesh size for FG2 (%$FG2m_{eff}$): Decrease (%$\Delta FG2m_{eff} \leq$ -10%)	No change (10% > %$\Delta FG2m_{eff}$ > -10%)	Increase (%$\Delta FG2m_{eff} \geq$ 10%)	Total
Decrease (%$\Delta FG1m_{eff} \leq$ -10%)	*1.1* FG1 contracts FG2 contracts A: $n_{1.1}$= 13; $\pi_{1.1}$= .110 B: $n_{1.1}$= 8; $\pi_{1.1}$= .068 **C: $n_{1.1}$= 52; $\pi_{1.1}$= .441** **D: $n_{1.1}$= 82; $\pi_{1.1}$= .695**	*1.2* FG1 contracts FG2 no change A: $n_{1.2}$= 4; $\pi_{1.2}$= .034 B: $n_{1.2}$= 4; $\pi_{1.2}$= .034 C: $n_{1.2}$= 16; $\pi_{1.2}$= .136 D: $n_{1.2}$= 9; $\pi_{1.2}$= .076	*1.3* FG1 contracts FG2 expands A: $n_{1.3}$= 1; $\pi_{1.3}$= .008 B: $n_{1.3}$= 0; $\pi_{1.3}$= 0 C: $n_{1.3}$= 21; $\pi_{1.3}$= .178 D: $n_{1.3}$= 8; $\pi_{1.3}$= .068	*1.+* FG1 contracts A: $n_{1.+}$= 18; $\pi_{1.+}$= .152 B: $n_{1.+}$= 12; $\pi_{1.+}$= .102 **C: $n_{1.+}$= 89; $\pi_{1.+}$= .755** **D: $n_{1.+}$= 99; $\pi_{1.+}$= .839**
No change (10% > %$\Delta FG1m_{eff}$ >-10%)	*2.1* FG1 no change FG2 contracts **A: $n_{2.1}$= 52; $\pi_{2.1}$= .441** **B: $n_{2.1}$= 46; $\pi_{2.1}$= .390** C: $n_{2.1}$= 4; $\pi_{2.1}$= .034 D: $n_{2.1}$= 5; $\pi_{2.1}$= .042	*2.2* FG1 no change FG2 no change A: $n_{2.2}$= 33; $\pi_{2.2}$= .280 B: $n_{2.2}$= 35; $\pi_{2.2}$= .297 C: $n_{2.2}$= 13; $\pi_{2.2}$= .110 D: $n_{2.2}$= 10; $\pi_{2.2}$= .085	*2.3* FG1 no change FG2 expands A: $n_{2.3}$= 7; $\pi_{2.3}$= .059 B: $n_{2.3}$= 22; $\pi_{2.3}$= .186 C: $n_{2.3}$= 8; $\pi_{2.3}$= .068 D: $n_{2.3}$= 0; $\pi_{2.3}$= 0	*2.+* FG1 no change **A: $n_{2.+}$= 92; $\pi_{2.+}$= .780** **B: $n_{2.+}$= 103; $\pi_{2.+}$= .813** C: $n_{2.+}$= 25; $\pi_{2.+}$= .212 D: $n_{2.+}$= 15; $\pi_{2.+}$= .127
Increase (%$\Delta FG1m_{eff} \geq$ 10%)	*3.1* FG1 expands FG2 contracts A: $n_{3.1}$= 5; $\pi_{3.1}$= .042 B: $n_{3.1}$= 1; $\pi_{3.1}$= .008 C: $n_{3.1}$= 0; $\pi_{3.1}$= 0 D: $n_{3.1}$= 0; $\pi_{3.1}$= 0	*3.2* FG1 expands FG2 no change A: $n_{3.2}$= 1; $\pi_{3.2}$= .008 B: $n_{3.2}$= 0; $\pi_{3.2}$= 0 C: $n_{3.2}$= 0; $\pi_{3.2}$= 0 D: $n_{3.2}$= 0; $\pi_{3.2}$= 0	*3.3* FG1 expands FG2 expands A: $n_{3.3}$= 2; $\pi_{3.3}$= .017 B: $n_{3.3}$= 2; $\pi_{3.3}$= .017 C: $n_{3.3}$= 4; $\pi_{3.3}$= .034 D: $n_{3.3}$= 4; $\pi_{3.3}$= .034	*3.+* FG1 expands A: $n_{3.+}$= 8; $\pi_{3.+}$= .067 B: $n_{3.+}$= 3; $\pi_{3.+}$= .025 C: $n_{3.+}$= 4; $\pi_{3.+}$= .034 D: $n_{3.+}$= 4; $\pi_{3.+}$= .034
Total	*+.1* FG2 contracts **A: $n_{+.1}$= 70; $\pi_{+.1}$= .593** **B: $n_{+.1}$= 55; $\pi_{+.1}$= .466** **C: $n_{+.1}$= 56; $\pi_{+.1}$= .475** **D: $n_{+.1}$= 87; $\pi_{+.1}$= .737**	*+.2* FG2 no change A: $n_{+.2}$= 38; $\pi_{+.2}$= .322 B: $n_{+.2}$= 39; $\pi_{+.2}$= .331 C: $n_{+.2}$= 29; $\pi_{+.2}$= .246 D: $n_{+.2}$= 19; $\pi_{+.2}$= .161	*+.3* FG2 expands A: $n_{+.3}$= 10; $\pi_{+.3}$= .084 B: $n_{+.3}$= 24; $\pi_{+.3}$= .203 C: $n_{+.3}$= 33; $\pi_{+.3}$= .280 D: $n_{+.3}$= 12; $\pi_{+.3}$= .102	

Note: columns represent categories of percent change in $FG2m_{eff}$ (%$\Delta FG2m_{eff}$). Rows represent categories of percent change in $FG1m_{eff}$ (%$\Delta FG1m_{eff}$). For each outcome, labeled as $i_{.j}$, land-cover dynamics are described, and changes in m_{eff} are illustrated. FG1 includes forested and agricultural/open land covers combined; FG2 includes forested land covers. Date intervals are as follows: A) 1975-1985; B) 1985-1995; C) 1995-2005; D) 1975-2005. Results are reported by date intervals as the number of cases for each outcome (n_{ij}), and the joint probability of the outcomes (π_{ij}; $n = 118$). Total row and columns give the marginal distributions; denoted by $\pi_{i.}$ for the row and $\pi_{.j}$ for the column. Bold type indicates greatest proportion of cases for that particular date interval.

Landscape connectivity dynamics

Areas of land-cover type changed substantially in some classes and less in others. Wooded lands declined from 1975 to 2005, with most of the decline occurring in the first decade. Agricultural/open lands, in contrast, increased in 1975-1995, but then, over 1985-2005 decreased substantially. For the entire watershed, m_{eff} decreased in the SFRW from 1975 to 2005, as the number of patches increased, the size of the largest patch decreased, and the number and area covered by large patches generally declined. This trend held true for both fragmentation geometries. The decline in m_{eff} was more pronounced in the third decade, 1995-2005, and most evident in FG1 (Table 3).

Effective mesh values did not decrease uniformly across the watershed. Sub-basins with the greatest decreases in $FG1m_{eff}$ were in the east (Figure 4), northwest of Gainesville, and along the corridor between Waldo and Lawtey.

Change in m_{eff} also varied from one decade to the next in the watershed. Median values for change in both $FG1m_{eff}$ and $FG2m_{eff}$ were lower in the first and third decades, suggesting greater fragmentation during those periods. The range of decadal changes in $FG2m_{eff}$ and $FG1m_{eff}$ also narrowed as variability in change values decreased during the second decade.

In the three decades, changes in $FG2m_{eff}$ in some sub-basins did not always concord with changes in $FG1m_{eff}$. (Table 4). In most cases, especially in the final decade, the two values correspondingly decreased. However, for each decade there were alternative outcomes: where one or both m_{eff} values increased; where one m_{eff} value increased and the other decreased, or where one or both values for m_{eff} did not change.

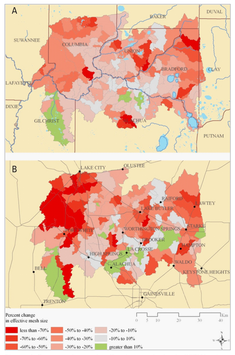

Figure 4. Percent change in effective mesh size in SFRW sub-basins from 1975 to 2005. A) FG1 (wooded, agricultural/open lands) with lakes and rivers in blue, B) FG2 (wooded lands) with roads and towns. Red sub-basins showed a decrease in effective mesh size. Green sub-basins showed an increase in effective mesh size.

Discussion

All measures of extent clearly indicated that the SFRW road network expanded considerably, especially in the last decade, 1995-2005. The increase in the proportion of first-order vertices, i.e. dead-end roads, relative to higher-order vertices, i.e. intersections, suggests that a major cause of the SFRW road network expansion, particularly in 1985-1995, was the creation of new dead-end roads penetrating the landscape (Figure 5). Each time one of these small roads connected to the wider network it created a junction, thereby splitting the road into two segments where there had been only one. The cumulative topological effects of this repeated action overwhelmed the effects that any new connector roads might have had, driving the network toward a more tree-like topological configuration, resulting in a relatively less connected, less accessible and more elaborate road network with a greater capability of accessing unroaded rural areas.

Roads were an important fragmenting factor in the SFRW, especially in 1995-2005. However, wooded lands have also been fragmented by agricultural expansion, particularly in 1975-1985. Variability of changes in fragmentation was the lowest during 1985-1995, although fragmentation tended to increase for both wooded lands (FG2) and the combined wooded/agricultural/open lands (FG1). During 1995-2005, there was a sharp increase in the extent of the road network and urban land area, with substantial increases in fragmentation for both land cover types. In some areas, fragmentation of agricultural/open lands was accompanied with woodland expansion, as might be expected in suburban expansion.

Road network and landscape fragmentation dynamics in the SFRW experienced a fundamental shift over the thirty-year study period. In 1975-1985, fragmentation and land-cover change patterns expressed agricultural expansion and ongoing intensive commercial forestry. The comparatively low variability in m_{eff} changes in 1985-1995, coupled with the increased development of dead-end roads signified a period of transition in land-use dynamics. In 1995-2005 several sub-basins in the watershed shifted toward urbanization and suburbanization. These sub-basins were concentrated along highway corridors and near urban areas, suggesting that new dead-end roads facilitated land-cover conversion in these areas. Whether or not land-use dynamics in the watershed were shifting as a result of dead-end road development, might be further demonstrated with a spatial analysis of land cover, economic and productivity indicators from this period, and their relationship to the locations of dead-end roads.

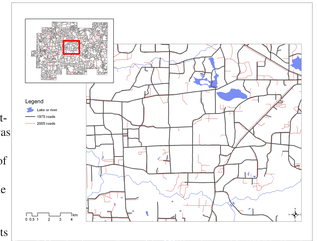

Figure 5. Map showing a small area of the SFRW road network in 1975 (black) and accumulated changes in 2005 (red), illustrating the common addition of new dead end roads during the thirty year period.

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