A COMPARISON OF THE ENVIRONMENTAL EFFECTS OF TRADITIONAL INTENSIVE FORESTRY AND THE SUSTAINABLE FORESTRY INITIATIVE: A MODELING APPROACH AT THE LANDSCAPE LEVEL

A Dissertation

by

JOÃO CARLOS AZEVEDO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2003

Major Subject: Forestry

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Approved to the style and content by:

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ABSTRACT

A Comparison of the Environmental Effects of Traditional Intensive
Forestry and the Sustainable Forestry Initiative: A Modeling Approach at
the Landscape Level. (December 2003)
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Changes in landscape pattern caused by changes in forest management, namely the Sustainable Forestry Initiative (SFI), and the implications of these structural changes on landscape processes were analyzed. Landscape structure was studied based upon the comparison of landscapes with different management histories. Ecological processes were analyzed based upon simulation of stand and landscape attributes of habitats for several vertebrate species and upon simulation of hydrological processes such as water and sediment yield. A methodology to integrate landscape and stand pattern and dynamics with landscape processes was developed for this work. It integrates a forest landscape structure model, several stand level growth and yield models, vertebrate habitat models, and a hydrological model.

The comparisons among landscapes revealed that forest management has a strong influence on landscape structure. The SFI program increases fragmentation of the landscape indicated by the presence of more and smaller patches, more edges, more complex shapes, and less and smaller core areas. Traditional intensive and extensive management show comparable patterns characterized by high aggregation and connectivity.

Landscapes managed according to the SFI program show higher Habitat Suitability Index (HSI) values for American woodcock, American beaver, wild turkey, fox squirrel, and gray squirrel. HSI is higher for pine warbler in the landscape not managed according to the SFI program. Downy woodpecker and barred owl present very reduced HSI values in either landscape. The SFI program induced fragmentation of the habitat of pine warbler and the establishment of narrow and elongated habitats in a network structure for the remaining species. Both patterns are determined by SMZs.

The scenario representing management according to the SFI program presents higher sediment yield at the watershed level than the scenario representing management not according to the SFI program due to higher channel erosion related to the absence of buffer strips in the non-SFI scenario.

In general, management according to the SFI program increases landscape diversity and evenness, habitat suitability for most species, potential vertebrate diversity, and provides habitat structure suitable for most species. This management also decreases sediment loss at the watershed level.

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CHAPTER I

INTRODUCTION

Sustainability is the current goal in forestry. From the UN Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992 until the present day, forest sustainability has moved from general statements of principles to enforceable national laws and concrete programs presently implemented worldwide in private and public forests and in the context of forest industry and forest conservation. The Helsinki Process in Europe and the Montréal Process in North and South America, Russia, Asia, and Oceania, became leaders of sustainable forestry at the continental and global scales defining principles and practices to be adopted in individual states. In the United States sustainability became the goal in national forests (USDA Forest Service 2000) and in industry (Cantrell 1998). The Sustainable Forestry Initiative (SFI) is the sustainability program of the American Forest and Paper Association (AF&PA). Launched in 1994, it is currently followed on 55 million hectares of forestland (AF&PA 2003), more than 90% of the industry-owned forest in North America (AF&PA 2002).

Addressing sustainability requires a multiple-scale approach (Christensen et al. 1996). The landscape scale is a necessary level of analysis and management in forestry when sustainability is addressed since several of the key processes in maintenance of sustainable forests ecosystems occur at the landscape level (Lubchenco et al. 1991, Forman 1995, Andersson et al. 2000). The landscape perspective is also taken into consideration in many of the measures of sustainable forestry. Several of the criteria and indicators of the Montréal Process and of the Pan European Forest Certification program, such as water, species and habitat conservation, maintenance and encouragement of productive functions of forests, or maintenance of ecosystem health rely strongly on the spatial characteristics of the ecosystems considered at broad scales

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This manuscript follows the style of Forest Science.

and require also broader scales to be defined and applied (Montréal Process Working Group 1999, Ministerial Conference On The Protection Of Forests In Europe 2003).

Forests in East Texas have a great economic importance. Timberlands occupy approximately 4.8 million hectares in this region. Although most of this land is nonindustrial private forest, forest industry owns approximately 1.5 million hectares (Rosson 2000). This land is currently managed according to the SFI program. Some of the measures applied within the SFI program, namely riparian buffer zones, wildlife corridors, harvest size limits, and adjacency rules have expression at the landscape level. and this scale is required to analyze them properly. The measures mentioned have the potential to change landscape structure in industrial forested landscapes and the implications of those changes in terms of physical and biological processes and the effect of both types of change in the sustainability of East Texas landscapes need to be investigated.

With this work I intended to analyze the effects of the application of the SFI program in forested landscapes of East Texas. Specifically, I attempted to answer the following questions:

- Is the SFI program able to change the pattern of intensively managed forested landscapes in East Texas?
- Do changes in structure, if any, affect ecological processes at the landscape level in this region? Which processes? How?
- Do changes in structure and function, if any, contribute to the sustainability of the forest landscapes in East Texas? How?

Based upon common knowledge in landscape ecology and forest science I hypothesized that the SFI program has an impact in both structure and function in these landscapes and that sustainable forestry as defined and applied in the SFI program improves the sustainability of landscapes in East Texas.

In this research I initially studied landscape structure in the absence of particular processes, comparing landscapes with different management histories based upon structural attributes measured by landscape metrics. Later, functional implications of the implementation of the SFI program were analyzed. Stand and landscape attributes of suitable habitat of several vertebrate species were used to evaluate processes associated with wildlife at the stand and landscape levels. Water and sediment yield were used to evaluate hydrological processes in this intensively managed and dynamic mosaic.

For these analyses to be done I developed a methodology to integrate landscape and stand pattern and dynamics with landscape processes. It is based upon modeling and simulation, often the only alternative in studies in landscapes given the difficulty in performing experiments at this temporal and spatial scale (Turner 1989). This methodology combines a series of available and reliable models to simulate the application of SFI rules on landscape structure and to simulate the effects of pattern on the biological and physical processes mentioned. It includes a forest landscape structure model (HARVEST), several stand level growth and yield models (Compute P-Lob, SouthPro, and FVS), vertebrate habitat models (Habitat Suitability Index models), and a hydrological model (APEX). This methodology can also be used by planners and managers in testing management decisions in terms of effects on landscape structure and function and evaluate their role in the context of sustainable forestry.

For the purposes of this work I consider sustainable forestry as the management of forest ecosystems maintaining essential ecological structures and functions and the integration of economic, social, and environmental dimensions in forest management.

CHAPTER II

EFFECTS OF THE FOREST SUSTAINABILITY INITIATIVE ON LANDSCAPE STRUCTURE

Introduction

The landscapes we see today are the outcome of the combination of natural, economical, and political elements acting through time. Before human expansion in North America during the Holocene, landscape change was driven by natural disturbances and climatic change. Growing populations modified considerably the structure and function of the landscape until the arrival of European settlers to the continent (Denavan 1992). Landscape change then became dominated by the expansion of agriculture (Meyer 1995) and later by growth of urban centers and infrastructures (Olson and Olson 1999). Forests decreased in area until the early twentieth century and have increased slightly since then with the abandonment of agriculture and regrowth of cut areas (Meyer 1995). In ancient forested landscapes recent change has been marked by intensive cutting and conversion of old growth into second growth forests (Ripple et al. 1991) and by fire suppression (Baker 1992). In East Texas current forested landscapes result mostly from reforestation campaigns that took place during the twentieth century and from natural establishment of forest in abandoned agriculture areas following the intensive exploitation of the nineteenth century. They are also the product of the forest management philosophy and practices followed during the past century.

Industrial forestry is currently following the standards of the Sustainable Forestry Initiative (SFI), the sustainability program of the American Forest and Paper Association (AF&PA), launched in 1994. It is currently followed on 55 million hectares of forestland (AF&PA 2003), more than 90% of the industry-owned forest in North America (AF&PA 2002). The SFI program includes measures relevant at the landscape level such as limitation in size of harvest units, establishment of wildlife corridors, establishment of buffer zones along streams, and application of adjacency rules. These measures might have a profound effect on current landscape structure, and potential changes in structure and function need to be understood.

The adoption of landscape scales in ecological research and planning and the recognition of the interdependency of landscape pattern and function (Turner 1989) contributed to the development of quantitative methods to describe landscape structure. The most common among these are landscape metrics (e.g. O’Neill et al. 1988, McGarigal & Marks 1995). In spite of the limitations often reported, namely redundancy, interaction, correlation, ambiguousness, and sensitivity to map resolution (Tischendorf 2001), landscape metrics are regularly used to analyze landscape pattern on categorical maps and to relate structure and function (Gustafson 1998). Several computer packages are available to calculate many of the metrics including the popular FRAGSTATS (McGarigal & Marks 1995) and PATCH ANALYST (Elkie et al. 1999).

Patterns of forested landscapes have been quantified to evaluate changes caused by natural and human-induced processes (e.g. Baker 1992, Mladenoff et al. 1993, Crow et al. 1999) and to examine the effects of particular forest management practices on landscape pattern, namely size, location, and aggregation of clearcuttings and harvest scheduling (e.g. Franklin and Forman 1987, Gustafson and Crow 1996, Baskent 1999). Also, effects of forest policy on spatial pattern have been studied (Hagan and Boone 1997, Cissel et al. 1998).

The goal of this work is to analyze implications of forest management on landscape structure. The specific objective is to detect the types and nature of change in landscape structure caused by the application of the Sustainable Forestry Initiative in intensively managed forested landscapes in the eastern region of Texas. It is hypothesized that the application of the SFI program changes the pattern of the landscape as measured by landscape metrics. If this is true then landscapes managed according to SFI are different in structure from landscapes managed according to other principles.

Methods

Study Areas

Three areas managed according to different management perspectives were chosen for this study. One area (SFI area) has been managed utilizing intensive forest management according to the Sustainable Forestry Initiative principles since 1991. Another area (IM) has been managed according to more traditional intensive forest management approaches followed by the timber industry in the region. Although there are changes in confined parts of this landscape due to recent application of SFI practices, it still reflects the pattern characteristics of past management. The third area (EM) has been managed for wildlife and timber utilizing extensive forest management. All the areas are owned and managed by Temple-Inland Forest Products Corporation, Diboll, TX.

The three areas are located in southeastern Texas, USA (Figure 1) in identical ecological conditions. Maximum linear distance among areas is 90 km and minimum is 45 km. It is assumed that differences among areas in terms of geomorphology, pedology, hydrology, and others, do not have a strong influence on their landscape pattern. Management at the stand level is intensive in SFI and IM including mechanical site preparation, vegetation control, use of genetically improved vegetative material, fertilization, thinning, and harvesting. Rotations are usually around 30 years.

SFI area is approximately 5000 ha in size. It is located in Sabine County near the western border with San Augustine County. Dominant soils are Utilsols of the Kirvin, Sacul, Woodtel, and Malbis series on the ridges and upper slopes and Inceptisols of the Mantachie series and Alfisols of the Guyton series on the lower slope and stream side positions. Average elevation is around 90 m above sea level (ASL) and slopes are usually below 3%. The IM area is located in Angelina County. In its 5200 ha, Utilsols of the Rosenwall series dominate. Several Alfisols are also important such as Alazan, Diboll, Moten, and Multey series. Bottomlands are entirely Inceptisols of the Pophers series. Mean elevation is approximately 70 m ASL and slopes are usually below 3%. The EM area is 4400 ha in size and is located in Trinity County. Two large flat bottomlands border the area. Slopes are mostly below 1% reaching eventually 8%, the maximum value observed. Soils are mainly Alfisols of the Fuller, Keltys, Kurth, Moten, and Multey series. The bottomlands are dominated by the Ozias (Vertisols) and Pophers (Inceptisols) series. Mean elevation is 65 m ASL.

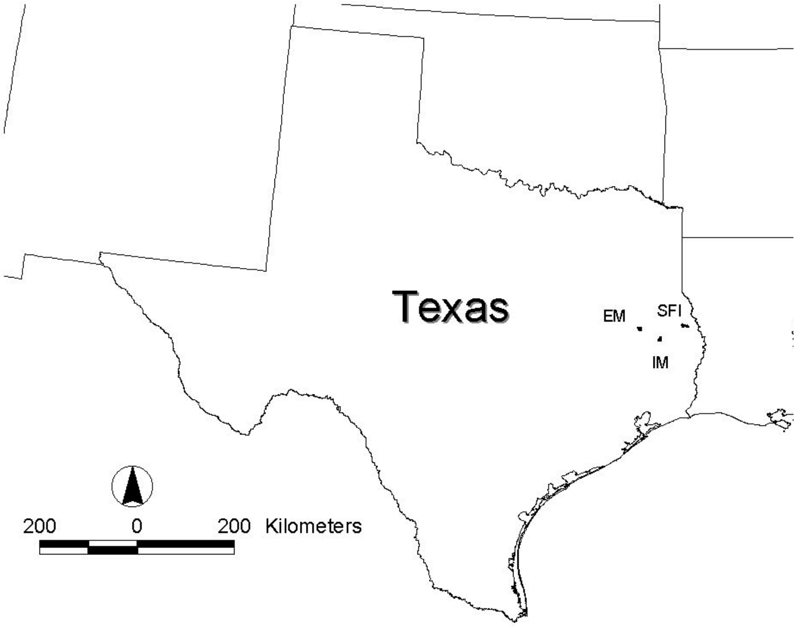

Figure 1. Location of the study areas. SFI: area managed according to the SFI program; IM: area managed according to traditional forest management; EM: area managed by extensive management.

Graphic and tabular data were provided by Temple-Inland for the three study areas. Information relative to tree species, age, and a set of dendrometric variables for each stand was available from the tables. Other data provided included distributions of density, height, and basal area per diameter class and management scheduling in each stand. All data refer to the year 2000.

Comparison of Structure Among Management Types

Classification

Classification is always a critical step in pattern analysis since the criteria followed have a great effect on what is perceptible on the landscape (Gustafson 1998). Given the high variability in stand level conditions (species, ages, densities, etc.) two classification systems were defined. The first system comprises the general classes pine, hardwood, and mixed pine-hardwood stands. Comparisons based upon this system might provide information on general characteristics of the major forest types.

A more detailed classification system was established with the purpose of differentiating structural conditions among the stands of the same forest type assuming that vertical (height, number of strata) and horizontal (density, basal area) structure of the stands is related to ecosystem function. It is also assumed that these conditions are related to structure and function at broader scales. Data concerning distributions of density (stems per acre, SPA), basal area, height, and age by diameter at 1.3 m above ground (DBH) class for both loblolly pine and hardwoods were used to define this classification. For loblolly pine stands a total of 97 observations from the three areas of study were considered. Stands younger than 10 years include data on density only. Based upon visual interpretation of the variables plotted against stand age, three general classes for loblolly pine stands were defined. These classes can be described in terms of age since they are related to the development of the stand: stands younger than 10 years; stands 10 to 40 years old; and stands older than 40 years.

The nine initial years were considered to be the time from stand establishment until past crown closure. Stands older than 40 years represent conditions of relatively mature pine forest, more open and with some advanced regeneration of both pine and hardwood species. Also after this age pine SPA distribution by DBH classes becomes inverse-J-shaped, in opposition to younger stands, which are usually normally distributed, and BA presents increasing weight in the smaller diameter classes. Hardwoods in these older pine stands increase considerably both in terms of BA and density. From ages 10 to 40 stands decrease considerably in density, and individual trees increase in size and height. Thinning occurs at the beginning of this period. Both of the age limits, 10 and 40 years, were arbitrarily established.

This classification for pine stands was partially validated by multivariate discriminant analysis and clustering methods applied to the data. Misclassification rates were relatively small for the discriminant analysis when all the variables were used as predictors (11.4%). Smaller errors could be obtained for a more reduced number of variables which included pine height, shown to be the most important variable in discriminating among the three groups. Classes 1 (<10 years) and 3 (>40 years) present usually reduced or very reduced error. Class 2 (10-40 years) has higher misclassification error, being sometimes classified as class 3. Single, complete and average linkage clustering methods using Euclidean distances for three clusters, formed clusters very similar to the three classes established when pine height and pine density were the variables considered.

Hardwood data are available exclusively for very young and old stands and the range of ages and stand characteristics necessary to the definition of a more adequate classification could not be considered. For this reason the same number of classes considered for loblolly pine was adopted for hardwood stands. Mixed pine-hardwood stands are abundant only in the SFI area. Since all the stands are relatively old (above 44 years) a single class for this type of stand was considered (Table 1).

Raster files were created for each of the study areas classified according to each of the classifications systems and were used as input files in FRAGSTATS (McGarigal & Marks 1995). This program calculates a large set of landscape metrics at the stand, class, and landscape levels that were used to compare the structure of the landscapes. A 10-m resolution was preferred to a lower resolution to allow the maintenance of the narrow streamside stands, a major structural component of the landscape. A distance of 100 m was considered for core area determination and a distance of 1000 m was considered for proximity index determination.

Table 1. Classes in the detailed classification system.

Class number	Forest type	Age (years)
1		0 - 9
2	Pine	10 - 40
3		> 40
4		0 - 9
5	Hardwood	10 - 40
6		> 40
7	Pine-Hardwood	All ages

Statistical Comparisons

Multivariate analysis of variance (MANOVA) was performed to test for differences in structure among landscapes. Small watersheds classified according to the seven-class system were selected in each study area (Table 2). There was no inclusion among samples. The size of the watersheds area is reduced because only small sizes would allow the existence of a reasonable number of observations to make the application of statistical methods possible.

Table 2. Small watersheds considered in the statistical comparison of the landscapes.

		Area				
Landscape Name	N	Mean (ha)	St. Dev (ha)	SE (ha)	Min. (ha)	Max. (ha)
SFI	11	163.5	39.8	12.0	100.6	229.7
IM	14	162.7	52.9	14.1	91.8	248.1
EM	10	149.1	35.9	11.3	104.3	234.6

MANOVA was performed sequentially with all the metrics computed by FRAGSTATS (except variability measures), with the variables that graphically showed to be the best discriminants among areas of study in a hierarchical analysis performed previously, and with the variables that presented significant differences among areas of study in univariate analysis of variance (ANOVA) for the 95% level and 99% levels.

Additionally, larger watersheds were considered to test for statistical differences among landscapes. Given the relatively reduced size of the study areas, it was possible to consider only three watersheds in each management scenario (Table 3). The "Hydrologic Modeling Sample Extension" in ArcView was used in the watersheds delineation of several orders using 30 m resolution Digital Elevation Model (DEM) data (USGS). All the statistical analyses were performed in MINITAB.

Table 3. Large watersheds used in the statistical comparison of the landscapes.

	Area (ha)		
Watershed	SFI	IM	EM
1	543	509	487
2	693	697	593
3	796	407	993
Average (ha)	677.3	537. 7	691
St. Dev (ha)	127.2	147.1	266.9
St. Error (ha)	73.5	84.9	154.1

Results

Descriptive Comparison of the Landscapes

Simple Classification

The study areas are comprised of pine, hardwood, or pine-hardwood forest types (Figure 2). The way these classes are represented in each landscape can be assessed using evenness indices as well as diversity indices since the number of landscape classes is constant (Table 4). All indices increase as the proportion of the area of the 3 classes becomes more equitable. Overall evenness is medium in SFI and EM and low in IM, in spite of variations among the indices considered.

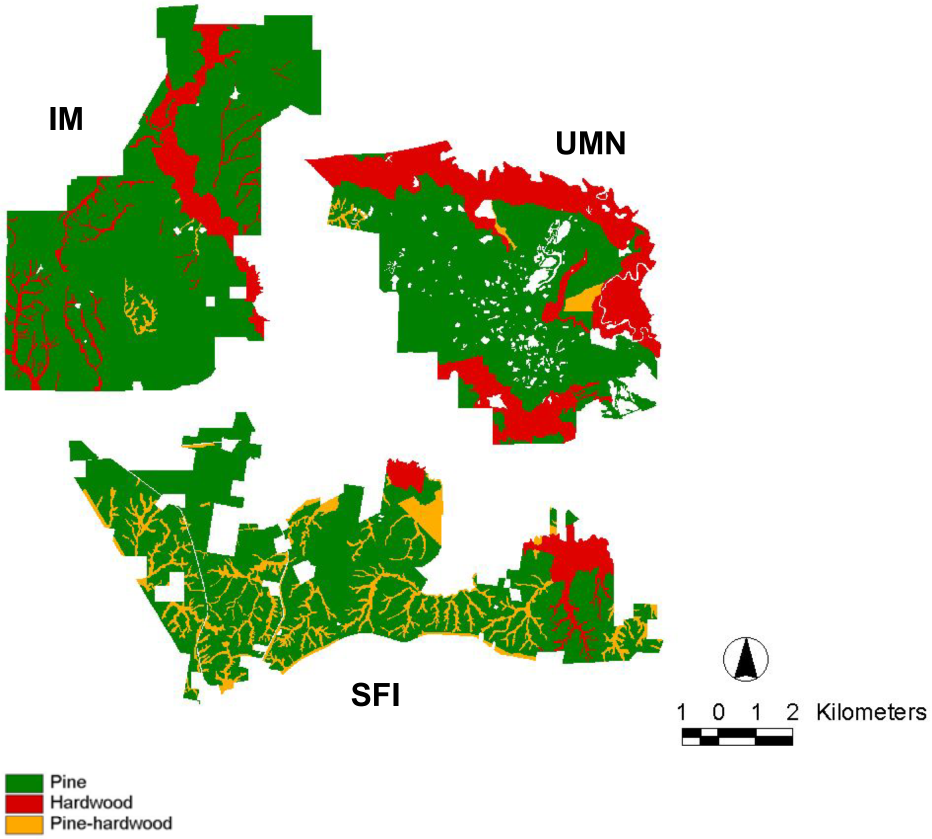

Figure 2. Study areas classified by forest type. SFI: area managed according to the SFI program; IM: area managed according to traditional forest management; EM: area managed by extensive management.

The Largest Patch Index (LPI) value observed at the landscape level was in EM where one single patch occupies 62% of the area. LPI is 55% in IM and 25% in SFI. All these areas correspond to pine patches (Table 5).

The SFI landscape contains a total of 99 individual patches, more than twice the numbers observed in the other landscapes. There are differences among the landscapes in terms of distribution of patch frequency for the three forest types. For pine stands SFI shows a large number of stands smaller than 10 ha and a decreasing number of patches in successive size classes (Figure 3). It presents one patch larger than 1000 ha (1272 ha). IM presents few pine patches in the smallest classes and has a more even distribution in all of the size classes. It includes two patches larger than 1000 ha (1193 and 2877 ha). In EM the largest number of pine patches is in the smallest class. A patch larger than 1000 ha (2714 ha) is observed and there are no pine patches in the 100-1000 ha class.

Table 4. Summary of landscape metrics; landscape level.

		Landscape		
Variable	Acronym	SFI	IM	EM
Total Area (ha)	TA	4998.4	5205.8	4368.6
Largest Patch Index (%)	LPI	25.5	55.3	62.1
Number of patches	NP	99	46	36
Patch Density (#/100 ha)	PD	1.98	0.88	0.82
Mean Patch Size (ha)	MPS	50.5	113.2	121.4
Patch Size Coeff of Variation (%)	PSCV	306.1	398.3	383.2
Total Edge (m)	TE	352640	194280	73810
Edge Density (m/ha)	ED	70.6	37.3	16.9
Landscape Shape Index	LSI	17.2	8.6	9.9
Mean Shape Index	MSI	2.93	3.16	2.27
Area-Weighted Mean Shape Index	AWMSI	6.3	5.7	6.7
Double Log Fractal Dimension	DFLD	1.52	1.42	1.32
Mean Patch Fractal Dimension	MPFD	1.15	1.17	1.13
Area-Weighted Mean Fractal Dimension	AWMPFD	1.23	1.2	1.22
Total Core Area (ha)	TCA	1573.6	3148.3	2450.3
Number of Core Areas	NCA	142	45	50
Core Area Density (#/100 ha)	CAD	2.84	0.86	1.14
Mean Core Area 1 (ha)	MCA1	15.9	68.4	68.1
Core Area Coefficient of Variation 1 (%)	CACV1	426.14	445.38	406.01
Mean Core Area 2 (ha)	MCA2	11.1	70.0	49.0
Core Area Coefficient of Variation 2 (%)	CACV2	358.8	450.1	347.4
Total Core Area Index (%)	TCAI	31.5	60.5	56.1
Mean Core Area Index (%)	MCAI	5.4	8.9	10.5
Mean Nearest Neighbor (m)	MNN	117.5	159.8	162.2
Nearest Neighbor Coefficient of Variation (%)	NNCV	286.5	158.2	270.3
Mean Proximity Index	MPI	7543.7	9631.9	58376.2
Shannon's Diversity Index	SHDI	0.7	0.45	0.72
Simpson's Diversity Index	SIDI	0.39	0.26	0.47
Modified Simpson's Diversity Index	MSIDI	0.5	0.3	0.64
Shannon's Evenness Index	SHEI	0.63	0.41	0.66
Simpson's Evenness Index	SIEI	0.59	0.39	0.71
Modified Simpson's Evenness Index	MSIEI	0.45	0.27	0.58
Interspersion/Juxtaposition Index (%)	IJI	33.1	29.9	58.8
Contagion (%)	CONTAG	61.4	75.3	64.8

Table 5. Summary of landscape metrics; class level.

Metrics		Landscape								
		SFI			IM			EM		
	Acronym	1	2	3	1	2	3	1	2	3
Class Area	CA	3785.8	327.7	885	4418.8	749.2	37.9	2806.1	1485.2	77.3
Percent of Landscape (%)	%LAND	75.7	6.6	17.7	84.9	14.4	0.7	64.2	34	1.8
Largest Patch Index (%)	LPI	25.5	5.2	3.0	55.3	8.0	0.6	62.1	20.6	1.0
Number of patches	NP	41	3	55	14	28	4	18	10	8
Patch Density (#/100 ha)	PD	0.82	0.06	1.1	0.27	0.54	0.08	0.41	0.23	0.18
Mean Patch Size (ha)	MPS	92.3	109.2	16.1	315.6	26.8	9.5	155.9	148.5	9.7
Patch Size Coefficient of Variation (%)	PSCV	247.0	101.3	183.0	244.7	290.8	129.5	398.0	181.1	140.5
Total Edge (m)	TE	350920	38340	316020	194030	175380	19150	71460	58400	17760
Edge Density (m/ha)	ED	70.2	7.7	63.2	37.3	33.7	3.7	16.4	13.4	4.1
Landscape Shape Index	LSI	17.1	6.1	15.9	8.6	7.9	2.5	9.8	9.3	7.7
Mean Shape Index	MSI	2.52	3.17	3.23	2.14	3.62	3.55	2.04	2.51	2.49
Area-Weighted Mean Shape Index	AWMSI	6.1	5.3	7.5	5.8	5.6	5.8	8.0	4.3	2.2
Double Log Fractal Dimension	DLFD	1.41	1.45	1.73	1.38	1.47	1.75	1.33	1.34	1.33
Mean Patch Fractal Dimension	MPFD	1.12	1.14	1.17	1.09	1.21	1.21	1.11	1.13	1.16
Area-Weighted Mean Fractal Dimension	AWMPFD	1.22	1.21	1.28	1.2	1.23	1.28	1.24	1.18	1.12
Core % of Landscape (%)	C%LAND	27.5	3.0	1.0	56.3	4.2	0	37.3	18.4	0.4
Total Core Area (ha)	TCA	1374.9	149.5	49.1	2928.6	219.7	0	1630.1	802.0	18.7
Number Core Areas	NCA	127	6	9	35	10	0	28	21	1
Core Area Density (#/100 ha)	CAD	2.54	0.12	0.18	0.67	0.19	0	0.64	0.48	0.02
Mean Core Area 1 (ha)	MCA1	33.5	49.8	0.9	209.2	7.9	0	90.6	80.2	2.3
Core Area CV 1 (%)	CACV1	300.7	95.6	666.2	250.2	481.0	0	408.3	194.7	264.6
Mean Core Area 2 (ha)	MCA2	10.8	24.9	5.5	83.7	22.0	0	58.2	38.2	18.7
Core Area CV 2 (%)	CACV2	548.7	168.2	253.5	414.2	276.0	0	51478	301.0	0
Total Core Area Index (%)	TCAI	36.3	45.6	5.6	66.3	29.3	0	58.1	54	24.2
Mean Core Area Index (%)	MCAI	10.0	32.5	1.0	22.4	3.4	0	6.7	21.5	5.3
Mean Nearest Neighbor (m)	MNN	32.8	1201.9	121.5	29.6	154.6	651.8	81.9	17.7	523.7
Nearest Neighbor Coefficient of Variation (%)	NNCV	140.9	108.5	164.7	74.2	54.6	94.8	196.2	100.2	152.2
Mean Proximity Index	MPI	17441.5	11.1	576.1	31552.1	47.7	0.6	104307.7	22381.3	23.7
Interspersion/Juxtaposition Index (%)	IJI	48.3	26.4	4.9	46.1	1.6	10.0	75.2	24.3	56.4

Classes: 1- Pine: 2 – Hardwood: 3 – Pine-Hardwood

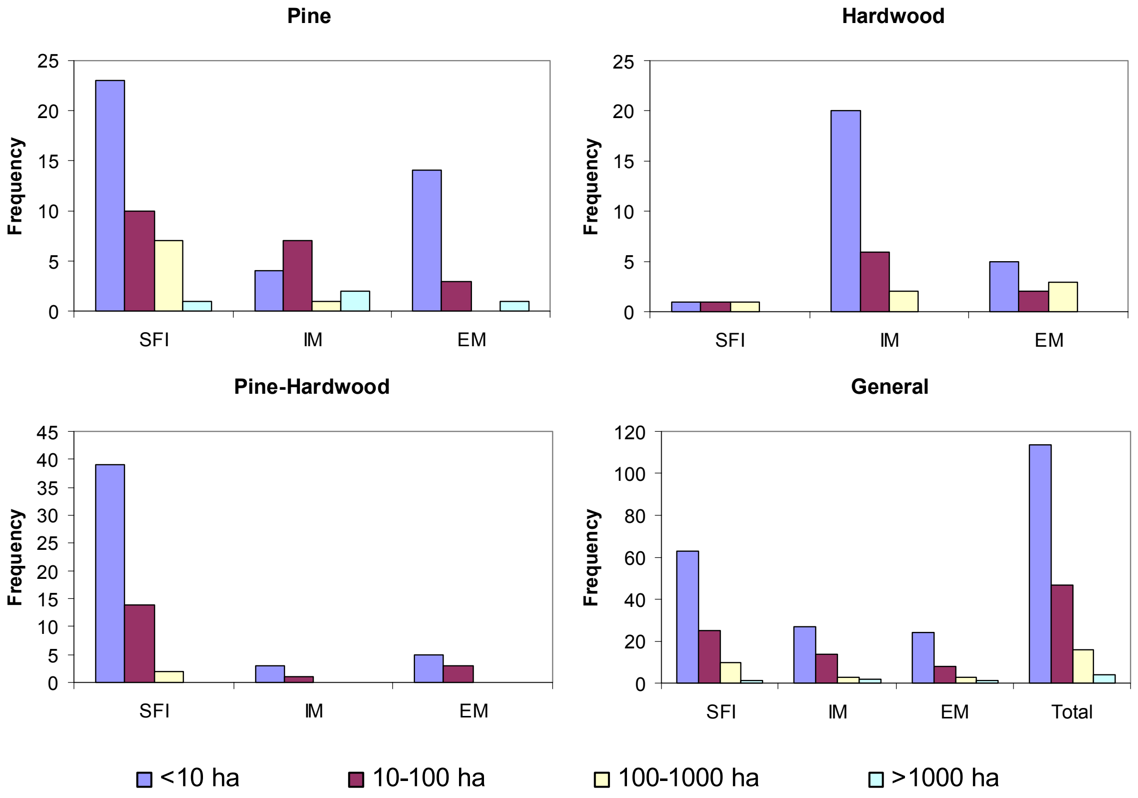

Figure 3. Distribution of number of patches by patch size class in each landscape.

Hardwood and Pine-hardwood stands are not well represented in some of the study areas. They tend to show a negative exponential distribution when the proportion of these classes in the landscape is relatively high (Hardwood in the IM and Pine-hardwood in the SFI) (Figure 3). The distribution of the total number of patches in the three areas of study is also approximately negative exponential.

When analyzed in terms of area (Figure 4) the distributions are J-shaped for the generality of the cases. For Pine there are extreme cases of this type of distribution in the IM and EM landscapes where most of the area is comprised of very large stands. SFI is dominated by pine stands in the 100-1000 ha size class and pine-hardwood stands in the 10-100 ha size class. Mean patch size for the overall landscapes is 50.5, 113.2, and 121.4 ha in SFI, IM, and EM landscapes, respectively, reflecting in part the distributions observed.

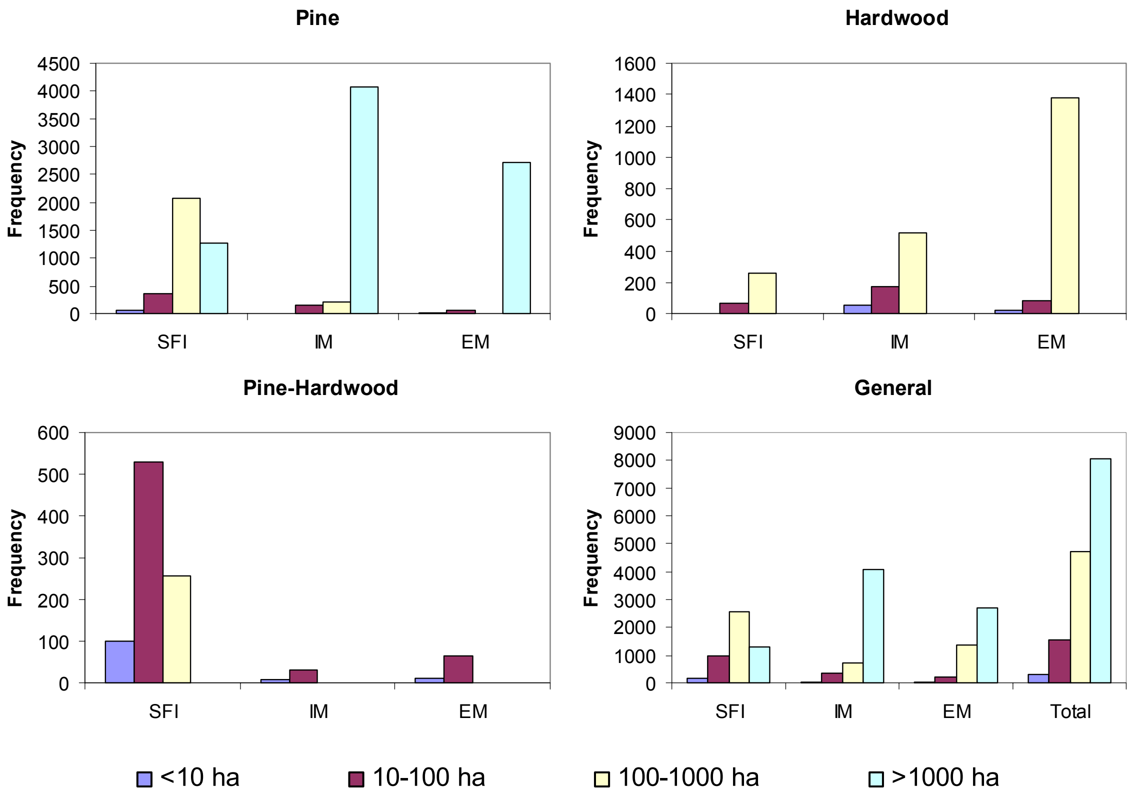

Figure 4. Distribution of summed patch area by patch size class in each landscape.

Landscape metrics that can be useful in describing the spatial arrangement of patches include neighborhood metrics (Mean Nearest-Neighbor Distance, MNN, and Mean Proximity Index, MPI), Interspersion and Juxtaposition Index (IJI) and Contagion Index (CONTAG). At the class level, MNN measures the mean nearest distance among patches of the same type being indicative of isolation within a particular class. At the landscape level the index averages the nearest distances of all the classes in the landscape. SFI exhibits a landscape Mean Nearest-Neighbor Distance smaller than the remaining areas. At the class level, pine presents smaller values in IM (29.6 m) and SFI (32.8 m) than in EM (81.9 m), where hardwoods present the smallest distance (17.7 m). In general, higher distances correspond to lower proportion of the forest types in the landscape.

Mean Proximity Index (MPI) indicates also the degree of isolation of patches. In its calculation both distance between patches of the same type and their area are considered within a search buffer of defined size. Higher values indicate less isolation and less fragmentation among patches of the same type (McGarigal & Marks 1995). EM presents a very high MPI value compared to the values obtained in the other landscapes (Table 4). In this landscape Pine and Hardwood classes show extremely high values (Table 5). The small number of very large and close patches in this landscape might explain these values. Pine has a lower Mean Proximity Index value in SFI than in the remaining areas.

Interspersion and Juxtaposition Index (IJI) and Contagion Index (CONTAG) are metrics of landscape configuration (McGarigal & Marks 1995). CONTAG measures the aggregation of landscape elements based upon the evaluation of adjacencies among patch types. IJI measures the interspersion of patch types. Both indices range from 0 to 100 but are inversely related. High values of CONTAG indicate the presence of few large elements in the landscape. High values of IJI indicate even distribution of adjacencies among patch types (McGarigal & Marks 1995). Contagion Index works on a cell basis while Interspersion and Juxtaposition Index works on a patch basis. For this reason IJI is not directly affected by the size, contiguity and dispersion of the patches but only by the adjacency types, contrarily to CONTAG (McGarigal & Marks 1995). The results for these metrics indicate some differences among the landscapes (Table 4). EM presents the highest evenness of adjacencies at the patch level, considerably higher than in SFI and in IM. The cell-based approach indicates that all the landscapes present relatively high levels of aggregation; however, IM presents the highest contagion value and SFI the lowest (Table 4). Each forest type can be analyzed individually using Interspersion and Juxtaposition Index. Pine presents much higher values in the EM landscape than in the other landscapes where IJI is relatively similar (Table 5).

The shape of patches in the landscapes can be evaluated by metrics as Mean Shape Index (MSI), Landscape Shape Index (LSI) or Area-Weighted Mean Shape Index (AWMSI). Fractal dimension metrics such as Double Log Fractal Dimension (DLFD), Mean Patch Fractal Dimension (MPFD), and Area-Weighted Mean Patch Fractal Dimension (AWMPFD) also provide information about shape complexity. Edges (Total Edge (TE) and Edge Density (ED)) are also related to shape since more complex shapes have a tendency to present larger absolute and relative to area edge lengths.

Mean Shape Index is an average of a perimeter to area ratio of the patches of a certain class (class level) or all patches in the landscape (landscape level). Hardwood and Pine-hardwood always present higher MSI values than Pine in the landscapes (Table 5). EM presents the lowest MSI values of all three classes. Pine MSI is higher in SFI than in the other areas. At the landscape level IM presents the highest value followed by SFI and EM. Area-Weighted MSI is highest at EM and lowest in IM (Table 4).

Double Log Fractal Dimension (DLFD) is based upon the perimeter-area relationship A=kP2/D (McGarigal & Marks 1995). The logarithmic transformation of this expression results in the equation of a straight line relating log (A) with log (P) and having 2/D as the slope. The fractal dimension is obtained regressing log (A) on log (P) and estimating D from the slope of the regression. The average fractal dimension of the patches within a class (class level) or within a landscape (landscape level), the Mean Patch Fractal Dimension (MPFD), is an alternative way of determining fractal dimension when the number of patches is small. Since some forest types have fewer than 20 patches this index will also be considered. The fractal dimension of a particular patch is calculated as a perimeter to area relationship.

SFI presents the highest Double Log Fractal Dimension value among the three landscapes (1.52), followed by IM (1.42) and EM (1.32) (Table 4). Given the relatively high number of patches in the landscapes this variable might be considered the best indicator of general complexity of the shapes present. At the class level (Table 5) some of the classes cannot be correctly interpreted given the small number of patches observed. In general stands of Hardwood and Pine-hardwood are more complex than Pine patches, according to Mean Patch Fractal Dimension (Table 4).

Total Edge (TE) or Edge density (ED) measure the absolute or relative extent of edge for a particular type of patches (patch level) or for all the patches present in that landscape (landscape level). SFI is the landscape with larger edge extent (353 km; 70.1 m/ha) followed by IM (194 km; 37.3 m/ha) and EM (74 km; 16.9 m/ha) (Table 4). At the class level edges are higher for pine, the class with larger representation in all the landscapes (Table 5). Classes with reduced representation in the landscape have edge values comparable to the pine class in some cases such as Pine-hardwood in SFI and Hardwood in NSF and EM.

Landscape Shape Index is a function of the total extent of edges, including boundaries, divided by the square root of the area of the landscape for each class and for the entire landscape. It seems to provide more information on edges than on shape. Its results follow very closely the results obtained for edge metrics (Table 4, Table 5).

Other metrics might also give some indication of configuration and fragmentation such as the core area metrics. At the landscape level, IM presents the highest Total Core Area (TCA) and Total Core Area Index (TCAI), relatively similar to that observed in EM (Table 4). SFI presents much lower values of these metrics. Core areas are distributed by a relatively large number of core areas in SFI but much more reduced in the other cases (Table 4). Mean core areas, both considering the total number of patches (MCA1) and the total number of patches presenting core areas (MCA2), indicate that on average core areas in IM and UNM are larger than in SFI (Table 4). At the class level it can be observed that Pine is the forest type exhibiting the highest Total Core Area and Number of Core Areas as well as the highest percentage of the landscape (C%LAND) (Table 5). Mean core area (MCA1 and MCA2) usually reflects this tendency except for SFI where the mean size of core areas is higher for hardwood than for pine. Total Core Area Index (TCAI) indicates that a great part of the area of Hardwood stands in SFI and EM is comprised of core areas (Table 5). Mean Core Area Index (MCAI) results agree with other core area metrics.

Detailed Classification

Contrary to the previous case, there are major differences in composition among the landscapes considering the detailed classification (Figure 5). Middle age and young stands of pine species (classes 2 and 1) dominate both SFI and IM landscapes. The proportion of forest classes is more even in the SFI landscape. In IM, one single class (class 2) occupies 60% of the landscape. EM is dominated by stands of the oldest classes of both pine and hardwood species. Evenness indices increase considerably in SFI and IM relative to the previous classification. SFI is the landscape presenting highest evenness for all the evenness metrics calculated (Table 6).

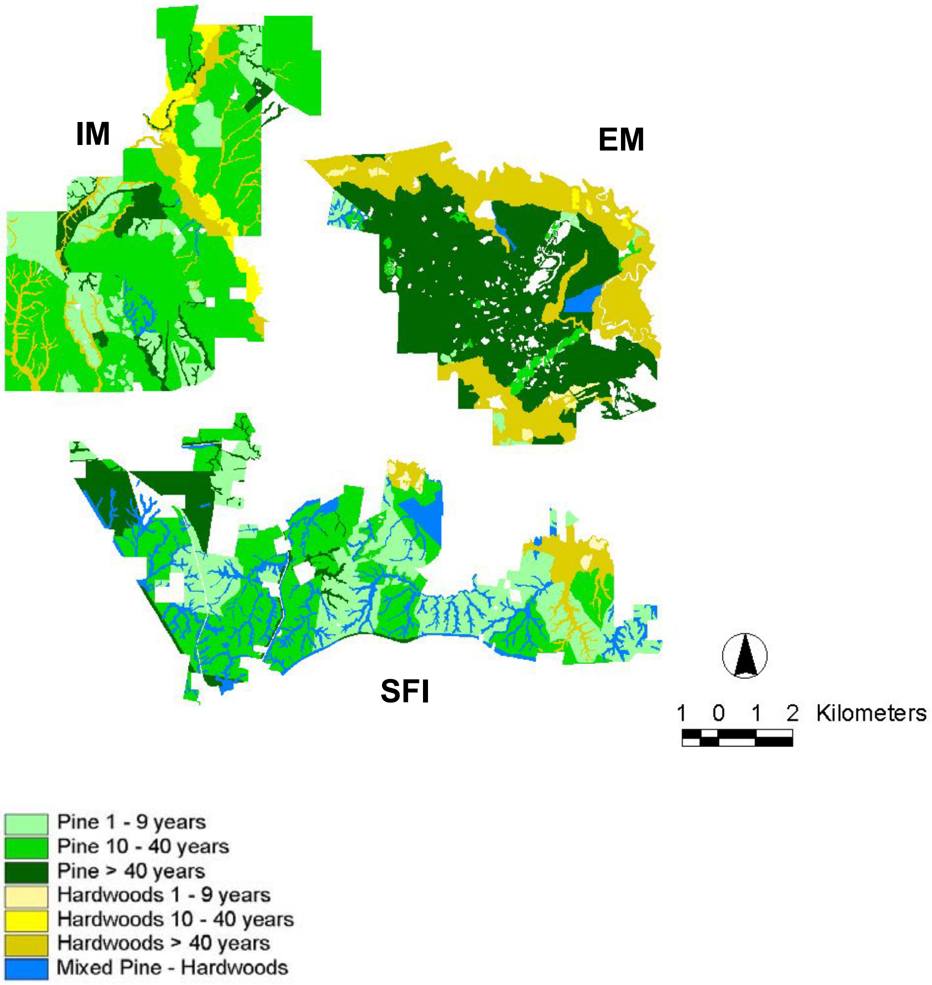

Figure 5. Study areas classified according to the detailed system. SFI: area managed according to the SFI program; IM: area managed according to traditional forest management; EM: area managed by extensive management.

Table 6. Summary of landscape metrics for the seven-class system; landscape level.

		Landscape		
Variable	**acronym**	**SFI**	**NSF**	**EM**
Total Area (ha)	TA	4943.7	5109.3	4368.6
Largest Patch Index (%)	LPI	6.5	23.8	48.3
Number of patches	NP	207	118	77
Patch Density (#/100 ha)	PD	4.19	2.31	1.76
Mean Patch Size (ha)	MPS	23.9	43.3	56.7
Patch Size Coefficient of Variation (%)	PSCV	195.6	294.22	460.78
Total Edge (m)	TE	444050	319540	108140
Edge Density (m/ha)	ED	89.8	62.5	24.8
Landscape Shape Index	LSI	20.7	13.5	11.2
Mean Shape Index	MSI	2.45	2.67	2.06
Area-Weighted Mean Shape Index	AWMSI	4.4	4.1	5.4
Double Log Fractal Dimension	DFLD	1.49	1.42	1.35
Mean Patch Fractal Dimension	MPFD	1.13	1.15	1.12
Area-Weighted Mean Fractal Dimension	AWMPFD	1.2	1.17	1.2
Total Core Area (ha)	TCA	1014.2	2090.3	2252.1
Number of Core Areas (#)	NCA	188	121	66
Core Area Density (#/100ha)	CAD	3.8	2.37	1.51
Mean Core Area 1 (ha)	MCA1	4.9	17.71	29.25
Core Area Coefficient of Variation 1 (%)	CACV1	321.05	420.78	537.33
Mean Core Area 2 (ha)	MCA2	5.39	17.28	34.12
Core Area Coefficient of Variation 2 (%)	CACV2	335.23	415.83	578.7
Total Core Area Index (%)	TCAI	20.51	40.91	51.55
Mean Core Area Index (%)	MCAI	5.5	10.6	5.8
Mean Nearest Neighbor (m)	MNN	79.5	148	195.5
Nearest Neigh Coefficient of Variation (%)	NNCV	172.5	175.1	220.9
Mean Proximity Index	MPI	1594.5	4205.8	9485.1
Shannon's Diversity Index	SHDI	1.48	1.21	0.99
Simpson's Diversity Index	SIDI	0.74	0.59	0.54
Modified Simpson's Diversity Index	MSIDI	1.35	0.9	0.77
Shannon's Evenness Index	SHEI	0.83	0.67	0.51
Simpson's Evenness Index	SIEI	0.89	0.71	0.63
Modified Simpson's Evenness Index	MSIEI	0.75	0.5	0.4
Interspersion/Juxtaposition Index (%)	IJI	64.4	73.9	67.9
Contagion (%)	CONTAG	52.5	61.6	72.6

In SFI the largest patch (Pine, younger than 10 years) is 319 ha in size occupying 6.5% of the landscape (Table 7). The largest patch in IM (Pine, 10-40 years) is 1217 ha in size and occupies 23.8% of the landscape (Table 8). EM is still dominated by a single patch of a particular forest type in this system. This is a pine stand older than 40 years occupying 2108 ha, 48% of the landscape (Table 9). SFI presents the highest number of patches among the landscapes (Table 6). In all the landscapes the majority of patches belong to the two youngest pine classes (Table 7, Table 8, and Table 9).

As in the previous classification, there is a tendency for the forest classes to present negative exponential curves for frequency when the number of patches is high When considered in terms of area, the tendency of J-shaped curves observed in the three classes system is not maintained and the distributions tend to have a bell shape. Classes of older stands (3 and 6) tend to present higher area in the larger size classes.

Table 7. Summary of landscape metrics for the seven-class system; class level, SFI landscape.

		Forest Type					
Variable	**acronym**	**1**	**2**	**3**	**4**	**6**	**7**
Class Area (ha)	CA	1449.9	1753.0	528.1	42.6	285.1	885.0
Percent of Landscape (%)	%LAND	29.33	35.46	10.68	0.86	5.77	17.90
Largest Patch Index (%)	LPI	6.45	3.49	4.5	0.21	4.89	3.08
Number of patches	NP	39	75	28	6	4	55
Patch Density (#/100 ha)	PD	0.79	1.52	0.57	0.12	0.08	1.11
Mean Patch Size (ha)	MPS	37.18	23.37	18.86	7.1	71.26	16.09
Patch Size Coefficient of Variation (%)	PSCV	169.53	166.06	273.46	42.01	140.17	183.02
Total Edge (m)	TE	200920	252130	68230	10020	45920	310880
Edge Density (m/ha)	ED	40.64	51	13.8	2.03	9.29	62.88
Landscape Shape Index	LSI	12.07	13.89	7.35	5.28	6.55	15.98
Mean Shape Index	MSI	2.23	2	2.43	1.65	3.44	3.23
Area-Weighted Mean Shape Index	AWMSI	4.03	3.16	3.6	1.65	6.5	7.52
Double Log Fractal Dimension	DLFD	1.5	1.35	1.4	1.37	1.43	1.73
Mean Patch Fractal Dimension	MPFD	1.11	1.11	1.15	1.09	1.17	1.17
Area-Weighted Mean Fractal Dimension	AWMPFD	1.19	1.16	1.18	1.09	1.25	1.28
Core % of Landscape (%)	C%LAND	5.51	7.98	4.18	0.04	1.81	0.99
Total Core Area (ha)	TCA	272.62	394.36	206.62	1.89	89.56	49.13
Number Core Areas	NCA	79	84	4	3	9	9
Core Area Density (#/100 ha)	CAD	1.6	1.7	0.08	0.06	0.18	0.18
Mean Core Area 1 (ha)	MCA1	6.99	5.26	7.38	0.31	22.39	0.89
Core Area CV 1 (%)	CACV1	228.11	237.03	363.74	120.83	157.01	666.17
Mean Core Area 2 (ha)	MCA2	3.45	4.69	51.65	0.63	9.95	5.46
Core Area CV 2 (%)	CACV2	340.08	253.23	101.64	47.95	260.71	253.48
Total Core Area Index (%)	TCAI	18.8	22.5	39.12	4.44	31.42	5.55
Mean Core Area Index (%)	MCAI	8.37	7.77	3.92	3.51	12.41	1.01
Mean Nearest Neighbor (m)	MNN	50.77	33.3	144.59	109.97	150	121.46
Nearest Neigh Coefficient of Variation (%)	NNCV	152.38	212.83	97.94	58.04	86.67	164.73
Mean Proximity Index	MPI	2464.7	2301.2	1013.2	32.3	273.8	576.1
Interspersion/Juxtaposition Index (%)	IJI	69.11	59.49	66.43	24.68	70.92	54.32

Table 8. Summary of landscape metrics for the seven-class system; class level, IM landscape.

		Forest Type					
Variable	**acronym**	**1**	**2**	**3**	**5**	**6**	**7**
Class Area (ha)	CA	918.4	3059.3	344.5	242.4	506.8	37.9
Percent of Landscape (%)	%LAND	17.98	59.88	6.74	4.74	9.92	0.74
Largest Patch Index (%)	LPI	3.63	23.82	2.74	2.31	4.23	0.6
Number of patches	NP	38	23	22	4	27	4
Patch Density (#/100 ha)	PD	0.74	0.45	0.43	0.08	0.53	0.08
Mean Patch Size (ha)	MPS	24.17	133.01	15.66	60.6	18.77	9.47
Patch Size Coefficient of Variation (%)	PSCV	175.51	194.1	183.01	56.46	234.82	129.52
Total Edge (m)	TE	126290	206520	93040	27750	166330	19150
Edge Density (m/ha)	ED	24.72	40.42	18.21	5.43	32.55	3.75
Landscape Shape Index	LSI	6.75	9.56	5.59	3.31	8.15	3.01
Mean Shape Index	MSI	1.87	2.11	3.18	2.65	3.72	3.55
Area-Weighted Mean Shape Index	AWMSI	2.84	4.08	3.9	3.17	6.66	5.76
Double Log Fractal Dimension	DLFD	1.34	1.38	1.6	2.22	1.53	1.75
Mean Patch Fractal Dimension	MPFD	1.1	1.1	1.19	1.14	1.22	1.21
Area-Weighted Mean Fractal Dimension	AWMPFD	1.14	1.16	1.2	1.16	1.27	1.28
Core % of Landscape (%)	C%LAND	5.17	31.98	1.17	1.14	1.45	0
Total Core Area (ha)	TCA	264.19	1633.93	59.96	58.34	73.87	0
Number Core Areas	NCA	39	54	9	9	10	0
Core Area Density (#/100 ha)	CAD	0.76	1.06	0.18	0.18	0.2	0
Mean Core Area 1 (ha)	MCA1	6.95	71.04	2.73	14.59	2.74	0
Core Area CV 1 (%)	CACV1	289.26	217.79	401.31	46.03	485.55	0
Mean Core Area 2 (ha)	MCA2	6.77	30.26	6.66	6.48	7.39	0
Core Area CV 2 (%)	CACV2	293.49	353.33	244.9	131.4	284.64	0
Total Core Area Index (%)	TCAI	28.77	53.41	17.4	24.07	14.58	0
Mean Core Area Index (%)	MCAI	10.18	28.01	3.33	24.99	1.81	0
Mean Nearest Neighbor (m)	MNN	76.87	45.32	176.61	214.97	227.72	651.77
Nearest Neigh Coefficient of Variation (%)	NNCV	234.87	175.78	106.52	135.73	126.51	94.76
Mean Proximity Index	MPI	1200.3	18814.2	594.9	1105.9	15.8	0.58
Interspersion/Juxtaposition Index (%)	IJI	68.9	82.84	69.4	56.69	65.87	15.07

Table 9. Summary of landscape metrics for the 7-class system; class level, EM landscape.

		Forest Type						
Variable	**acronym**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Class Area (ha)	CA	78.75	116.12	2611.19	52.56	19.7	1412.93	77.31
Percent of Landscape (%)	%LAND	1.8	2.66	59.77	1.2	0.45	32.34	1.77
Largest Patch Index (%)	LPI	0.57	0.94	48.26	0.22	0.23	19.71	1.01
Number of patches	NP	12	25	10	11	3	8	8
Patch Density (#/100 ha)	PD	0.27	0.57	0.23	0.25	0.07	0.18	0.18
Mean Patch Size (ha)	MPS	6.56	4.64	261.12	4.78	6.57	176.62	9.66
Patch Size Coeff. of Variation (%)	PSCV	102.19	179.16	240.93	58.17	36.83	156.97	140.48
Total Edge (m)	TE	17520	21300	73140	15180	5020	66360	17760
Edge Density (m/ha)	ED	4.01	4.88	16.74	3.47	1.15	15.19	4.07
Landscape Shape Index	LSI	7.72	7.86	9.82	7.63	7.25	9.57	7.73
Mean Shape Index	MSI	1.71	1.78	2.79	1.65	2.04	2.7	2.49
Area-Weighted Mean Shape Index	AWMSI	2.12	2.57	6.14	1.71	1.95	4.94	2.23
Double Log Fractal Dimension	DLFD	1.44	1.37	1.3	1.5	0.42	1.44	1.33
Mean Patch Fractal Dimension	MPFD	1.09	1.11	1.15	1.09	1.13	1.13	1.16
Area-Weighted M. Fractal Dim.	AWMPFD	1.12	1.15	1.22	1.09	1.12	1.2	1.12
Core % of Landscape (%)	C%LAND	0.05	0.11	35.09	0.02	0	15.84	0.43
Total Core Area (ha)	TCA	2.22	4.89	1532.95	1.05	0.04	692.19	18.74
Number Core Areas	NCA	6	7	24	2	1	25	1
Core Area Density (#/100 ha)	CAD	0.14	0.16	0.55	0.05	0.02	0.57	0.02
Mean Core Area 1 (ha)	MCA1	0.19	0.2	153.29	0.1	0.01	86.52	2.34
Core Area CV 1 (%)	CACV1	262.85	439.7	253.89	226.08	141.42	162.25	264.58
Mean Core Area 2 (ha)	MCA2	0.37	0.7	63.87	0.52	0.04	27.69	18.74
Core Area CV 2 (%)	CACV2	171.89	216.64	410.73	33.33	0	321.73	0
Total Core Area Index (%)	TCAI	2.82	4.21	58.71	2	0.2	48.99	24.24
Mean Core Area Index (%)	MCAI	1.43	0.64	15.68	1.19	0.14	25.03	5.32
Mean Nearest Neighbor (m)	MNN	258.62	132.4	143.04	119.65	377.78	71.03	523.69
Nearest Neigh Coeff. of Var. (%)	NNCV	185.23	283.38	142.16	232.7	81.41	171.96	152.24
Mean Proximity Index	MPI	65.2	413.9	55073.7	71.0	1.9	20939.4	23.7
Intersp./Juxtaposition Index (%)	IJI	63.62	44.41	68.88	37.63	0	68.94	71.77

Mean Nearest Neighbor at the landscape level indicates that on average patches of the same class in SFI are closer to each other than in the other landscapes (Table 6). Mean Proximity Index at the landscape level is much lower when the seven-class system is used. The order of magnitude among the landscapes is not changed, however (Table 6). At the class level, the highest values for particular classes are observed in EM for classes 3 and 6.

IM presents the highest Interspersion and Juxtaposition Index values among the landscapes, followed by EM and SFI (Table 6). The order of magnitude is different from the previous classification where UNM presented much higher values for this index. The values for the three landscapes are relatively similar. At the class level the classes in each landscape have in general medium to high IJI values. Contagion Index is much higher in the EM landscape thus reflecting the higher aggregation observed in this landscape. SFI presents the lowest CONTAG value.

IM shows slightly higher Mean Shape Index values than SFI and EM at the landscape level (Table 6). This is the same order observed for the three classes system. Considering the size patches as weighting factor, AWMSI is higher in the EM landscape, followed by SFI and IM. At the class level the forest types showing the highest MSI in general present the highest Area-Weighted Mean Shape Index. In all cases the larger patches have a shape more irregular than average patches. At the landscape level the influence of the irregularity of the largest patches seems to be more evident in EM where MSI has the lowest value and AWMSI has the highest value among the landscapes.

Landscape Shape Index, another measure of shape, does not coincide with MSI and AWMSI. As in the previous classification, SFI is the landscape with highest values, followed by EM and IM, with relatively similar results. Pine-hardwood, Pine 10-40 years and Pine <10 years stands are the classes responsible for the high score of LSI in SFI (Table 4). IM Pine 10-40 years and Hardwood >40 present the highest LSI values (Table 5). In EM all the classes present relatively similar LSI.

Double Log Fractal Dimension and Mean Patch Fractal Dimension show non-coincident results for the landscapes and respective classes. At the landscape level Double Log Fractal Dimension indicates higher complexity in SFI than in IM and EM as it did in the three-class system. Mean Patch Fractal Dimension indicates IM as having the highest complexity, followed by SFI and EM although the results are very similar. At the class level there is a tendency for Hardwoods >40 years and Pine-hardwoods to present higher complexity indicated by both Double Log Fractal Dimension and Mean Patch Fractal Dimension although exceptions occur. Double Log Fractal Dimension should be interpreted carefully at this level since some classes present less than 20 patches.

EM and IM present large Total Core Area and Total Core Area Index. SFI presents much lower values for these metrics (Table 6). Mean core area indices MCA1 and MCA2 also preserve this pattern. The Number of Core Areas is much higher in SFI. Mean Core Area Index indicates that IM has the highest percentage of the area of the patches occupied by core areas. EM and SFI both have lower MCAI values. At the class level there is a tendency of the classes that present higher area in the landscapes to have larger Total Core Area. Exceptions occur in SFI and IM where the highest values are observed for Pine > 40 years and Hardwood > 40 years that occupy just 10.7 % and 5.8 % of the landscape. This is probably due to relatively large and regular areas of these classes in the landscape and is indicative of lower fragmentation in these classes. The opposite occurs for Pine-hardwood with a Total Core Area Index value of 5.6% occupying 17.9% of the landscape. In this case there seems to exist high fragmentation in core areas in this class. Hardwood 10-40 years in spite of having the second lowest %LAND in IM (4.7%) presents the third highest Total Core Area Index (24.1%). EM presents the highest Total Core Area Index value among all classes and all landscapes. In this landscape the TCAI values seem to follow closely Percent of Landscape values.

Statistical Comparison of the Landscapes

Small Watersheds

Descriptive statistics for the landscape metrics by area of study are presented in Appendix 1. The Ryan-Joiner test used in the evaluation of normality shows that some variables cannot be considered univariate normal. Distributions of the variables considered two by two, however, present ellipse shapes and the variables seem to be approximately bivariate normal in all the cases. Given the reduced number of observations in each population and considering the bivariate distributions normal we assume that there is multivariate normality in the data set. Transformations towards normality increase correlation among variables limiting certain analyses. Equality of covariance matrices is very difficult to verify in this case. Although some covariances are comparable there are many cases where the maximum difference of $\sigma 1,ii=4\ \sigma 2,ii$ (Johnson & Wichern 1998) is exceeded in the covariance matrices of the three populations. Multivariate analysis of variance was conducted in spite of this limitation.

MANOVA was initially performed with all the variables with the exception of Contagion (CONTAG), Simpson's Evenness Index (SEI), Modified Simpson's Evenness Index (MSEI), and Relative Patch Richness (RPR) (Appendix 2A). The exclusion of these variables was due to the impossibility of the analysis to be conducted in the presence of very highly correlated variables. Significant differences among the three areas of study might exist. The null hypothesis Ho: $\tau 1= \tau 2= \tau 3=0$ (no difference among the groups) is rejected and the alternative hypothesis, H1: at least one $\tau\neq 0$, is accepted at the 0.05 level according to two of the criteria used (Wilk's and Pillai's).

With the variables that seemed to better discriminate among landscapes in an analysis of the pattern at multiple scales conducted previously as responses (Number of Patches, Total Edge, Edge Density, Landscape Shape Index, Total Core Area, Number Core Areas, Core Area Density, Mean Core Area 1 and 2, and Mean Proximity Index), results indicate that there are differences among the landscapes of interest at the 0.001 level for any of the criteria (Appendix 2B).

Most of the variables individually show significant differences among the landscapes although the significance level might be different as seen in the univariate ANOVA results (Table 10). MANOVA, performed with the variables for which univariate ANOVA presents significant differences among areas of study at the 0.05 level, also indicates significant differences among landscapes although in this case they are observable at the 0.01 level for two of the criteria and 0.05 in the remaining (Appendix 2C). Maintaining in the model exclusively the variables that in the ANOVA showed significant differences at the 0.001 level (NP, PD, MPS, TE, ED, LSI, AWMSI, DFLD, AWMPFD, TCA, MCA1, TCAI, and MCAI) results in the rejection of the null hypothesis at the 0.001 level (Appendix 2D).

Table 10. Results of ANOVA for the landscape metrics considering the three areas of study simultaneously.

Variable	Acronym	F	p
Largest Patch Index (%)	LPI	7.40	0.002 **
Number of patches	NP	11.12	0.000 ***
Patch Density (#/100 ha)	PD	12.64	0.000 ***
Mean Patch Size (ha)	MPS	32.04	0.000 ***
Total Edge (m)	TE	26.32	0.000 ***
Edge Density (m/ha)	ED	70.44	0.000 ***
Landscape Shape Index	LSI	13.70	0.000 ***
Mean Shape Index	MSI	5.88	0.007 **
Area-Weighted Mean Shape Index	AWMSI	8.17	0.001 **
Double Log Fractal Dimension	DFLD	11.20	0.000 ***
Mean Patch Fractal Dimension	MPFD	3.36	0.047 *
Area-Weighted Mean Fractal Dimension	AWMPFD	9.84	0.000 ***
Total Core Area (ha)	TCA	11.04	0.000 ***
Number Core Areas	NCA	3.61	0.039 *
Core Area Density (#/100 ha)	CAD	5.27	0.010 *
Mean Core Area 1 (ha)	MCA1	26.15	0.000 ***
Mean Core Area 2 (ha)	MCA2	5.88	0.007 **
Total Core Area Index (%)	TCAI	22.00	0.000 ***
Mean Core Area Index (%)	MCAI	30.90	0.000 ***
Mean Nearest Neighbor (m)	MNN	2.70	0.082 ns
Mean Proximity Index	MPI	1.99	0.153 ns
Shannon's Diversity Index	SHDI	5.03	0.013 *
Simpson's Diversity Index	SIDI	3.98	0.029 *
Modified Simpson's Diversity Index	MSIDI	3.60	0.039 *
Patch Richness	PR	3.92	0.030 *
Patch Richness Density (#/100ha)	PRD	1.27	0.295 ns
Relative Patch Richness (%)	RPR	3.92	0.03 *
Shannon's Evenness Index	SHEI	4.85	0.014 *
Simpson's Evenness Index	SIEI	4.02	0.028 *
Modified Simpson's Evenness Index	MSIEI	3.68	0.036 *
Interspersion/Juxtaposition Index (%)	IJI	0.17	0.845 ns
Contagion (%)	CONTAG	9.26	0.001 **

* - difference at the 0.05 level; ** - difference at the 0.01 level; *** - difference at the 0.001 level

Throughout the analyses just described, high correlation among many of the variables was observed. Therefore a smaller number of variables could be used in distinguishing effectively the structure of the landscapes. These variables could be those representing different components of heterogeneity and at the same time proven useful in discriminating among landscapes, namely Number of Patches (or Patch Density), Mean Patch Size or Contagion for arrangement, Landscape Shape Index for shape, Total Edge or Edge Density for edges, Total Core Area Index or Mean Core Area Index 1 or 2, or Total Core Area for core areas, and Shannon's Diversity Index for composition. The combination of NP, CONTAG, LSI, TE, TCAI, and SHDI indicate significant differences among areas of study in MANOVA at the 0.001 level (Appendix 2E). Similar results are obtained using PD or MPS replacing NP or ED replacing TE. An even more reduced number of variables results also in significant differences among landscapes (Appendix 2F). The same is observed when four, three and two variables among the variables considered are used as responses. In the extreme univariate case, many variables indicate statistically significant differences among the areas of study (Table 10).

To identify the variables and components of structure (effects) that contribute most to the observed differences in the multivariate populations, simultaneous confidence intervals (Bonferroni approach) for the 0.05 level were established to compare the three landscapes pairwise for the 26 variables for which univariate ANOVA presents significant differences among areas of study for the 0.05 level (Table 11).

Table 11. Lower and upper limits of Bonferroni simultaneous confidence intervals for comparisons among the three landscapes based upon small watersheds. Underlined values indicate significant differences for the 95% confidence level.

		SFI- IM		SFI-EM		IM -EM	
Variable	Acronym	lower	upper	lower	upper	lower	upper
Largest Patch Index (%)	LPI	-46.99	14.80	-67.58	-0.57	-49.72	13.77
Number of patches	NP	-4.45	12.28	2.10	20.25	-1.34	15.85
Patch Density (#/100 ha)	PD	-2.79	6.14	1.38	11.07	-0.04	9.14
Mean Patch Size (ha)	MPS	-9.22	4.46	-22.01	-7.17	-19.24	-5.18
Total Edge (m)	TE	422.5	13949.9	6718.7	21388.3	-83.2	13817.8
Edge Density (m/ha)	ED	21.0	71.0	57.7	111.9	13.1	64.5
Landscape Shape Index	LSI	0.06	2.77	0.46	3.39	-0.88	1.90
Mean Shape Index	MSI	-0.12	0.54	-0.04	0.67	-0.23	0.45
Area-Weighted Mean Shape Index	AWMSI	-0.04	2.06	-0.12	2.16	-1.06	1.10
Double Log Fractal Dimension	DFLD	-0.01	0.29	0.03	0.36	-0.10	0.20
Mean Patch Fractal Dimension	MPFD	-0.02	0.04	-0.01	0.05	-0.02	0.04
Area-Weighted M. Fractal Dimension	AWMPFD	0.00	0.11	0.00	0.12	-0.05	0.06
Total Core Area (ha)	TCA	-61.45	1.01	-73.38	-5.65	-41.39	22.80
Number Core Areas	NCA	-2.66	6.03	-1.37	8.06	-2.81	6.12
Core Area Density (#/100 ha)	CAD	-0.82	3.31	-0.37	4.11	-1.50	2.75
Mean Core Area 1 (ha)	MCA1	-6.99	1.31	-12.97	-3.97	-9.90	-1.37
Mean Core Area 2 (ha)	MCA2	-28.74	8.72	-38.66	1.97	-27.59	10.91
Total Core Area Index (%)	TCAI	-34.83	-4.46	-44.15	-11.22	-23.64	7.56
Mean Core Area Index (%)	MCAI	-8.22	1.11	-15.43	-5.31	-11.61	-2.02
Shannon's Diversity Index	SHDI	-0.31	0.47	-0.08	0.76	-0.14	0.66
Simpson's Diversity Index	SIDI	-0.16	0.32	-0.07	0.45	-0.13	0.36
Modified Simpson's Diversity Index	MSIDI	-0.33	0.56	-0.15	0.82	-0.23	0.68
Patch Richness	PR	-1.79	0.49	-1.10	1.37	-0.39	1.96
Shannon's Evenness Index	SHEI	-0.13	0.45	-0.06	0.57	-0.20	0.40
Modified Simpson's Evenness Index	MSIEI	-0.17	0.51	-0.11	0.63	-0.26	0.44
Contagion (%)	CONTAG	-27.68	4.19	-36.69	-2.12	-24.04	8.72

SFI and IM are different due to edges, expressed in terms of both extension (TE) or density (ED), shape (LSI, AWMPFD) and core area (TCAI). Average Total Edge is 422 to 13950 m more extensive in SFI than in IM. Average Core Area is 4 to 35 % larger in IM than in SFI. Other core area metrics are very close to a significant difference between these two landscapes.

It can be speculated that edges, shapes, and core areas are the major factors differentiating SFI and IM. LSI, as seen before, seems to follow edge metrics closely. These factors seem also to have a great deal of interaction. The presence of buffer strips along streams with elongated shapes and curly edges are possibly the structural elements responsible for the differences in the variables observed.

Number of Patches and Mean Patch Size have a strong tendency to differentiate the landscapes when the area of the sample units is large. However in this test sample areas have small size thus artificially biasing patch density. Average patch density is 10.4, 8.7, and 4.2 patches/100ha for sample areas whereas in the total area of study it is 4.2, 2.3, and 1.8 patches/100ha for SFI, IM, and EM, respectively (Table 6). Edge density in samples is 104.1, 58.1, and 19.4 m/ha for SFI, IM, and EM and in the landscape it is 89.8, 62.5, and 24.8 m/ha for SFI, IM, and EM, respectively. Most of the variables are affected by change in scale (extension) although the same proportions among values are usually kept. Analysis of results should be cautious for this reason. SFI is different from EM in many other metrics. LPI, NP, PD, MPS, TE, ED, LSI, DFLD, AWMPFD, MCA1, TCAI, MCAI, and CONTAG all showed to be important effects in distinguishing between these two landscapes. SFI and EM share basically diversity and evenness.

The differences analyzed concern landscape fragments of reduced size. The results of the analysis at this scale ensure only that there are differences at this level. However it can be speculated that if these differences can be observed at this scale they should be able to be observed at other scales where they might be more important. It is reasonable to assume also that other variables can also be responsible for differences between landscapes at different scales.

Large Watersheds

The attempt of comparing the study landscapes at a larger extent was constrained by the reduced number of observations that were possible to define within each study area. When more than five variables are considered simultaneously in MANOVA the degrees of freedom for the Lawley-Hotelling test become 0. Another problem is the error matrix that becomes a singular matrix when many variables are included. Finally the correlation among variables seems to be more serious now and many fewer variables can be considered simultaneously. For that reason MANOVA was run for small sets of variables at a time. Many combinations of variables resulted in non-significant differences among the three landscapes at the 0.05 level. Others indicate significant differences at the same level. Appendix 3 presents the outputs of some combinations that resulted in significant differences. Table 12 provides limits of Bonferroni intervals calculated for the same combinations.

In spite of the reduced sample size there are cases where differences among the three areas of study are significant (Appendix 3). Some combinations of variables (TE, AWMPFD, TCA, CONTAG, for example) provide better indication of these differences than others. In most of the cases at least one of the test statistics indicates non-significant differences among the landscapes. It seems reasonable to consider that the null hypothesis can be rejected for all the models shown in Appendix 3. Analyzing the particular effects responsible for the rejection of the null hypothesis, edges either in the form of ED or TE are the main responsible for the differences found (Table 12). Edge Density indicates significant differences for all the comparisons among landscapes. TE shows differences between SFI and EM when five variables are considered simultaneously and SFI and IM and SFI and EM in the remaining cases. In some cases the areas seem also to be different in terms of core areas although significant effects were not found for any of the variables related to this attribute. CAD, TCAI, and TCA are mainly different between SFI and EM. These same two areas are also different in terms of CONTAG but not significantly. IM seems not to be different from EM in four of the six models shown. SFI is not different from IM in one model. SFI is always different from EM.

Table 12. Lower and upper limits of Bonferroni simultaneous confidence intervals for comparisons among the three landscapes based upon large watersheds. Underlined values indicate significant differences for the 95% confidence level.

		SFI-IM		SFI-EM		IM-EM	
Model	Acronym	lower	upper	lower	upper	lower	upper
Patch Density (#/100 ha)	PD	-7.53	8.28	-4.26	11.55	-4.64	11.18
Edge Density (m/ha)	ED	13.75	57.71	56.87	100.83	21.14	65.10
Core Area Density (#/100 ha)	CAD	-1.89	5.85	-0.87	6.87	-2.85	4.89
Contagion (%)	CONTAG	-36.13	19.22	-50.13	5.22	-41.67	13.67
Patch Density (#/100 ha)	PD	-7.90	8.66	-4.63	11.93	-5.01	11.55
Edge Density (m/ha)	ED	12.71	58.75	55.83	101.87	20.10	66.14
Core Area Density (#/100 ha)	CAD	-2.08	6.04	-1.06	7.06	-3.04	5.08
Area-Weighted M. Fractal Dimension	AWMPFD	-0.01	0.17	-0.05	0.13	-0.13	0.05
Contagion (%)	CONTAG	-37.44	20.52	-51.44	6.52	-42.98	14.98
Number of patches	NP	-47.16	64.49	-33.83	77.83	-42.49	69.16
Total Edge (m)	TE	363.2	61723.4	20503.2	81863.4	-10540.10	50820.10
Total Core Area (ha)	TCA	-277.09	122.59	-381.22	18.46	-303.96	95.72
Contagion (%)	CONTAG	-36.13	19.22	-50.13	5.22	-41.67	13.67
Total Edge (m)	TE	363.2	61723.4	20503.2	81863.4	-10540.10	50820.10
Area-Weighted M. Fractal Dimension	AWMPFD	-0.01	0.16	-0.05	0.13	-0.12	0.05
Total Core Area (ha)	TCA	-277.09	122.59	-381.22	18.46	-303.96	95.72
Contagion (%)	CONTAG	-36.13	19.22	-50.13	5.22	-41.67	13.67
Total Edge (m)	TE	2174.6	59912.1	22314.6	80052.1	-8728.75	49008.75
Area-Weighted M. Fractal Dimension	AWMPFD	-0.01	0.16	-0.04	0.12	-0.12	0.05
Total Core Area (ha)	TCA	-265.29	110.79	-369.42	6.66	-292.16	83.92
Total Edge (m)	TE	-1087.79	63174.39	19052.2	83314.4	-11991.09	52271.09
Area-Weighted M. Fractal Dimension	AWMPFD	-0.01	0.17	-0.05	0.13	-0.13	0.05
Total Core Area Index (%)	TCAI	-55.59	17.79	-69.27	4.12	-50.37	23.02
Shannon's Diversity Index	SHDI	-0.80	0.89	-0.32	1.37	-0.37	1.32
Contagion (%)	CONTAG	-37.44	20.52	-51.44	6.52	-42.98	14.98

The results seem to be markedly affected by an “outlier” in SFI (the third watershed). These results cannot be fully compared to those obtained for smaller areas given the limitations of the reduced number of samples used. Edge metrics seem, however, to share a main role in distinguishing among landscapes. ANOVA results (Table 13) also indicate this tendency with TE and ED as the variables showing the most significant differences.

Table 13. Results of ANOVA for the larger watersheds considering the three areas of study simultaneously.

Variable	Acronym	F	P	
Largest Patch Index (%)	LPI	12.06	0.008	**
Number of patches	NP	1.59	0.28	ns
Patch Density (#/100 ha)	PD	2.59	0.155	ns
Mean Patch Size (ha)	MPS	2.22	0.19	ns
Total Edge (m)	TE	28.46	0.001	**
Edge Density (m/ha)	ED	129.85	0.0000	***
Landscape Shape Index	LSI	3.45	0.101	ns
Mean Shape Index	MSI	1.8	0.244	ns
Area-Weighted Mean Shape Index	AWMSI	4.98	0.053	ns
Double Log Fractal Dimension	DFLD	7.18	0.026	*
Mean Patch Fractal Dimension	MPFD	0.66	0.552	ns
Area-Weighted M. Fractal Dimension	AWMPFD	7.78	0.022	*
Total Core Area (ha)	TCA	8.35	0.018	*
Number Core Areas	NCA	2.85	0.135	ns
Core Area Density (#/100 ha)	CAD	6.24	0.034	*
Mean Core Area 1 (ha)	MCA1	3.75	0.088	ns
Mean Core Area 2 (ha)	MCA2	1.52	0.293	ns
Total Core Area Index (%)	TCAI	8.78	0.017	*
Mean Core Area Index (%)	MCAI	2.06	0.209	ns
Mean Nearest Neighbor (m)	MNN	0.36	0.715	ns
Mean Proximity Index	MPI	0.46	0.651	ns
Shannon's Diversity Index	SHDI	5.22	0.049	*
Simpson's Diversity Index	SIDI	3.2	0.113	ns
Modified Simpson's Diversity Index	MSIDI	3.26	0.11	ns
Patch Richness	PR	7	0.027	*
Patch Richness Density (#/100ha)	PRD	2.54	0.159	ns
Relative Patch Richness (%)	RPR	7	0.027	*
Shannon's Evenness Index	SHEI	4.36	0.068	ns
Simpson's Evenness Index	SIEI	2.88	0.133	ns
Modified Simpson's Evenness Index	MSIEI	3	0.125	ns
Interspersion/Juxtaposition Index (%)	IJI	0.11	0.899	ns
Contagion (%)	CONTAG	6.76	0.029	*

* - difference at the 0.05 level; ** - difference at the 0.01 level; *** - difference at the 0.001 level; ns-not significantly different

Discussion

Differences in edges and other variables detected in this work can be explained mainly by the introduction in the landscape of Streamside Management Zones (SMZs), stream buffer zones wider than 30 m, established according to the SFI program. These long, narrow elements break the large blocks of pine forest into smaller units increasing the number of patches, decreasing their size, and simultaneously increasing edge length. Core areas decrease in size and increase in number. This corresponds to dissection, the spatial process described by Forman (1995).

The results suggest that the application of the SFI program causes fragmentation of the landscapes. Although fragmentation is often seen as a function of the organism or function taken under consideration (Loyn and McAlpine 2001) it can also be understood in a more general sense as the division of habitat into smaller pieces (Forman 1995, Turner et al. 2001). In such an approach seral stages, communities, or ecosystems are taken as surrogates of population or physical processes.

Typical effects of forest fragmentation include increase in number of patches and edge length and decrease in patch size and core area (Franklin and Forman 1987, Ripple et al. 1991). Isolation among patches of interest increases also with fragmentation (Saunders 1991, Andrén 1994). The sustainable landscape (SFI) presents many more and smaller patches than the non-sustainable (IM) or reference (EM) landscapes although differences among landscapes for these attributes were statistically significant for the ANOVA analysis at the small watersheds level only. SFI presents the highest extension of edges, a fact reflected by most of the variables that consider this attribute in their calculation. This was observed in the descriptive analysis considering both classification systems and in the statistical analysis of the landscapes. Considering pine only, the dominant cover, a similar pattern is observed although not tested statistically.

Isolation in terms of MPI and MNN was not considered a major differentiating factor among the landscapes. Average distances at the landscape level are usually smaller in SFI than in IM for any of the classification systems used. Considering pine stands as the target cover in the simple classification we observe a slightly higher MNN and considerably lower MPI in SFI than in IM. In the detailed classification system however all the pine classes show shorter distances in the SFI landscape (or proximity noticeably higher). This is also an effect of the introduction of the SMZs in the landscape. These elements breaking pine stands create several stands that are in average separated from other stands of the same type only by a very short distance defined by the buffers width making average distance decrease. Isolation is usually more evident in extreme fragmentation scenarios where area of habitats of interest is very reduced (Gustafson and Parker 1992).

Fragmentation in primeval forests as a result of management or land use change is well known. The results of this work indicate that fragmentation results also from the application of sustainable forestry practices in intensively managed landscapes. This kind of process has been described previously. Li et al. (1993) through simulation in theoretical maps have detected increasing fragmentation with decreasing harvesting size (through edge density, patchiness, shape and interior habitat) and for certain percentage of the landscape harvested (less than 40-45%) edge density was higher when stream networks were considered as constraints. Hagan and Boone (1997), simulating the application of the Maine Forest Practices Act program noticed increasing fragmentation measured in terms of edges, core areas, and mature forest remaining. This fragmentation resulted from the reduction in clearcut size and from separation distances and separation zones established between clearcuts. Cissel et al. (1998) simulated the implementation of a management plan developed based upon the standards, guidelines and assumptions of the Northwest Forest Plan in Oregon and observed that it resulted in increasing fragmentation compared to the existing pattern. This plan among many other aspects includes the creation of riparian reserves along streams. Patches increase very significantly in number and decrease in size and edges increase abruptly. In both cases buffer strips play a major role in the landscape pattern. The separation zones in the case of Hagan and Boone (1997) and the riparian reserves in the case of Cissel et al. (1998) associated with a reduction in harvest units produce the same type of pattern observed in the application of the SFI program. The effect of the reduction of harvest unit size seems in both cases to be less important than the establishment of buffer strips.

The results of this work raise several questions. The first one is whether changes detected in structure are relevant in terms of biological or physical processes in these forested industrial managed landscapes. In biological terms increasing isolation, number of generalists, number of multihabitat species, number of edge species, number of exotic species, nest predation and extinction rate, and decreasing dispersal of interior specialists, large-home-range species and richness of interior species (Forman 1995) are usually associated to changes detected here. The most important question, however, is whether the landscapes that SFI is creating in east Texas are sustainable landscapes. The answer is not easy to provide and substantial research has to be directed to the multidisciplinary study of patterns and processes in the region.

Some caution is recommendable in the interpretation of the results due to the statistical assumptions that could not be met, to the effect of size of sampling areas (small watersheds) on landscape metrics, and to sample size (large watersheds). Also, particular processes of interest, essential in the analysis of landscape structure (Cale and Hobbes 1994, Gustafson 1998) were not defined in this work. Instead a higher level of generalization was preferred as a way of exploring potential perspectives of research.

Summary

The descriptive analysis considering both classification systems and the statistical analysis at two scales indicate that there are differences among the landscapes compared. For the three-class system SFI is the landscape presenting more and smaller patches, more edges, more complex shapes, less and smaller core areas, and shorter distances among patches. EM and IM are relatively similar in the sense that they are comprised of larger blocks of the same forest type, which is reflected by most of the metrics quantified. For the seven-class system SFI does not present a strong predominance of any particular class or particular patches as observed in the other landscapes. SFI presents many more patches on average much smaller than the other landscapes, the same pattern being observed for core areas. Edge length is much higher, and nearest distance between patches of the same type is much smaller in SFI than in the other landscapes. There is also a tendency for SFI to present more complex shapes. Differences mentioned are detected by the landscape metrics independently of the detail used in the classification system.

The statistical analyses indicate that SFI has more edges, more complex shapes, and less core area that the remaining landscapes. The IM landscape seems in many ways to have more in common with EM than with SFI in spite of SFI and IM being intensively managed. Both landscapes show high aggregation and connectivity. The similarity between these landscapes could be even stronger if some of the areas in IM had not been submitted to the SFI program recently.

The Sustainable Forestry Initiative is changing the pattern of forested landscapes in East Texas. These changes indicate that fragmentation is increasing as a result of the application of the SFI program. Further research is necessary to evaluate the physical and biological consequences of this fragmentation in the region.

CHAPTER III

DEVELOPMENT OF A METHODOLOGY FOR THE ASSESSMENT OF SUSTAINABILITY IN INTENSIVELY MANAGED FORESTED LANDSCAPES IN EAST TEXAS

Introduction

Sustainability has become a major issue for politicians, managers, scientists, and the public in general (Christensen et al. 1996, Mebratu 1998). In forestry, sustainability has become the most important goal in planning and management. Several international and national initiatives started defining concepts, guidelines, and strategies for sustainable management at global, regional and local scales. The UN Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992 represented the first major international event where sustainability in forests was addressed. The "Statement of Forest Principles" and the "Convention on Biodiversity" defined expressly priorities and guidelines for sustainable management of forests. The Montréal Process in North and South America, Russia, Asia, and Oceania, and the Helsinki Process in Europe assumed the importance of sustainable forestry at the global and continental scales and defined principles and practices to be adopted by signatory states. Virtually every country is currently defining and/or applying sustainability measures in their forests.

In the United States sustainability became the goal in national forests (Thomas 1995, USDA Forest Service 2000) that have been managed according to approaches such as ecosystem management (Szaro et al. 1998) and ecosystem health (USDA Forest Service 2000) or ecosystem integrity (Vora 1997). The Sustainable Forestry Initiative (SFI), a program developed by the American Forest and Paper Association (AF&PA) in 1994, defined principles and practices timber companies must follow to achieve sustainability on the land they manage (Cantrell 1998). The American Tree Farm

System and the Forest Stewardship Program (FSP) provide means to plan and manage non-industrial private forests according to sustainable forest management.

The concepts of sustainability and sustainable development were initially part of the World Conservation Strategy of 1980 (IUCN 1980) although these terms were never mentioned in the document. Sustainable development became later defined by the Brundtland Commission in the World Commission in Environment and Development Report "Our Common Future" in 1987 (WCED 1987). More recently, diverse academic disciplines presented particular interpretations of the concept (Mebratu 1998). Within forestry, slightly different concepts have been offered including sustainable ecosystem management (Swanson and Franklin 1992, Szaro et al. 1998), sustainable forestry (Cantrell 1998), or sustainable forest management (Peng 2000). These concepts overlap to a great extent. All are management concepts. All are based upon the maintenance of vital structures and functions of the forest ecosystems. All require the integration of environmental, social, and economic perspectives in the management of forest ecosystems.

Addressing sustainability requires a multiple scale approach (Christensen et al. 1996) given the interrelationships among processes and structures at different levels of organization. Broad scales have been supported within land planning, nature conservation, and land management, including forest management, as essential scales to address sustainability in both natural and managed systems (Lubchenco et al. 1991, Christensen et al. 1996). The landscape scale has increasingly been used within the context of sustainability. Forman (1995) considers landscape and region as the proper scales to address sustainability. Rapport et al. (1998) apply the concepts of ecosystem health and integrity to landscapes in a broader context of sustainability. Among the indicators of ecosystem health summarized by Vora (1997) some landscape level variables are present such as habitat fragmentation, extent of undisturbed communities, habitat diversity, and horizontal patchiness. Andersson et al. (2000) realize the need for a landscape approach in forestry research in Europe to address problems related to biodiversity and water quality as well as related to management practices that sustainable forestry requires.

The landscape perspective is also present in many of the recommendations and measures in sustainable forestry. Many of the criteria and indicators of the Montréal Process and of the Pan European Forest Certification program, although not very spatially oriented, require broader scales to be defined and applied (Montréal Process Working Group 1999, Ministerial Conference On The Protection Of Forests In Europe 2003). Criteria like water conservation, habitat and species conservation, maintenance and encouragement of productive functions of forests, or maintenance of ecosystem health, rely strongly on the spatial characteristics of the ecosystems considered at broad scales. At the national level programs such as The Sustainable Forestry Initiative (SFI) in the USA, provide guidelines to be addressed at the landscape scale, namely riparian buffer zones, wildlife corridors, harvest size limits, and adjacency rules.

Implications of forest management practices at the landscape level have received particular attention by researchers. Typically work done in this field has been focused on either the study of the structure of the forested landscapes submitted to different management strategies or plans (e.g. Spies et al. 1994, Crow et al. 1999) or modeling and simulation of structure as determined by management practices, usually regeneration method, harvesting frequency, and harvesting spatial pattern or several of these (e.g. Gustafson and Crow 1996, Baskens 1999, Shifley et al. 2000). Also forest policy has been simulated in terms of spatial pattern generated (Hagan and Boone 1997, Cissel et al. 1998).

In this work a methodology to be used in the assessment of the sustainability of forest landscapes in east Texas is defined combining landscape structure with biological and physical processes based upon a modeling and simulation approach. It is a simple integration of available and reliable models aimed to provide planners and managers with a tool useful in testing planning and management decisions with landscape expression in the structure and function of landscapes. Vertebrate habitats and hydrological processes are here used as major components of landscape function to be related to forest and landscape structure. This methodology is tested for the case of the Sustainable Forestry Initiative (SFI), the sustainability program of the American Forest and Paper Association (AF&PA). This program was lunched in 1994 being currently followed on 55 million hectares of forestland (AF&PA 2003) and more than 90% of all the industry owned forest in North America (AF&PA 2002). The SFI program includes measures at the landscape level such as limitation in size of harvest units, establishment of wildlife corridors, establishment of buffer zones along streams and application of adjacency rules. Although established with the purpose of minimizing effects of forestry on water, soil, and wildlife these measures have not been explicitly analyzed in the landscape context.

Other cases of integration of landscape pattern and process applied to management are described in the literature. Hansen et al. (1992) integrated a habitat model with a landscape pattern simulator to analyze effects of landscape change on avian communities. The LEEMATH model (Li et al. 2000) was designed to evaluate management strategies at the landscape level based upon timber production and habitat quality in the Southeast. TELSA simulates the effects of management on plant succession and disturbance (Kurz et al. 2000). LANDIS (Mladenoff and He 1999) is a model of forest landscape dynamics integrating succession, windthrow, fire, and management. It allows other model components to be integrated providing a way of simulating effects of management or natural induced changes on timber harvesting (Gustafson et al. 2000), plant processes (He et al. 2002b), metapopulation dynamics (Akçakaya 2001), fire spread (Pennanen and Kuuluvainen 2002), or climate change (He et al. 2002a). Weber et al. (2001) integrated an ecological and a hydrological model with an agro-economical simulation model to analyze impacts of land use change on economics, landscape pattern, biodiversity and water processes in agriculturally dominated landscapes.

The methodology presented here shares many aspects with the systems above. It is different from them because it uses components that are suitable for East Texas, is relatively simple to use, available, and requires minimal input data. Additionally, the methodology is focused on the dynamics of intensively managed forested landscapes that rely on short rotations and small temporal and spatial resolution.

Methodology

Approach

A landscape approach to forest sustainability requires integration of structure and function at several scales in a multidisciplinary perspective. The methodology presented here includes a landscape structure model and forest stand level model to simultaneously simulate the dynamics of landscapes and forest stands as a function of management rules (Figure 6). Dynamics of wildlife habitat suitability and spatial pattern as well as water and sediment yield are evaluated at these scales. A GIS, ArcView 3.2, is the center of the process linking simulations, displaying, converting, editing and analyzing data from and to the models.

Modeling and simulation are often the only alternatives in landscape studies given the difficulty in performing experiments at this scale (Turner 1989) and the time required to find satisfactory responses in contrast with the immediate need of results to support management decisions. Processes used as criteria or indicators of sustainability of a system, namely hydrological and biological processes, are among the most urgent to be simulated in landscapes in order to evaluate the implications of the decision making process in forest management.

For the purposes of this work sustainable forestry is the management of forest systems providing essential ecological structures and functions are maintained. Criteria of sustainable forestry are the elements defining the scope and outputs of forest management (Brand 1997). According to the dominant philosophy they are the key components of the forest systems including environmental, social and economic dimensions. The criteria selected in this work are water, soil, and biodiversity. Although fundamental, economic and social components of the sustainable forestry concept are beyond the scope of this work. Water and soils were chosen since they are the most important physical components of the ecosystem and play a key role in productivity and plant and animal distribution in the landscape, i.e., the distribution of water and soil defines to a great extent the composition and patchiness of the landscape. This corresponds broadly to criterion 5 of the Helsinki Process (Ministerial Conference on the Protection of Forests in Europe 2003) and criterion 4 of Montreal Process (Montréal Process Working Group 1999). Biodiversity represents the living part of the ecosystem. It is in relation to biodiversity that many of the matters concerned with sustainability have been addressed due to their sensibility and the irreversibility of the impacts it suffers from human activities. This corresponds broadly to criteria 4 and 1 of the Helsinki and Montreal Process, respectively.

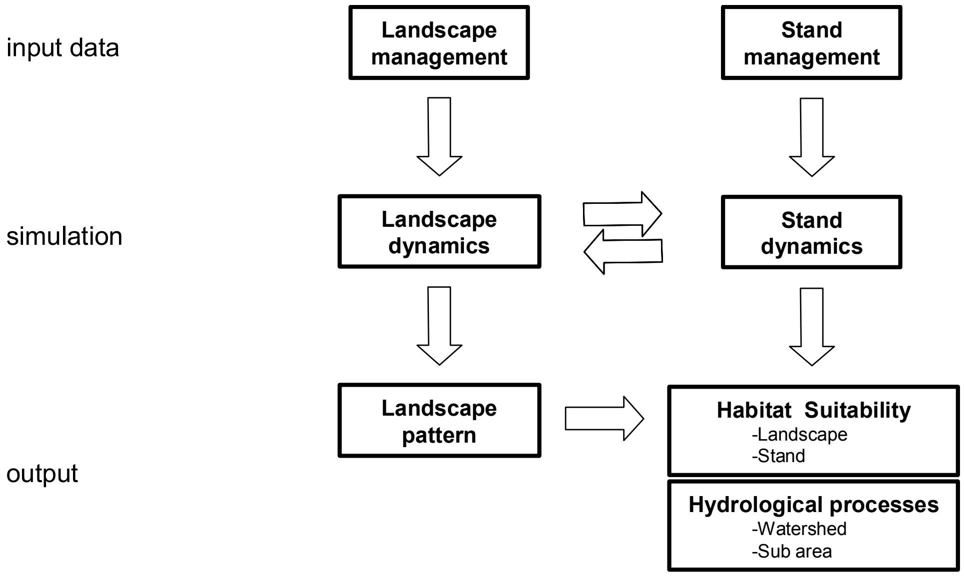

Figure 6. Representation of the methodology and relations about components.

Indicators were considered as measurable features of the criteria (Brand 1997) or variables that could be used to measure the status of a system or process (Mendoza and Prabhu 2003). The indicators considered here are:

- soil loss

- water yield
- habitat diversity, area, quality, and spatial structure for a set of vertebrate species

Indicators are scale dependent (Prabhu et. al. 2001). At the landscape level the indicators chosen seem to provide useful information on the state of the system under analysis. Soil loss is a good indicator of soil at local and landscape scales. Mean, minimum, and maximum values of soil loss are known for several circumstances, including East Texas, and these values can be used to evaluate current and simulated soil loss rates. Water yield indicates the water available for other uses and provides useful information on plant cover, biomass at the watershed level. Annual and monthly water yield can be compared with forested and non-forested, natural and non-natural watersheds to evaluate the impacts of management on this component. Although indicator species is a controversial matter (Simberloff 1998), the analysis of structural elements of ecosystems and landscapes related to habitats of species and their analyses at the landscape level is an acceptable way of accessing biodiversity at this scale of work (Lindenmayer and Franklin 1997, Lindenmayer et al. (2000).

Study Area

The study was conducted in an area of 5773 ha located in Angelina County, Texas, USA. It is part of the watershed of Shawanee Creek, Neches River. This area is for the most part owned by Temple-Inland Forest Products Corporation, Diboll, Texas, and managed for industrial forestry. Actual forest types are pine, mainly loblolly pine *(Pinus taeda* L.), 4727 ha (82% of the area), hardwoods, 796 ha (14%), and pine-hardwood mixed stands, 251 ha (4%). Aproximately 70% of the area is managed by even-aged silviculture (clearcutting system). Soils are predominantly Ultisols (Rosenwall series) and Alfisols (Diboll series). The limits of the study area were defined using the watershed delineation process of the SWAT 2000 model, ArcView interface (Di Luzio et al. 2002).

Landscape Simulation

Management measures were simulated at the landscape level with the forest landscape dynamics model HARVEST 6.0 (Gustafson and Crow 1999). This is a raster model designed to simulate even- and uneven-aged silvicultural systems. It incorporates parameters usually considered in forest management such as silvicultural method, harvest unit size, total area harvested, rotation length, and green up interval, among others (Gustafson and Crow 1999). It requires maps on forest types, age of stands, management zones, and stand identification. HARVEST time step length is variable being the minimum 2 years, which seems to be adequate for short rotation systems. This model has been extensively used in analysis of forest patterns as affected by forest management (e.g. Gustafson and Crow 1996, Gustafson and Crow 1998, Gustafson and Rasmussen 2002).

A GIS coverage provided by Temple-Inland was used as initial data for the definition of management scenarios. Existing blank areas were classified in terms of forest cover and stand age based upon Digital Orthophoto Quadrangles (DOQs), 1m resolution, originally 1:40,000 NAPP coverage from 1994-96, obtained from the Texas Natural Resources Information System (TNRIS).

A scenario where SFI management practices were simulated was compared with a reference scenario managed without particular sustainable forestry criteria in mind. The SFI scenario resulted from the application of the following constraints:

- Harvest unit size:
    - pine: limited to 49 ha
    - hardwoods: limited to 12 ha
- Buffer zones: Streamside Management Zones (SMZs), 30 m or wider along perennial and intermittent streams
- Adjacency: unit must have three-year-old trees before adjacent areas can be harvested.

Previously to the simulations in HARVEST, buffer zones were created around all temporary and permanent streams in the area and pine stands remaining larger than 49 ha were subdivided. Forest type is comprised of pine, hardwood, and pine-hardwood classes. The management types considered were pine-clearcutting system, hardwood-clearcutting system, pine-selection system, hardwoods-selection system, and pine-hardwoods-selection system (Table 14,Figure 7). The pine-clearcutting system was applied in all pine stands actually managed according to this system. Hardwood-clearcutting was applied to hardwood stands not included in SMZs and presently managed according to this system. Hardwoods-selection was applied in the stands currently managed according to this system and in all stands to be considered as belonging to SMZs. It was assumed that in the future SMZs tend to be comprised of hardwoods and will be managed by the selection system. Pine-hardwoods-selection was applied in non-SMZ pine-hardwood stands.

Table 14. Area by management type in the SFI and Non-SFI scenarios.

			SFI		Non-SFI	
Management type	Forest type	Silvicultural system	Area (ha)	Area (%)	Area (ha)	Area (%)
1	Pine	clearcutting	3964.3	68.7	4993.3	86.5
2	Hardwood	clearcutting	265.8	4.6	595.2	10.3
3	Pine	selection	164.4	2.8	183.5	3.2
4	Hardwood	selection	1260.4	21.8	-	-
5	Mixed	selection	116.9	2.0	-	-

The reference scenario (Non-SFI) is obtained by simplification of the initial coverage. Mixed stands were converted into pine stands. Existing SMZs were dissolved into the pine stands and no new SMZs were established. Stands with similar forest type, age, and site index were merged. Forest types are pine and hardwood only (Table 14) and management types were reduced to pine-clearcutting system, hardwood-clearcutting system, and pine-selection system.

Maps for forest age, forest type, management, and stand ID were created in the GIS to be used as input files in HARVEST. Runs of 400 years were made for a 2-yr “Time Step Length”. For each scenario five replications with number seeds randomly generated were used.

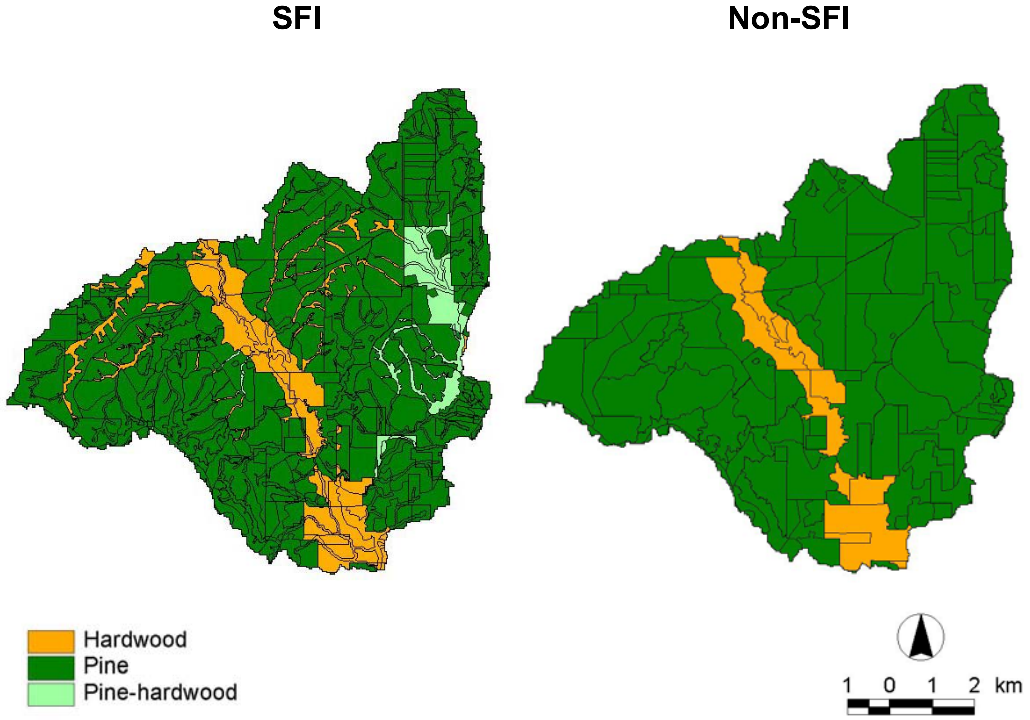

Figure 7. Study area classified by forest type classes for SFI and Non-SFI scenarios.

Simulations in HARVEST are done by management type areas. For pine-clearcutting the maximum clearcut area limit of 49 ha was accomplished partially in the data preparation stage of the work by subdividing stands larger than this value in area. In HARVEST the “fill stands” option was checked to ensure the entire stand is harvested simultaneously. Detailed settings for this management type are presented in Table 15.

For hardwood-clearcutting, given the size of the existing stands compared to the maximum size allowed per clearcut, harvesting was done by a stochastic process of definition of location and size of harvest area according to the settings in Table 15.

The “only apply adjacency constraints to the same MA”option was unchecked in the general settings to allow the adjacency constraints to be applied among management types. Since pine, hardwood and pine-hardwood stands managed by the selection system, do not present a dynamic similar to the clearcutting system, they were not considered in the context of HARVEST and therefore the areas classified under these management types are left unmanaged in the model. The stand-level model will drive management in these areas.

For the non-sustainable scenario no limit per harvest unit was defined for pine stands and no contingency rules were applied during the simulations. For hardwoods a limit of 50 ha was established but the harvesting process is similar to the SFI scenario (Table 15).

Table 15. Settings used in HARVEST for management types 1 and 2 in the SFI and Non-SFI Scenarios.

	SFI		Non-SFI	
Settings	Management type 1	Management type 2	Management type 1	Management type 2
Forest type	Pine	Hardwood	Pine	Hardwood
Harvest size (ha)				
Average	Fill Stands	12	Fill Stands	50
Standard deviation	-	4	-	50
Minimum	-	0	-	4
Maximum	-	12	-	20
Dispersion method	Dispersed	Dispersed	Dispersed	Dispersed
Proportion to Cut in Stands	-	-	-	-
Minimum age for harvest	30	40	30	40
Amount to harvest	100 %	100 %	100 %	100 %
Adjacency constraints	Yes	Yes	No	No
Green-up interval (years)	3	3	-	-
Riparian buffers	No	No	No	No

Stand Simulation

Stand level attributes were simulated with growth and yield models. These models provide the majority of the data required for the analysis of habitat suitability and hydrological processes. Stand models have been used to simulate microhabitat structure for bird communities (Urban and Smith 1989) and mammals (Brand et al. 1986). For the ecological condition of East Texas (West Gulf Coastal Plain) a set of models corresponding to the species and silvicultural systems likely to be applied were chosen. All these models are relatively simple to use and are available to the public.

For planted even-aged loblolly pine stands, Compute P-Lob (Baldwin and Feduccia 1987) was chosen. This is a stand-level model for thinned and unthinned site-prepared loblolly pine plantations. P-Lob estimates height, basal area, density, biomass, and volume distributions by diameter classes. It allows simulation of stand management practices in terms of initial density, site index value, age and number of thinnings, and residual basal area or density of thinning operations.

A simple management scheme was established for the pine-clearcutting system. It included a plantation of 1360 trees/ha, thinning at age 15 for a residual basal area of 13.8 m^2/ha, and clearcut at age 30. Compute P-Lob (Baldwin and Feduccia 1987) was run for each Site Index (50 years) observed in the study area, ranging from 24 to 40 m, according to settings corresponding to the management defined.

SouthPro (Schulte et al. 1998) was chosen for uneven-aged stands. This is a site- and density-dependent, multi-species matrix model that estimates growth of uneven-aged stands of loblolly pine and hard and soft hardwoods (Lin et al. 1998). Regeneration, growth, and mortality are affected by stand density, site productivity, and interactions among trees of different species and sizes (Schulte et al. 1998). SouthPro calculates distributions by diameter size intervals based upon initial distributions and according to target distributions. It provides numerous variables of economic and ecological interest with multiple applications in forestry and other related fields (Schulte et al. 1998). This model was used for uneven-aged loblolly pine, hardwood, and pine-hardwood mixed stands.

The use of uneven-aged management is justified by the fact that it is practiced in the actual study area and by the fact that SMZ's are managed areas that require selective harvesting in order to maintain a minimum stocking. We assume this management type respects the SFI guidelines as long as the minimum basal area meets the required 11.5 m^2/ha (Texas Forest Service 2000).

Initial distributions were established based upon actual data on some of the stands, although it was observed later that initial data do not affect stand dynamics for more than a few decades. For pine and hardwoods, target distributions were defined by the BDq method with q=1.44 (5-cm dbh classes), BA=13.8 m^2/ha, minimum dbh=10 cm and maximum dbh=63.5 cm. Length of management cycle was set to 10 years. Site Index (50 years) ranged from 17 to 35 m for pine and 21 to 32 m for hardwoods.

For pine-hardwood mixed stands target distributions were defined also by the BDq method with q=1.44 (5 cm dbh classes), pine BA=8 m^2/ha, hardwood BA=5.7 m^2/ha , minimum dbh=10 cm, maximum dbh=62.5 cm. Length of management cycle was 10 years. Site Index (50 years) ranged from 21 to 33 m.

The Forest Vegetation Simulator (FVS) (Donnelly et al. 2001) is an individual tree growth model used in this work to simulate hardwood stands managed by the clearcutting system. Although more complex than the models above given the larger number of parameters considered, it is the only possibility found to simulate stand dynamics and management in hardwoods for which there are no available models in the South. The Suppose version 1.14 was used here.

The modeling exercise was done assuming natural regeneration after harvesting, thinning at age 20, and harvest at age 40 or more. All hardwoods stands in this management category were considered as bottomland hardwoods.

Based upon observations of Messina et al. (1997) in 60-70-yr old bottomland hardwood stands in the Neches River bottomland in a location near the study area, a general forest type for these bottomlands was assumed. It is equivalent to the sweetgum-water oak forest type, the most common component of bottomland hardwood forests (Walter and Watterson 1972). It is characteristic of flats in the floodplains of rivers in the South (Hodges 1994). According to Walter and Watterson (1972) this type occurs in first bottoms and terrace flats. This association, included by Hodges (1994) in a broader type group designated by mixed bottomland-hardwoods, contains species as sweetgum (*Liquidambar styraciflua* L.), water oak (*Quercus nigra* L.), willow oak (*Q. phellos* L.), nuttall oak (*Q. nuttallii* Palmer), swamp chestnut oak (cow oak) (*Q. michauxii* Nutt.), cherrybark oak (*Q. falcata* Michx.), green ash (*Fraxinus pennsylvanica* Marsh.), sugarberry (*Celtis laevigata* Willd.), American elm (*Ulmus Americana* L.), overcup oak (*Q. lyrata* Walt.), and water hickory (*Carya aquatica* (Michx. f.) Nutt.).

In this work all the stands are comprised solely of the following five species: sweetgum, water oak, swamp chestnut oak or cow oak, cherrybark oak, and American hornbeam or musclewood (*Carpinus caroliniana* Walt.) (ironwood in Messina et al. (1997)). Several densities and combinations of proportions for these species were tested. The one that resulted in a more balanced stand and also closer to the stand structure described in Messina et al. (1997) has an initial density of 7413 trees/ha distributed by sweetgum, 2471 trees/ha (33%), water oak, 3212 trees/ha (43%), American hornbeam, 618 trees/ha (8%), swamp chestnut oak, 618 trees/ha (8%), and cherrybark oak, 494 trees/ha (7%).

Stand growth was initially simulated in the absence of management (thinning). The results in terms of dbh and height growth rates and yield are in accordance with values indicated by Hodges (1994). Composition and diversity are close to observed in unmanaged stands (Messina et al. 1997).

A thinning operation at age 20 was defined to reduce density to 494 trees/ha. Age of thinning was determined according to the stocking guide of Goelz (1995) and the results of simulations without management. The stand is always overstocked (above the 100% stocking line of Goelz (1995)) from the beginning of its development due to the excessively high initial density. At age 20, for instance, stocking is 199% and 189% for the poorest and richest sites simulated, respectively. Thinning as early as 20 years of age would be recommended as a way of increasing growing space for the trees and improve size and value.

For water oak plantations, Meadows and Goelz (2001) recommend 50-60% stocking levels for residual stands after thinning. Meadows and Goelz (2002) also found good combination of stand growth and tree diameter growth with minimal epicormic branching with a reduction in stocking for 50-55% levels in a 60-yr-old stand with composition similar to that defined in this work. Hodges (1994) recommends a first commercial thinning when dbh is 20-25 cm. In the simulated stands in this work it would mean thinning starting at age 45-50. Residual basal area in this case should be 14-16 m^2/ha. The B-line of Goelz (1995) is the major reference adopted: thinning is done to a level located around the B-line level. In some cases it can be slightly inferior to these values given the fact that only one thinning will be performed during the life of the stand.

A reduction to 494 trees/ha by thinning at age 20 corresponds to stocking values ranging from 26% to 38%, for the poorest to the richest sites simulated. Fourty years after thinning stocking ranges from 67% to 80%. After thinning the stands will be slightly below the B-Line of Goelz (1995) but relatively close to it. They will be very distant however from the C10 line of Goelz and Meadows (1997). This thinning is quite heavy. However a lighter thinning would make a second thinning necessary. Thinning was from below.

Habitat Suitability

Habitat suitability at the stand and landscape levels was evaluated using Habitat Suitability Index (HSI) models (Schamberger et al. 1982). These single-species models were developed in the 1980's with the purpose of quantifying impacts of water or land use changes (Schamberger et al. 1982). They are standardized models allowing habitat suitability quantification on a 0 to 1 scale assuming a direct linear relationship between HSI values and carrying capacity of the land unit evaluated (Fish and Wildlife Service 1981). These are not carrying capacity models, however, since other variables affecting abundance (e.g. predation, weather, competition) are not included (Schamberger and O'Neil 1986).

HSI values are calculated based upon quantitative relationships between suitability and measurable components of the habitat, particularly structural components. For most of the forest animal species and species that use forest stands, habitat variables can often be obtained from inventory data or estimated from vegetation or growth and yield models. The latter case makes possible the use of HSI in simulation approaches. Variables such as basal area, height, density, dbh, or canopy cover are often used.

There are HSI models available for an extensive list of species making them possible to apply in diverse regions and under different land use conditions. These models are suited for conditions subjected to change (Schamberger and O'Neil 1986) usually the case in analysis in forest management.

An important part of the process is the selection of species to be considered in the analysis. Several approaches can be followed such as the use of guilds, indicator species, keystone species or simply species with commercial or cultural value.

HSI models allow each particular land unit, often the forest stand, to be quantified in terms of suitability. At the landscape level it is more important to know the spatial characteristics of contiguous areas of suitable habitat. FRAGSTATS (McGarigal and Marks 1995), a program to quantify landscape structure, is used to calculate landscape metrics of suitable habitat at the patch, class, and landscape levels.

The Habitat Suitability Index model for pine warbler, *Dendroica pinus*, (Schroeder 1982a) was selected to illustrate the application of the methodology to the SFI case. This is a breeding season habitat model. It considers cover and reproduction in the same life requisite since both are considered to be met under the same habitat characteristics (Schroeder 1982a). Food availability is assumed to be always less limiting than cover and reproductive requirements (Schroeder 1982a). Only forest types including pine trees were considered in the application of the model.

Habitat suitability at the stand level is estimated by

$$HSI = (SIV1 * SIV2 * SIV3)^{1/2}$$

where

SIV1: suitability index correspondent to variable V1 – percent tree canopy closure of overstory pines (percent of the ground surface that is shaded by a vertical projection of the canopies of all overstory pine trees, excluding white, sand, or pond pine; assumed to refer to the top 80% tall pine trees as other variables)

SIV2: suitability index correspondent to variable V2 – successional stage of stand (the structural condition of a forest community which occurs during its development: pole or sapling; young; mature or old growth)

SIV3: suitability index correspondent to variable V3 – percent of dominant canopy pines with deciduous understory in the upper one-third layer (self-explanatory).

For pine stands, the equations in Crookston and Stage (1999) were used directly in cover estimation with P-Lob generated data, namely frequency and dbh per size class. Canopy percent cover (C') is calculated by:

$$C' = 100(\sum p_i\, a_i\,)A^{-1}$$

where

p_i = trees per acre for the i^th^ sample tree
a_i = projected crown area for the i^th^ tree in ft^2 /acre
A = ft^2 /acre (43560)

Projected crown area is obtained from crown size-dbh relationships. Crown section is assumed circular in all the cases. For loblolly pine the equation of Gering and May (1995) established from trees growing in stands in Tennessee was chosen:

$$\mathit{Crown\ diameter} = 2.9660 + 1.4038\ \mathit{dbh}$$

For uneven-aged pine stands, equations in Gering and May (1995) were used with the overlap correction of Crookston and Stage (1999) given the spatial distribution of trees in stands and to account for the presence of ingrowth in the stand:

$$C = 100\,[1 - \exp(-0.01\,C')]$$

where

C = percent canopy cover that accounts for overlap,

C' = canopy cover

For hardwood stands, cover was calculated as the sum of cover for all the species corrected with the overlap equation in Crookston and Stage (1999). Dbh distributions from FVS (even-aged stands) and SouthPro (uneven-aged stands) were used with the crown size equations in Table 16.

A similar treatment was followed in pine-hardwood stands with the equation of Gering and May (1995) for softwoods, Francis (1986) sweetgum equation for soft hardwoods, and water oak (willow oak equation) equation for hard hardwoods. The overlap correction of Crookston and Stage (1999) was also applied.

In terms of successional stage, pine stands were classified as pole or sapling if more than 50% of trees were smaller than 23 cm in dbh and young if more than 50% of trees were larger or equal to 23 cm in dbh. Mature or old growth stands were not considered possible to occur since the oldest stand during the 400 years of simulations is 37 years old. Mature stands of loblolly pine could be expected for ages above 80 years (White and Lloyd 1998). Pine stands managed under the selection system and pine-hardwood mixed stands are considered as mature for the purposes of this model (White and Lloyd 1998).

Table 16. Equations for the estimation of crown size in hardwood species.

Species	Equation	Source
Sweetgum	$CR = 2.35 + 0.735\ dbh$	(Francis 1986)
Water Oak (willow oak equation)	$CR = 1.33 + 0.832\ dbh$	(Francis (1986)
Cherrybark Oak (codominant scarlet oak equation)	$CW = 3.3 + 1.8\ dbh$	(Minckler and Gingrich 1970)
American hornbeam (American helm equation)	$CR = 3.36 + 0.776\ dbh$	(Francis 1986)
Swamp chestnut oak (codominant white oak equation)	$CW = 3.5 + 1.7\ dbh$	(Minckler and Gingrich 1970)

CR - Crown radius; *CW* - Crown width

The third variable was assumed null for pine stands and 100% for hardwood stands. It was calculated as the ratio of dominant pine cover to the hardwoods cover in the upper 1/3 in the mixed stands. Estimation of tree height was based on the empirical equations of Lin et al. (1998) used with SouthPro:

Pine $H_t = -5.2 + 0.060\ BA + 35.3 \ln(dbh) - 4.6\ SITE$

Soft hardwoods $H_t = -11.5 + 0.070\ BA + 33.0 \ln(dbh) - 2.7\ SITE$

Hard hardwoods $H_t = -9.2 + 0.070\ BA + 30.5 \ln(dbh) - 2.9\ SITE$

where

H_t = total tree height (in feet)

BA = basal area in sq. ft. / acre

dbh = diameter at breast height (in inches)

$SITE$ = Loblolly pine site productivity classes for total heights of average dominant and co-dominant trees - class 4 = 80-94 ft, 50 years; class 3=95-109 ft, 50 years (Schulte et al. 1998).

Overall HSI is calculated as the HSI average weighted by the size of the stands. Besides the calculation of the overall HSI value for the entire study area also spatial pattern of suitable areas needs to be accessed. For that, assuming a linear relationship between HSI and carrying capacity (Fish and Wildlife Service 1981) five habitat suitability classes were considered:

- class 0: $HSI=0$
- class 1: $0.01 < HSI < 0.25$
- class 2: $0.25 < HSI < 0.5$
- class 3: $0.5 < HSI < 0.75$
- class 4: $0.75 < HSI < 1$

The landscape pattern of the HSI classes was analyzed with FRAGSTATS (McGarigal and Marks 1995), version 3.3.

Water and Sediment Yield

The effects of management on water yield and soil loss were simulated with the Agricultural Policy/Environmental eXtender (APEX) model, version 1310 (Williams et al. 2000). This is a mechanistic model that combines the EPIC model (Erosion-Productivity Impact Calculator) (Williams et al. 1984) with routing capabilities allowing the analysis of processes occurring simultaneously at the field and watershed levels. The main purpose of APEX is to estimate long-term sediment, nutrient, and pesticide yields from whole farms and small watersheds (Williams et al. 2000). Processes include runoff, sediment deposition and degradation, nutrient transport, and groundwater flow in the subarea and landscape (Williams et al. 2000). The model has been recently modified to better describe hydrology in forested areas (Saleh et al. 2003). APEX is also able to account for the effects of buffer strips, one of the major management changes implemented by sustainability programs.

A small watershed was selected from the study area to compare effects of the SFI program on sediment loss and stormflow volume at the watershed level. In this area, landscape structure reflects the application of the SFI program at the landscape level (SFI scenario) or its absence (Non-SFI scenario). Soils are exclusively Alfisols of the Diboll and Alazan series. Slopes are very gentle, on average 1.5% with maximum of 3%.

Table 17. Characteristics of subareas in the example area; SFI scenario.

Subarea code	Size (ha)	Cover	Soil series	Slope (%)	Slope length (m)	Reach length (km)	Reach Slope (%)	Buffer
99	3.2	Pine	Alazan	0.7	50			
100	2.5	Pine	Alazan	1.0	150			
101	0.5	Hardwood	Alazan	0.5	30	0.210	0.9	SMZ
102	3.0	Pine	Diboll	3.0	60			
103	16.1	Pine	Diboll	1.2	150			
104	0.9	Hardwood	Alazan	1.0	30	0.320	1.5	SMZ
105	3.8	Pine	Alazan	1.5	50			
106	3.7	Pine	Alazan	1.0	50			
107	0.8	Hardwood	Alazan	0.8	30	0.236	1.1	SMZ
108	10.0	Pine	Diboll	1.2	90			
109	0.9	Hardwood	Diboll	1.2	30	0.550	1.6	SMZ
110	5.6	Pine	Alazan	1.5	50			
111	0.8	Hardwood	Alazan	0.9	30	0.138	0.1	SMZ
112	11.7	Pine	Alazan	3.0	60			
113	13.0	Pine	Diboll	1.5	100			
114	1.6	Hardwood	Alazan	0.8	30	0.397	0.8	SMZ

The 'Watershed Delineation" module of SWAT 2000, ArcView interface (Di Luzio et al. 2002), was used in the delineation of subareas with DEM data (USGS, 30 m resolution) and a streams coverage. These subareas where further subdivided to reduce variability of soil series and cover. Outputs from the landscape dynamics component (HARVEST) were used in the definition of stand limits and age. Each forest stand constitutes a subarea for modeling purposes (Table 17, Table 18). In the SFI scenario subareas are more numerous than in the Non-SFI scenario since application of SFI rules (buffer zones along streams, harvesting size limits, and green up interval) results in higher landscape heterogeneity.

Table 18. Characteristics of subareas in the example area; Non-SFI scenario

Subarea	Size (ha)	Cover	Soil series	Slope (%)	Slope length (m)	Reach length (km)	Reach slope (%)
46	3.0	Pine	Diboll	3.0	60		
47	16.0	Pine	Diboll	1.3	150	0.732	1.8
48	7.2	Pine	Alazan	1.0	75		
49	8.3	Pine	Alazan	1.0	50	0.236	1.1
50	5.2	Pine	Alazan	1.5	50	0.138	1.1
51	12.1	Pine	Diboll	1.0	90	0.72	1.6
52	26.3	Pine	Diboll	1.2	80	0.397	0.8

Each stand is managed by individual operation schedules according to composition and age. For pine, plantation and harvesting year for each stand were defined according to the sequence of clearcuttings in HARVEST. Stands were planted at an initial density of 950 trees/ha and thinned, at age 15, to a density of 475 trees/ha. The stands are kept fallow between clearcutting and planting (April to December). Thinning is applied in August. Buffer zones, in the SFI scenario, are comprised of sweetgum. For simplification and assuming cover permanent in these stands, SMZs have a constant density of 450 trees/ha. The model is run 30 years prior to the period of interest to allow stabilization of the system and stand growth. Weather data were generated by APEX based upon parameters for Lufkin, Texas. Three seed numbers sequences were followed in the runs to allow for variability of weather conditions.

Subareas files (sub-files) were built using an application developed by J.R. Williams (Texas A&M Blackland Research and Extension Center, Temple, personal communication) using as inputs soil and operation schedule file codes, area, channel length and slope, upland slope, reach length and slope, when applicable.

Results and Discussion

Temporal Pattern

Landscape simulations produce a regular temporal pattern in the study area in both scenarios. The five simulations run for each scenario show very similar results among them including harvested area (Figure 8 and Figure 9). After an initial adjustment period of a few rotations, harvests become distributed cyclically in the landscape. Every cycle broadly matches the rotation for loblolly pine stands, 30 years. Hardwood stands do not show the same regularity given the harvesting process followed showing instead some random variation. The influence of these hardwood stands in the overall harvested area is negligible in terms of overall pattern.

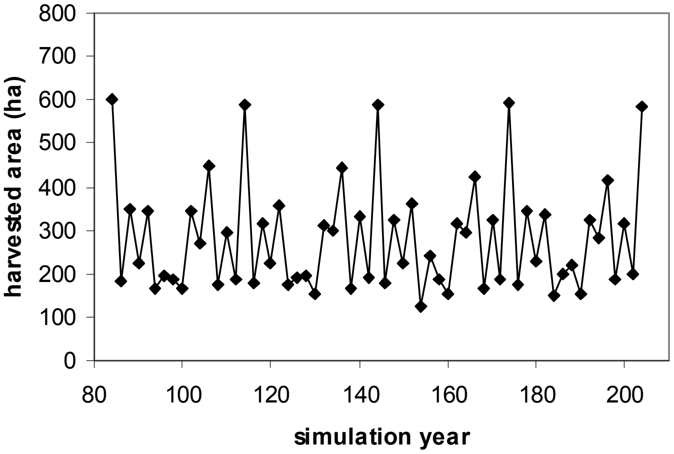

Figure 8. Harvest simulation for the SFI scenario. Run#1.

For the 400 years that the landscapes were simulated, mean harvested area was 132 ha/yr for pine and 5 ha/yr for hardwoods in the SFI scenario. Minimum harvested area observed in the five repetitions by simulation time unit (2 yr) was 91 ha for pine and 0 ha for hardwood. Maximum values were 583 ha/2 yr and 55 ha/2 yr for pine and hardwoods, respectively. The harvested area in the Non-SFI scenario reached more extreme values. In average pine area harvested was 167 ha/yr. The minimum was 31 ha/2 yr and the maximum was 654 ha/2yr. Hardwoods were harvested on average per year 11 ha (0 ha/2yr, minimum, 117 ha/2yr, maximum). The stands managed by uneven-aged systems are not considered among these results.

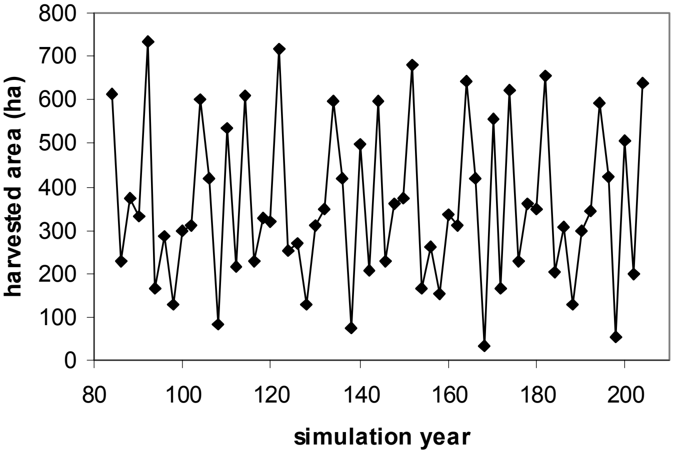

Figure 9. Harvest simulation for the Non-SFI scenario. Run#1.

Given the periodicity of the pattern shown, analysis of results in terms of habitats and hydrological processes was limited to a period of 30 years, specifically between simulation years 144 and 174. Since variability between runs was reduced, just three from the initial five runs for each scenario were considered, namely runs 1, 3, and 5.

Pine Warbler Habitat

HSI

HSI for the landscape in its total extent ranged from 0.15 to 0.23 (mean=0.19) in the SFI scenario and from 0.17 to 0.28 (mean=0.23) in the Non-SFI scenario (Table 19; Figure 10). Repeated measures ANOVA with management as a fixed effect (SFI or No-SFI) and subjects (runs) as a random effect was used to test for differences between scenarios. Given the small variability among runs, differences in HSI values are statistically significant ($p<0.001$). Temporal variation of HSI within scenarios is also very reduced (Figure 10).

Table 19. Global HSI values for pine warbler by scenarios and HARVEST runs.

	SFI scenario				Non-SFI scenario			
Run #	Mean	Min.	Max.	SD	Mean.	Min.	Max	SD
1	0.19	0.15	0.23	0.029	0.23	0.17	0.28	0.033
3	0.19	0.15	0.22	0.026	0.23	0.17	0.28	0.033
5	0.19	0.15	0.23	0.027	0.23	0.17	0.28	0.033

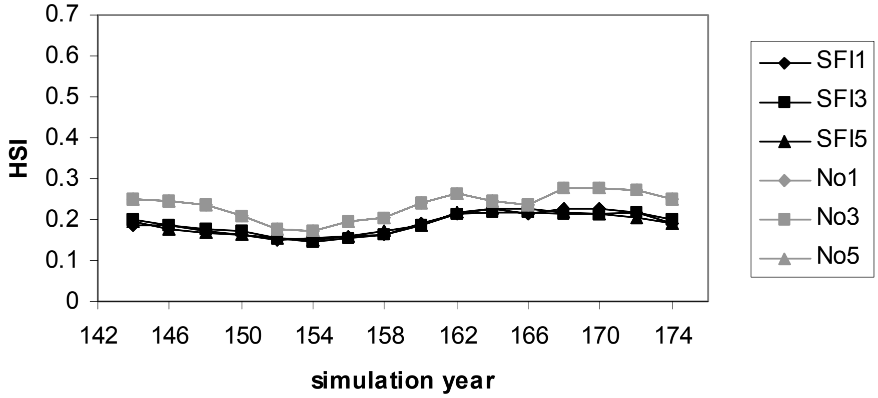

Figure 10. Variation of pine warbler HSI in the sampling period for the SFI and Non-SFI scenarios.

Differences between scenarios seem to a great extent to be attributable to changes in proportions of forest-management types. From SFI to Non-SFI there is an increase in area submitted to the pine-clearcutting system, from 3964 ha to 4993 ha (20 %) (Table 14). This corresponds basically to the increase in the general HSI value from 0.19 to 0.23 (0.21 %). HSI at the stand level changes according to the management type. Maximum values for each of the cases considered are presented in Table 20.

Table 20. Maximum HSI value per management type in the study area within the 30-year sampling period.

	Management type				
Scenario	Pine Clearcutting	Hardwood Clearcutting	Pine Selection	Hardwood Selection	Pine-Hardwood Selection
SFI	0.71	-	0.50	-	0.30
Non-SFI	0.71	-	0.50	-	-

Habitat Spatial Pattern

More relevant than the overall HSI values is the way suitable habitat is distributed spatially in the landscape. Habitat suitability classes were represented visually and analyzed in terms of spatial pattern using landscape metrics. Figure 11 illustrates the distribution of habitat suitability in five dates of the 30-year sampling period. Table 21 shows average landscape metrics for all the dates in this period. Temporal variability of some landscape metrics is presented in Figure 12.

The highest suitability index value reached by pine warbler in the landscape is equivalent to class 3 (Table 20). Although the percentage of the landscape occupied by these habitat classes in both scenarios is not extremely different, there are many important differences in configuration detected by the indices (Figure 12, Table 21). There are many more patches of much smaller size in SFI than in Non-SFI. Patches in the Non-SFI scenario are more aggregated and more distant apart. Edges are more abundant in SFI. Core areas are more numerous and smaller in size in SFI. Total core area is much larger in the Non-SFI scenario. This can be described as fragmentation of the most valuable breeding habitat for pine warblers observed in the SFI scenario when compared with the Non-SFI scenario (Figure 12, Table 21).

It is not clear whether pine warbler is an area-sensitive interior species (Rodewald et al. 1999). In Ontario, Canada, it is considered area-sensitive requiring minimum habitat from 15 to 30 ha (OMNR 2000). Boulinier et al. (1998), however, based upon the work of Robbins et al. (1989) and Whitcomb et al. (1981), include pine warblers within non-area-sensitive species.

In the HSI model followed here, Schroeder (1982a) considers a minimum habitat area of 10 ha for the species but minimum area size has been indicated to be as large as 30 ha for breeding populations (Rodewald et al. 1999). Assuming the species is area sensitive and requires minimum suitable habitat patches of 10 ha, more than 87% of the total habitat area is annually comprised of patches larger than that size (Figure 13). For the extreme case, patches larger than 30 ha always represent more than 60% of the total available area of class 3.

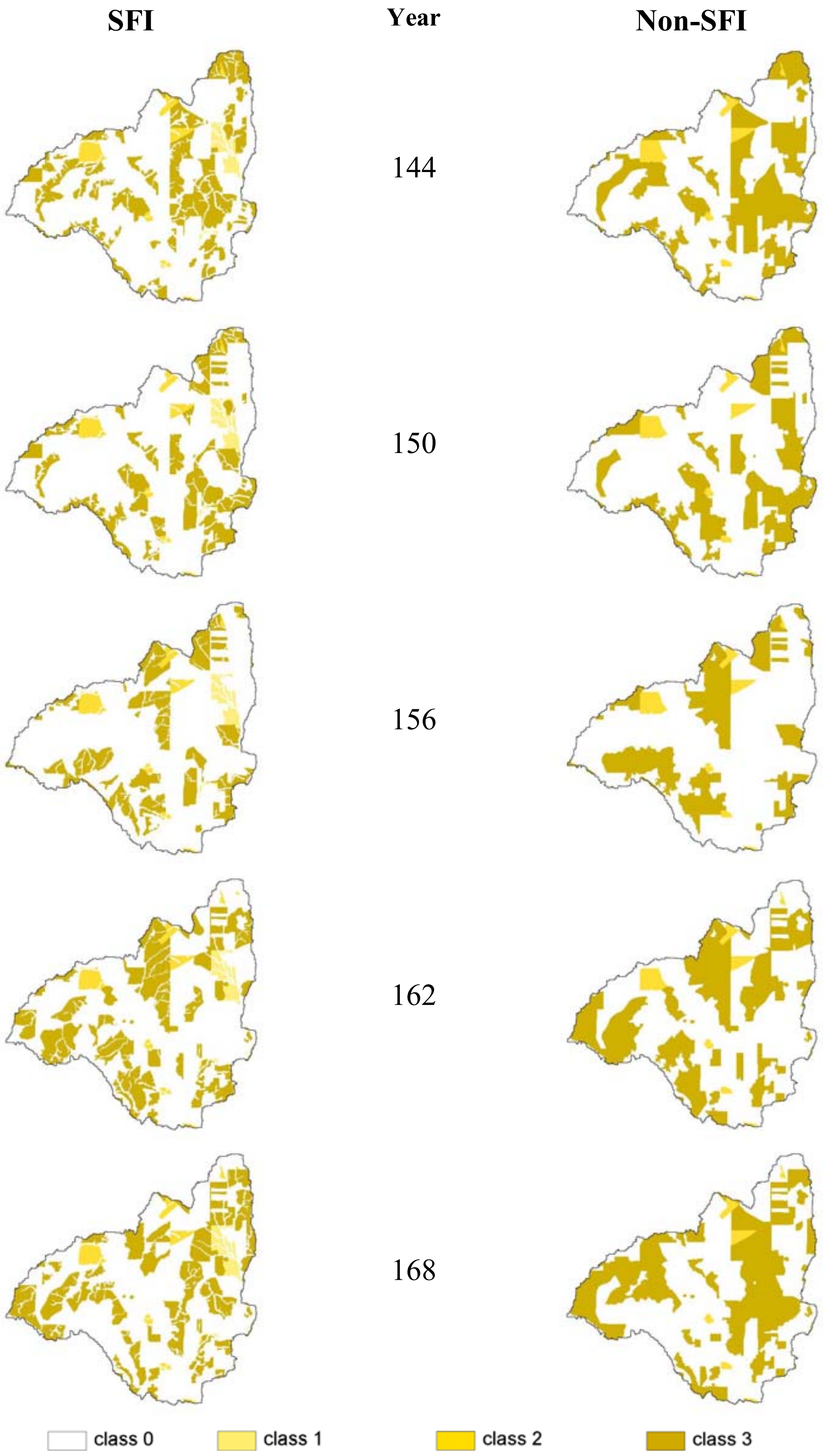

Figure 11. Distribution of suitable habitat according to the HSI model classes for 5 dates within the simulation period for the SFI and Non-SFI scenarios. Pictures from run #1 in both scenarios.

Table 21. Selected landscape metrics for pine warbler habitat class 3. All values are averages for three simulation runs and 15 observation dates.

Variable	Acronym	Class 3	
		SFI	Non-SFI
Percentage of Landscape (%)	PLAND	25.8	32.9
Patch Density (#/100 ha)	PD	1.3	0.4
Edge Density (m/ha)	ED	37.4	19.7
Largest Patch Index (%)	LPI	2.9	13.7
Landscape Shape Index	LSI	15.0	7.5
Mean Patch Area (ha)	AREA_MN	20.8	89.3
Mean Fractal Dimension Index	FRAC_MN	1.10	1.09
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.13	1.13
Core Area Percentage of Landscape (%)	CPLAND	4.8	17.3
Mean Core Area (ha)	CORE_MN	3.9	47.0
Mean Core Area Index (%)	CAI_MN	8.2	19.9
Mean Proximity Index	PROX_MN	334.1	447.0
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	80.6	212.2
Interspersion and Juxtaposition Index (%)	IJI	14.6	23.7

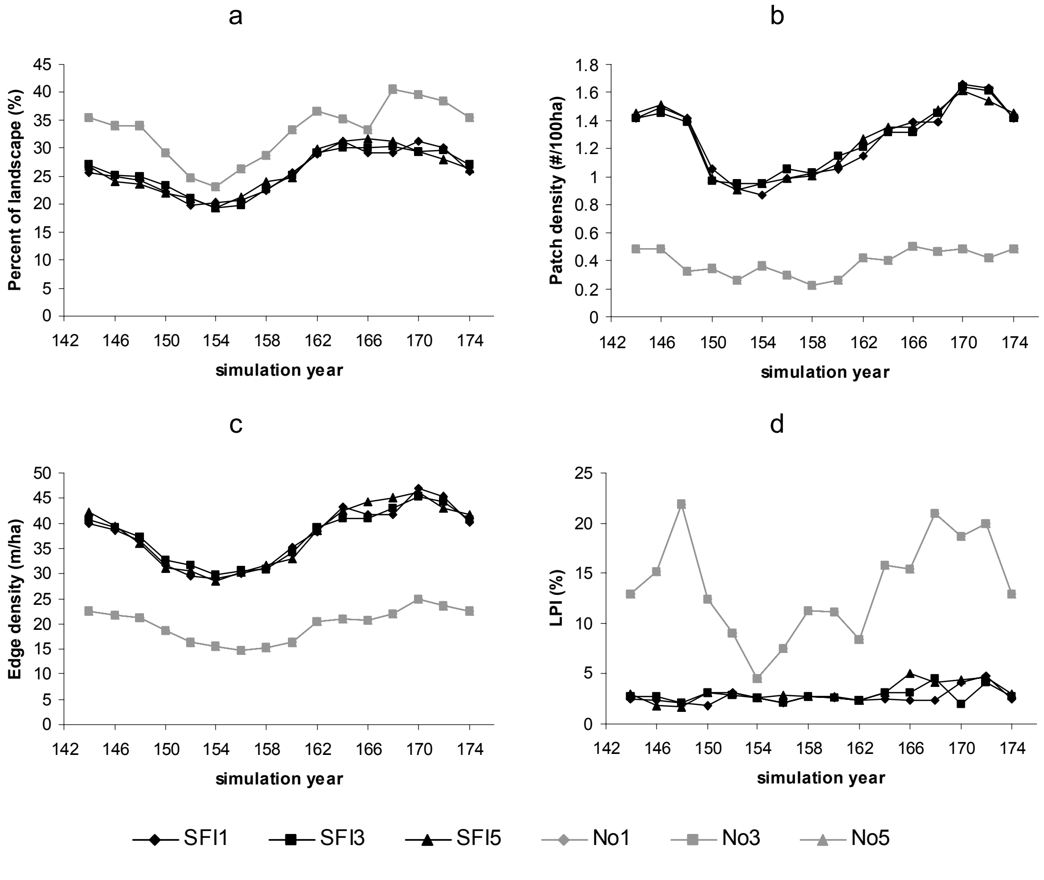

Figure 12. Variation of selected landscape metrics for class 3 habitat along the sampling period for SFI and Non-SFI scenarios. a) Percentage of Landscape; b) Patch Density; c) Edge Density; d) Largest Patch Index; e) Landscape Shape Index; f) Mean Patch Area; g) Mean core area; h) Mean Euclidean Nearest Neighbor Distance.

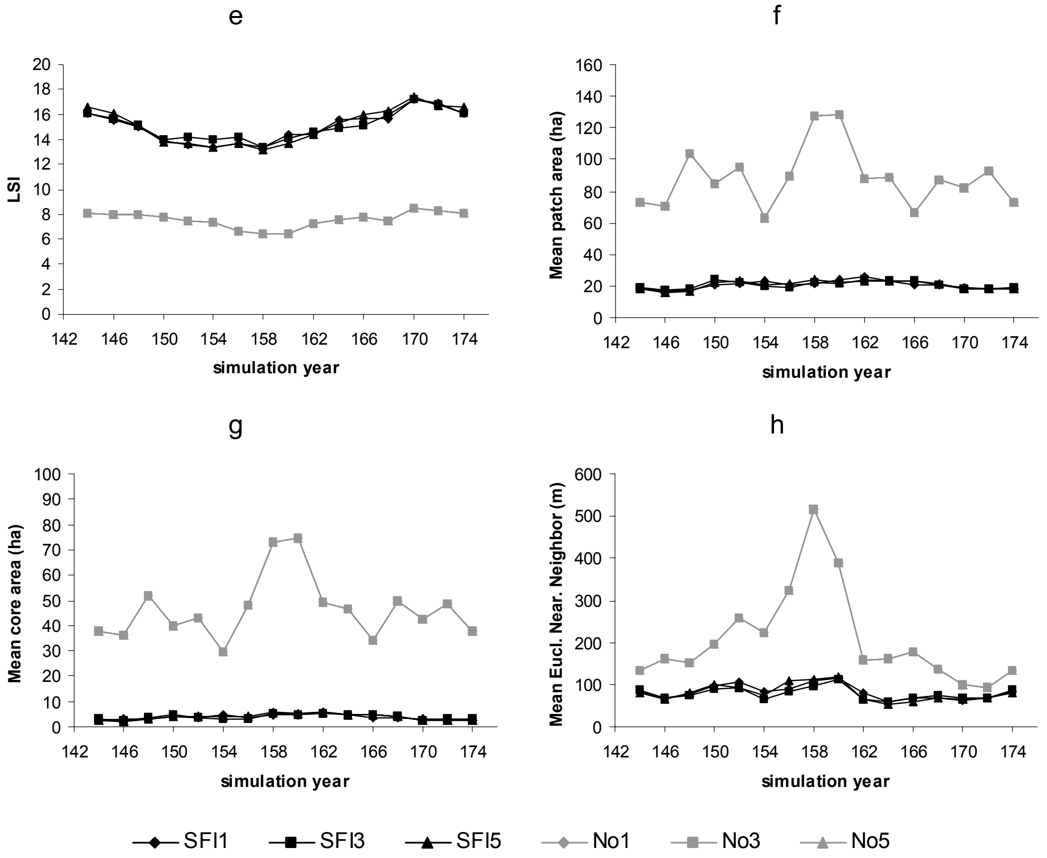

Figure 12 (continued).

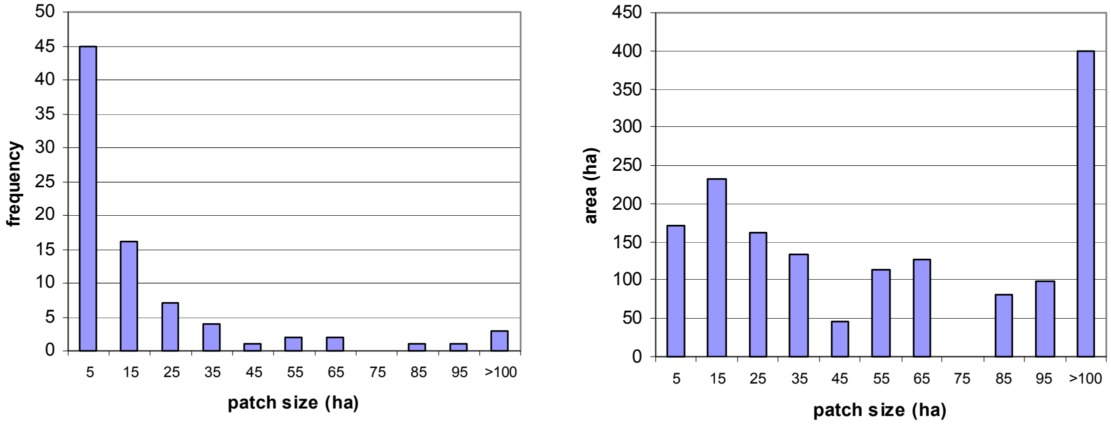

Figure 13. Example of the distribution of number of patches and patch area by patch size class for pine warbler habitat class 3 (year 144, sim. yr. 154; run#3).

In the literature it is not clear if area refers to forested area or area of suitable habitat exclusively, old pine stands supposedly. On the other hand the concept of minimum area is often used in the sense of area required for the maintenance of minimum viable populations. Much of the reduction in patch size observed in the SFI scenario results from the dissection of larger areas by means of narrow SMZs. The reduced width of these buffers, their composition and structure, and their permanent character makes it reasonable to speculate that habitat patches separated by 50 m, on average, of permanently forested buffers might be part of the same functional land unit. Moreover, patch size is possibly not a limiting factor for the species in this scenario. Sensitivity of pine warble to edges is not clear either in the literature. It is considered as a forest interior species in Ontario, Canada, (Environment Canada 1998), in Missouri (Thompson et al. 1992), and in Georgia (McIntyre 1995). In a hammock in Florida, pine warblers were considered as edge-attracted-species by Noss (1991). In case the species rejects edges, core areas of class 3 habitat provide reduced habitat area. On average, only 45% of the total habitat is contained in core areas considering an edge width of 50 m. Core areas larger than 10 ha are 36% of the habitat area and core areas larger than 30 ha are 25% of this habitat. For a 100-m edge, average core habitat is only 18.6% of the total habitat. Core areas larger than 10 ha can be as low as 4% of the habitat area and core areas larger than 30 ha are usually absent from the landscape. In the Non-SFI scenario 98% of class 3 habitat is in patches larger than 10 ha and 96% larger than 30 ha. For an edge 50 m wide, core areas represent 72% of the total habitat, core areas larger than 10 ha are 72% of the habitat area, and core areas larger than 30 ha 67% of the class habitat; core area is 52% of total area, 51% in areas larger than 10 ha and 50% in patches larger than 30 ha for a 100-m wide edge

In the analysis SMZs are considered as a source of edges. As discussed above, these buffers are forested and permanent. The edges they create in adjacent pine stands during the time they are suitable for pine warblers (19 years or older) are different in contrast from the edges between forest and open areas usually considered in the literature and possibly pine warblers do not respond negatively to these edges. The fact that pine warblers breed in hardwood stands with scattered or grouped pine trees (Rodewald et al. 1999) can be indicative of that. The real effect of edges on the habitat of pine warblers in this area is however unknown. If edges do not affect the breeding habitat of the species then the habitat patches approximate the initial distributions presented. If SMZs can be integrated in the pine warbler habitat units then the habitat structure resembles much more the Non-SFI scenario and fragmentation is merely apparent. This fragmentation, however, might be critical for other species that use mature pine stands and should be taken into consideration when measures as implementation of SMZ are planned.

Water and Sediment Yield

Runoff and sediment loss observed during the simulations (Table 22) are generally small and within the range of values observed in forested watersheds in East Texas and other areas in the south (Yoho 1980, Ursic 1991b, Ursic 1986). The watershed when managed by the SFI program shows lower runoff and sediment yield than when managed according to the Non-SFI management (Table 22). Although sediment averaged by subbarea (YS) is not different between scenarios, sediment yield at the watershed level (YW) is higher in the Non-SFI scenario. This is mainly due to channel degradation occurring in the Non-SFI scenario, particularly associated to intense storm events. In the SFI scenario degradation has lower expression. This phenomenon is common in forested areas and many times responsible for most of the erosion observed in forest watersheds (Ursic 1986, Marion and Ursic 1993, Blackburn et al. 1990).

Table 22. Average annual precipitation, stormflow and sediment loss in three simulations for the study watershed.

Run	Precipitation (mm)	QSS (mm)	QSW (mm)	QTS (mm)	QTW (mm)	YS (t/ha)	YW (t/ha)
SFI							
1	1093.9	20.70	20.59	26.48	26.34	0.02	0.04
2	1056	16.02	15.92	19.57	19.44	0.02	0.04
3	1074.2	18.75	18.64	23.39	23.25	0.02	0.03
Average	1074.7	18.49	18.38	23.15	23.01	0.02	0.04
Non-SFI							
1	1093.9	23.56	23.56	28.95	28.94	0.02	0.07
2	1056	18.36	18.36	22.16	22.15	0.02	0.06
3	1074.2	21.40	21.40	25.84	25.82	0.01	0.06
Average	1074.7	21.11	21.11	25.65	25.64	0.02	0.06

QSS-average surface water yield; QSW-surface water yield; QTS-average water yield; QTW- water yield; YS-average sediment; YW-sediment yield.

Figure 14 illustrates the variation in water yield and sediment loss at the landscape level within the 30-yr period of observation for three different simulations. Most of sediment is usually produced in a reduced number of years. Within these years it is concentrated in a reduced number of months, corresponding to periods of high precipitation during which evapotranspiration and soil storage are much smaller that precipitation, increasing runoff considerably. There are also usually a reduced number of subareas contributing to most the yield observed (Table 23). The high sediment observed in the Non-SFI scenario in the simulation year 154 in run 2 (Figure 14), for example, is due to 1.2 t/ha of sediment loss observed in subarea 46 during January and February when precipitation was 387.7 and 104.5 mm, respectively. Values in the other subareas are in general low or very low within the same year and months. High stormflow volumes increase also channel erosion increasing sediment at the watershed level, as described above.

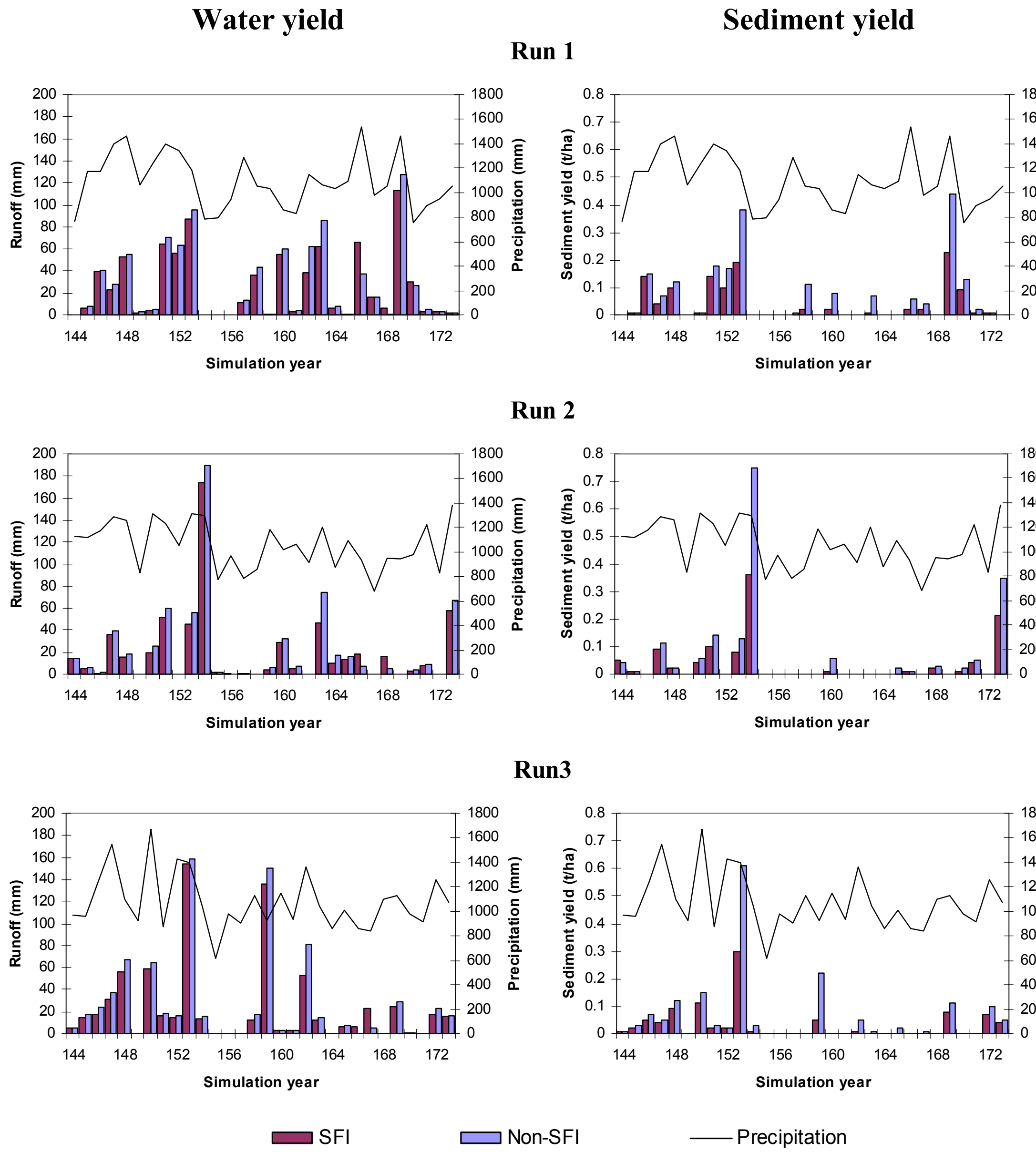

Figure 14. Average precipitation, runoff and sediment yield within the 30-yr period for the two management scenarios.

Table 23. Water and sediment yield per subarea for the two management scenarios. All values are averages for 30 years.

SFI			Non-SFI		
Subarea	Q (mm)	Y (t/ha)	Subarea	Q (mm)	Y (t/ha)
99	8.5	0.00	46	27.7	0.12
100	8.9	0.00	47	25.4	0.02
101	8.4	0.02	48	8.8	0.00
102	27.5	0.12	49	8.7	0.00
103	25.8	0.02	50	9.0	0.00
104	8.5	0.03	51	25.4	0.02
105	9.2	0.00	52	25.4	0.02
106	8.8	0.00			
107	8.6	0.02			
108	25.7	0.02			
109	25.5	0.12			
110	8.9	0.00			
111	8.6	0.02			
112	10.1	0.01			
113	26.3	0.03			
114	8.5	0.02			

Q-water yield; Y-sediment yield

Higher water and sediment yields at the subarea level seem to be associated to upland slope and slope length (Table 23). Also forest type seems to be related to yields. Hardwoods tend to show higher runoff and sediment yield than pine stands. Increase of yields after harvesting was not observed here. The effects of harvesting are difficult to observe in this case due to irregularity of precipitation and soil moisture content. In the simulations done no site preparation was considered what might explain also in part the lack of responses observed. Harvesting in gentle slopes (1-3% in the case of the study watershed) seems to have minimal effect in terms of erosion and is felt for a very reduced number o years only (Ursic 1986, Ursic 1991a, Marion and Ursic 1993).

Summary

The implementation of the SFI affects both the habitat of pine warbler and sediment yield at the watershed level. There is an increase in the fragmentation of the most suitable habitat in the area managed according to this program, reflected by an increase in the number of patches and extension of edges and a decrease in patch size, core area size, and core area in the landscape. The fragmentation detected is caused mainly by SMZs that dissect existing pine stands. Considering, however, the composition and permanent character of these features, the forested landscape context in which the suitable habitat is included, and the behavior of the species it is unlikely that pine warblers are strongly affected by this fragmentation.

SFI scenario shows slightly lower stormflow volume than the Non-SFI scenario. Sediment yield in considerably higher in the Non-SFI scenario due to increasing channel degradation possibly associated to higher runoff.

Independent of the results obtained, the methodology developed in this work provides a useful tool in comparing effects of management practices on the landscape pattern and process in intensively managed forested landscapes in East Texas. This methodology is simple to implement, relies on simple models that require minimal data to work, and provides results helpful in the evaluation of management alternatives. Since it provides indication of ecological processes it is useful in linking pattern with process, a major component of ecology.

The methodology is an open methodology in the sense that allows other illations to be obtained from the results. Economical considerations on the implementation of particular management practices, for instance, could be developed directly from the growth and yield models. It is open also in the sense that other models can be integrated and effects on other components of the systems be evaluated.

CHAPTER IV

EFFECTS OF THE SUSTAINABLE FORESTRY INITIATIVE ON THE QUALITY, ABUNDANCE, AND CONFIGURATION OF WILDLIFE HABITATS

Introduction

Nature conservation has relied on few, small, and isolated reserves. The majority of rare and endangered species exist outside reserves and there is lack of representation of species and ecosystems in the existing reserves (Soulé and Terborgh 1999). Increasing reserves in number or size as a solution to this problem has limitations. Reserves will never include all biodiversity and might be insufficient for some species that require very large areas (Lindenmayer and Franklin 1997). Reserves are expensive to acquire (Simberloff 1998) and optimal areas that needed to be included are usually extremely large (Mann and Plummer 1993, Soulé and Sanjayan 1998). On the other hand there is currently limited area available for the constitution of reserves (Lindenmayer and Franklin 2002) and resources for conservation are scarce (Skole and Compton 1993).

The major limitation to reserve centered conservation policies derives, however, from biological and ecological factors that make biodiversity dependent on processes occurring at scales that exceed the scale of the reserves (Lindenmayer et al. 2000). It has been assumed that areas between reserves can ensure these processes (Soulé and Terborgh 1999). There is no clear indication that these more or less intensively managed in-between areas have played that role. Managed agriculture and forest areas and human settlements occupy 95% of the terrestrial environment (Pimentel et al. 1992). Agriculture-dominated landscapes have a low capacity to support diversity (Paoletti 1999). In the tropics and many temperate regions managed areas outside reserves are expected to lose their capacity to support native species and ecosystems by 2050 (Soulé and Sanjayan 1998). In the US destruction and degradation of habitats, introduction and spread of alien species, pollution, over exploitation, and diseases threaten biodiversity seriously (Wilcove et al. 1998).

The facts above suggest that areas outside reserves have to play a more decisive role in conservation than they have in the past. Complementary to networks of reserves, this approach might create conditions for conservation at larger scales. Management in intermediate areas needs, for that reason, to be adjusted to guarantee the processes required in the maintenance of biodiversity. Urban growth is probably the major threat to biodiversity (Main et al. 1999) and no signs of inversion on their effects on species and ecosystems are actually visible. There are prospects, however, that agriculture and forestry can become sustainable activities and contribute to the conservation of biodiversity. Examples of maintenance of high biodiversity levels in agricultural systems are found in temperate and tropical regions (Pimentel et al. 1992, Paoletti 1995, 1999, Lotter 2003). Forestry is under important changes worldwide through sustainable management and certification processes (Gullison 2003). In the tropics sustainable forestry is able to decrease loss of biodiversity (Pearce et al. 2003) and is also believed to maintain biodiversity in managed forests in other regions of the world (Wigley 2000). In the United States sustainability has become the dominant management philosophy in national forests (USDA Forest Service 2000a) and within the forest industry (Cantrell 1998).

The Sustainable Forestry Initiative (SFI) is the sustainability program of the American Forest and Paper Association (AF&PA). It was launched in 1994 and is currently followed on 55 million hectares of forestland (AF&PA 2003), more than 90% of all the industry-owned forest in North America (AF&PA 2002a). The program includes measures at the landscape level such as limitation size of harvest units, establishment of wildlife corridors, establishment of buffer zones along streams and application of adjacency rules that are able to change landscape structure and function.

Among other objectives SFI aims to “manage the quality and distribution of wildlife habitats and contribute to the conservation of biological diversity by developing and implementing stand- and landscape-level measures that promote habitat diversity and the conservation of forest plants and animals including aquatic fauna” (AF&PA 2002b). However, can industrial forests maintain biodiversity in levels comparable to other systems? Can industrial forests managed according to the SFI be considered as part of conservation strategies at the regional and national scale? In spite of all the optimism around sustainable forestry the answers to questions like these cannot be given until the application of SFI measures is evaluated in the mid and long terms. Preliminary research indicates that industrial forests managed according to SFI principles can present high diversity and productivity of birds and high diversity of herpetofauna including many species of high conservation interest (Wigley et al. 2000). Other research indicates that some of the measures included in SFI have a positive effect on the maintenance of animal diversity in forested landscapes (e.g. Dickson and Huntley 1987, Dickson et al. 1995b, Lance and Phinney 2001). Before more field data can be gathered and treated to analyze impacts of sustainable forestry in intensively managed landscapes other approaches can be developed in order to build a better understanding of the effects of the application of the SFI program on wildlife communities, particularly at broader scales.

It was observed previously that the implementation of the SFI program is changing landscape structure in east Texas (Chapter II). Assessment of the importance of these changes in terms of major processes, namely those related to wildlife and their habitats, requires specific treatment. The goal of this work is to study the implications of the implementation of sustainable forestry on wildlife communities. More specifically, the objective of this research is to evaluate the changes caused by the application of the SFI landscape measures in terms of quality, abundance and configuration of habitat of vertebrate species in east Texas. It is hypothesized that SFI changes composition, diversity, and spatial structure of habitats and that these changes increase diversity at the landscape scale.

The approach followed is based upon modeling and simulation at the stand and landscape levels. Structural components of the forest stands are simulated at the landscape scale to evaluate habitat suitability of several vertebrate species. These habitats are analyzed spatially to investigate changes SFI might cause in habitat patterns. It is an approach similar to the intermediate approach of Hansen et al. (1993), between the coarse and the fine filter approaches, where habitat suitability and life history attributes are used as surrogates for demographic data. It is centered on stand and landscape structure, connectivity and heterogeneity, following Lindenmayer et al. (2000).

Methods

Study Area

The study was conducted in an area of 5773 ha located in the Angelina County, Texas, USA, part of a watershed of the Chawanee Creek, Neches River. This area is for the most part owned by Temple-Inland Forest Products Corporation, Diboll, and managed for industrial forestry. Actual forest types are pine, mainly loblolly pine *(Pinus taeda)*, 4727 ha (82% of the area), hardwoods, 796 ha (14%), and pine-hardwood mixed stands, 251 ha (4%). Approximately 70% of the area is managed by even-aged silviculture (clearcutting system). Soils are predominantly Ultisols of the Rosenwall series and Alfisols of the Diboll series.

Landscape and Stand Modeling and Simulation

Landscape and stand models were combined to simulate the dynamics of the landscape and its components in the study area. Landscape dynamics is simulated using HARVEST 6.0 (Gustafson and Crow 1999). This raster model simulates even- and uneven-aged silvicultural systems at the landscape scale incorporating parameters usually considered in forest management such as harvest unit size, total area harvested, rotation length, and green up interval, among others (Gustafson and Crow 1999). Several growth and yield models were used to simulate stand level dynamics: Compute P-Lob (Baldwin and Feduccia 1987) for planted even-aged loblolly pine stands, SouthPro (Schulte et al. 1998) for uneven-aged pine, hardwood, and mixed pine-hardwood stands, and the southern variant of the Forest Vegetation Simulator (FVS) (Donnelly et al. 2001) for even-aged hardwood stands. One scenario (SFI scenario) was established based upon the application of SFI landscape measures, namely Streamside Management Zones (SMZs) ≥ 30 m wide along perennial and intermittent streams, limits in harvest unit size (pine 49 ha; hardwoods 12 ha) and a three-year green up interval. For comparison purposes a reference scenario (Non-SFI scenario) was established in the absence of these rules. The detailed description of the methods is presented in chapter III.

Species Selection

All the 266 species of vertebrates (83 herps, 132 birds, 51 mammals) potentially occurring in the region where the study area is located were grouped in guilds of similar breeding and foraging requirements. Pine, hardwood and pine-hardwood breeding and foraging habitats were divided in layers according to the vertical stratification of the forest ecosystem (Table 24). Particular aspects of these systems, namely tree bole and water surfaces were also considered. This partition was adapted from Short (1984). It includes a complete range of breeding and feeding conditions and has been applied in the context of habitat suitability index models.

Table 24. Breeding and foraging habitat layers used in the species classification.

Code	Name	Description
1	Terrain surface and subsurface	Below ground to 15 cm above surface
2	Understory	From 15 cm above surface to 0.5 m above surface
3	Midstory	From 0.5 m to 8 m in height
4	Tree canopy or overstory	Upwards from 8 m
5	Tree bole	Dbh > 20 cm
6	Water	Water surfaces
7	Elsewhere	Other features within forest (snags, logs, etc)

Information on birds' occurrence was obtained from Wolf et al. (2001). Information on habitat requirements was obtained from an extensive list of resources including Ehrlich et al. (1988) and websites from the USDA Forest Service, (http://www.fs.fed.us/ database/feis/animals/bird/, September 2001), The Georgia Museum of Natural History and Georgia Department of Natural Resources, University of Georgia, (http://museum.nhm.uga.edu/gawildlife/birds/birds.html, September 2001), Animal Diversity Web, Museum of Zoology, The University of Michigan (http://animaldiversity.ummz.umich.edu/index.html, September 2001) and several fascicles of The Birds of North America form the American Ornithologists' Union, Washington, D.C., and Academy of Natural Sciences.

The Mammals of Texas, online edition, (William B. Davis and David J. Schmidly, http://www.nsrl.ttu.edu/tmot1/, September 2001) was used in the definition of potential mammal species. Habitat requirements were based mainly upon that source, the Forest Service database (http://www.fs.fed.us/database/feis/animals/ mammal/, September 2001), and Texas Parks & Wildlife (http://www.tpwd.state.tx.us/nature/wild/mammals /bats/species/index.htm, September 2001).

Herpetofauna was based upon Ernst et al. (1994), Tennant (1998), and Werler and Dixon (2000) and the web sites of Herps of East Texas, Texas Memorial Museum, University of Texas, (http://www.zo.utexas.edu/research/txherps/, September 2001), Georgia Museum of Natural History and Georgia Department of Natural Resources, University of Georgia (http://museum.nhm.uga.edu/gawildlife/gaww.html, September 2001), Animal Diversity Web, Museum of Zoology, University of Michigan, (http://animaldiversity.ummz.umich.edu/index.html, September 2001), and Florida Museum of Natural History, University of Florida, (http://www.flmnh.ufl.edu, September 2001).

A total of 42 binary variables (code 0 or 1) were created for the seven habitat layers (Table 24), three forest types (pine, hardwoods, and mixed pine-hardwoods), and two types of habitat requirements considered (breeding and feeding). One breeding and one feeding variable were additionally considered for habitat conditions other than forest. This type of organization of the data was chosen to account for the possibility of simultaneous selection.

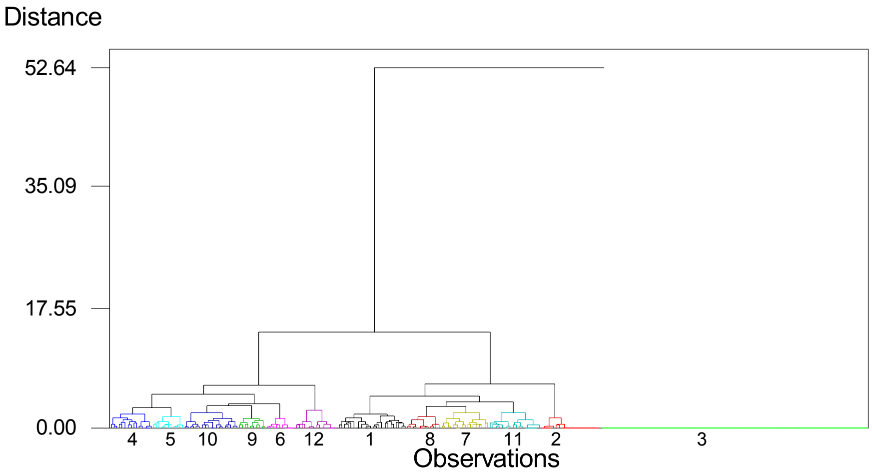

Figure 15. Dendrogram for the clusters analysis with Ward's minimum variance and distances based upon Jaccard's coefficient of similarity. Numbers in the x-axis refer to the cluster number.

Clusters of species with similar habitat requirements were defined using the Ward's minimum variance clustering method with distances based upon Jaccard's coefficient of similarity (Lapointe and Legendre 1994). Other methods and distance matrices were also applied to the data, including hierarchical agglomerative clustering methods (single, average, and complete linkage) and, McQuitty's similarity analysis with Euclidean, Squared Euclidean, Pearson, and Squared Pearson distances. Ward's minimum variance clustering method produced more interesting results independently of the similarity measure used. The distribution of species by groups, the size of the clusters generated, and the meaning of the groups was however clearer when the Jaccard's coefficient of similarity was used with the Ward's method. This coefficient eliminates the influence of the absence of the same attribute in the two items compared. A distance matrix, D, was obtained by subtracting 1 by the matrix of similarity coefficient values, S (Lapointe and Legendre 1994). S is the number of characteristics possessed (code 1) by both species under comparison divided by the number of characteristics present in either species (Lapointe and Legendre 1994).

Based upon the analysis of dendrograms, cluster composition, and combinations of habitat characteristics, 12 clusters were considered (Figure 15, Figure 16, Table 25, Appendix 4). A smaller number of clusters resulted in larger and heterogeneous groups difficult to interpret. A larger number resulted in the division of the smallest clusters, which improved their meaning but also increased the number of species to be considered.

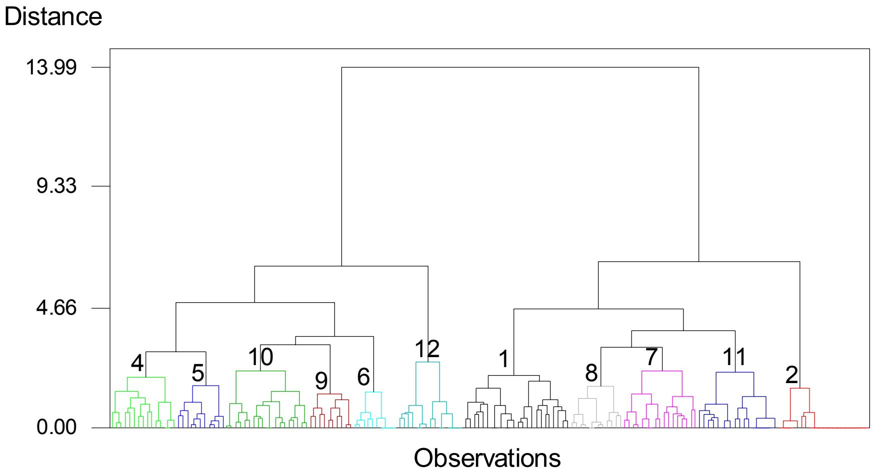

Figure 16. Detail of the dendrogram inlcuding forest species only. Numbers in the chart indicate cluster number.

From the initial 12 clusters only eight were considered for this study. Three clusters were excluded: cluster 3, comprised of species not associated with forest habitats; cluster 11, comprised of species relying upon habitat characteristics difficult to estimate with the resolution of the data used in this research (temporary water surfaces, for example); and cluster 12, comprised of species associated with environments not present in the study area, namely aquatic. Cluster 6 includes no species with published HSI model and for that reason was not considered either.

Table 25. Composition and description of the 12 clusters considered.

	Number of species				
Cluster	Total	Mammals	Birds	Herps	Description
1	24	6	10	8	Ground hardwood species
2	21	6	2	13	Exclusive ground, generalists
3	94	12	49	33	Non-forest species
4	15	8	6	1	Cavity and canopy breeding
5	11	1	10	0	Exclusive cavity birds
6	10	1	8	1	Middle/high hardwood and mixed canopy birds
7	17	1	13	3	Ground feeding, diverse breeding
8	12	6	4	2	Ground and shrub, generalist
9	10	1	8	1	Exclusive hardwood (diverse)
10	19	8	6	5	Feeding in all layers, breeding diverse
11	18	1	1	16	Water breeding, ground feeding species
12	15	0	15	0	Mid/High Canopy breeding (no feeding in forest)

Habitat Suitability Index Models

Habitat suitability at the stand and landscape levels was evaluated using Habitat Suitability Index (HSI) models (Schamberger et al. 1982). These single-species models were developed in the 80’s with the purpose of quantifying impacts of water or land use changes in wildlife habitats (Schamberger et al. 1982). They are standardized models allowing habitat suitability quantification in a 0 to 1 scale assuming a direct linear relationship of HSI with carrying capacity of the land unit evaluated (Fish and Wildlife Service 1981). These are not carrying capacity models since they do not include other variables affecting abundance (Schamberger and O’Neil 1986).

For each cluster defined above one species was selected to represent the general habitat requirements (Table 26). Selected species are not indicator species as defined in Noss (1990), Simberloff (1998), or Lindenmayer et al. (2000) since the requirements to be considered as such in any of their possible meanings were not tested and are unknown for these species. Indicator species require knowledge on the presence and abundance of populations, which is out of the scope of this work. They intend only to represent certain combinations of habitat requirements, mainly structural features that can be useful in exploring the effects of stand and landscape management on vertebrate habitats. In spite of heterogeneity within clusters, species that belong to the same group are closer in terms of habitat requirements than species that belong to different groups. Every species has its particular habitat requirements and the species selected cannot always represent specific conditions of other species in the same cluster. This is particularly true when considering attributes at the landscape scale that are related to species mobility. However it is not practical to conduct analysis of habitats for hundreds of species simultaneously. Grouping species is a way of reducing dimensionality in wildlife communities for analysis purposes used often in research (Simberloff and Dayan 1991).

The selection of species was strongly conditioned by the availability of HSI models. For terrestrial environments these models usually target large animals, namely birds and mammals. Some of the species selected have been used as management indicator species by the USDA Forest Service: barred owl and pine warbler in Wisconsin (Niemi et al. 1997), pine warbler and downy woodpecker in Mississippi (USDA Forest Service 2002), gray squirrel in Kentucky (USDA Forest Service 2000b) and pine warbler, gray and fox squirrels in Arkansas (USDA Forest Service 2001). In Canada, pine warbler, barred owl and beaver are used as indicator species in Ontario (McLaren et al. 1998).

Table 26. Selected species and corresponding Habitat Suitability Index models.

Cluster	Species	Model
1	American beaver, *Castor canadensis*	Allen (1983)
2	American woodcock, *Scolopax minor*	Cade (1985)
4	Pine warbler, *Dendroica pinus*	Schroeder (1982a)
5	Downy woodpecker, *Picoides pubescens*	Schroeder (1982b)
7	Barred owl, *Strix varia*	Allen (1987b)
8	Wild turkey, *Meleagris gallopavo sylvestris*	Schroeder (1985)
9	Fox squirrel, *Sciurus niger*	Allen (1982)
10	Gray squirrel, *Sciurus carolinensis*	Allen (1987a)

Model Variables

For forest species and species that use forests in some degree HSI models are based upon structural and compositional attributes of the forest stands described by model variables. Physical elements of the system are seldom required. These variables were calculated directly or indirectly from simulated data provided by the growth and yield models and in few cases from assumptions based upon published data. Variables included in the models are described in Appendix 5. Equations used in the models are in Appendix 6. Quantification of variables that are not calculated directly from stand level models is explained in detail in Appendix 7.

Models and Application

The variables considered in each model are used as independent variables in Suitability Index graphs to estimate Suitability Index Values (SIV). These values are then used in the calculation of the life requisites for each species combined in an HSI value at the land unit level (stand). HSI for the overall study area is calculated as the average of the stand HSI values weighted by the area of the units.

American beaver, *Castor canadensis* (Allen 1983)

This is a year round habitat model. Only the riverine component, as defined in US Fish and Wildlife Service (1981), was considered. It requires a minimum habitat length of 0.8 km of river to be applied. All the management types[1] are considered in the model since it is possible for the streams to intercept stands of any type and all types show at least some habitat quality. As life requisites the model considers winter food and water. This model is applied within buffer zones defined by distances of 100 and 200 m from the streams. Water life requisite is the lowest of Suitability Index corresponding to

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[1] Management type refers to the combination of forest type and management system; management types are: pine-clearcutting, pine-selection, hardwood-clearcutting, hardwood-selection, and pine-hardwood-selection (Chapter III).

variables V7 and V8. HSI is calculated as the lowest life requisite of winter food and water in each stand.

American woodcock, *Scolopax minor* (Cade 1985)

This model describes the wintering habitat of American woodcock. The model assumes that suitable open areas for nocturnal habitat are not limiting during winter and that suitable diurnal habitat is determined by structure of vegetation and soil characteristics. The model considers food and cover life requisites. Shrubland habitat is considered only for very young plantations when the structure of the vegetation is closer to shrublands than to forest. HSI is the lowest of the values calculated for food and cover in any cover type. This comparison is done in the GIS between food suitability values associated to SSURGO (Soil Survey Geographic Data Base, USDA - Natural Resources Conservation Service) soil maps and cover values associated to forest stands since the spatial distribution of soils is not coincident with stand distribution.

Pine warbler, *Dendroica pinus* (Schroeder 1982a)

This is a breeding season habitat model. It considers cover and reproduction in the same life requisite since both are considered to be met under the same habitat characteristics. Food availability is assumed to be always less limiting than cover and reproductive requirements. Only stand types including pine trees were considered.

Downy woodpecker, *Picoides pubescens* (Schroeder 1982b)

This HSI covers the year round needs of the species. Includes food and reproduction as life requisites and assumes that cover needs are met by food and reproductive requirements and water is not limiting. HSI equals the lowest life requisite value. It was applied in stands with hardwoods only (Shackelford and Conner 1997).

Barred owl, *Strix varia* (Allen 1987b)

This model is centered on the reproductive habitat of the barred owl. It is assumed that this habitat is the most limiting component of the year-round habitat. Reproductive habitat is the only life requisite in the model. Pure pine stands will be excluded from the habitat of the species since the species is usually associated with hardwood bottomlands (Shackelford and Conner 1996).

Fox squirrel, *Sciurus niger* (Allen 1982)

This is a year-round habitat model. Includes food, particularly winter food, and cover and reproduction and life requisites. Only stands with hardwoods were considered. HSI is equal to the lowest life requisite value.

Gray squirrel, *Sciurus carolinensis* (Allen 1987a)

This year-round habitat model is based upon the assumption that all habitat requirements can be satisfied in deciduous forests and deciduous forested wetlands. It assumes also that the most limiting components of the habitat are hard mast production and den sites in tree cavities. Life requisites are winter food and cover/reproduction. Only management types containing hardwoods were considered. HSI is equal to the lowest life requisite value.

Eastern wild turkey, *Meleagris gallopavo sylvestris* (Schroeder 1985)

The application of this year round habitat model requires that the life requisites "summer food/brood habitat", "fall, winter, spring food", and "cover" to be evaluated simultaneously in each area using the habitat composition variables V14, V15, and V16. These variables are calculated by multiplying the life requisite value of each land unit by its relative area and summing all the units' values for the entire area under consideration. Overall HSI is calculated as the minimum value among index values of variables V14, V15 and V16 obtained by their respective suitability index curves. This procedure does not allow a spatial representation of HSI values but only of its components. In the “summer food/brood” habitat evergreen forest stands are not considered. Pine stands younger that 5 yr are considered as shrublands in the context of the HSI model. Hardwood stands younger than 9 yr will also be considered as shrublands. In the “fall, winter, spring food” habitat all cover types are considered. Young stands are considered shrublands as in the previous case. For “cover” all cover types are considered.

Spatial Pattern of Suitable Habitat

Each of the models above is applied over the study area in the GIS joining imported tables relating stand age, SI(50 years), and HSI to the stands’ coverages for different years. Two scenarios were used for comparison reasons. Assuming a linear relationship between HSI and carrying capacity, we consider five habitat suitability classes:

- class 0: $HSI=0$
- class 1: $0 < HSI < 0.25$
- class 2: $0.25 < HSI < 0.5$
- class 3: $0.5 < HSI < 0.75$
- class 4: $0.75 < HSI < 1$

Stands are classified by HSI value according to this system. For each species and year maps for classes 3 and 4 including the areas with higher habitat suitability were analyzed visually and in terms of landscape pattern using landscape metrics calculated in FRAGSTATS (McGarigal and Marks 1995), version 3.3.

Results

The dynamics of the landscape structure presents a return interval of 30 years in the simulations (see Chapter III). For that reason all the results will refer to a period of this duration, namely between simulation years 144 and 174.

Stand Level HSI

Habitat suitability index values at the stand level depend on forest type, management, and stand age (Figure 17). Suitability is often below the potential maximum values (Table 27). The main limiting factors are summarized in Table 28.

American beaver is limited, minimally, by the presence of pine in management types 1 and 3 and by reduced shrub cover in management 1. Both variables are part of the food component.

American woodcock in pine stands is limited by insufficient herbaceous and shrub cover and by low density of trees, both part of the cover component. Tree density is the only limiting factor in all the remaining management types except management 2 where vigorous vegetative growth after clearcutting and thinning operations increases density to extreme levels.

The relatively low maximum value reached by pine warbler in pine stands is due to the variable "successional stage of stand". Maximum value is reached only for mature or old-growth, absent from short rotation stands. In the case of other pine management types, overstory pine cover is the major limiting factor. Irregular pine stands do not allow maximum dominant cover to be reached. In mixed stands the presence of hardwoods additionally decreases the quality of the stands.

For year-round habitat of downy woodpecker basal area (food component) and density of snags larger than 15 cm dbh (reproduction component) are the limiting conditions in the hardwood stands managed by the clearcutting system. Basal area is often below or above the optimal interval of 10-20 m^2/ha. Snags are often abundant but their occurrence is not synchronized with optimum basal area. Snags are the limiting factor in the uneven-aged stands due to the fact that periodic harvestings reduce mortality.

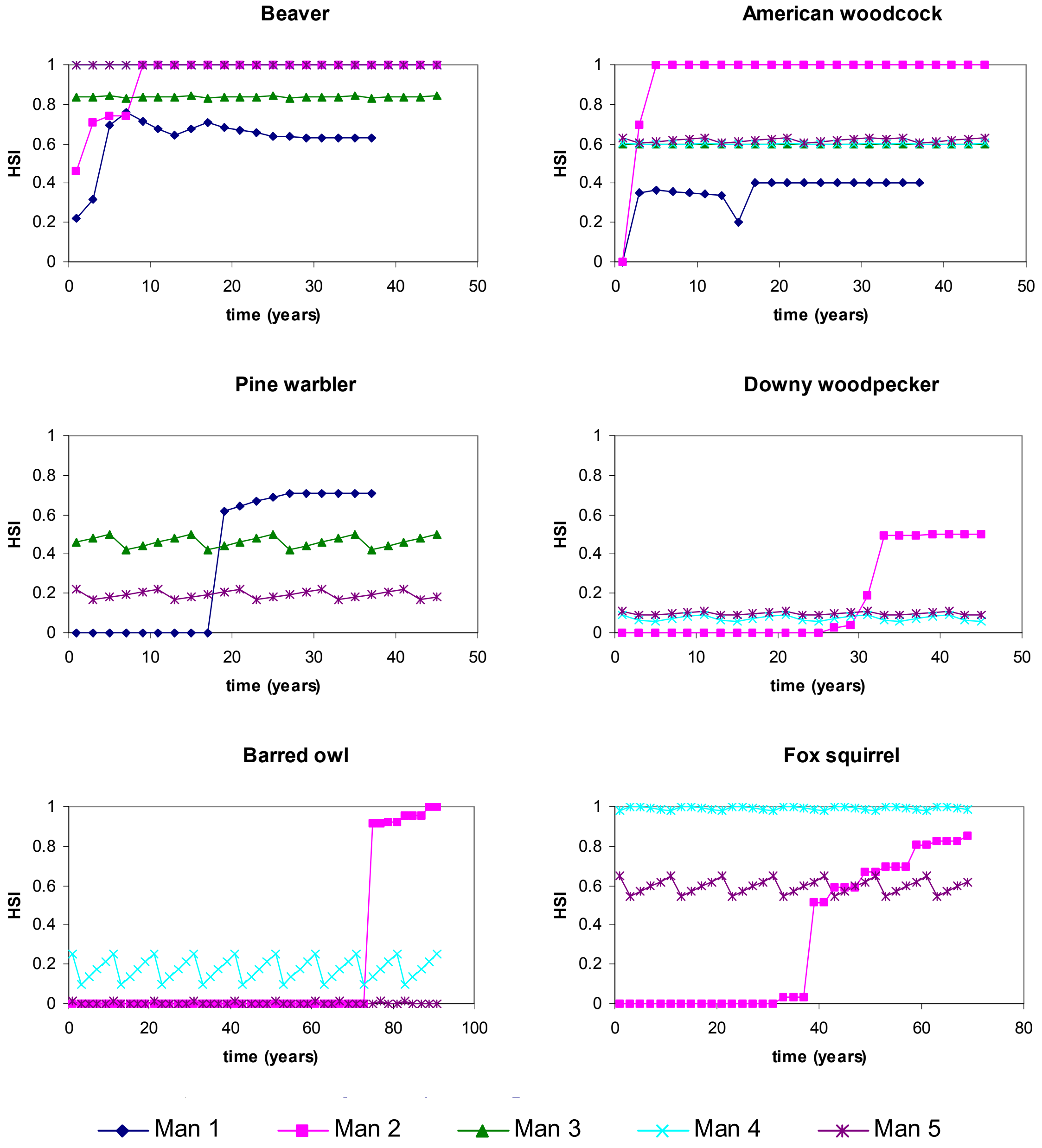


Figure 17. Habitat suitability index values per species along stand development for average site index. SI(50) for Man 1, 2, 3, and 4= 27 m; for Man 5 = 26 m. For simplicity HSI for American woodcock was based on FSI=1. Notice x-axes are not coincident among the plots.

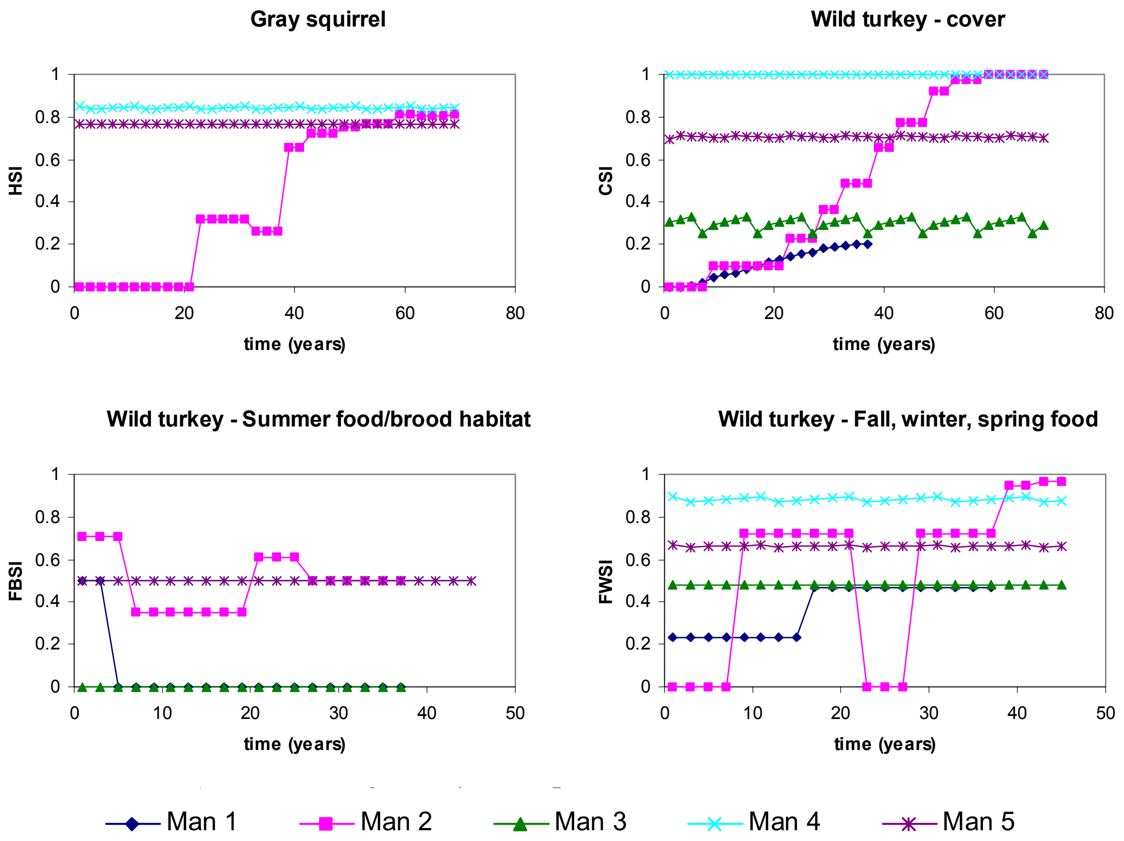


Figure 17 (continued).

Table 27. Maximum HSI values observed at the stand level by species and management type within the 30-yr period of observations.

Species	Management type 1	2	3	4	5
American beaver	0.76	1	0.84	1	1
American woodcock	0.45	1	0.60	0.70	0.63
Pine warbler	0.71	-	0.50	-	0.30
Downy woodpecker	-	0.66	-	0.09	0.11
Barred owl	-	1	-	0.32	0.02
Fox squirrel	-	0.86	-	1	0.65
Gray squirrel	-	0.87	-	1	0.78
Eastern wild turkey					
- Cover	0.20	1	0.33	1	0.71
- Summer	0.50	0.71	-	0.50	0.50
- Fall/Winter/Spring	0.47	0.97	0.48	0.91	0.67

1-pine-clearcutting; 2-hardwoods-clearcutting; 3-pine-selection; 4-hardwoods-selection; 5-pine-hardwoods-selection

Table 28. Limiting variables in the Habitat Suitability Models per species and management type.

Species	Management type				
	1	2	3	4	5
American beaver	V3 - shrub cover V5 - composition	Not limited	V5 - composition	Not limited	Not limited
American woodcock	V3 - herbaceous and shrub cover V4 - tree density	Not limited	V4 - tree density	V4 - tree density	V4 - tree density
Pine warbler	V2 - stage	-	V1 - pine cover	-	V1 - pine cover V3 - deciduous cover
Downy woodpecker	-	V1 - Basal area V2 - snags	-	V2 - snags	V2 - snags
Barred owl	-	V1 - trees ≥ 51 cm V2 - dbh	-	V3 - dbh	V3 - dbh
Fox squirrel	-	V3 - dbh	-	Not limited	V1 - hard mast cover
Gray squirrel	-	V1 - hard mast % V5 - dbh	-	Not limited	V1 - hard mast %
Eastern wild turkey					
Cover	V13 - evergreens	Not limited	V13 - evergreens	Not limited	V13 - evergreens
Summer	V1 - herbaceous cover	V1 - herbaceous cover	-	V1 - herbaceous cover	V1 - herbaceous cover
Fall/Winter/Spring	V4 - hard mast V5 - soft mast	V5 - soft mast	V4 - hard mast V5 - soft mast	V4 - hard mast V5 - soft mast	V4 - hard mast V5 - soft mast

Barred owl reproductive habitat is mainly limited by mean dbh of overstory trees. In the management type 2 the number of trees larger than 51 cm is even more limiting until around age 70. In management 4, harvests regularly decrease average dbh.

Fox squirrel in management 2 is limited by dbh of overstory trees (cover) and in management 5 is limited by cover of hard mast trees larger than 25.4 cm dbh (winter food). It is not limited in uneven-aged hardwood stands. Habitat of gray squirrel provided by management 2 is partially limited by the proportion of canopy comprised of hard mast producing trees (winter food) and by dbh of overstory trees (cover). This is also the limiting factor in management 5.

Wild turkey cover is limited in the management types with pine trees (1, 3, and 4) precisely by their presence. Summer habitat is strongly limited by the reduced herbaceous cover in all management types. Notice this habitat component is estimated in pine stands only after clearcutting. "Fall/winter/spring" habitat is limited naturally in the pine and mixed stands by lack of hard and soft mast producing trees.

Overall HSI

The SFI and Non-SFI scenarios show several differences in terms of general habitat suitability for the species analyzed (Table 29). Pine warbler shows lower HSI values in SFI than in Non-SFI. Given the similarity among runs, observed differences between management scenarios are statistically significant ($p<0.001$; repeated measures ANOVA with management as a fixed effect and runs as random subjects). American beaver and American woodcock present higher HSI values in the SFI landscape (Table 29). Differences for American beaver are considerable. Wild turkey, fox squirrel, and gray squirrel show substantial differences between scenarios. For these species HSI values in the Non-SFI scenario are close to zero but habitat suitability in the SFI scenario is relatively high. Barred owl and downy woodpecker present HSI values very reduced and practically negligible in both cases. HSI is very stable along the period of time considered for all the species in both management scenarios (Figure 18).

Table 29. Statistical parameters of the HSI scores for the study area by species and management scenario. Values refer to a 30-year simulation cycle.

		SFI scenario				Non-SFI scenario			
Species	Run #	Mean	Min	Max	SD	Mean	Min	Max	SD
American woodcock	1	0.45	0.43	0.46	0.009	0.41	0.39	0.44	0.015
	2	0.45	0.43	0.46	0.006	0.41	0.39	0.44	0.014
	3	0.45	0.43	0.46	0.007	0.41	0.39	0.44	0.014
American beaver*	1	0.63	0.61	0.64	0.008	0.55	0.53	0.57	0.013
	2	0.63	0.61	0.64	0.007	0.55	0.53	0.57	0.013
	3	0.63	0.62	0.64	0.007	0.55	0.53	0.57	0.012
Pine warbler	1	0.19	0.15	0.23	0.029	0.23	0.17	0.28	0.033
	2	0.19	0.15	0.22	0.026	0.23	0.17	0.28	0.033
	3	0.19	0.15	0.23	0.027	0.23	0.17	0.28	0.033
Downy woodpecker	1	0.03	0.02	0.03	0.003	0.03	0.02	0.03	0.001
	2	0.03	0.02	0.04	0.003	0.03	0.02	0.03	0.003
	3	0.03	0.03	0.04	0.003	0.03	0.02	0.03	0.003
Barred owl	1	0.04	0.02	0.06	0.013	0.003	0.001	0.005	0.002
	2	0.04	0.02	0.06	0.013	0.002	0.000	0.004	0.001
	3	0.04	0.02	0.06	0.013	0.002	0.000	0.005	0.002
Eastern wild turkey	1	0.53	0.52	0.55	0.010	0.06	0.03	0.10	0.020
	2	0.54	0.52	0.55	0.008	0.06	0.03	0.10	0.020
	3	0.54	0.52	0.56	0.013	0.05	0.02	0.08	0.018
Fox squirrel	1	0.24	0.23	0.24	0.002	0.02	0.02	0.03	0.003
	2	0.24	0.23	0.24	0.002	0.02	0.02	0.03	0.004
	3	0.24	0.24	0.24	0.001	0.02	0.02	0.03	0.003
Gray squirrel	1	0.21	0.21	0.21	0.002	0.03	0.03	0.04	0.002
	2	0.21	0.21	0.22	0.002	0.04	0.03	0.04	0.004
	3	0.21	0.21	0.22	0.002	0.03	0.03	0.04	0.003

*Calculated for the area within buffers only

The SFI landscape is comprised of stands of five different management types whereas Non-SFI presents only three types (Table 30). Hardwood cover is more abundant in SFI than in Non-SFI. Approximately 1000 ha of hardwoods in SFI result from the "conversion" of pine in hardwoods within SMZ buffer strips. Evenness among management types is higher in SFI.

Differences in HSI values between landscapes can be explained by differences in composition of forest and management types and by stand level HSI values (Table 30).

For the species that show near zero HSI values in the Non-SFI scenario (wild turkey, fox and gray squirrels) hardwood habitats show the highest HSI values at the stand level whereas pine habitats show reduced or null HSI values (Table 27). Changes in forest types do not affect pine warbler in the same proportion. Although there is considerably more pine habitat in Non-SFI, the habitat type where stand level HSI reaches the maximum values, HSI at the landscape level increases only slightly in this scenario. These differences are explained by several factors simultaneously: relatively low maximum possible stand HSI (max HSI=0.7), general small HSI (Table 29), short period of time that pine stands show high HSI values (11 years) (Figure 17), and null HSI in stands younger than 19 years.

Certain measures play a great role in the changes in composition in the landscape, namely the implementation of SMZs in pine stands assumed to become hardwood dominated in the future. Also assuming that all actual mixed stands are pure pine stands in the Non-SFI scenario caused differences among management types. American beaver's habitat quality is higher in the SFI scenario. The difference is due to the fact that stands under management 4 and 5 that are always very suitable (HSI=1) are absent from the Non-SFI scenario. Pine stands managed either by the clearcutting or selection system show high suitability above certain age.

Table 30. Area by management type in the SFI and Non-SFI scenarios.

			SFI		Non-SFI	
Management type	Forest type	Silvicultural system	Area (ha)	Area (%)	Area (ha)	Area (%)
1	Pine	clearcutting	3964.3	68.7	4993.3	86.5
2	Hardwood	clearcutting	265.8	4.6	595.2	10.3
3	Pine	selection	164.4	2.8	183.5	3.2
4	Hardwood	selection	1260.4	21.8	-	-
5	Mixed	selection	116.9	2.0	-	-

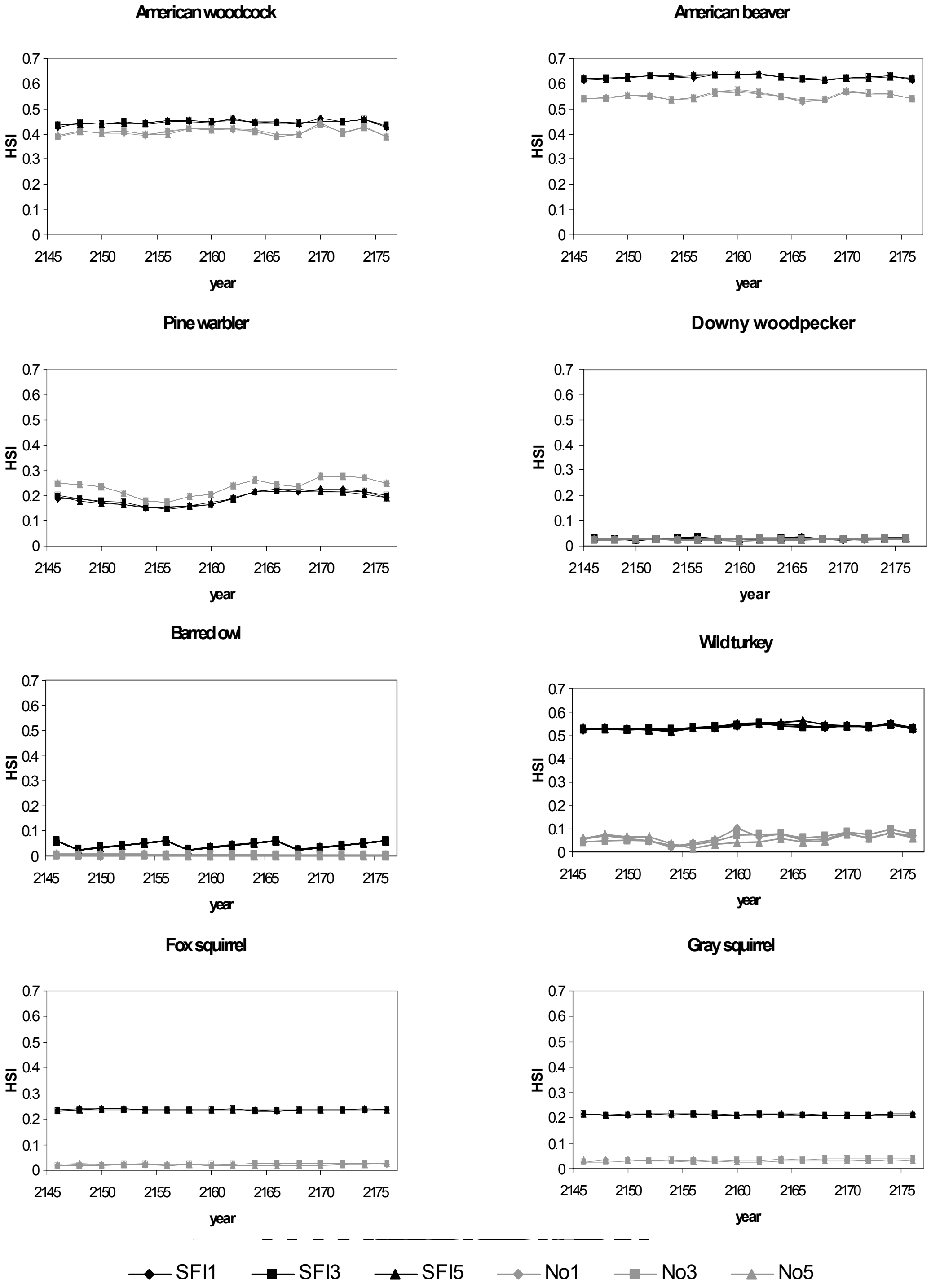


Figure 18. Variation of HSI values in the study period in the SFI and Non-SFI scenarios.

HSI for barred owls and downy woodpeckers reflect the rarity or inexistence of very suitable habitat and the low HSI value for the SMZs network in the SFI scenario. For barred owl in the Non-SFI scenario the class 4 values observed result from the application of adjacency constraints in the hardwood areas that allow very small hardwoods fragments to grow for long periods of time. Downy woodpeckers do not find suitable habitat of classes above 2. Fox and gray squirrel and turkey HSI values are intimately related to management 4, but also management 2 and 5 as seen above.

Spatial Pattern

HSI calculated for the entire study area provides an indication of general suitability for each species and allows comparisons between management scenarios. A better understanding of the effects of the application of SFI at the landscape level can be obtained if general HSI information is complemented with information on composition and spatial arrangement of suitable habitat areas.

The analysis of spatial attributes of American beaver habitat is complex (Table 31). Landscape metrics are very difficult to interpret and sometimes meaningless given the way HSI is calculated (within 0-100 and 100-200m buffers).

Table 31. Selected landscape metrics for American beaver habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

		Class 3		Class 4	
Variable	Acronym	SFI	Non-SFI	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	34.0	48.5	29.8	11.6
Patch Density (#/100 ha)	PD	3.8	1.3	0.4	0.5
Edge Density (m/ha)	ED	117.6	64.1	81.2	16.2
Largest Patch Index (%)	LPI	3.4	25.0	29.6	5.3
Landscape Shape Index	LSI	36.7	17.1	26.5	8.6
Mean Patch Area (ha)	AREA_MN	9.1	39.3	77.5	24.6
Mean Fractal Dimension Index	FRAC_MN	1.13	1.11	1.11	1.10
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.25	1.24	1.39	1.19
Core Area Percentage of Landscape (%)	CPLAND	0.0	7.1	2.7	1.9
Mean Core Area (ha)	CORE_MN	0.0	5.8	6.9	4.1
Mean Core Area Index (%)	CAI_MN	0.0	2.2	0.6	2.8
Mean Proximity Index	PROX_MN	479.3	4387.7	5076.4	359.7
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	48.7	75.5	70.8	206.4
Interspersion and Juxtaposition Index (%)	IJI	54.6	44.0	41.0	49.2

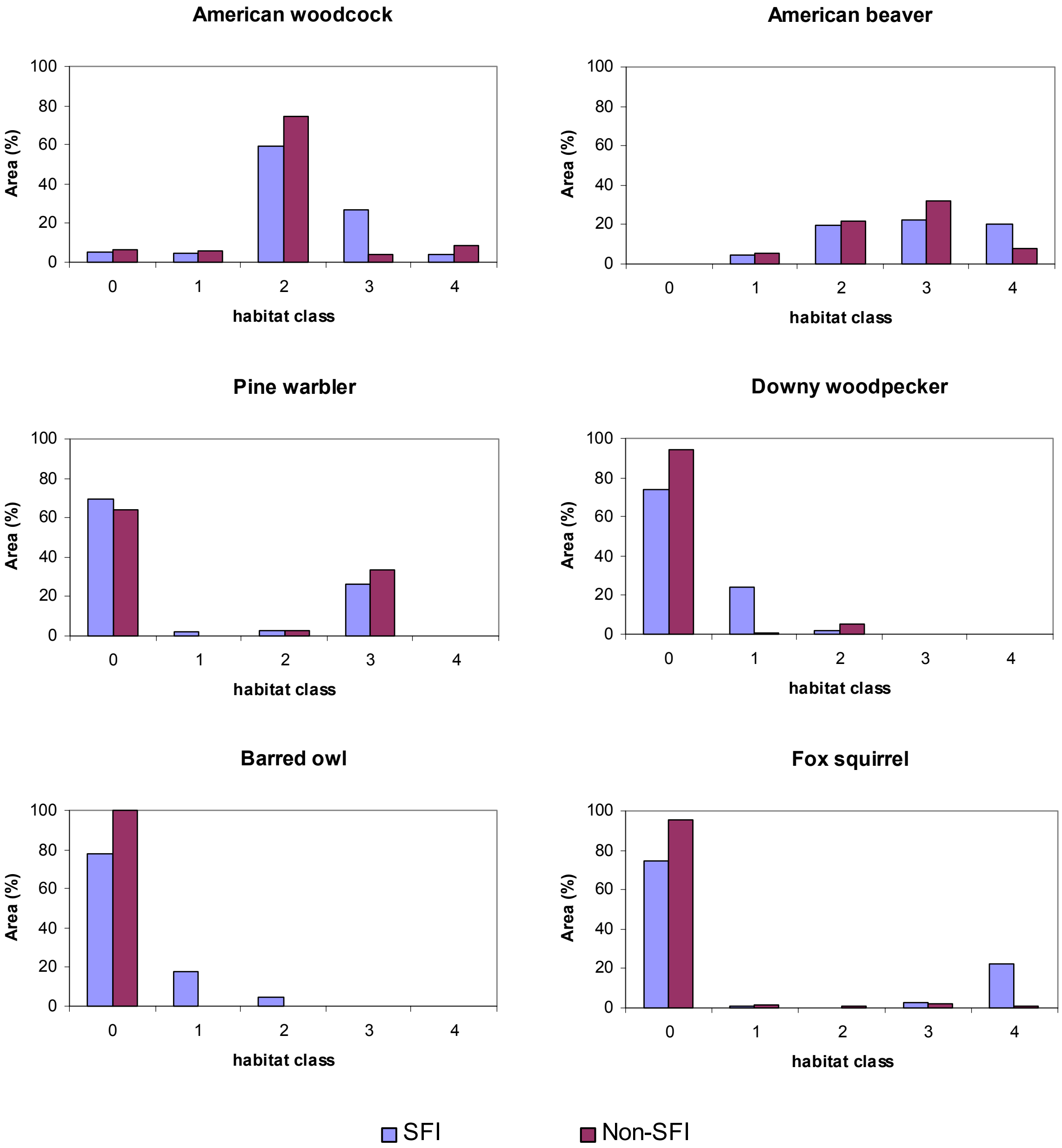


Figure 19. Distribution of area per habitat suitability class for the species considered. Average values of 15 dates and three runs per scenario.

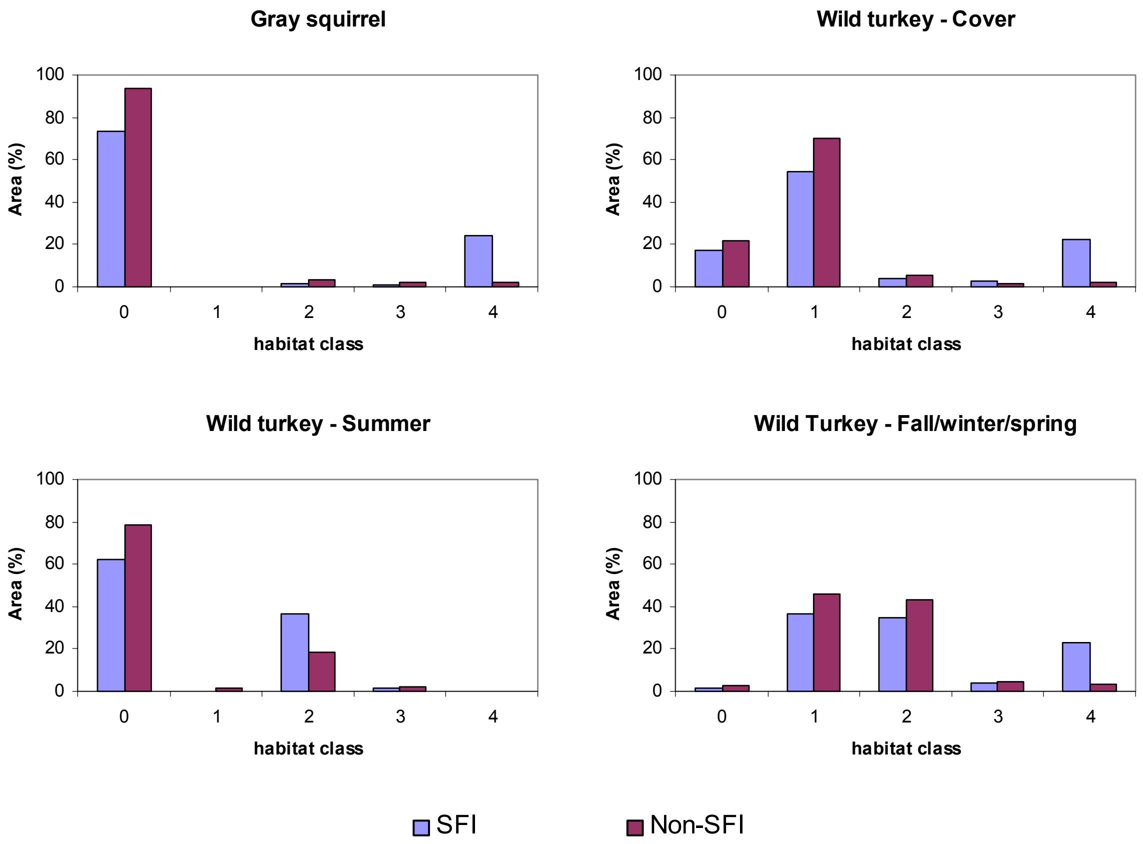


Figure 19 (continued).

American woodcock habitat is mainly class 2 habitat in both scenarios (Figure 19). Class 3 is relatively abundant in the SFI landscape only (27% of the area). This habitat class is distributed by very few patches spread over the landscape, has an extremely large edge length, and reduced core areas (Table 32). LPI practically equals the Percent of Landscape value indicating that near 100% of the area of this class is contained in a single patch. All the metrics are nearly constant through time. This class corresponds mainly to the SMZs network established in the SFI scenario (Figure 20). In the Non-SFI landscape class 3 has minor expression. Class 4 in the SFI scenario is comprised of several small and dispersed patches. In the Non-SFI scenario the same class presents larger area comprised mainly of two very large patches located in the central bottomland of the landscape.

Class 3 habitat of pine warbler shows higher area in the Non-SFI scenario than in the SFI scenario (Table 33, Figure 19, Figure 20). In the Non-SFI scenario, compared to the SFI scenario, this habitat is comprised of fewer larger patches, more aggregated, with fewer edges, but also more isolated among them (Table 33). Core area is larger in Non-SFI distributed by fewer larger interior units. Pine warbler shows practically no suitable habitat in classes lower than 3.

Table 32. Selected landscape metrics for American woodcock habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

		Class 3		Class 4	
Variable	Acronym	SFI	Non-SFI	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	26.8	4.1	4.0	8.8
Patch Density (#/100 ha)	PD	0.2	0.2	0.4	0.1
Edge Density (m/ha)	ED	69.7	4.8	6.8	6.6
Largest Patch Index (%)	LPI	26.8	1.6	0.7	5.0
Landscape Shape Index	LSI	25.7	4.9	7.0	4.5
Mean Patch Area (ha)	AREA_MN	165.4	22.9	10.4	185.7
Mean Fractal Dimension Index	FRAC_MN	1.13	1.10	1.09	1.13
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.39	1.07	1.10	1.15
Core Area Percentage of Landscape (%)	CPLAND	5.9	1.4	0.5	4.4
Mean Core Area (ha)	CORE_MN	36.3	7.8	1.2	93.0
Mean Core Area Index (%)	CAI_MN	2.3	15.0	4.8	38.9
Mean Proximity Index	PROX_MN	1645.4	12.9	60.2	543.1
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	153.0	722.8	160.5	192.4
Interspersion and Juxtaposition Index (%)	IJI	51.9	69.0	53.7	77.3

Suitable habitat for barred owl and downy woodpecker is extremely scarce for any of the management scenarios. Few, very small, and isolated class 4 patches provide the only quality habitat for barred owl, when present (Table 34). In SFI the SMZ network provides relatively abundant class 1 habitat for both species although the HSI value for downy woodpecker is very reduced (Figure 19, Table 35).

The remaining species do not allow a fair comparison between scenarios since there is almost no quality habitat in Non-SFI as compared to SFI. Class 4 habitat for fox squirrel and gray squirrel comprises the majority of suitable habitat in SFI. As in class 3

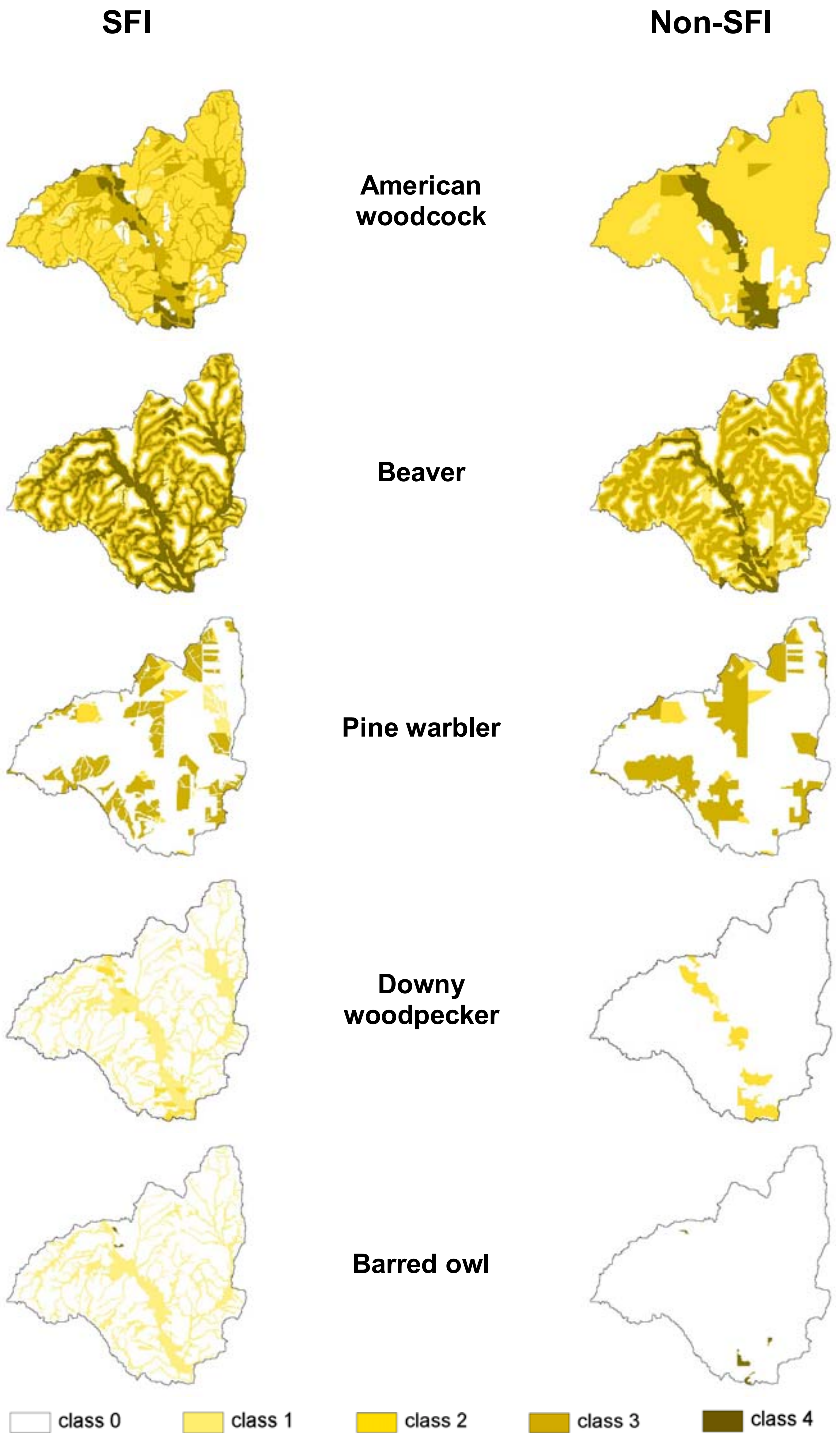


Figure 20. Examples of spatial pattern of habitat suitability classes for the study area in alternative management scenarios. Images refer to simulation year 156.

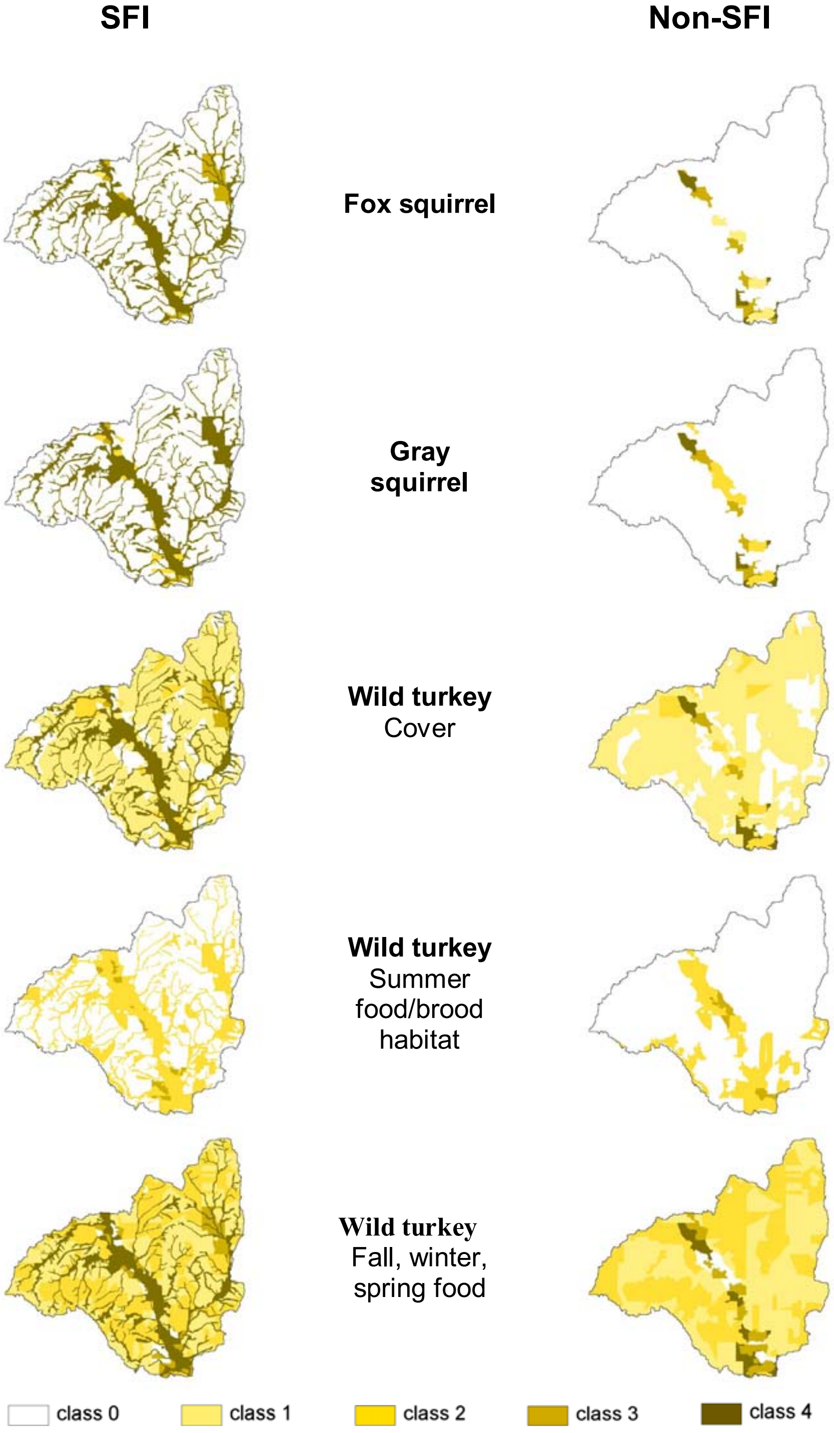


Figure 20 (Continued).

Table 33. Selected landscape metrics for pine warbler habitat class 3. All values are averages for three simulation runs and 15 observation dates.

		Class 3	
Variable	Acronym	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	25.8	32.9
Patch Density (#/100 ha)	PD	1.3	0.4
Edge Density (m/ha)	ED	37.4	19.7
Largest Patch Index (%)	LPI	2.9	13.7
Landscape Shape Index	LSI	15.0	7.5
Mean Patch Area (ha)	AREA_MN	20.8	89.3
Mean Fractal Dimension Index	FRAC_MN	1.10	1.09
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.13	1.13
Core Area Percentage of Landscape (%)	CPLAND	4.8	17.3
Mean Core Area (ha)	CORE_MN	3.9	47.0
Mean Core Area Index (%)	CAI_MN	8.2	19.9
Mean Proximity Index	PROX_MN	334.1	447.0
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	80.6	212.2
Interspersion and Juxtaposition Index (%)	IJI	14.6	23.7

Table 34. Selected landscape metrics for barred owl habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

		Class 4	
Variable	Acronym	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	0.1	0.2
Patch Density (#/100 ha)	PD	0.1	0.0
Edge Density (m/ha)	ED	0.6	0.6
Largest Patch Index (%)	LPI	0.1	0.2
Landscape Shape Index	LSI	3.4	2.4
Mean Patch Area (ha)	AREA_MN	2.0	6.8
Mean Fractal Dimension Index	FRAC_MN	1.13	0.88
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.13	0.88
Core Area Percentage of Landscape (%)	CPLAND	0.0	0.0
Mean Core Area (ha)	CORE_MN	0.0	1.2
Mean Core Area Index (%)	CAI_MN	0.0	4.1
Mean Proximity Index	PROX_MN	0.3	3.3
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	1010.4	1090.5
Interspersion and Juxtaposition Index (%)	IJI	73.0	N/A

Table 35. Selected landscape metrics for downy woodpecker habitat class 2. All values are averages for three simulation runs and 15 observation dates.

		Class 2	
Variable	Acronym	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	2.3	5.3
Patch Density (#/100 ha)	PD	0.3	0.1
Edge Density (m/ha)	ED	5.2	5.3
Largest Patch Index (%)	LPI	0.4	2.3
Landscape Shape Index	LSI	7.0	4.7
Mean Patch Area (ha)	AREA_MN	7.3	51.7
Mean Fractal Dimension Index	FRAC_MN	1.10	1.11
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.10	1.12
Core Area Percentage of Landscape (%)	CPLAND	0.1	2.0
Mean Core Area (ha)	CORE_MN	0.4	19.5
Mean Core Area Index (%)	CAI_MN	2.4	22.7
Mean Proximity Index	PROX_MN	36.2	51.1
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	233.3	272.4
Interspersion and Juxtaposition Index (%)	IJI	91.8	34.7

Table 36. Selected landscape metrics for fox squirrel habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

		Class 3		Class 4	
Variable	Acronym	SFI	Non-SFI	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	2.9	2.2	22.1	0.9
Patch Density (#/100 ha)	PD	0.4	0.1	0.1	0.1
Edge Density (m/ha)	ED	6.2	3.3	70.5	1.8
Largest Patch Index (%)	LPI	0.7	0.9	22.0	0.5
Landscape Shape Index	LSI	7.0	4.3	28.6	3.9
Mean Patch Area (ha)	AREA_MN	8.1	26.4	154.9	13.3
Mean Fractal Dimension Index	FRAC_MN	1.11	1.12	1.17	1.13
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.09	1.12	1.41	1.12
Core Area Percentage of Landscape (%)	CPLAND	0.4	0.5	3.2	0.1
Mean Core Area (ha)	CORE_MN	1.0	5.8	22.5	1.6
Mean Core Area Index (%)	CAI_MN	3.5	13.8	1.8	5.6
Mean Proximity Index	PROX_MN	56.4	17.4	1193.6	2.2
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	172.6	670.0	128.1	1227.2
Interspersion and Juxtaposition Index (%)	IJI	58.4	54.1	19.4	54.3

Table 37. Selected landscape metrics for gray squirrel habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

Variable	Acronym	Class 3 SFI	Class 3 Non-SFI	Class 4 SFI	Class 4 Non-SFI
Percentage of Landscape (%)	PLAND	0.7	1.7	24.4	1.7
Patch Density (#/100 ha)	PD	0.1	0.1	0.1	0.1
Edge Density (m/ha)	ED	1.8	2.4	69.7	2.9
Largest Patch Index (%)	LPI	0.2	0.8	24.3	0.7
Landscape Shape Index	LSI	4.3	3.6	26.9	4.5
Mean Patch Area (ha)	AREA_MN	5.4	30.2	169.6	17.8
Mean Fractal Dimension Index	FRAC_MN	1.10	1.11	1.17	1.13
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.10	1.12	1.40	1.12
Core Area Percentage of Landscape (%)	CPLAND	0.0	0.4	4.7	0.3
Mean Core Area (ha)	CORE_MN	0.1	6.7	32.8	3.1
Mean Core Area Index (%)	CAI_MN	1.1	16.5	2.3	8.4
Mean Proximity Index	PROX_MN	4.8	9.0	1392.3	11.5
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	641.9	1214.1	126.3	715.4
Interspersion and Juxtaposition Index (%)	IJI	86.2	75.0	17.2	76.9

Table 38. Selected landscape metrics for wild turkey cover habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

Variable	Acronym	Class 3 SFI	Class 3 Non-SFI	Class 4 SFI	Class 4 Non-SFI
Percentage of Landscape (%)	PLAND	2.6	1.4	22.5	2.0
Patch Density (#/100 ha)	PD	0.3	0.1	0.1	0.1
Edge Density (m/ha)	ED	5.2	2.0	70.7	3.1
Largest Patch Index (%)	LPI	0.7	0.8	22.5	0.9
Landscape Shape Index	LSI	6.2	3.2	28.4	4.5
Mean Patch Area (ha)	AREA_MN	8.7	31.5	157.7	21.0
Mean Fractal Dimension Index	FRAC_MN	1.10	1.11	1.17	1.12
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.09	1.11	1.41	1.12
Core Area Percentage of Landscape (%)	CPLAND	0.4	0.3	3.3	0.4
Mean Core Area (ha)	CORE_MN	1.2	7.6	23.4	4.4
Mean Core Area Index (%)	CAI_MN	4.1	17.3	1.8	10.1
Mean Proximity Index	PROX_MN	65.0	7.3	1262.1	15.7
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	260.2	1487.0	126.3	672.9
Interspersion and Juxtaposition Index (%)	IJI	69.4	77.7	61.4	78.9

Table 39. Selected landscape metrics for wild turkey summer food/brood habitat classes 3 and 4. All values are averages for three simulations and 15 observation dates.

		Class 3	
Variable	Acronym	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	1.1	2.1
Patch Density (#/100 ha)	PD	0.2	0.1
Edge Density (m/ha)	ED	2.6	2.9
Largest Patch Index (%)	LPI	0.2	1.0
Landscape Shape Index	LSI	5.0	3.8
Mean Patch Area (ha)	AREA_MN	5.8	33.7
Mean Fractal Dimension Index	FRAC_MN	1.09	1.09
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.09	1.10
Core Area Percentage of Landscape (%)	CPLAND	0.0	0.4
Mean Core Area (ha)	CORE_MN	0.2	6.4
Mean Core Area Index (%)	CAI_MN	1.3	13.3
Mean Proximity Index	PROX_MN	9.2	73.8
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	467.2	1113.2
Interspersion and Juxtaposition Index (%)	IJI	63.8	52.5

Table 40. Selected landscape metrics for wild turkey fall/winter/spring habitat classes 3 and 4. All values are averages for three simulation runs and 15 observation dates.

		Class 3		Class 4	
Variable	Acronym	SFI	Non-SFI	SFI	Non-SFI
Percentage of Landscape (%)	PLAND	4.1	4.5	23.1	3.4
Patch Density (#/100 ha)	PD	0.5	0.1	0.1	0.1
Edge Density (m/ha)	ED	8.4	4.9	70.8	4.4
Largest Patch Index (%)	LPI	0.7	2.2	23.0	1.3
Landscape Shape Index	LSI	8.1	4.5	28.2	4.9
Mean Patch Area (ha)	AREA_MN	8.3	63.8	160.3	31.2
Mean Fractal Dimension Index	FRAC_MN	1.10	1.12	1.17	1.12
Area-weighted Mean Fractal Dimension Index	FRAC_AM	1.09	1.13	1.41	1.12
Core Area Percentage of Landscape (%)	CPLAND	0.4	1.5	3.6	0.9
Mean Core Area (ha)	CORE_MN	0.9	21.6	25.2	8.4
Mean Core Area Index (%)	CAI_MN	3.4	25.3	1.9	15.3
Mean Proximity Index	PROX_MN	53.5	123.5	1409.5	28.9
Mean Euclidean Nearest Neighbor Distance (m)	ENN_MN	146.4	504.5	124.9	366.8
Interspersion and Juxtaposition Index (%)	IJI	70.8	93.6	72.9	91.5

for American woodcock metrics reflect the characteristics of the SMZ network: few patches, one patch containing more than 90% of the class area, considerable total area occupied, low aggregation, small core area percentage, and small distances (Table 36, Table 37).

HSI of wild turkey depends upon the combination of habitat components and each habitat component has to be considered individually. Cover is the limiting component in both scenarios. The structure of class 4 cover habitat shares the properties described above for networks of SMZs (Table 38). The same applies to class 1 of “summer food/brood” habitat (Table 39) and class 4 of “fall, winter, spring food” habitat (Table 40). Very large patches of classes 1 and 2 dominate the Non-SFI scenario.

Discussion

Habitat Pattern

The major effects of the SFI program on the spatial pattern of the habitats observed are fragmentation and establishment of narrow and elongated habitats in a network structure corresponding to the SMZs. The first effect is observed for pine warbler and the second for American woodcock, fox and gray squirrel, and wild turkey, and for the less suitable habitat of downy woodpecker and barred owl.

The case of pine warbler was discussed previously (Chapter III). Fox squirrels have preference for edges (Alexander 1994, Derge and Yahner 2000) and can use open agricultural fields among habitat patches (Nupp and Swihart 2000). Management practices to improve fox squirrels habitat in East Texas include patches that maximize edge proportion as well as corridors for movement (Alexander 1994). Gray squirrel is considered a more interior species than fox squirrel (Derge and Yahner 2000, Zollner 2000) but is common in a wide range of habitat types including urban and open systems such as cemeteries and campus providing trees, preferable hardwoods, are present (Williamson 1983). The species is affected by habitat patch size and isolation in agriculturally fragmented landscapes (Goheen et al. 2003). In these conditions the species requires patches larger than 5 ha connected by corridors, including riparian strips, to other forest areas (Nupp and Swihart 2000). SMZs in the SFI scenario provide a structure similar to the one just described. Fischer and Holler (1991) found narrow hardwoods buffers along streams to be important components of gray squirrel habitat in Alabama. Dickson and Huntley (1987) found SMZs to be preferable habitat of both squirrel species in east Texas. There is no indication that SMZ structure can negatively affect fox and gray squirrels in this scenario.

Winter habitat of American woodcock is also dominated by the network of riparian buffers. The species uses several types of land uses including open fields, recently harvested stands, and dense hardwood stands (Keppie and Whiting 1994, Berdeen and Krementz 1998) but bottomlands are among the preferred habitats (Dessecker and McAuley 2001). Class 3 habitat follows the network structure of the SMZs and adjacent mixed stands. There is no indication that this structure affects negatively the species. The fact that this habitat class is spread all over the area and contains a large contact surface with other habitats might eventually be of interest for the species. Class 4 habitat patches are relatively small and isolated but since they are in contact with the network they improve the overall conditions of the structure.

The network of SMZs and the adjacent mixed pine-hardwoods stands provide simultaneously the three components of the habitat required by wild turkey including cover, the critical component in the overall HSI. Turkeys are not confined to particular habitats and move frequently among them. In the south, SMZs are used by turkeys during all seasons and are key habitat to sustain viable populations in managed pine forests (Burk et al. 1990, Hurst and Dickson 1992). High edge length seems to be positively related with turkey densities in New York State (Glennon and Porter 1999). Predation of turkeys in stream valleys and in forest edges can however be higher than in other habitats (Thogmartin and Schaeffer 2000). The spatial pattern of the habitat does not seem to have a negative effect on wild turkeys.

Barred owl has only accidental very reduced and isolated patches of the most suitable habitat. There is however low HSI habitat in the SFI scenario within the SMZs network. There is no suggestion in the literature that downy woodpeckers avoid edges. The species is often considered as a generalist (Whitaker and Montevecchi 1999) and uses open habitats frequently, residential areas and forest edges (Jackson and Quellet 2002), and buffer strips (Dickson et al. 1995). The most suitable habitat of downy woodpeckers in the SFI scenario is distributed by several small patches in comparison to the Non-SFI scenario. Schroeder (1982b) indicates 4 ha as the minimum size of potentially useable habitat for the species. Considering as useable habitat classes 1 and 2 the majority of habitat is in or contiguous to the SMZ network and therefore the minimum habitat areas should not be a limiting factor in the landscape.

Given the dependence of beaver on streams and the suitability of all types of stands the species is unaffected spatially.

SMZs

SMZs play a main role in the maintenance of habitat for a great number of species in short rotation pine plantations. SMZs increase diversity of habitats and increase niches available by creating edges (Thurmond and Miller 1994), habitat features such as den trees and snags (Wigley and Roberts 1997), and mast and forage producing plants (Dickson et al. 1995). Several species use these buffers including species that are not able to use pine habitats and can be preserved only due to the presence of SMSz (Thurmond and Miller 1994). Other species use SMZs temporarily after disturbance caused by harvesting (Cockle and Richardson 2003). At the landscape level these zones are important also in terms of movement of organisms within the network (Machtans et al. 1996, Burbrink et al. 1998). SMZs make the spread of organisms over more unsuitable habitats possible (e.g., gray squirrels in pine stands (Fischer and Holler 1991)).

One critical issue of SMZs is their width. These features were initially developed with hydrological purposes but became recognized as key elements of wildlife maintenance (Thurmond and Miller 1994, Dickson et al. 1995). References in the literature to buffer strip width vary according to biogeographic region, animal group studied, buffer composition, structure, management, contrast with surrounding units, time lag since harvesting, and position of stream in the watershed. Therefore, generalizations are difficult to make and to adopt in the study area.

Narrow SMZs can retain important components of animal communities after logging. Abundance of songbirds and small mammals in Georgia was not different among selectively harvested hardwood-dominated SMZs of different widths (15-18 m; 28-30 m; 49-53 m) (Thurmond and Miller 1994, Thurmond et al. 1995). Neotropical migrant songbirds were absent from SMZs of any width and were present in the control mature stands only. Some small mammals were found in the wide SMZ and control stand only. Buffers 30 m wide (one side) seem adequate for reducing short-term impacts of logging on small mammals in managed forest in British Columbia (Cockle and Richardson 2003). Vesely and McComb (2002) indicate that 20-m wide buffers on each side of streams can preserve a great percentage of several salamander species in Oregon. Buffers 15-23 m wide (one side) in Kentucky are able to maintain high richness including edge and some mature songbird species after clearcutting (Triquet et al. 1990). In Newfoundland, Canada, buffers 20-50m (one side) wide provide habitat for large bird communities and are essential in maintaining diversity in managed forests but additional actions are necessary to maintain interior bird species (Whitaker and Montevecchi 1999). Buffer strips in tributaries (20-40 m) and main channels (60-100 m, one side) in Maine have densities and richness comparable to reference areas (Meiklejohn and Hughes 1999). SMZs favor edge and short distance migrant species and retain low density and number of interior upland species. Buffers wider than 200 m around lakes are recommended for the conservation of forest songbirds in boreal forests (Hannnon et al. 2002).

In East Texas there is a positive relation between bird communities (breeding abundance and richness) and buffer width (Dickson et al. 1995). Narrow SMZs (15-25 m) are used by species associated with young pine stands and edge habitats whereas wide zones (50-95 m) were occupied by species associated with mature forest (Dickson et al. 1995). A minimum width of 30 m and a preferred width of 50 m are suggested to increase breeding birds in pine plantations. A similar minimum width, 30 m, is suggested by Rudolph and Dickson (1990) to maintain reptile and amphibian richness in managed pine stands. The highest density of downy woodpeckers in buffer zones in recently harvested pine stands was observed in intermediate and wide zones (30-40 and 50-95 m) (Dickson et al. 1995). Dickson and Huntley (1987) found abundant squirrels in buffers >50 m wide in east Texas. Smaller buffers (<25 m and 30-40 m) have null or very reduced observations. In Mississippi turkeys use SMZs of all sizes tested (30-45, 84-104, and 170-179 m) for traveling, roosting, feeding, loafing and summer cover (Burk et al. 1990).

In general SMZs are able to retain a large percentage of the local species after harvesting that otherwise would be lost to a great extent. SMZs decrease the short-term impacts of logging and allow later recolonization of the adjacent growing stands by late seral species refugees in the buffers (Cockle and Richardson 2003). There is a tendency of the buffers to maintain generalist and edge species and species associated with riparian environments. Some interior species are preserved as well in SMZs but others are excluded from relatively narrow SMZs.

Darveau et al. (2001) noticed that some species prefer large buffers with non-riparian conditions and others prefer narrow riparian buffers. Some species associated with mature conditions that require refuge after logging might not prefer riparian environments. This was also observed by Vesely and McComb (2002).

Crowding of SMZs following harvesting is a phenomenon potentially occurring in managed forests with implications for foraging and reproduction of wildlife (Hagan et al. 1996, Warkentin et al. 2003, Hanowski et al. 2003). The results of some studies on buffers might eventually be biased by this post-harvest effect (Lance and Phinney 2001).

In the study area, SMZs are usually of limited size, on average around 50 m, ranging from 30 to more than 250 m. The major bottomland is an exception where SMZs can be much wider. Although minimum width is difficult to define since it is species dependent (Spackman and Hughes 1995), according to the discussion above and the requirements of the species considered in this work, the SMZs width seems to be generally not limiting in terms of maintenance of the species associated with these habitats. The effects of the width of the SMZs, particularly in upper areas, on other species potentially using the buffers regularly or after logging are unknown.

Implications for Management

The SFI landscape is able to offer suitable habitat for species representing a wider range of habitat conditions than the Non-SFI scenario. Management at the stand and landscape levels can, however, improve some of the habitat components.

At the stand level, extension of rotation seems to be important in even-aged hardwood stands in the case of the barred owl. Ages above 70 years seem to be required for these stands to present high suitability for reproduction habitat (Figure 17). Extended rotations in pine stands improve the pine warbler's habitat.

Retention of large trees or snags after harvesting in pine and hardwood stands can increase suitability for downy woodpeckers and barred owls. Control of regeneration in hardwood stands after clearcutting and thinning in order to provide larger trees in more abundance can decrease the period of time necessary to reach suitable habitat for barred owls. Uneven-aged stands could also be improved by stand management. In hardwood and mixed stands the number of larger trees can be increased by changing target distributions and maximum size of trees to harvest, improving habitat for downy woodpeckers, barred owls, and fox and gray squirrels. If these measures are directed to mast producer trees habitat improvement can be important also for squirrels and turkeys. Other measures that seem to be important include management of herbaceous and shrub vegetation (American woodcock and turkey).

Some of these measures have been presented and discussed in the literature. Long rotations can be used to increase structural complexity in managed forests (Franklin et al. 1997). This measure was defended to increase breeding bird diversity in pine-oak forests in Virginia (Conner et al. 1979). Partial retention either in the form of dead or live isolated or clustered trees or both is an important measure for the maintenance of birds in forests (Dickson et al. 1983, Lindmeyer and Franklin 1997, Merrill et al. 1998, Lance and Phinney 2001). Retention is a central procedure in conservation of forest diversity (e.g. Hunter 1990, Franklin et al. 1997, Lindmeyer and Franklin 1997).

At the landscape level the only eventual concern created by SFI is related to pine warbler. A proper evaluation of the spatial characteristics of the habitat cannot be done while the sensitivity of the species to patch size and edges is not better understood. In the best case scenario pine warbler habitat is not limited by structure constraint in the SFI scenario. In the worst case scenario (30-ha minimum core area, isolated patches, edge sensitivity) pine warbler presents no habitat in the SFI scenario. Although unlikely, this scenario could be partially inverted by increasing clearcut size. This has been defended to reduce fragmentation (Hagan et al. 1997). However the effect of the presence of a high density of SMZs is probably more important in the creation of fragmentation and the measure would likely be useless. Alternatively, mature pine stands can be set apart in the landscape for breeding of these species. According to the literature, 30 ha should maintain a breeding population of the species. Some of the pine stands currently under selective management could have that role.

Barred owls require large unfragmented old-growth forest areas (Mazur and James 2000) although minimum habitat area is unknown (Allen 1987b). In the Pacific Northwest the species was considered as a generalist as opposed to an interior species (Hansen et al. 1992a). Additional to the recommendations done at the stand level it is important to consider aggregation of hardwood stands to create reasonable areas of suitable breeding habitat. Large bottomlands present eventually better conditions to manage barred owl habitat but any of the upper SMZs can be managed in that perspective as well. The increasing suitability of management type 4 by stand level management would make barred owl habitat based upon the network of SMZs.

Strategies for the conservation of some of the species considered here rely upon SMZs, namely fox squirrel (Alexandre 1994), gray squirrel (Fischer and Holler 1991), and turkey (Burk et al. 1990, Hurst and Dickson 1992). Literature also suggests that downy woodpeckers benefit from SMZs after clearcutting (Dickson et al. 1995).

Combination of the measures that SFI applies with additional measures for particular circumstances might create conditions for better achievement of biodiversity objectives in forest management. SMZs, retention, and long rotations in partial areas are likely to contribute to the maintenance of habitat for species of all habitat requirements because they combine the stand and landscape habitat structural features that seem more important for overall biodiversity. Additionally wildlife corridors (not considered in this work) provide an interesting tool to deal with in special cases at the landscape level.

Final Remarks

The ability of the species considered in this work to represent other species in the same guilds is limited. Although the general habitat requirements can eventually be represented for each of the species in spite of the internal heterogeneity of the clusters, particular requirements can make habitats of species in the same group divergent. Also, processes associated with each of the species in a cluster are particular to that species. Those include, home ranges, mobility, area- and edge-sensitivity, dispersal, predation, parasitism, etc. The inclusion of variables that account for additional parameters could improve the usefulness of the process of species selection in this context. However, as realized for the case of pine warblers, there is insufficient and often contradictory information in the literature to base such an approach.

The problem of species misrepresenting other species is one of the limitations of the use of indicator species (Lindenmayer et al. 2000). It cannot be guaranteed that habitat quality for a species is also quality for other species it indicates or represents (Niemi et al. 1997). The species selected here, however, were able to provide indication of stand and landscape structural elements, or combination of both, useful in evaluating effects of management, namely the application of SFI. Pine warbler is mainly associated with mature pine stands, barred owl with mature hardwood stands, downy woodpecker with snags and low basal area hardwood stands, American woodcock with high density of small plants (regeneration areas), fox and gray squirrel with large hard mast producers, and American beaver with riparian zones. Wild turkeys indicate elements already detected by other species, namely small plant cover and mast producers, but is a good example of the combination of these characteristics in the same area.

Pine warbler, in spite of uncertainty about its area- and edge- sensitivity in mature pine habitats, raises a series of issues related to the maintenance of species with these characteristics that is useful in the analysis of the habitat for other species associated with mature pine forest. Barred owl habitat also provides indication of spatial attributes of the mature hardwood stands. Squirrel habitat allows considerations on the configuration of the streamside management zones and the other species (American woodcock, turkey) account for the need to maintain areas with different structures in the vicinity. The use of these elements to support the analysis corresponds in part to the approach of Lindenmayer and Franklin (1997) and Lindenmayer et al. (2000) that consider more important stand and landscape structure-based indicators including structural complexity, plant composition, connectivity and heterogeneity than indicator species whose relationships with diversity are still unknown (Lindenmayer et al. 2000).

The general issue this work tries to address is whether managed forested landscapes are able to maintain biodiverstity. Based upon simulation of stand and landscape structural elements, this work provides indications that landscapes managed according to the SFI program present better conditions to maintain diversity than the Non-SFI scenario. The conditions seem also to indicate the possibility of maintaining large populations of those species.

As for the specific objective of this work, SFI provides a group of measures that clearly benefits biodiversity in managed landscapes. The species selected indicate that there is more diversity of habitat conditions in the area and that the habitat landscape structure is not limiting for these species. Diversity and evenness of habitats is an important characteristic of the SFI landscape. The composition of the landscape can be considered, however, still insufficient in a perspective of maintenance of biodiversity. The major covers missing in this landscape are mature pine and hardwood stands. These stands are known for the richness and abundance they retain and provide particular habitat for species that are exclusively associated with these environments such as red-cockaded woodpecker (*Picoides borealis*) and brown-headed nuthatch (*Sitta pusilla*) in pine stands and prothonotary warbler (*Protonotaria citrea*) and Swainson's warbler

(*Limnothlypis swainsonii*) in hardwoods (Conner and Dickson 1997). These types of species can however be maintained by landscape and stand management that should be an important complement to the SFI program.

Most of the selected species seem to benefit from the implementation of SMZs in the area, particularly the species that find no suitable habitat in the alternative scenario. However, SMZs, combined with other measures simulated here, increase fragmentation of the pine cover. Species dependent on large blocks of pine habitats of older ages might be constrained by this effect. The corresponding increase in edges in the landscape could increase edge-related processes, namely nest predation and parasitism (Conner and Dickson 1997). Edge processes are landscape context dependent (Donovan et al. 1997) and the fact that the matrix in this landscape is forest and that SMZs are comprised of permanent forested areas might reduce this negative aspect.

Given the importance and extension of forests managed by forest products companies committed to the SFI in the South, this program can have an important role in the conservation of diversity at the local and broader scales. This is particularly relevant by the fact that only a small proportion of forest habitats in the region are under any conservation status.

CHAPTER V

EFFECTS OF LANDSCAPE LEVEL MEASURES OF THE SUSTAINABLE FORESTRY INITIATIVE ON HYDROLOGICAL PROCESSES

Introduction

Forest activities are able to affect soil loss and water quality and supply by interfering with physical, chemical and biological processes at the site and watershed scales. In the south, harvesting and site preparation methods used in intensive silviculture of pine species can increase stormflow and sediment loss (Beasley et al. 1986, Marion and Ursic 1993). The removal of forest biomass by harvesting reduces interception and evaporatraspiration by the canopies of the trees, increasing potential runoff (Chang et al. 1982, Ursic 1991a). Harvesting alone does not increase sediment concentration (Ursic 1986, Mcclurkin et al. 1987) but compaction and soil exposure during extraction can affect runoff and sediment yield by changes in soil structure.

Sediment yield is usually related to the proportion of mineral soil exposed in operations (Ursic 1986, Blackburn et al. 1986) which increases potential degradation and transport by erosion agents. For this reason site preparation has in many cases a strong effect on water yield and sediment loss, although variable according to the techniques used (Beasley and Granillo 1983, Ursic 1986, Blackburn et al. 1990).

All the effects mentioned have usually a duration of a small number of years (Beasley and Granillo 1988, Marion and Ursic 1993). The major and more permanent source of erosion in forest related activities are, however, forest roads that can account for up to 90% of all the sediment produced in forestlands (Grace 2002). As a result of forest activities site productivity might decrease and sediment pollution and loadings, as well as flow volume and regularity, might affect aquatic communities and humans (Sidle 1990).

Environmental concerns have lead to the implementation of measures to minimize impacts of forestry on water, particularly non-point source pollution. After the enactment of the Federal Water Pollution Control Act Amendments of 1972 and the amendments of 1977 and 1987, states developed enforceable or voluntary Best Management Practices (BMP) programs to be applied in forestry (Ice et al. 1997). More recently, forestry sustainability programs assumed water and soil as essential criteria of sustainable forestry (e.g. Montréal Process Working Group 1999 and Ministerial Conference On The Protection Of Forests In Europe 2003).

Industrial forestry in the US is currently following the Sustainable Forestry Initiative (SFI), the sustainability program of the American Forest and Paper Association (AF&PA 2003). The SFI program includes measures relevant at the landscape level such as limitation in size of harvest units, establishment of wildlife corridors, establishment of Streamside Management Zones (SMZs), and application of adjacency rules. In East Texas, landscape pattern in intensively managed forests is being changed by the implementation of the SFI program (Chapter II). These changes can be summarized as an increase in buffer zones that follow a configuration of the streams' network and as an increase in the fragmentation of upland pine stands resulting from the intrusion of SMZs and from the constraints imposed by the green up interval and limits on harvesting areas (see Chapter II for details).

The aim of this work is to analyze the effects of the SFI program on the hydrology of forested watersheds. The specific objective is to analyze the effects of changes in landscape pattern as determined by the SFI program on water and sediment yield in an intensively managed forested watershed in East Texas. It is hypothesized that changes in landscape structure have implications in terms of hydrological processes in the watershed. SMZs have shown to affect water and sediment transport and yield after harvesting and site preparation (Wynn et al. 2000). Fragmentation creates heterogeneity in the landscape decreasing the percentage of watershed or catchment area harvested simultaneously thus potentially reducing extreme water and sediment yields.

Methodology

The APEX Model

The Agriculture Policy/Environment eXtender (APEX) model (Williams et al. 2000), version 1310, was used in this work to model and simulate the hydrology of forested watersheds and to analyze the effects of landscape pattern on hydrological processes, namely runoff and erosion.

APEX is a mechanistic model that combines the Environmental Policy Integrated Climate (EPIC) model (Williams 1995) with routing capabilities allowing the analysis of processes occurring simultaneously at the field and watershed levels. The main purpose of APEX is to estimate long-term sediment, nutrient, and pesticide yields from whole farms and small watersheds (Williams et al. 2000).

EPIC, initially Erosion-Productivity Impact Calculator and later Environmental Policy Integrated Climate (Williams et al. 1998), was developed to determine the relationship between soil erosion and productivity (Williams et al. 1984). Its growing capabilities made it a powerful tool in the analysis of the effects of management strategies on production and soil and water resources at the field scale (Williams 1995). The model currently includes a series of components to simulate soil, plant, weather, and management processes at the field scale, namely weather, hydrology, erosion, nutrient cycling, pesticide fate, soil temperature, tillage, crop growth, crop and soil management, and economics (Williams 1990). It has been used widely in the most diverse applications in the US and other countries (Williams 1995, Williams et al. 1998).

EPIC assumes the land unit to be spatially homogeneous (Williams et al. 1984). APEX extends the scale of the model from the field to the whole farm or small watershed scale by allowing heterogeneity of fields and their spatial arrangement to be taken into account and by integrating routing components for water, sediment, nutrients, and pesticides (Williams et al. 2000). These routing components are able to simulate landscape processes, namely sediment transport, deposition, channel degradation, and lateral subsurface flow (Williams et al. 1998).

Although APEX was developed to compare management alternatives in agriculture, it has recently been modified to describe adequately hydrological processes in forested areas (Saleh 2003). Modifications were made in the canopy interception, litter, subsurface flow, and nutrient movement and enrichment ratios components (Saleh 2003). Additionally, APEX is able to account for the effects of buffer strips on water and sediment (Saleh 2003) which is of the maximum relevance in forestry since buffers along streams are one of the major measures in programs of sustainability.

Study Area

This study was conducted in part of a watershed of the Shawanee Creek, Neches River located in Angelina County, Texas, USA. This area has been studied in terms of landscape pattern resulting from the application of the SFI program and their consequences in terms of vertebrates' habitat suitability (see chapter III and IV). From this larger area, an 1190-ha watershed was chosen for the analysis of hydrological processes. Soils are mainly Alfisols of the Diboll and Alazan series and Ultisols of the Rosenwall series (Table 41). Slopes are usually gentle, 2% on average, maximum 7%.

Table 41. Soil series distribution in the study area.

Soil series	Area (ha)	 (%)
DIBOLL	493.8	41.5
ALAZAN	229.2	19.3
ROSENWALL	206.3	17.3
KELTYS	93.7	7.9
RAYLAKE	71.3	6.0
HERTY	60.9	5.1
KOURY	14.1	1.2
MOSWELL	10.3	0.9
KURTH	9.8	0.8

Landscape Simulation

The dynamics of the landscape structure was simulated with HARVEST 6.0 model (Gustafson and Crow 1999). One scenario (SFI scenario) was established based upon the application of SFI landscape measures, namely SMZs ≥ 30 m wide along perennial and intermittent streams, a 49-ha limit in harvest unit size in pine stands and a three-year green-up interval. For comparison purposes a reference scenario (Non-SFI scenario) was established in the absence of these rules. The detailed description of the methods followed in the landscape simulation is presented in Chapter III.

Watershed Discretization

The Watershed Delineation module of SWAT 2000, ArcView interface (Di Luzio et al. 2002) was used in the delineation of subareas based upon 30-m resolution digital elevation model (DEM) data (USGS). The minimum size of sub-basins chosen was 14 ha. The larger sub-basins created in spite of this constraint were manually subdivided to reduce soil and stand variability within subareas and to minimize the effect of the measurement of channel length that occurs in subareas larger than 20 ha in size. GIS coverages created in the process of delineation provide part of the data to be used in the preparation of the subareas files.

In each sub-basin defined previously additional discretization was done to account for the presence of different forest stands and buffer zones. Each of these units constitutes of a subarea for modeling purposes. Subareas smaller than 2 ha were excluded, unless they were buffer strips.

For each of the scenarios routing was schematized in a diagram based upon SWAT sub-basin coverages and stand maps outputted from HARVEST. Each entering subarea was quantified in terms of area (ha), channel length (km), channel slope (m/m), reach channel length (km), reach channel slope (when present) (m/m), average upland slope (m/m), and upland slope length (m). Receiving subarea, operation schedule file, and soil file were also associated to each entering subarea. Subareas files (sub-files) were built using an application developed by J.R. Williams (Texas A&M Blackland Research and Extension Center, Temple, TX, personal communication).

Soils series for the study area were obtained from a SSURGO digital map for Angelina County (Soil Survey Geographic Data Base, USDA - Natural Resources Conservation Service). Files with data for these series were provided by the Blackland Research Center, Temple, TX.

Operation Schedules

Each stand was managed by particular operation schedules according to composition and age. Operation schedule files intended to describe as accurately as possible the stand development along time, the management followed in the stands, and synchronize the stand dynamics in APEX with stand and landscape dynamics simulated in HARVEST. In this study four possible management types were followed: pine-clearcutting, pine-selection, hardwood-selection, and pine-hardwood-selection (Chapter III).

For pine-clearcutting, plantation and harvesting year for each stand were defined according to the sequence of clearcuttings in the landscape dynamics component (HARVEST). Since the rotation time is 30 years and the landscape dynamics model works on a two-year time step, 15 different operation schedule management plans were defined, one for each possible year of harvesting/planting. These files include plantation of 950 trees/ha, thinning to 450 trees/ha at age 15, and harvesting and kill at age 30. Plantation is preceded of an offset disk soil operation to simulate perturbation due to site preparation. Harvesting occurs in April, offset disk operation in October, and planting in December of the same year.

Hardwood stands are represented by sweetgum and mixed pine-hardwood stands are represented by a mixture of pine and sweetgum. These stands are considered not managed in terms of APEX and maintain a constant density of 450 trees/ha during the period of simulations.

Evaluation of the Model

In the absence of real data for the study area, the model could not go through a validation process as is usually performed in this kind of approach. Considering the fact that the main purpose of the use of APEX is to compare management scenarios it was considered acceptable to use the model without such validation and eventual calibration. Parameterization of the model for forest conditions in East Texas has been done by J.R. Williams (Texas A&M Blackland Research and Extension Center, Temple, personal communication) and A. Saleh (Texas Institute for Applied Environment Research, Stephenville, Texas) with data from the Alto Watersheds, Texas (Saleh 2003). Evaluation of the model for the study area was done in controlled subareas by submitting the model to different magnitudes and combinations of parameter values including soil series, crop type, initial density, thinning intensity, age to maturity, fraction of floodplain flow–partitions flow thru, and slope, among others. Different subarea delineations were also analyzed to evaluate the role of discretization on the processes simulated including the effect of buffer strips on runoff and sediment loss. Key parameters used as indicators of the model performance include runoff, sediment yield, percolation, deposition, degradation, crop biomass, leaf area index (LAI), and evapotranspiration. Published data were used in the evaluation of the model, namely from Pope and Graney (1979), Hebert and Jack (1997), Baldwin et al. (2000), and Gresham and Williams (2002) for biomass and LAI, and several works on sediment and runoff in forested catchments, especially in East Texas (e.g. Yoho 1980, Ursic 1986, Blackburn et al. 1990).

Simulations

Three simulations for each scenario (SFI and Non-SFI) were performed using different IGN (number of times random number generator cycles before simulations) to create variability of weather conditions. Results were obtained for a period of 30 years corresponding to a cycle in the landscape dynamics of the study area (see chapter III). Simulations were started 30 years before the 30-yr period of interest to allow crop growth and stabilization of the system. Weather data were generated by APEX based upon parameters for Lufkin, Texas.

Results and Discussion

Runoff and sediment loss observed during the simulations (Table 42) are generally reduced. These values are within the range of values observed in forested watersheds in East Texas and other areas in the south (Yoho 1980, Blackburn et al. 1986, Ursic 1986, Ursic 1991b) in spite of variation due to slope, soil, geology, land use history, and precipitation conditions of the areas where published data were collected. Runoff and sediment yield here are higher than measured values in non-disturbed pine catchments which should be expected since harvesting and, particularly, site preparation are part of the management of the simulated pine stands. These values are lower than published results for many managed stands which is also expected since measurements in the literature refer to a reduced number of years after the application of forest practices and the values here are averages for a period of 30 years. Other reasons that might explain these differences are the lower annual mean precipitation and nearly level slopes in the study area.

Table 42. Average annual precipitation, water and sediment yield in three APEX simulations for the study watershed.

Simulation	Precipitation (mm)	QSS (mm)	QSW (mm)	QTS (mm)	QTW (mm)	YS (t/ha)	YW (t/ha)
SFI							
1	1093.9	23.15	22.75	30.51	30.03	0.09	0.17
2	1056.0	17.97	17.62	23.21	22.78	0.08	0.16
3	1074.2	20.81	20.43	27.21	26.74	0.09	0.16
Average	1074.7	20.64	20.27	26.98	26.52	0.09	0.16
Non-SFI							
1	1093.9	23.10	22.90	30.27	30.00	0.09	0.42
2	1056.0	17.84	17.67	23.11	22.87	0.07	0.34
3	1074.2	20.80	20.62	27.15	26.89	0.09	0.38
Average	1074.7	20.58	20.40	26.84	26.59	0.08	0.38

QSS-average subarea surface water yield; QSW- average surface water yield; QTS-average subarea water yield; QTW- average water yield; YS-average subarea sediment yield; YW- average sediment yield.

SFI and Non-SFI management produce the same amount of runoff at the subarea and watershed levels (Table 42). In the SFI scenario runoff and sediment loss are lower in the buffer strips comprised of hardwoods than in the upper areas comprised of pine under the clearcutting system (Table 43). Slope is the major factor explaining these differences. Two stands with continuous pine cover show the highest average runoff and sediment. These variables should be similar to undisturbed pine stands (Beasley and Granillo 1988). The Non-SFI scenario is comprised of pine stands managed by the clearcut system and the two stands managed by selection system.

Table 43. Area, average slope, water, and sediment yield per forest type in the SFI scenario.

			QS (mm)				YS (t/ha)			
	Area (%)	Slope (%)	run 1	run 2	run 3	average	run 1	run 2	run 3	average
Pine-clearcut	75.4	2.2	23.23	18.00	20.90	20.71	0.08	0.06	0.08	0.07
Hardwood	10.8	1.2	17.50	13.78	15.89	15.72	0.03	0.03	0.03	0.03
Pine-selection	0.6	1.8	29.98	23.00	26.42	26.47	2.98	2.88	2.90	2.92
Pine-hardwood	13.2	1.5	26.99	20.97	24.10	24.02	0.05	0.05	0.04	0.05

QS-average subarea water yield; YS-average subarea sediment yield

The Non-SFI scenario shows considerably more sediment yield than the SFI scenario (Table 42). At the subarea level, however, it is approximately the same in both landscapes. The difference in watershed sediment yield results from the routing processes, mainly channel degradation. Sediment deposition occurs as well but it is very similar between landscape scenarios. The weight of the sediment retained by this process in the overall area of study is discrete even in the scenario presenting buffer strips. On average, deposition is around 0.01 t/ha at the watershed level. Maximum average deposition in a route was 0.2 t/ha. In the Non-SFI scenario buffers were used in particular cases whenever this type of discretization fitted better the arrangement of forest stands in the watershed which explains in part the similarities in deposition between watersheds. The main reason for the small differences observed, however, is the fact that sediment loss is usually very low due to the nearly level slopes in the area. Deposition is visible only during intense storm events when sediment yield is high. This fact indicates that buffers even in areas of gentle slopes might be important in reducing non-point source pollution during periods of intense precipitation which although infrequent occurred within the 30-yr period of simulations. Buffer zones are able to retain considerable amounts of sediment produced by forest activities and are recommended measures to maintain water quality in managed forested areas (Wynn et al. 2000, Carling et al. 2001)

Channel degradation is common in both scenarios. It is, however, higher in the Non-SFI scenario reaching annual average values of approximately 0.3 t/ha (0.08 t/ha in the SFI scenario). Higher channel degradation is responsible for the differences in watershed sediment yield between the two landscapes. Channel degradation occurs in higher extent in the Non-SFI scenario that presents fewer buffer zones and less fragmentation than the SFI and this landscape. As deposition, degradation occurs mostly in periods of intense precipitation. Channel degradation is often referred to in the literature as a major cause of erosion in forested watersheds (Ursic 1986, Ursic 1991b, Marion and Ursic 1993). Studies on erosion often use small catchments to avoid channel erosion and account for forestland erosion only (Ursic 1986).

Within the 30-yr period of simulations, water and sediment yield are very irregular and average annual precipitation seems not to have a very strong relation with annual yields (Figure 21 and Figure 22). Monthly precipitation is better related with yields although it cannot explain entirely differences between months (Figure 23). Daily precipitation has a strong influence on both annual and monthly results. Maximum values per simulation are more frequent in February and November. However high daily precipitation values in February are usually responsible for high runoff and erosion that can represent up to 90 and 95% of yearly runoff and sediment loss, respectively. Values in November are corresponded by small runoff and sediment yield. This is probably due to the higher frequency of previous rain days that keep soil moisture high and make soil saturation reached more quickly, increasing runoff and consequently erosion. Very low annual runoff and erosion values are usually produced in a single storm event. Blackburn et al. (1986) also observed that intense storms in East Texas have a very high weight in the annual water and sediment yield.

The effects of harvesting and site preparation on hydrological processes are not easily observed in the results. The fact that there are stands being harvested continuously in the watershed combined with the irregularity in the distribution of precipitation, soil moisture, plant biomass growth, and the nearly level slope, make these effects unclear in the results. Runoff and sediment increase considerably in the second and third years following major harvestings (Figure 24). These periods coincide, however, with years with either high annual or very high daily precipitation values and whether this pattern is due to rainfall or harvestings is unknown. Possibly both factors play a role in the processes. Concentration of precipitation and exposed soils after harvesting and site preparation make runoff and erosion increase considerably even in nearly level terrain. The role of each is, however, unknown.

The results of this study synthesize a series of processes and their interactions occurring simultaneously at the stand and landscape levels. The fact that the watershed is comprised of many stands in many growth stages, soil conditions, and positions in the watershed combined with irregular weather conditions make the results difficult to interpret. Although subarea processes can be compared with published data, the overall results cannot since references of work done in similar conditions it is not of our knowledge.

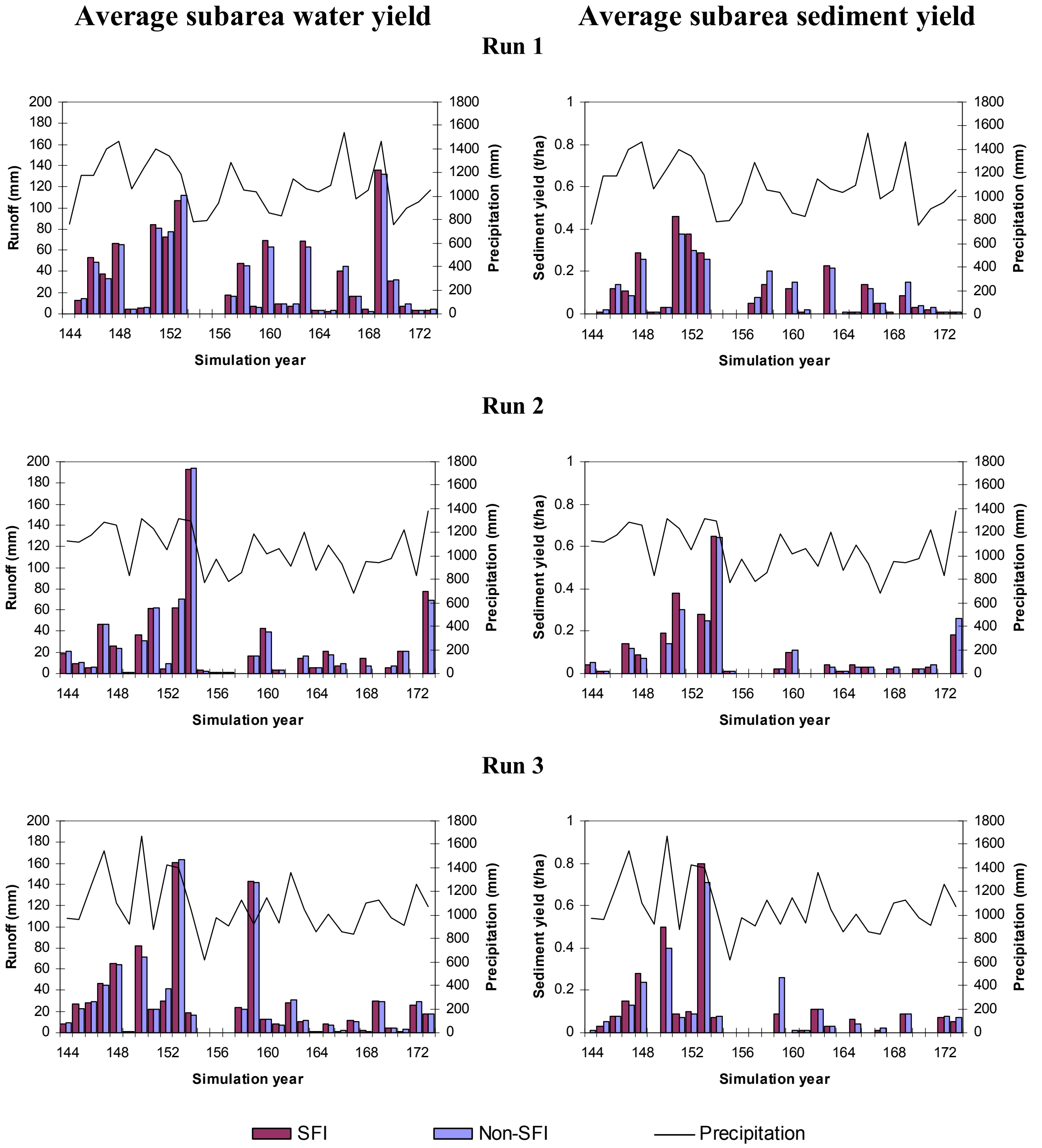
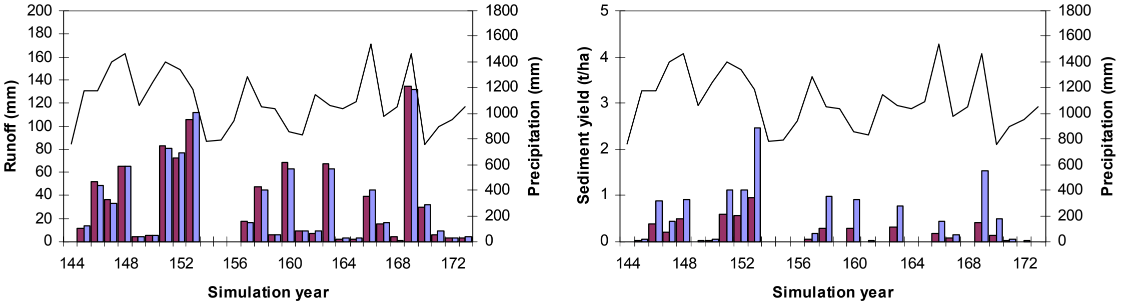


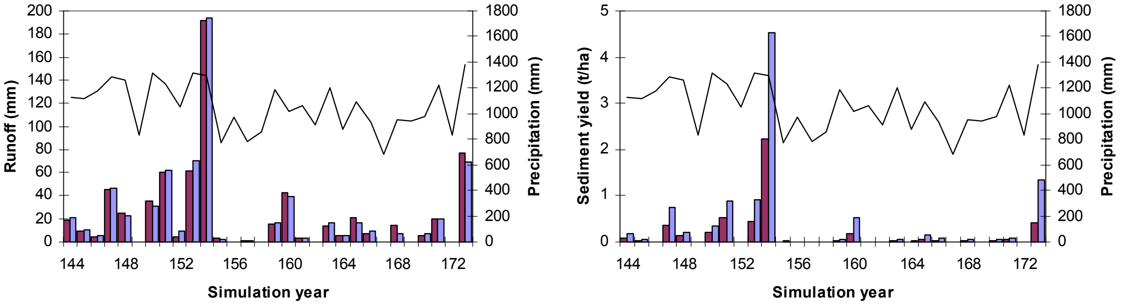
Figure 21. Average annual subarea water and sediment yield along the 30-yr period of observations.

Water yield **Sediment yield**

Run 1



Run 2



Run 3

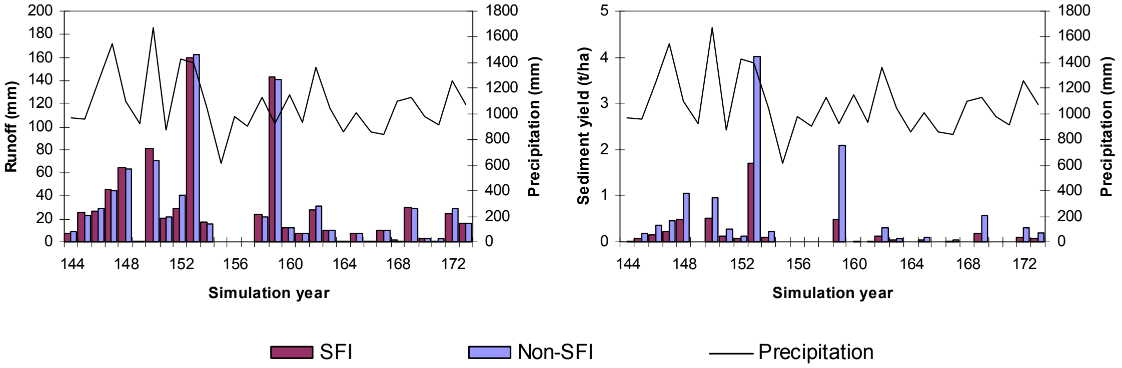


Figure 22. Average annual watershed water and sediment yield along the 30-yr period of observations.

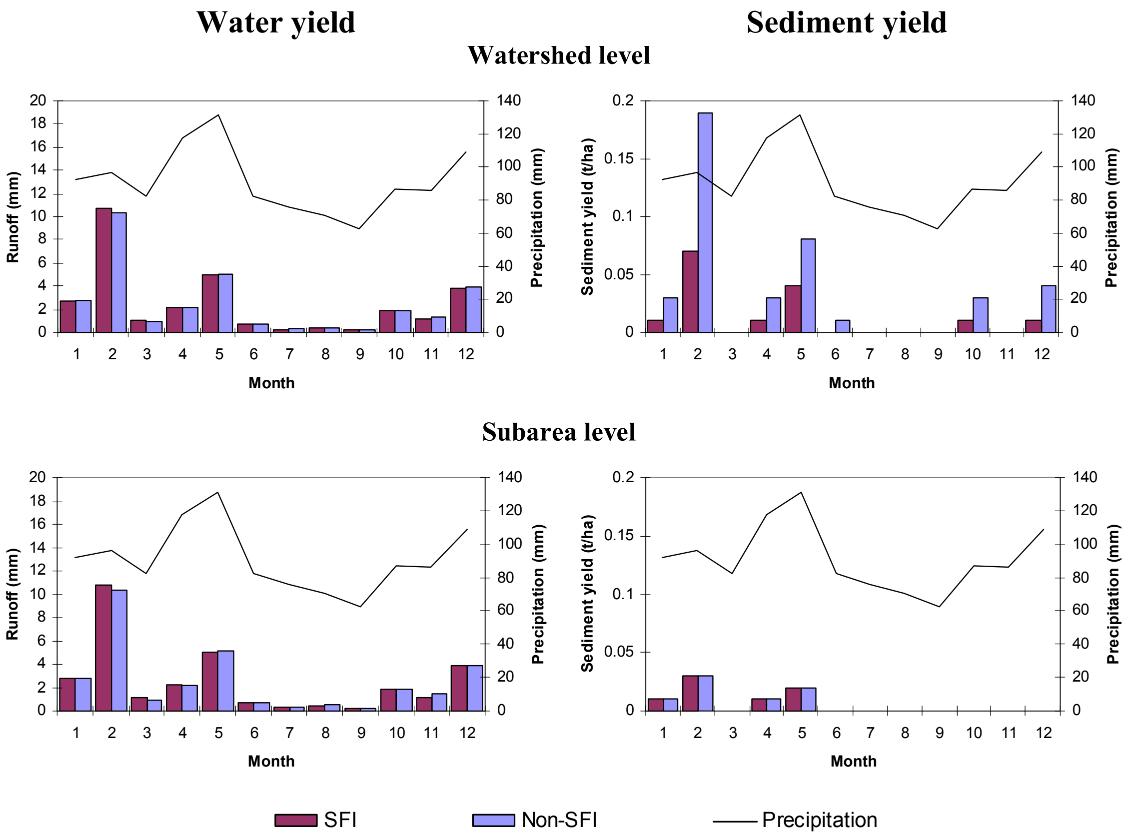


Figure 23. Average monthly watershed and subarea water and sediment yield for the 30-yr period of observations for simulation 1.

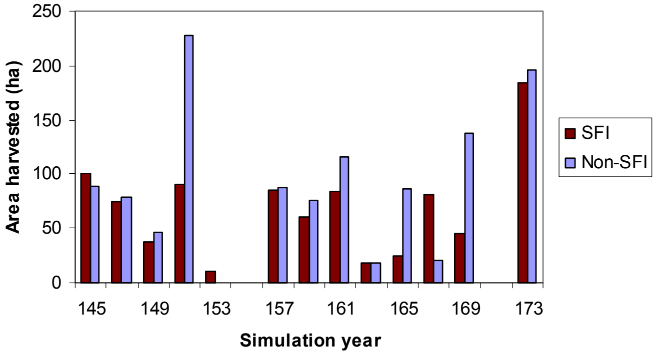


Figure 24. Area harvested in the study area during the simulation period for SFI and Non-SFI scenarios.

Summary

The results obtained at the subarea level are generally within expected values for forested watersheds in East Texas under the same conditions. Water and sediment yields are generally reduced in the study area and most of the runoff and erosion observed in this study area occurred during intense storm events. Although water and sediment yield at the subarea scale are similar between scenarios, Non-SFI presents higher watershed sediment yield than the SFI scenario, due to higher channel erosion. Measures implemented in the context of the SFI program seem to have a considerable effect on the reduction in watershed sediment loss mainly due to their effect on the reduction in channel erosion. The effect of buffer zones in terms of sediment deposition was not different between scenarios. SFI measures, including buffer zones, however, seem important in the reduction of channel degradation during major storm events. The effects of management practices, namely harvesting and site preparation, are confounded with the effects of intense precipitation. Hydrological processes at the landscape scale are more difficult to interpret than at the catchment level and additional research needs to be conducted to increase current knowledge of these processes.

Recent developments in APEX made the model suitable to the analysis of the effects of management on forest hydrology. Further application of the model at that scale in East Texas can contribute positively to the evaluation of sustainability of forests in this and other regions.

CHAPTER VI

CONCLUSIONS

This study indicates that the Sustainable Forestry Initiative program influences the structure of intensively managed forested landscapes in East Texas. It indicates also that the structural changes induced by this program affect functional aspects of the landscape, namely the selected physical and biological processes analyzed. Finally, it indicates that SFI contributes to the sustainability of these landscapes.

The comparison of landscapes with different management histories made in Chapter II revealed that management has a strong influence on landscape structure. Either the descriptive analysis based upon landscape metrics for two different stand classifications or the statistical analyses performed at two scales indicated that there are differences in terms of structure among landscapes. The landscape managed according to the SFI program presents on average more and smaller patches, more edges, more complex shapes, less and smaller core areas, and shorter distances among patches. The landscapes managed by extensive management and by traditional intensive management are comparable since both are comprised of larger blocks of forest of the same type showing high aggregation and connectivity. The similarity between these two landscapes could be even stronger if some of the portions of the area managed by intensive management had not been submitted to the SFI program recently. Streamside Management Zones (SMZ) play the major role in explaining the differences between SFI and the other landscapes These narrow and elongated elements break the large blocks of pine forest into smaller units increasing the number of patches, decreasing their size, and simultaneously increasing edge length.

The changes induced by the SFI program can also be described as an increase of fragmentation. The fragmentation created by the SFI program is strongly determined by the establishment of SMZs. Fragmentation of the same type has been associated with sustainable management of forested landscapes (Hagan and Boone 1997, Cissel et al. 1998) particularly with the establishment of narrow elements in the landscape.

The changes observed in structure affect habitats of vertebrate species when compared between a sustainable and a non-sustainable scenario (Chapter IV). Habitat suitability index values at the landscape level are higher in the landscape managed by the SFI principles for American woodcock, American beaver, wild turkey, fox squirrel, and gray squirrel. For the last three species HSI is close to zero in the Non-SFI scenario. HSI is higher for pine warbler in the landscape not managed according to the SFI program. Downy woodpecker and barred owl present very reduced HSI values in either landscape.

The major effects that the SFI program induced on the spatial pattern of habitats are fragmentation and establishment of narrow and elongated habitats in a network structure corresponding to the SMZs. The first effect is observed for pine warbler and the second for American woodcock, fox and gray squirrel, and wild turkey and for the less suitable habitat of downy woodpecker and barred owl.

Increasing fragmentation of the most suitable habitat for pine warbler in the SFI scenario is reflected by higher number of patches and extension of edges and lower patch size, core area size, and core area relative to the non-sustainable scenario. This fragmentation is caused mainly by SMZs that dissect existing pine stands. Considering the composition and permanent character of these features, the forested landscape context in which the suitable habitat is included, and the behavior of the species it is unlikely that pine warblers can be strongly affected by this type of fragmentation.

Fox and gray squirrels, American woodcock, and American beaver all benefit from the establishment of SMZs. These buffers present high habitat suitability values for these species and the spatial configuration associated with the SMZ does not affect negatively any of these species. On the contrary, it can make possible their existence in the generality of the landscape and increase the possibility of exploring multiple habitats. Barred owl and downy woodpecker find only very reduced and fragmented areas of suitable habitat in any of the landscape scenarios.

The species selected for this dissertation were able to provide indication of stand and landscape structural elements, or combination of both, useful in evaluating effects of management, namely the application of SFI on their habitats. Pine warbler is mainly associated with mature pine stands, barred owl with mature hardwood stands, downy woodpecker with snags and low basal area hardwood stands, American woodcock with high density of small plants (regeneration areas), fox and gray squirrel with large hard mast producers, and American beaver with riparian zones. Wild turkeys indicate elements already detected by other species, namely small plant cover and mast producers, but is a good example of the combination of these characteristics in the same area. Pine warbler, in spite of uncertainty about its area- and edge- sensitivity in mature pine habitats, raises a series of issues related to the maintenance of species with these characteristics that can be useful in the analysis of the habitat for other mature pine forest species. Barred owl habitat also indicates spatial attributes of the mature hardwood stands. Squirrel habitat allows considerations on the configuration of the SMZs and American woodcock and turkey account for the need to maintain areas with different structures in the vicinity of each other.

This work indicates that SFI management clearly benefits biodiversity in managed landscapes. The species considered in this work indicate that there is more diversity of habitat conditions in the area when managed by the SFI program and that the landscape structure of the habitat is not limiting for most of these species. The conditions created seem to indicate also the possibility of maintaining large populations of many species. The composition of the landscape can be considered, however, still insufficient in a larger perspective of maintenance of biodiversity. The major covers missing in this landscape are mature pine and hardwood stands. These stands are known for the richness and abundance they retain and provide particular habitat for species that are exclusively associated with these environments. These species could however be maintained with the combination of the SFI measures with particular landscape and stand management decisions, including extended rotations and partial retention of dead or live, isolated or clustered, trees that could be an important complement to the SFI program.

The results of the simulation of hydrological processes (Chapter V) indicated that water and sediment yields are generally reduced in the study area and most of the runoff and erosion observed occurred during intense storm events. Although water and sediment yields at the subarea scale are similar between scenarios, the non-sustainable scenario presents higher watershed sediment yield due to channel erosion. Measures implemented in the context of the SFI program seem to have a considerable effect on the reduction in watershed sediment loss mainly due to their effect in the reduction in channel erosion. The effect of buffer zones in terms of sediment deposition was not different between scenarios what was attributed to the nearly level slopes of the area. SFI measures, including buffer zones, however, seem important in the reduction of channel degradation during major storm events. The effects of management practices are confounded with the effects of intense precipitation. Hydrological processes at the landscape scale are more difficult to interpret than at the catchment level and additional research needs to be conducted to increase current knowledge of these processes.

The methodology developed for this research (Chapter III) seems to be useful in comparing effects of management practices on the landscape patterns and processes in intensively managed forested landscapes in East Texas. It is relatively simple to implement, relies on models that require minimal data to work, and provides results helpful in the evaluation of management alternatives. Since it considers ecological processes, it is useful in linking pattern with process, a major component of ecology. The methodology is an open methodology in the sense that allows other aspects to be considered simultaneously to those explored in this work.

Based upon the results of this work, the concept of sustainable forestry followed and the criteria and indicators of sustainability considered, this work indicates that SFI improves the sustainability of intensively managed forested landscapes in East Texas. Additional measures as discussed in Chapter IV will make the landscapes more sustainable. Increase of habitat diversity and evenness, suitability, and the spatial structure of the habitats improve the conditions to support more and larger populations of vertebrate species. On the other hand sediment loss decreases at the landscape level due to the implementation of the SFI program.

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APPENDIX 1

DESCRIPTIVE STATISTICS FOR THE LANDSCAPE METRICS QUANTIFIED AT THE LARGE WATERSHED LEVEL BY STUDY AREA

Variable	Landsc	N	Mean	Median	StDev	SE Mean	Minimum	Maximum
TA	1	11	163.5	161.4	39.8	12.0	100.6	229.7
	2	14	162.7	151.6	52.9	14.1	91.8	248.1
	3	10	149.1	141.8	35.9	11.3	104.3	234.6
LPI	1	11	36.36	36.74	11.55	3.48	22.54	53.18
	2	14	52.46	42.66	25.49	6.81	21.39	88.13
	3	10	70.43	73.83	19.33	6.11	37.08	94.77
NP	1	11	17.27	15.00	8.53	2.57	8.00	39.00
	2	14	13.36	14.50	4.11	1.10	8.00	20.00
	3	10	6.100	6.000	1.370	0.433	4.000	8.000
PD	1	11	10.41	9.00	3.55	1.07	6.88	19.10
	2	14	8.729	8.295	3.301	0.882	4.560	17.430
	3	10	4.179	4.340	0.889	0.281	2.850	5.380
MPS	1	11	10.452	11.110	2.864	0.864	5.230	14.540
	2	14	12.83	12.05	4.34	1.16	5.74	21.95
	3	10	25.04	23.07	5.94	1.88	18.60	35.07
TE	1	11	16965	15840	5238	1579	9490	28150
	2	14	9779	7870	5091	1361	3240	20070
	3	10	2912	2565	1450	459	1320	5860
ED	1	11	104.12	103.31	18.72	5.64	61.75	130.41
	2	14	58.11	60.25	18.69	4.99	29.84	92.76
	3	10	19.35	17.16	7.94	2.51	8.53	33.11
LSI	1	11	5.110	5.020	0.939	0.283	3.720	6.760
	2	14	3.694	3.480	0.746	0.199	2.610	5.130
	3	10	3.182	3.015	1.007	0.318	1.980	5.020
MSI	1	11	2.1545	2.1200	0.1897	0.0572	1.8600	2.4000
	2	14	1.9457	1.8800	0.2473	0.0661	1.5500	2.4500
	3	10	1.8390	1.8750	0.1949	0.0616	1.6100	2.2100
AWMSI	1	11	3.284	3.250	0.593	0.179	2.280	4.230
	2	14	2.276	2.205	0.628	0.168	1.530	3.660
	3	10	2.260	2.075	0.853	0.270	1.470	4.380
DFLD	1	11	1.3418	1.3200	0.0979	0.0295	1.2000	1.5400
	2	14	1.1993	1.1900	0.0775	0.0207	1.0800	1.3500
	3	10	1.1490	1.1100	0.1226	0.0388	1.0500	1.4500
MPFD	1	11	1.1273	1.1200	0.0142	0.0043	1.1100	1.1500
	2	14	1.1179	1.1150	0.0197	0.0053	1.0800	1.1500
	3	10	1.1070	1.1100	0.0189	0.0060	1.0800	1.1400
AWMPFD	1	11	1.1736	1.1700	0.0254	0.0077	1.1300	1.2100
	2	14	1.1193	1.1200	0.0356	0.0095	1.0700	1.1900
	3	10	1.1120	1.1050	0.0447	0.0141	1.0600	1.2100
TCA	1	11	17.94	18.71	14.27	4.30	4.22	56.39
	2	14	48.16	45.83	19.71	5.27	21.44	87.76
	3	10	57.45	57.34	26.55	8.40	24.52	121.19
NCA	1	11	7.545	7.000	2.162	0.652	4.000	11.000
	2	14	5.857	5.000	3.416	0.913	1.000	12.000
	3	10	4.200	3.000	2.616	0.827	2.000	9.000
CAD	1	11	4.692	4.790	1.103	0.333	2.560	6.320
	2	14	3.449	3.135	1.398	0.374	0.920	5.700
	3	10	2.821	2.115	1.534	0.485	0.850	5.090
MCA1	1	11	1.185	1.110	1.036	0.312	0.280	4.030
	2	14	4.022	3.680	2.252	0.602	1.340	9.750
	3	10	9.66	8.66	4.22	1.34	4.27	17.31

Variable	Landsc	N	Mean	Median	StDev	SE Mean	Minimum	Maximum
MCA2	1	11	2.624	1.900	2.073	0.625	0.600	7.050
	2	14	12.63	9.62	12.42	3.32	2.85	49.47
	3	10	20.97	19.11	17.59	5.56	3.50	60.60
TCAI	1	11	10.67	9.53	6.92	2.09	3.17	27.70
	2	14	30.31	27.26	10.05	2.69	15.80	45.85
	3	10	38.35	38.77	12.39	3.92	15.85	54.13
MCAI	1	11	2.675	2.760	1.348	0.406	0.860	4.920
	2	14	6.229	6.305	1.953	0.522	1.760	9.580
	3	10	13.04	13.77	5.08	1.61	3.35	18.19
MNN	1	11	90.5	84.9	35.8	10.8	44.6	163.8
	2	14	201.3	165.9	135.2	36.1	76.4	512.9
	3	10	210.3	174.8	193.7	61.3	20.0	660.0
MPI	1	11	364.5	338.9	250.7	75.6	27.6	906.2
	2	14	392	240	389	104	0	1021
	3	10	153.5	34.5	208.2	65.8	0.6	596.0
SHDI	1	11	0.9582	1.0000	0.0916	0.0276	0.8000	1.0800
	2	14	0.8779	0.9900	0.3452	0.0923	0.4000	1.4200
	3	10	0.6170	0.6000	0.2330	0.0737	0.2300	1.0400
SIDI	1	11	0.5509	0.5600	0.0680	0.0205	0.4200	0.6300
	2	14	0.4693	0.5350	0.1987	0.0531	0.2000	0.7100
	3	10	0.3580	0.3450	0.1593	0.0504	0.1000	0.6300
MSIDI	1	11	0.8091	0.8200	0.1431	0.0432	0.5500	0.9900
	2	14	0.695	0.765	0.377	0.101	0.220	1.240
	3	10	0.4740	0.4250	0.2666	0.0843	0.1100	1.0000
PR	1	11	3.636	4.000	0.505	0.152	3.000	4.000
	2	14	4.286	4.000	0.914	0.244	3.000	6.000
	3	10	3.500	3.000	0.707	0.224	3.000	5.000
PRD	1	11	2.336	2.160	0.617	0.186	1.690	3.610
	2	14	2.851	2.450	0.984	0.263	1.800	4.880
	3	10	2.484	2.380	0.816	0.258	1.280	3.840
RPR	1	11	51.95	57.14	7.20	2.17	42.86	57.14
	2	14	61.22	57.14	13.05	3.49	42.86	85.71
	3	10	50.00	42.86	10.10	3.19	42.86	71.43
SHEI	1	11	0.7600	0.7400	0.1356	0.0409	0.5700	0.9500
	2	14	0.6043	0.6650	0.2067	0.0552	0.3000	0.9200
	3	10	0.5050	0.4500	0.2152	0.0681	0.2100	0.9500
SIEI	1	11	0.7700	0.7700	0.1242	0.0374	0.5700	0.9400
	2	14	0.6136	0.6850	0.2485	0.0664	0.2700	0.9300
	3	10	0.5090	0.4900	0.2349	0.0743	0.1500	0.9500
MSIEI	1	11	0.6473	0.6300	0.1707	0.0515	0.4000	0.9000
	2	14	0.4779	0.5100	0.2434	0.0650	0.1500	0.8800
	3	10	0.3890	0.3450	0.2442	0.0772	0.1000	0.9100
IJI	1	11	60.99	61.75	19.95	6.01	20.02	91.02
	2	14	64.07	69.95	20.47	5.47	2.91	90.73
	3	10	59.10	54.70	23.28	7.36	31.83	98.83
CONTAG	1	11	53.05	54.75	7.73	2.33	43.13	62.19
	2	14	64.79	61.48	11.30	3.02	46.73	81.66
	3	10	72.45	75.60	11.74	3.71	48.16	88.24

1-SFI, 2-IM, 3-EM

APPENDIX 2

MANOVA OUTPUTS FOR THE COMPARISON OF LANDSCAPE STRUCTURE BASED UPON SMALL WATERSHEDS

A

Variables: all except CONTAG, MSIEI , SIEI, and RPR

```
                                s =  2    m = 12.5    n =     1.5
Criterion        Test Statistic          F              DF       P
Wilk's                  0.00387      2.693   ( 56,     10)  0.046
Lawley-Hotelling       32.54056      2.324   ( 56,      8)  0.102
Pillai's                1.86640      2.994   ( 56,     12)  0.021
Roy's                  22.57258
```

B

Variables: all that graphically seemed to better discriminate among landscapes at multiple scales (NP, TE, ED, LSI, TCA, NCA, CAD, MCA1, MCA2, and MPI)

```
                                s =  2    m =  3.5    n =    10.5
Criterion        Test Statistic          F              DF       P
Wilk's                  0.07053      6.360   ( 20,     46)  0.000
Lawley-Hotelling        6.91915      7.611   ( 20,     44)  0.000
Pillai's                1.37091      5.230   ( 20,     48)  0.000
Roy's                   5.84912
```

C

Variables: all that showed significant differences at the 0.05 level in ANOVA

```
                                s =  2    m = 11.5    n =     2.5
Criterion        Test Statistic          F              DF       P
Wilk's                  0.00514      3.486   ( 52,     14)  0.007
Lawley-Hotelling       28.11026      3.243   ( 52,     12)  0.015
Pillai's                1.84519      3.668   ( 52,     16)  0.003
Roy's                  19.72556
```

D

Variables: all that showed significant differences at the 0.001 level in ANOVA

```
                                s =  2    m =  5.0    n =     9.0
Criterion        Test Statistic          F              DF       P
Wilk's                  0.03418      6.783   ( 26,     40)  0.000
Lawley-Hotelling       11.39512      8.327   ( 26,     38)  0.000
Pillai's                1.54218      5.442   ( 26,     42)  0.000
Roy's                   9.64706
```

E

Variables: NP, CONTAG, LSI, TE, TCAI, and SHDI

```
                                s =  2    m =  1.5    n =    12.5
Criterion        Test Statistic          F              DF       P
Wilk's                  0.18100      6.077   ( 12,     54)  0.000
Lawley-Hotelling        3.44225      7.458   ( 12,     52)  0.000
Pillai's                1.01497      4.808   ( 12,     56)  0.000
Roy's                   3.09210
```

F

Variables: NP, CONTAG, LSI, ED, and SHDI

```
                                s =  2    m =  1.0    n =    13.0
Criterion        Test Statistic          F            DF       P
Wilk's                  0.12984      9.941   ( 10,    56)  0.000
Lawley-Hotelling        5.02624     13.571   ( 10,    54)  0.000
Pillai's                1.08768      6.915   ( 10,    58)  0.000
Roy's                   4.66730
```

APPENDIX 3

OUTPUTS OF MANOVA FOR DIFFERENT COMBINATIONS OF VARIABLES BASED UPON LARGE WATERSHEDS.

Variables: PD, ED, CAD, CONTAG

```
                                s =  2    m =  0.5    n =     0.5
Criterion        Test Statistic          F             DF       P
Wilk's                  0.01274      5.896   (  8,      6)  0.022
Lawley-Hotelling       60.81950     15.205   (  8,      4)  0.010
Pillai's                1.19993      1.500   (  8,      8)  0.290
Roy's                  60.54370
```

Variables: PD ED CAD AWMPFD CONTAG

```
                                s =  2    m =  1.0    n =     0.0
Criterion        Test Statistic          F             DF       P
Wilk's                  0.00060     15.880   ( 10,      4)  0.008
Lawley-Hotelling       97.15284      9.715   ( 10,      2)  0.097
Pillai's                1.94014     19.447   ( 10,      6)  0.001
Roy's                  76.88583
```

Variables: NP TE TCA CONTAG

```
                                s =  2    m =  0.5    n =     0.5
Criterion        Test Statistic          F             DF       P
Wilk's                  0.01473      5.429   (  8,      6)  0.027
Lawley-Hotelling       49.79475     12.449   (  8,      4)  0.014
Pillai's                1.23695      1.621   (  8,      8)  0.255
Roy's                  49.44928
```

Variables: TE AWMPFD TCA CONTAG

```
                                s =  2    m =  0.5    n =     0.5
Criterion        Test Statistic          F             DF       P
Wilk's                  0.00381     11.399   (  8,      6)  0.004
Lawley-Hotelling       74.34048     18.585   (  8,      4)  0.007
Pillai's                1.70907      5.874   (  8,      8)  0.011
Roy's                  71.73276
```

Variables: TE AWMPFD TCA

```
                                s =  2    m =  0.0    n =     1.0
Criterion        Test Statistic          F             DF       P
Wilk's                  0.00693     14.682   (  6,      8)  0.001
Lawley-Hotelling       47.41750     23.709   (  6,      6)  0.001
Pillai's                1.65749      8.065   (  6,     10)  0.002
Roy's                  45.30139
```

Variables: TE AWMPFD TCAI SHDI CONTAG

```
                                s =  2    m =  1.0    n =     0.0
Criterion        Test Statistic          F             DF       P
Wilk's                  0.00050     17.564   ( 10,      4)  0.007
Lawley-Hotelling      104.81246     10.481   ( 10,      2)  0.090
Pillai's                1.94704     22.059   ( 10,      6)  0.001
Roy's                  81.30881
```

APPENDIX 4

DISTRIBUTION OF VERTEBRATE SPECIES PER CLUSTER

Cluster 1

Virginia opossum, *Didelphis virginiana*
American beaver, *Castor canadensis*
Woodland vole, *Microtus pinetorum*
Eastern spotted skunk, *Spilogale putorius*
Striped skunk, *Mephitis mephitis*
River otter, *Lutra canadensis*
Turkey vulture, *Cathartes aura*
Wood duck, *Aix sponsa*
Greater roadrunner, *Geococcyx californianus*
Chuck-will 's-widow, *Caprimulgus carolinensis*
Carolina wren, *Thryothorus ludovicianus*
Black-and-white warbler, *Mniotilta varia*
Worm-eating warbler, *Helmitheros vermivorus*
Swainson 's warbler, *Limnothlypis swainsonii*
Kentucky warbler, *Oporornis formosus*
Northern cardinal, *Cardinalis cardinalis*
Southern prairie skink, *Eumeces septentrionalis obtusirostris*
Plainbelly water snakes, *Nerodia erythrogaster flavigaster*
Southern water snake, *Nerodia fasciata confluens*
Flathead snake, *Tantilla gracilis*
Woodhouse's toad, *Bufo woodhousii velatus*
Green treefrog, *Hyla cinerea*
Upland chorus frog, *Pseudacris triseriata feriarum*
Southern crawfish frog, *Rana areolata areolata*

Cluster 2

Southern short-tailed shrew, *Blarina carolinensis*
Nine-banded armadillo, *Dasypus novemcinctus*
Hispid cotton rat, *Sigmodon hispidus*
Coyote, *Canis latrans*
Red wolf, *Canis rufus*
Red fox, *Vulpes vulpes* (I)
Northern bobwhite, *Colinus virginianus*
American woodcock, *Scolopax minor*
Western slender glass lizard, *Ophisaurus attenuatus attenuatus*
Broadhead skink, *Eumeces laticeps*
Ground skink, *Scincella lateralis*
Ringneck snake, *Diadophis punctatus stictogenys*
Eastern hognose snake, *Heterodon platirhinos*
Common kingsnake, *Lampropeltis getula holbrooki*
Milk snake, *Lampropeltis triangulum amaura*
Coachwhip snake, *Masticophis flagellum flagellum*

Common garter snake, *Thamnophis sirtalis sirtalis*
Rough earth snake, *Virginia striatula*
Texas coral snake, *Micrurus tener*
Copperhead, *Agkistrodon contortrix contortrix*
Timber rattlesnake, *Crotalus horridus*

Cluster 3

Least shrew, *Cryptotis parva*
Eastern mole, *Scalopus aquaticus*
Eastern cottontail, *Sylvilagus floridanus*
Black-tailed Jackrabbit, *Lepus californicus*
Baird's pocket gopher, *Geomys breviceps*
Hispid pocket mouse, *Chaetodipus hispidus*
Marsh rice rat, *Oryzomys palustris*
Fulvous harvest mouse, *Reithrodontomys fulvescens*
Eastern harvest mouse, *Reithrodontomys humulis*
Common muskrat, *Ondatra zibethicus*
Nutria, *Myocastor coypus* (non native)
Long-tailed weasel, *Mustela frenata*
Pied-billed grebe, *Podilymbus podiceps*
Neotropic cormorant, *Phalacrocorax brasilianus*
Least bittern, *Ixobrychus exilis*
Little blue heron, *Egretta caerulea*
Tricolored heron, *Egretta tricolor*
Cattle egret, *Bubulcus ibis*
Black vulture, *Coragyps atratus*
Black-bellied Whistling-Duck, *Dendrocygna autumnalis*
Mallard, *Anas platyrhynchos*
Mottled duck, *Anas fulvigula*
Blue-winged Teal, *Anas discors*
Ruddy duck, *Oxyura jamaicensis*
King rail, *Rallus elegans*
Purple gallinule, *Porphyrula martinica*
Common moorhen, *Gallinula chloropus*
American coot, *Fulica americana*
Killdeer, *Charadrius vociferus*
Rock dove, *Columba livia* (I)
Eurasian collared-dove, *Streptopelia decaocto*
Inca dove, *Columbina inca*
Chimney swift, *Chaetura pelagica*
Belted kingfisher, *Ceryle alcyon*
Western kingbird, *Tyrannus verticalis*
Eastern kingbird, *Tyrannus tyrannus*
Scissor-tailed Flycatcher, *Tyrannus forficatus*
Loggerhead shrike, *Lanius ludovicianus*
White-eyed Vireo, *Vireo griseus*
Bell 's Vireo, *Vireo bellii*
Horned lark, *Eremophila alpestris*
Purple martin, *Progne subis*
Tree swallow, *Tachycineta bicolor*
Northern rough-winged swallow, *Stelgidopteryx serripennis*
Cliff swallow, *Petrochelidon pyrrhonota*

Barn swallow, *Hirundo rustica*
Eastern bluebird, *Sialia sialis*
Northern mockingbird, *Mimus polyglottos*
Brown thrasher, *Toxostoma rufum*
European starling, *Sturnus vulgaris* (I)
Prairie warbler, *Dendroica discolor*
Common yellowthroat, *Geothlypis trichas*
Yellow-breasted Chat, *Icteria virens*
Lark sparrow, *Chondestes grammacus*
Grasshopper sparrow, *Ammodramus savannarum*
Dickcissel, *Spiza americana*
Red-winged blackbird, *Agelaius phoeniceus*
Eastern meadowlark, *Sturnella magna*
Great-tailed Grackle, *Quiscalus mexicanus*
House finch, *Carpodacus mexicanus*
House sparrow, *Passer domesticus* (I)
Texas horned lizard, *Phrynosoma cornutum*,
Texas spiny lizard, *Sceloporus olivaceus*
Six-lined racerunner, *Cnemidophorus sexlineatus sexlineatus*
Common snapping Turtle, *Chelydra serpentina*
Alligator snapping turtle, *Macroclemys temminckii*
Chicken turtle, *Deirochelys reticularia*
Oachita map turtle, *Graptemys ouachitensis sabinensis*
False map turtle, *Graptemys pseudogeographica*
Eastern river cooter, *Pseudemys concinna metteri*
Ornate box turtle, *Terrapene ornate*
Slider, *Trachemys scripta*
Eastern mud turtle, *Kinosternon subrubrum*
Razorback musk turtle, *Sternotherus carinatus*
Common musk turtle, *Sternotherus odoratus*
Spiny softshell, *Apalone spinifera pallidus*
Racer, *Coluber constrictor anthicus*
Racer, *Coluber constrictor oaxaca*
Mud snake, *Farancia abacura*
Western hognose snakes, *Heterodon nasicus*
Diamondback water snake, *Nerodia rhombifer*
Graham's crayfish snake, *Regina grahamii*
Gulf crayfish snake, *Regina rigida sinicola*
Brown snake, *Storeria dekayi texana*
Western ribbon snake, *Thamnophis proximus proximus*
Three-toed Amphiuma, *Amphiuma tridactylum*
Gulf coast waterdog, *Necturus beyeri*
Western lesser siren, *Siren intermedia nettingi*
Gulf coast toad, *Bufo valliceps*
Cricket frogs, *Acris crepitans crepitans*
Great plains Narrowmouth Toad, *Gastrophryne olivacea*
Bullfrog, *Rana catesbeiana*
Bronze frog, *Rana clamitans clamitans*
Pickerel frog, *Rana palustris*

Cluster 4

Southeastern myotis, *Myotis austroriparius*
Eastern pipistrelle, *Pipistrellus subflavus*
Big brown bat, *Eptesicus fuscus*
Hoary bat, *Lasiurus cinereus*
Northern yellow bat, *Lasiurus intermedius*
Seminole bat, *Lasiurus seminolus*
Evening bat, *Nycticeius humeralis*
Brazilian free-tailed bat, *Tadarida brasiliensis*
Hooded merganser, *Lophodytes cucullatus*
American kestrel, *Falco sparverius*
Eastern screech-owl, *Otus asio*
Red-headed woodpecker, *Melanerpes erythrocephalus*
Fish crow, *Corvus ossifragus*
Pine warbler, *Dendroica pinus*
Prairie kingsnake, *Lampropeltis calligaster*

Cluster 5

Silver-haired bat, *Lasionycteris noctivagans*
Red-bellied woodpecker, *Melanerpes carolinus*
Downy woodpecker, *Picoides pubescens*
Hairy woodpecker, *Picoides villosus*
Red-cockaded woodpecker, *Picoides borealis*
Pileated woodpecker, *Dryocopus pileatus*
Great crested flycatcher, *Myiarchus crinitus*
Carolina chickadee, *Poecile carolinensis*
Tufted titmouse, *Baeolophus bicolor*
White-breasted nuthatch, *Sitta carolinensis*
Brown-headed nuthatch, *Sitta pusilla*

Cluster 6

Eastern red bat, *Lasiurus borealis*
Eastern wood-pewee, *Contopus virens*
Warbling vireo, *Vireo gilvus*
Blue-gray gnatcatcher, *Polioptila caerulea*
Northern parula, *Parula americana*
Yellow-throated warbler, *Dendroica dominica*
American redstart, *Setophaga ruticilla*
Summer tanager, *Piranga rubra*
Orchard oriole, *Icterus spurius*
Fence lizard, *Sceloporus undulatus hyacinthinus*,

Cluster 7

Rafinesque's big-eared bat, *Plecotus rafinesquii*
Swallow-tailed kite, *Elanoides forficatus*
White-tailed kite, *Elanus leucurus*
Bald eagle, *Haliaeetus leucocephalus*
Red-shouldered hawk, *Buteo lineatus*
Broad-winged hawk, *Buteo platypterus*

Mourning dove, *Zenaida macroura*
Great horned owl, *Bubo virginianus*
Barred owl, *Strix varia*
Northern flicker, *Colaptes auratus*
Bachman 's sparrow, *Aimophila aestivalis*
Chipping sparrow, *Spizella passerina*
Field sparrow, *Spizella pusilla*
Common grackle, *Quiscalus quiscula*
Louisiana pine snake, *Pituophis ruthveni*
Dwarf salamander, *Eurycea quadridigitata*
Central newt, *Notophthalmus viridescens louisianensis*

Cluster 8

Swamp rabbit, *Sylvilagus aquaticus*
Deer mouse, *Peromyscus maniculatus*
Golden mouse, *Ochrotomys nuttalli*
Bobcat, *Lynx rufus*
Feral pig, *Sus scrofa* (I)
White-tailed Deer, *Odocoileus virginianus*
Wild turkey, *Meleagris gallopavo*
American robin, *Turdus migratorius*
Gray catbird, *Dumetella carolinensis*
Blue grosbeak, *Guiraca caerulea*
Five-lined skink, *Eumeces fasciatus*
Redbelly snake, *Storeria occipitomaculata*

Cluster 9

Eastern fox squirrel, *Sciurus niger*
Yellow-billed cuckoo, *Coccyzus americanus*
Yellow-throated vireo, *Vireo flavifrons*
Red-eyed Vireo, *Vireo olivaceus*
Prothonotary warbler, *Protonotaria citrea*
Hooded warbler, *Wilsonia citrina*
Indigo bunting, *Passerina cyanea*
Painted bunting, *Passerina ciris*
Baltimore oriole, *Icterus galbula*
Rough green snake, *Opheodrys aestivus*

Cluster 10

Eastern gray squirrel, *Sciurus carolinensis*
Eastern flying squirrel, *Glaucomys volans*
Cotton mouse, *Peromyscus gossypinus*
White-footed Mouse, *Peromyscus leucopus*
Eastern woodrat, *Neotoma floridana*
Common gray fox, *Urocyon cinereoargenteus*
Ringtail, *Bassariscus astutus*
Common raccoon, *Procyon lotor*
Sharp-shinned hawk, *Accipiter striatus*
Cooper 's hawk, *Accipiter cooperii*
Ruby-throated hummingbird, *Archilochus colubris*

Acadian flycatcher, *Empidonax virescens*
Eastern phoebe, *Sayornis phoebe*
Blue jay, *Cyanocitta cristata*
Green anole, *Anolis carolinensis*
Corn snake, *Elaphe guttata*
Eastern rat snake, *Elaphe obsoleta*
Cope's gray treefrog, *Hyla chrysoscelis*
Squirrel treefrog, *Hyla squirella*

Cluster 11

Mink, *Mustela vison*
Louisiana waterthrush, *Seiurus motacilla*
Southern coal skink, *Eumeces anthracinus pluvialis*,
Eastern box turtle, *Terrapene carolina*
Cottonmouth, *Agkistrodon piscivorus leucostoma*
Pigmy rattlesnake, *Sistrurus miliarius streckeri*
Spotted salamander, *Ambystoma maculatum*
Marbled salamander, *Ambystoma opacum*
Mole salamander, *Ambystoma talpoideum*
Smallmouth salamander, *Ambystoma texanum*
Eastern tiger salamander, *Ambystoma tigrinum tigrinum*
Southern dusky salamander, *Desmognathus auriculatus*
Gray treefrog, *Hyla versicolor*
Northern spring peeper, *Pseudacris crucifer crucifer*
Strecker's chorus frog, *Pseudacris streckeri*
Eastern narrowmouth toad, *Gastrophryne carolinensis*
Hurter's spadefoot toad, *Scaphiopus hurterii*
Southern leopard frog, *Rana sphenocephala*

Cluster 12

Double-crested cormorant, *Phalacrocorax auritus*
Anhinga, *Anhinga anhinga*
Great blue heron, *Ardea herodias*
Great egret, *Ardea albus*
Snowy egret, *Egretta thula*
Green heron, *Butorides virescens*
Black-crowned night-heron, *Nycticorax nycticorax*
Yellow-crowned night-heron, *Nyctanassa violacea*
White ibis, *Eudocimus albus*
Osprey, *Pandion haliaetus*
Mississippi kite, *Ictinia mississippiensis*
Red-tailed hawk, *Buteo jamaicensis*
American crow, *Corvus brachyrhynchos*
Wood thrush, *Hylocichla mustelina*
Brown-headed cowbird, *Molothrus ater*

I – introduced species

APPENDIX 5

VARIABLES USED IN SELECTED HSI MODELS AND CORRESPONDING DEFINITIONS

Variable	Definition
Beaver	
V1: Percent tree canopy closure	The percent of the ground surface that is shaded by a vertical projection of the canopies of woody vegetation ≥ 5.0m (16.4ft) in height)
V2: Percent of trees in 2.5 to 15.2 cm (1 to 6 inches) dbh size class	The percent of trees with a dbh of 2.5 to 15.2 cm (1 to 6 inches)
V3: Percent shrub crown cover	The percent of the ground surface shaded by a vertical projection of the canopies of woody vegetation < 5 m (16.5 ft) in height
V4: Average height of shrub canopy	The average height from the ground surface to the top of those shrubs that comprise the uppermost shrub canopy
V5: Species composition of woody vegetation (trees and/or shrubs)	Refer to Allen (1983), page 12
V7: Percent stream gradient	The vertical drop in meters or feet per kilometer or mile of stream or river channel
V8: Average water fluctuation on an annual basis	Refer to (Allen 1983), page 13
American woodcock	
V1: Soil texture and drainage class	The relative proportion of sand, silt, and clay particles in the soil, and frequency and duration of periods when the soil is not saturated
V2: Percent canopy coverage of vegetation and down fall ≤ 30 cm above ground	Proportion of the area ≤ 30 cm (12 inches) in height above the ground surface that is covered by vegetation and downed woody material (e.g., limbs, branches)
V3: Percent herbaceous and shrub canopy cover > 0.5m high	Percent of the ground surface that is shaded by a vertical projection of herbaceous and shrub vegetation > 0.5m (20 inches) and <5.0m tall (16.4 ft), including climbing vines
V4: Stem density of trees	The number of woody stems ≥ 5.0 m (16.4ft) tall/ha or acre

V5: Average height of shrub canopy	The average vertical distance from the ground to the highest point of the tallest woody plants < 5m (16.4 ft) tall
Pine warbler	
V1: Percent tree canopy closure of overstory pines	Percent of the ground surface that is shaded by a vertical projection of the canopies of all overstory pine trees, excluding white, sand, or pond pine [assumed to refer to the top 80% tall pine trees as other variables]
V2: Successional stage of stand	The structural condition of a forest community which occurs during its development: pole or sapling; young; mature or old growth
V3: Percent of dominant canopy pines with deciduous understory in the upper one-third layer	Self-explanatory
Downy woodpecker	
V1: Basal area	Self-explanatory
V2: Number of snags > 15 cm dbh/0.4 ha	The number of standing dead or partly dead trees, greater than 15 cm (6 inches) diameter at breast height (1.4 m/4.5 ft), at least 1.8 m (6 ft) tall.
Barred Owl	
Vl: Number of trees ≥ 51 cm dbh/0.4 ha	Number of trees, either living or snags, ≥ 51 cm (20 inches) diameter at breast height/acre
V2: Mean dbh of overstory trees	The mean diameter at breast height (1.4 m or 4.5 ft) of trees that are 80% of the height of the tallest tree in the stand
V3: Percent canopy cover of over-story trees	The percent of the ground surface that is shaded by a vertical projection of the canopies of all trees that are 80% or higher of the height of the tallest tree
Wild turkey	
V1: Percent herbaceous canopy cover	The percent of the ground surface that is shaded by a vertical projection of all non-woody vegetation
V2: Average height of herbaceous canopy (summer)	Average vertical distance from the ground surface to the dominant height stratum of the herbaceous vegetative canopy
V3: Distance to forest or tree savanna cover types	The distance from random points to the nearest edge of a forest or tree savanna cover type
V4: Number of hard mast producing trees/ha that are ≥ 25.4cm dbh	Actual or estimated number of hard mast producing trees per ha that are ≥ 25.4cm (10 inches) diameter at 1.4 (4.5ft) above ground

V5: Percent canopy closure of soft mast producing trees	The percent of the ground surface that is shaded by the vertical projection of the canopies of trees that produce seeds encased in a pulpy mass (e.g. cherry, hawthorn, etc.)
V6 and **V7**: Percent shrub crown cover	The percent of the ground surface that is shaded by a vertical projection of the canopies of woody vegetation ≤5.0m (16.4ft) tall
V8: Percent of shrub crown cover comprised of soft mast producing shrubs	The relative percent of the amount of soft mast producing shrubs compared to all shrubs based on crown cover
V11: Percent tree canopy closure	The percent of the ground surface that is shaded by a vertical projection of the canopies of woody vegetation ≥ 5.0m (16.4ft) in height
V12: Average dbh of overstory trees	Same as above
V13: Percent of forest canopy comprised of evergreens	The relative percent of the amount of evergreen tree canopy compared to the total tree canopy
V14: percent of area providing equivalent optimum summer food/brood habitat	Self-explanatory
V15: percent of area providing equivalent optimum fall, winter, spring food	Self-explanatory
V16: percent of area providing equivalent optimum cover	Self-explanatory
Fox squirrel	
V1: Percent canopy closure of trees that produce hard mast trees ≥ 25.4 cm dbh	The percent of the ground that is shaded by the vertical projection of the canopies of trees which produce a hard shelled fruit and have a dbh of at least 25.4 cm
V2: Distance to available grain	The linear distance from sample point to grain crops that are available to fox squirrels
V3: Average dbh of overstory trees	Same as above
V4: Percent tree canopy closure	Same as above
V5: Percent shrub crown cover	The percent of the ground surface that is shaded by a vertical projection of the canopies of woody vegetation ≤ 5.0m (16.4ft) tall
Gray squirrel	
V1: Proportion of the total tree canopy that is hard mast producing trees ≥ 10 inches	Canopy cover of hard mast producing trees ≥ 10 inches divided by the total canopy cover of all trees

V2: Number of hard mast tree species	The number of three species present in the stand or sample site that produce hard mast
V3 and **V4**: Percent canopy cover of trees	The percent of the ground surface that is shaded by a vertical projection of the canopies of all woody vegetation > 6.0m (20ft) tall
V5: Mean dbh of overstory trees	Same as above

APPENDIX 6

EQUATIONS OF THE HSI MODELS USED

American beaver, *Castor canadensis* (Allen 1983)

Winter food life requisite is calculate by:

$$\text{WF} = \frac{(b+c)}{1.5}$$

where

b = woody vegetation within 100 m from the water's edge, calculated by

$$b = \left[(V_1 * V_2)^{0.5} * V_5\right]^{0.5} + \left[(V_3 * V_4)^{0.5} * V_5\right]^{0.5}$$

c = woody vegetation value within 100 m to 200 m from the water's edge, calculated by

$$c = 0.5\left[(V_1 * V_2)^{0.5} * V_5\right]^{0.5} + \left[(V_3 * V_4)^{0.5} * V_5\right]^{0.5}$$

American woodcock, *Scolopax minor* (Cade 1985)

Food : $FSI = SIV1 * SIV2$

Cover:

Forest $CSI = SIV3 + SIV4$ (to a maximum value of 1.0)

Shrubland $CSI = (SIV3 * SIV5)^{1/2}$

Pine warbler, *Dendroica pinus* (Schroeder 1982a)

$$HSI = (SIV1 * SIV2 * SIV3)^{1/2}$$

Downy woodpecker, *Picoides pubescens* (Schroeder 1982b)

HSI equals the lowest life requisite value.

Barred owl, *Strix varia* (Allen 1987b)

HSI is equal to the reproduction suitability index (*SIR*):

$$HSI = SIR = (SIV1 * SIV2)^{1/2} * SIV3$$

Fox squirrel, *Sciurus niger* (Allen 1982)

Winter food: $WF = \frac{(3SIV1 * SIV2)}{3}$

Cover/reproduction: $CR = (SIV3 * SIV4 * SIV5)^{1/3}$

Gray squirrel, *Sciurus carolinensis* (Allen 1987a)

Winter food: $SIWF = (SIV1 * SIV2)^{1/2} * SIV3$

Cover/reproductive: $SICR = (SIV4 * SIV5)^{1/2}$

Eastern wild turkey, *Meleagris gallopavo sylvestris* (Schroeder 1985)

Summer food/brood habitat

Forest $FBSI1 = (SIV1*SIV2)^{1/2}$

Shrubland $FBSI2 = (SIV1*SIV2)^{1/2}*SIV3$

Fall, winter, spring food

Forest: $FWSSI1 = \frac{(SIV4 + SIV5) + (SIV6 + SIV8)}{2} * SIV7$,

max $SIV4+SIV5=1$

Shrubland: $FWSSI2 = \frac{(SIV6 + SIV8)}{2} * SIV7 * SIV3$

Cover

$$CSI = SIV11 * SIV12 * SIV13$$

APPENDIX 7

METHODOLOGY FOR THE QUANTIFICATION OF VARIABLES OF THE HSI MODELS USED

Snags

Number of snags per area unit was estimated based upon mortality and snag longevity. Snag longevity is a function of snag size (diameter and height), species, cause of death, season of death, micro-environment, percentage of heartwood, soil type and moisture, forest type, and prevalence of windstorms (Bull et al. 1997, Everett et al. 1999). In this work only dead trees resulting from competition within the stand are considered. It is assumed that a dead tree in the study area remains standing on average 3 yr after death. This includes trees of all possible sizes in the study area above a 15-cm dbh limit. Dickson et al. (1983) found that 59% of hardwood snags in a clearcut in East Texas remained 4 yr after being killed. Cain (1996) describes snags dynamics in an uneven-aged stand dominated by old loblolly and shortleaf pines after injection of hardwoods with herbicide in Arkansas. He found decline rates depended on diameter. However, the general regression relating snag density and time after injection indicates that 4 yr after injection the number of standing snags was less than 50% of the snags present 2 yr after injection. Moorman et al. (1999) found in the South Carolina Piedmont snag longevity lower than 3 yr after death for all the species and forest types considered that included loblolly pine, sweetgum, and some oaks such as red oak. In other regions and for other species snag longevity is very variable depending on the factors mentioned above but it is usually higher than in the Southeast (Harrod et al. 1998, Everett et al. 1999).

Considering the microenvironment of the region where the study area is located, the published data for this region and other regions, and the conditions and dimensions of the trees developing in the stands in the study area I assumed that 3 yr for pine and hardwoods describes snag longevity in East Texas. The 3-yr value is a general value including all size classes where smaller size classes include the highest density.

Mortality and total number of snags was calculated according to each particular forest type, management, and model used. For pine-clearcutting system, average annual mortality was calculated as the average difference in number of trees in consecutive output years. Total number of snags per year is calculated as the dead trees of the previous 3 yr. Number of snags above 15 cm dbh is obtained by multiplying the total number of snags by the proportion of trees above 15 cm. The results obtained by this process are comparable to those found in the literature (Moorman et al. 1999). For stands younger than 10 yr number of snags is assumed to be 0 since in poor sites very few trees above 15 cm are observed and in richer sites mortality is extremely reduced.

For hardwood-clearcutting system number of snags is calculated in a similar way with mortality values output by dbh class and mortality above 15 cm directly from FVS. Given the 5-year length step of the model, mortality had to be divided by 5 before further calculations.

For management types 3, 4, and 5, mortality is obtained from the mortality equations of the SouthPro model (Lin et al. 1998):

Pine and other softwoods

$$Mortality = 0.052 + 0.00020\,BA^2 - 0.0064\text{ dbh} + 0.0019\,dbh^2$$

Soft Hardwoods

$$Mortality = 0.03 - 0.0041\,dbh + 0.0016\,dbh^2$$

Hard Hardwoods

$$Mortality = 0.038 - 0.0045\,dbh + 0.0015\,dbh^2$$

where

BA^2= (basal area)^2 in x10^3 ft^4/acre

dbh=diameter at the breast height in inches
dbh^2=(diameter at the breast height)^2 in x10 in^2

Tree Cover

Pine

The equations in Crookston and Stage (1999) were used directly with P-Lob generated data, namely frequency and dbh per size class, to estimate cover. Canopy percent cover (C') can be calculated by:

$$C' = 100(\sum p_i\, a_i)A^{-1}$$

where
p_i = trees per acre for the ith sample tree
a_i = projected crown area for the ith tree in ft^2 /acre
A = ft^2 /acre (43560)

Projected crown area is obtained from crown size-dbh relationships. Crown section is assumed circular in all the cases. For loblolly pine the equation of Gering and May (1995) established from trees growing in stands in Tennessee was chosen:

$$\mathit{Crown\ diameter} = 2.9660 + 1.4038\, dbh$$

For uneven-aged pine stands, equations in Gering and May (1995) were used with the overlap correction of Crookston and Stage (1999) given the spatial distribution of trees in stands and to account for the presence of ingrowth in the stand:

$$C = 100\,[1 - \exp(-0.01\, C')]$$

where

C = percent canopy cover that accounts for overlap,

C' = canopy cover

Hardwoods

Cover was calculated as the sum of cover for each species corrected with overlap equation in Crookston and Stage (1999). Dbh distributions from FVS (even-aged stands) and SouthPro (uneven-aged stands) were used with the crown size equations as follows:

Species	Equation	Source
Sweetgum	$CR = 2.35 + 0.735\ dbh$	(Francis 1986)
Water oak (willow oak equation)	$CR = 1.33 + 0.832\ dbh$	(Francis (1986)
Cherrybark oak (codominant scarlet oak equation)	$CW = 3.3 + 1.8\ dbh$	(Minckler and Gingrich 1970)
American hornbeam (American helm equation)	$CR = 3.36 + 0.776\ dbh$	(Francis 1986)
Swamp chestnut oak (codominant white oak equation)	$CW = 3.5 + 1.7\ dbh$	(Minckler and Gingrich 1970)

CR - Crown Radius; CW - Crown width

Pine-hardwoods

Similar treatment as in uneven-aged pine and hardwoods stands with equation of Gering and May (1995) for softwoods, Francis (1986) sweetgum equation for soft hardwoods, and Water Oak (willow oak equation) equation for hard hardwoods. Overlap correction of Crookston and Stage (1999) was also applied.

Shrub Crown Cover

Pine

Shrub cover was established based upon data in the literature, particularly Stransky et al. (1986), Cain (1991), Miller et al. (1995b), Zutter and Miller (1998), Cain (1999), Zutter et al. (1999), and Cain and Barnett (2002). A woody vegetation growth pattern marked by a gradual increase in the first years of development of the stand is assumed. It is also assumed that initial shrub cover is very reduced in intensively managed stands. In the first 10-15 years in an intensively managed stand cover values could show an increase to relatively higher values then stabilizing after this age. Thinning can cause a positive response of shrub growth in loblolly pine stands (Peitz et al. 2001). A general cover value of 10% was assumed for ages 1 to 15 years and 20% above 15 yr for pine stands managed by the clearcutting system. A woody vegetation cover of 30% was assumed for all ages in the uneven-aged stands.

Hardwoods and Pine-hardwoods

Data from Castleberry et al. (2000) suggest cover values around or below 30% in a mature bottomland hardwood forest before felling. A cover value of 30% was assumed in hardwood stands for all the ages with exception of the particular cases described next. Given the fact that shrub cover definitions include woody plants smaller than 5 m tall, regeneration must be included. At young ages and after thinning there is a strong development of regeneration observed in the FVS outputs that has to be taken into account. For age 1 to 7 yr estimated cover value is 95% due to the presence of a dense layer of regeneration 3 m high. For ages 23, 25, and 27 there is a strong vegetative regeneration after thinning that creates a layer smaller than 5 m that makes cover to be approximately 90%. For uneven-aged stands a woody vegetation cover of 30% was assumed in all the cases. A cover value of 30% was also assumed for all the ages in Pine-hardwood stands.

Herbaceous Canopy Cover

This variable is used for very young stands when they are used as shrublands in the models. Herbaceous cover was established based upon data in literature references. For loblolly pine stands the major references used were Cain (1991), Miller et al. (1995a), Miller et al. (1995b), Schultz (1997), Zutter and Miller (1998), Cain (1999), Zutter et al. (1999), Hedman et al. (2000), Clendenin and Ross (2001), and Cain and Barnett (2002). In intensive forestry young loblolly pine stands are strongly controlled in terms of herbaceous vegetation. There is artificial control at the plantation both mechanically and chemically and natural control at the time of crown closure (around 5 yr) by reduction of light intensity. In spite of control there might be some herbaceous and other plant species before crown closure and in older ages. Herbaceous cover for ages 1 and 3 was assumed to be 30%.

For even-aged hardwood stands estimates were based on Johnson et al. (1995), Castleberry et al. (2000), Devall et al. (2001), and Gilliam (2002). These stands have a very high density of trees in the beginning of their development. Therefore shading of intolerant herbaceous plants should keep them in relatively lower cover levels. Herbaceous cover was assumed to be 40% from age 1 to 5 and 25% for age 7.

Hardwood and mixed uneven-aged stands should present more herbaceous plants than older stands managed by the clearcut system since they are more open. Tree canopy cover by tall trees is much more reduced to allow regeneration and development of trees in lower layers. Herbaceous cover should not however be much higher since there is a strong natural control exerted by trees in the smallest diameter classes that are quite abundant in this system. A constant 30% cover value was considered for these stands.

Canopy Coverage of Vegetation and Down Fall ≤ 30 cm Above Ground

Given the suitability index curve shape for this variable (SI = 1 from 0 to 50% of cover) in American woodcock and considering that there is never a great preponderance of non-tree plants in any of the stands a maximum value of 50% was assumed for all management types.

Height of Herbaceous

We assume this variable to range from 20 to 50 cm, which is represented by the same *SIV* value, 1 in wild turkey habitat model.

Successional Stage of Stand

This variable is used in the pine warbler model only. Possible outcomes are: A) pole or sapling; B) young; C) mature or old growth). In this work these are the size classes followed:

Tree Size Class	**Pine Diameter**	**Hardwood Diameter**
Seedling / Sapling	<5"	<5"
Poletimber	>5" and <9"	>5" and <11"
Sawtimber	>=9"	>=11"

According to the classes defined by the HSI model pine stands were classified in

A) Pole or sapling if more than 50% of trees <9” in dbh.
B) Young if more than 50% of trees ≥ 9” in dbh

Mature or old growth stands were not considered possible to occur since the oldest stand during the 400 years of simulations is 37 years old. Mature stands of loblolly pine could be expected for ages above 80 years (White and Lloyd 1998).

Pine stands managed under the selection system and pine-hardwood mixed stands are considered as mature for the purposes of this work since they keep an irregular structure with few very large trees and other characteristics that resemble mature stands (White and Lloyd 1998).

Percent of Dominant Canopy Pines with Deciduous Understory in the Upper One-Third Layer

This variable was considered as the ratio of hardwood canopy cover to pine cover of all the trees in the upper 1/3 of the stand. It is a raw estimate since the variable is dependent on spatial distribution of trees in the stand. For pine, hardwood, and pine-hardwood stands managed by the selection system, tree height was estimated using the empirical equations of Lin et al. (1998) part of the SouthPro model:

Pine

$$H_t = -5.2 + 0.060\,BA + 35.3\ln(dbh) - 4.6\,SITE$$

Soft hardwoods

$$H_t = -11.5 + 0.070\,BA + 33.0\ln(dbh) - 2.7\,SITE$$

Hard hardwoods

$$H_t = -9.2 + 0.070\,BA + 30.5\ln(dbh) - 2.9\,SITE$$

where

H_t = total tree height (in feet)

BA = basal area in sq. ft. / acre

dbh = diameter at breast height (in inches)

$SITE$ = Loblolly pine site productivity classes for total heights of average dominant and co-dominant trees - class 4 = 80-94 ft, 50 years; class 3=95-109 ft, 50 years (Schulte et al. 1998).

This proportion was considered 100% in hardwood stands and negligible in pine stands managed by the clearcutting system.

Hard Mast Producing Trees

This variable is used in the wild turkey habitat only. Pine is a dry mast producer and therefore not part of the calculations for this variable. Water oak, cherrybark oak, swamp chestnut oak and American hornbeam (hardwood clearcutting) are hard mast producers. In uneven-aged stands only hard hardwoods are considered.

Soft Mast Producing Trees

Pine is a dry mast producer and therefore not included in the calculations. Although no soft mast producing tree species are part of the composition of the hardwood stand as defined in FVS for hardwoods, clearcutting system, the diversity of bottomland hardwood forests is so high that it is likely that considerable canopy cover of these types of trees is also present. Some of the species included in the understory (see below) are also small trees. Since most of these species are soft mast producers we assume a value of 20% for management type 2. This assumption was extended to stands in the hardwood, selection system. In pine-hardwood stands half of this value was assumed.

Soft Mast Producing Shrubs

The main shrub species associated with loblolly pine ecosystems (Baker and Langdon 1990), their fruit type and use by wildlife (Halls 1977), and their distribution (Burns and Honkala (1990) and USDA NRCS Plants Database (http://plants.usda.gov, November 2002) were considered. Since the most abundant shrubs, dogwood (*Cornus florida* L.), American holly (*Ilex opaca* Ait.), inkberry (Galberry) (*Ilex glabra* (L.) Gray), yaupon (*Ilex vomitoria* Ait.), hawthorn (*Crataegus* spp. L.), southern bayberry (*Morella cerifera* (L.) Small), and sumac (*Rhus* spp. L.) are soft mast producers, a value of 90% for percent of shrub cover comprised of soft mast producing shrubs in pine stands will be assumed.

Also for hardwoods the most relevant shrubs and understory trees are soft mast producers, including hawthorn (*Crataegus* spp. L.), bush palmetto (*Sabal minor* (Jacq.) Pers.), common elderberry (*Sambucus nigra* L. ssp. *canadensis* (L.) R. Bolli), southern arrowwood (*Viburnum dentatum* L.), poison oak (*Rhus radicans* L.), supplejack (*Berchemia scandens* (Hill) K. Koch), greenbrier (*Smilax* spp. L.), and blackberry (*Rubus* spp. L.) (Halls 1977; NRCS Plants Database, http://plants.usda.gov, November 2002; Texas Parks and Wildlife, http://www.tpwd.state.tx.us, November 2002). A value of 90% for this proportion is also assumed here. For young stands however (ages 1, 3, 5, and 7 years) a value of 20% is assumed since young individuals of hard mast producers provide the majority of the cover. In uneven-aged stands (pine, hardwood, and pine-hardwood) the same value of 90% is assumed.

Data Outside the Range of the Models

Percentage of Trees in the 2.5 to 15.2 cm dbh Class

Below age 10 estimates were based upon dbh data from Miller et al. (1995b) for ages 1 to 8 years in the Southeast and upon the standard deviation calculated for dbh at age 10. We assume standard deviation decreases from age 10 to age 3 in a predictable way. Values for estimated mean dbh (Miller et al. 1995b) and standard deviation estimates are also presented in the table. Intervals of the mean ±1, 2, and 3 standard deviations were established to help defining the percentage within the interval 1 to 6 inches knowing these intervals contain 68%, 95%, and 99.7% of the data, respectively. These are gross estimates given the true standard deviation for small sizes is unknown and outputs are provided in 2 inches (5 cm) diameter classes. The estimates used here are presented in the following table by Site Index (50 years) interval:

Age (years)	Mean dbh (cm)	Standard deviation	Percent estimate (%)	Age (years)	Mean dbh (cm)	Standard deviation	Percent estimate (%)
SI: 72-80				SI: 81-90			
1			0	1			0
3	1	0.3	60	3	1.1	0.4	60
5	3	0.6	100	5	3.5	0.7	100
7	5	0.8	95	7	5.1	0.9	95
9	5	1	90	9	5.5	1.1	80
SI: 91-100				SI>100			
1			0	1			0
3	1.3	0.5	60	3	1.5	0.6	70
5	3.5	0.8	100	5	4	0.9	100
7	5.2	1	90	7	5.5	1.1	70
9	6	1.2	70	9	6.5	1.3	50

Average dbh of Overstory Trees

For management type 1 and 3 the variable is obtained directly from the outputs for ages above 10 years. For age 9 years dbh was considered equal to 14 cm (SI(50) 72-88), 15 (SI(50) 89-102), or 16.5 (SI(50) 104-118). *SIV*12 is insensitive to dbh below 13 cm and for that reason no particular dbh values were considered.

Cover

Since P-Lob simulates stands 10 years or older, cover for stands younger than that age was estimated by using the tendency of the curves with calculations on cover based upon density and canopy width at small diameters as shown in the following table:

	Cover (%)	
Age (years)	SI(50) 22-26 m	SI(50) 27-36 m
1	0	0
3	0	0
5	10	20
7	30	50
9	60	80

Tree Height

Pine

Pine trees were also considered as shrubs in young plantations (1 to 3 years) when average tree height is lower than 5 m. Total height for stands younger than 10 yr was estimated as a rough average of total height on several sites located mainly in Mississipi, Alabama, and Georgia (Miller et al. 1995b). Since the values presented refer to top height we reduced the height at age 3 from 8.9 to 6.6 ft. At ages 5 and more years pine trees are higher than 5 m according to data presented in Miller et al. (1995b) and Cain (1999) and in the site index curves of Dean and Baldwin (1993) built based upon data collected in the South including East Texas. Age 5 and thereafter a height value of 2 m is assumed as shrub height average. This value was chosen given the relationship between shrub height and the suitability index that becomes constant for values 2 or higher. Estimates of stand height of young pine stands are as follows.

Age (years)	Total height (ft)	Total height (m)
1	1.6	0.5
3	6.6	2
>3	6.6	2

Hardwoods

As in the previous case trees smaller than 5 m are considered as shrubs. Average height for age 5 is 3.2m. Average height is estimated to be above 5 m at age 9 only. Height values from age 1 to age 7 are based upon a linear function established for each of the four SI cases. After age 7 an average shrub height of 3 m is assumed. This value is higher than in pine stands given the natural and artificial control of the former stands. Estimates area presented in the following table.

Age (years)	Total height (ft)	Total height (m)
1	1	0.3
3	5.57	1.7
5	10.5	3.2
7	14.8	4.5
>7	9.8	3

Other variables

Stream Gradient

Stream gradient was analyzed in the GIS with a slope function applied to the DEM data. Areas with slope above 6% (value above which *SIV*7 in beaver model starts decreasing from 1 in the suitability graphs or functions) occupy only 15.7ha (0.27% of the study area) and only occasionally there is a coincidence of these areas with the streams. Even assuming the inadequacy of the 30 m resolution of the DEM to capture fine scale gradients higher than 6%, it was considered that in the study area stream gradient is always below 6%.

WaterFluctuation

This is a discrete variable in the beaver model with three possible outputs: A) Small fluctuations that have no effect on burrow or lodge entrances, B) Moderate fluctuations that affect burrow or lodge entrances, and C) Extreme fluctuations or water absent during part of year. USGS data for the Neches River near Diboll, TX, (USGS 08033000) indicates that moderate fluctuations occur in the region and type B fluctuations are assumed for the entire area. A uniform value for the study area allows the effect of vegetation cover on habitat suitability to be better evaluated.

Soil Texture and Drainage Class

This variable describes habitat conditions for earthworms, the main food requirement for American woodcock. The top 10 cm are the most important zone for these organisms. Spatial and attribute data from the Soil Survey Geographic (SSURGO) database for Angelina County, published by the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) - National Cooperative Soil Survey was used to quantify this variable. The Drainage variable in the "comp" table of the attribute data comprises the following categories defined in USDA (1995): E-Excessively, SE-Somewhat excessively, MW - Moderately well, W-Well, SP-Somewhat poorly, P-Poorly, and VP-Very poorly. These classes were assigned to the three drainage classes of the HSI model (excessively, well, and poorly) according to the following table.

Drainage Class	
HSI model	SSURGO
Excessively drained (dry)	Excessively Somewhat excessively
Well drained (moist)	Well Moderately well
Poorly drained (wet)	Somewhat poorly Poorly Very poorly

The Surface Soil Texture (surftex) (in the "comp" table) was used to describe texture. Surftex codes were simplified to match the 12 texture categories of the HSI model: **C** –clay, CL-clay loam, L-loam, LS-loamy sand, S-sand, SC-sandy clay, SCL-sandy clay loam, SI-silt, SIC-silty clay, SICL-silty clay loam, SIL-silt loam, and SL-sandy loam.

Distance to Forest

This variable was calculated only for the Non-SFI scenario. For management type 1 in the SFI scenario very few pine stands ages 1 to 3 years include inner zones distant from a forest edge. For management type 2, clearcut areas are always very small to be considered under this perspective. Calculation of V3 was performed in the GIS based upon distance functions over shrub areas (pine 1 to 3 years; hardwood 1 to 7 years).

Distance to Available Grain

Tthis distance is considered to be above the critical limits (600 m) since this is a continuous forested area with no grain available.

VITA

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