

**FUNCTIONAL HETEROGENEITY OF THE RED-COCKADED WOODPECKER
HABITAT IN THE SAM HOUSTON NATIONAL FOREST: A GEOGRAPHIC
INFORMATION SYSTEM APPROACH**

A Thesis

by

JOÃO CARLOS MARTINS DE AZEVEDO

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

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December 1995

Major Subject: Forestry

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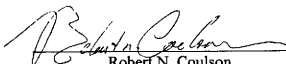
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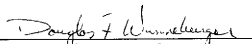
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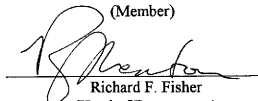
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ABSTRACT

Functional Heterogeneity of the Red-cockaded Woodpecker Habitat in the Sam Houston

National Forest: A Geographic Information System Approach. (December 1995)

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Red-cockaded woodpecker (RCW) populations are maintained by dispersal of fledglings and adults among clusters of cavity trees, the distribution of which is affected by fragmentation of the pine forest and savanna landscapes. A spatially explicit model of the distribution of RCW as related to landscape characteristics was developed in this study using a Geographic Information System (GIS). The study area was the Raven District of the Sam Houston National Forest, East Texas.

Conceptually, the model was based on the functional heterogeneity of the landscape in the study area. A GIS coverage resulting from the conjunction of habitat suitability pattern and RCW distribution and group size was the base for the application of the functional heterogeneity indices of Angular Moment of Inertia, Connectivity, Weighted Connectivity, and Spatial Interaction. Five approaches were used in the definition of the habitat suitability corresponding to 5 levels of fragmentation. Two scales of observation were used in the calculation of the indices.

The functional heterogeneity indices seem to be an effective way to detect areas of the forest most important for the maintenance of RCW populations. These areas are those

presenting the best demographic, habitat, and landscape conditions for the species. The Angular Moment of Inertia, Weighted Connectivity, and Spatial Interaction indices detected the same areas of the Raven District as those which are more important for the birds given actual distribution, group size, habitat conditions, and landscape conditions. These areas are located in the east and west of the southwestern region and had the highest values for the Angular Moment of Inertia, Weighted Connectivity, and Spatial Interaction indices for all the levels of fragmentation and the two scales used. Other areas presenting high indices values were detected in the north and in the center of the same region.

Fragmentation in terms of loss of only roosting and nesting habitat but not foraging habitat does not seem to interfere considerably in the maintenance of spatial conditions within the areas most important for the species. Fragmentation in terms of loss of roosting, nesting, and foraging seems to allow the maintenance of the main centers of RCW

To Alice, my lovely wife.

ACKNOWLEDGEMENTS

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A special thanks to Tony McKinney, the first person to suggest the RCW-forest landscape relationship as a possible field for my thesis.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION.....	v
ACKNOWLEDGEMENTS.....	vi
TABLE OF CONTENTS	vii
LIST OF FIGURES	x
LIST OF TABLES.....	xii
 CHAPTER	
I INTRODUCTION.....	1
Objectives	3
Hypotheses	3
II LITERATURE REVIEW	5
The Red-cockaded Woodpecker.....	5
Social Organization of the Red-cockaded Woodpecker.....	6
Movements Red-cockaded Woodpeckers in the Landscape	8
Red-cockaded Woodpecker Habitat	10
Nesting and Roosting Habitat	10
Age.....	10
Diameter at the Breast Height	15
Basal Area	15
Total Basal Area	16
Overstory Basal Area	16
Midstory Basal Area..	17
Foraging Habitat	19
Fragmentation and Connectivity of the Red-cockaded Woodpecker Habitat.....	24
Landscape Ecology and Geographic Information Systems	27

CHAPTER	Page
III STUDY AREA	32
Forest Stands in the Raven District.....	32
Red-cockaded Woodpecker in the Raven District.....	36
IV METHODOLOGY	39
Material	39
Data.....	39
The GIS Stands Coverage.....	39
The Red-cockaded Woodpecker Table.....	43
Red-cockaded Woodpecker Habitat Suitability Classification.....	47
Combination of Habitat Suitability and Red-cockaded Woodpecker Information	52
The Functional Heterogeneity Indices.....	54
Angular Moment of Inertia (AMI)	54
Connectivity (H).....	55
Weighted Connectivity (WH).....	56
Spatial Interaction (SI).....	56
The Application of the Functional Heterogeneity Indices	57
V RESULTS	59
Habitat Suitability Maps.....	59
Habitat/RCW Maps.....	66
Functional Heterogeneity Indices Maps	66
21 x 21 Window Size.....	66
Angular Moment of Inertia (AMI)	67
Connectivity (H)	69
Weighted Connectivity (WH)	73
Spatial Interaction (SI).....	77
41x41 Window Size	81
Angular Moment of Inertia (AMI)	84
Connectivity (H)	86
Weighted Connectivity (WH)	86
Spatial Interaction (SI)	89
VI DISCUSSION	97
The Meaning of the Approaches	97
The Meaning of the Indices	99

CHAPTER	Page
Angular Moment of Inertia (AMI)	99
Connectivity (H).....	100
Weighted Connectivity (WH)	101
Spatial Interaction (SI)	102
The Meaning of the Window Size.	102
Analysis of the Results	103
The Areas Detected by the Indices	103
Angular Moment of Inertia (AMI)	103
Connectivity (H)	104
Weighted Connectivity (WH)	105
Spatial Interaction (SI)	106
The Areas Indicated by the Overall Results.	106
Fragmentation...	107
Differences Between Window Sizes.....	110
The Metapopulation Theory as Related to the Raven	
District Red-cockaded Woodpecker Population	112
Final Considerations	113
Eventual Limitations of the Study	115
VII CONCLUSIONS	117
VIII RECOMMENDATIONS FOR THE CONSERVATION	
OF THE RED-COCKADED WOODPECKER.....	119
REFERENCES	122
APPENDICES	129
VITA	144

LIST OF FIGURES

FIGURE	Page
1	Location of the Raven District of the Sam Houston National Forest. 33
2	Compartments in the Raven District. 34
3	Forest Type Distribution in the Raven District. 35
4	Distribution of Active and Inactive Colonies in the Raven District 38
5	Habitat Suitability Map for Approach 1. 60
6	Habitat Suitability Map for Approach 2. 61
7	Habitat Suitability Map for Approach 3. 62
8	Habitat Suitability Map for Approach 4. 63
9	Habitat Suitability Map for Approach 5. 64
10	<i>AMI</i> ; Approach 1, 21 x 21 Window Size. 68
11	<i>AMI</i> ; Approach 3; 21 x 21 Window Size. 70
12	<i>AMI</i> ; Approach 5; 21 x 21 Window Size 71
13	<i>H</i> ; Approach 1; 21 x 21 Window Size 72
14	<i>H</i> ; Approach 3; 21 x 21 Window Size 74
15	<i>H</i> ; Approach 5; 21 x 21 Window Size. 75
16	<i>WH</i> ; Approach 1; 21 x 21 Window Size. 76
17	<i>WH</i> ; Approach 3; 21 x 21 Window Size. 78
18	<i>WH</i> ; Approach 5; 21 x 21 Window Size. 79
19	<i>SI</i> ; Approach 1; 21 x 21 Window Size 80
20	<i>SI</i> ; Approach 3; 21 x 21 Window Size. 82

FIGURE	Page
21 <i>SI</i> ; Approach 5; 21 x 21 Window Size	83
22 <i>AMI</i> ; Approach 1; 41 x 41 Window Size	85
23 <i>AMI</i> ; Approach 3, 41 x 41 Window Size.	87
24 <i>AMI</i> ; Approach 5; 41 x 41 Window Size.	88
25 <i>WH</i> ; Approach 1; 41 x 41 Window Size.	90
26 <i>WH</i> ; Approach 3; 41 x 41 Window Size.	91
27 <i>WH</i> ; Approach 5; 41 x 41 Window Size.	92
28 <i>SI</i> ; Approach 1; 41 x 41 Window Size.	93
29 <i>SI</i> ; Approach 3, 41 x 41 Window Size	94
30 <i>SI</i> ; Approach 5, 41 x 41 Window Size.	96

LIST OF TABLES

TABLE		Page
1	Classes of RCW Group Size.	53
2	Distribution of Area by Habitat Suitability Class and Approach Followed.	65
3	Ranges and Classification of the Outputs of the Functional Heterogeneity Indices, 21 x 21 Window Size	67
4	Ranges of the Outputs of the Functional Heterogeneity Indices; 41 x 41 Window Size.	84

CHAPTER I

INTRODUCTION

Landscape measurements have been developed in recent years which utilize Geographic Information Systems (GISs), creating methods to perform spatial analyses over large areas (Turner 1990) and allowing the relationship between patterns and ecological processes to be explored at the landscape level (Turner 1989). In fragmented populations a goal of landscape ecology research is to “link the landscape pattern with the key processes that determine the chance of survival in the region” (Opdam *et al.* 1995). Dispersal movements of animals are in many situations the determinant processes responsible for the survival of populations. Dispersal movements of animal populations make it necessary to discern the arrangement of habitats across landscapes to understand the ecology of these populations and to improve their management (Turner *et al.* 1995). The red-cockaded woodpecker (RCW) is an endangered species threatened by loss of habitat and a decrease in conditions amenable to dispersal within the pine forests of the southern United States (Conner and Rudolph 1991; Rudolph and Conner 1994). The spatial attributes of the habitat of the RCW have been evaluated in the Sam Houston National Forest in Texas, and maintenance of active colonies is related to spatial landscape attributes such as fragmentation, connectivity, and isolation in the pine landscape mosaic (Conner and

This thesis follows the style of Landscape Ecology.

Rudolph 1991; Rudolph and Conner 1994; Thomlinson 1993). Despite these efforts, however, exactly how the forest landscape pattern affects the demographic processes of RCW in that particular landscape, at a broad scale and from a spatially explicit point of view, is not sufficiently understood. A spatially explicit analysis of fragmentation-population relationships is an important and necessary continuation of the previous work done on this subject and constitutes the goal of this study

Functional heterogeneity, defined as the way organisms perceive and respond to their environment (Kolasa and Rollo 1991), can provide a useful approach for the integration of landscape structure and animal behavior (Coulson *et al.* 1994). In this work, functional heterogeneity is the basic concept chosen to address the RCW - forest pattern relationship. The habitat conditions required by the RCW are known, and this knowledge has led to such practices as reducing the hardwood midstory component and the maintenance of vegetation cover within 400 m of identified colonies. The USDA Forest Service has created recruitment and replacement stands in the Sam Houston National Forest for the propose of maintaining the existing active colonies and to allow the colonization of new areas by the RCW (Thomlinson 1993). What is not well known is where these practices should best be applied, in terms of spatial location, for maximum benefit to the species. The procedures outlined in this proposal will contribute to the optimization of these conservation efforts and will provide a means to forecast RCW responses to landscape change

OBJECTIVES

The objectives of this work are to: (1) analyze the effect of the forest landscape pattern on the RCW colony distribution and group size; (2) apply the functional heterogeneity concept to the landscape pattern - red-cockaded woodpecker relationship; (3) create a spatially explicit model of the distribution of RCW as a function of landscape conditions; (4) identify the areas where RCW groups are more threatened; and (5) identify the areas presenting landscape conditions to be used in the expansion of the actual red-cockaded population.

HYPOTHESES

I will pursue the hypothesis presented by Rudolph and Conner (1994): when suitable habitat conditions are present, the maintenance of RCW populations is primarily dependent on the movement of individuals among clusters, and predominantly the dispersal of fledgling females. Further, the movements of the individuals comprising a cluster includes their flights to access foraging areas (Rudolph and Conner 1994). If these hypotheses are true, then measurements of landscape isolation and connectivity will be highly correlated with the distribution of clusters in the landscape and also with the group size of the clusters. In other terms, it is expected that the active clusters in the Raven District of the Sam Houston National Forest are distributed over the areas where the forest landscape possesses high connectivity.

Additionally, I hypothesize that the areas containing a high density of clusters and large group sizes can be described as networks with high connectivity. Areas where cluster

density and group sizes are low should possess a patchy pattern with reduced connectivity and with functional isolation between colonies. Groups of connected colonies might be isolated from other groups of connected colonies, or individual colonies may be isolated in the same landscape. If this additional hypothesis is true, the population of RCW in the area of study can be characterized by spatial and demographic behaviors representative of metapopulations. A metapopulation is defined as a *set* of populations distributed over a number of habitat fragments, as long as the sub-units are interconnected by dispersing individuals (Opdam 1991)

CHAPTER II

LITERATURE REVIEW

THE RED-COCKADED WOODPECKER

The red-cockaded woodpecker (*Picoides borealis*) inhabits the mature pine forests of the Southeastern United States. Its range of distribution is coincident with the Atlantic and Gulf Coastal Plains from Virginia to East Texas.

The Red-cockaded woodpecker (RCW) was considered an endangered species by the Endangered Species Conservation Act of 1969 and by the subsequent Endangered Species Act of 1973. Several factors have contributed to the decline of the RCW populations. The primary causes are the reduction of nesting and roosting habitat due to extensive timber harvesting of mature pine forests (Conner and Rudolph 1989, Conner and Rudolph 1991; Walters 1991) and hardwood encroachment due to artificial reduction of fire in the forests of the Southern United States (Conner and Rudolph 1989). The effects of this reduction of suitable areas for nesting and roosting are reflected in reduction of patch size, isolation of colonies, and a decrease in movement conditions in the pine landscapes. These can be considered as the direct reasons for the decrease in population size observed in the last decades (Conner and Rudolph 1989; Conner and Rudolph 1991; Walters 1991; Thomlinson 1993).

Social Organization of the Red-cockaded Woodpecker

The species is organized into a cooperative breeding system with nonbreeding individuals remaining in the groups (clans) as helpers (Walters *et al.* 1988). The functions of the helpers are associated with the help of the reproductive pair and related young birds, and with the defense of cavities and territories (Ligon 1970; Walters *et al.* 1988). Helpers are usually close relatives of the breeders they assist (Walters *et al.* 1988).

A clan's composition can vary from a single male individual, to a breeding pair, to a breeding pair with male helpers (Walters *et al.* 1988). Each individual in a group occupies one roost cavity (Walters 1991). Each group occupies a cluster of cavity trees, but in some instances the group can occupy more than one cluster of cavity trees (Walters *et al.* 1988). The activity of clans with more than one cluster is, however, still concentrated in one predominant cluster of cavity trees (Walters *et al.* 1988). Breeding birds in the colonies are sedentary and can remain in the same trees for up to four years (Ligon 1970).

Abandonment of clusters and capture of active or inactive clusters by different groups are dynamic processes in the RCW populations (Walters *et al.* 1988; Doerr *et al.* 1989). Recently abandoned clusters are more quickly reoccupied than long-abandoned clusters (Doerr *et al.* 1989), and territories abandoned for more than 2 years will not be reoccupied (Walters 1991). Population density positively affects the recolonization rates of abandoned colonies (Doerr *et al.* 1989). Creation of new colonies is, however, very rare (Doerr *et al.* 1989; Ligon *et al.* 1986; Walters 1991; Conner and Rudolph 1989).

Red-cockaded woodpeckers generally compete for a breeding position in the group to which they belong rather than searching for a new territory and creating a new group

(Walters 1991). This behavior is due to the time and energy investment involved with the excavation of cavities in new territories (Walters 1991). New cavities are often excavated in existing clusters which increases their extent or shifts their location (Walters *et al.* 1988; Doerr *et al.* 1989) A new clan can also result from a colony breaking into two groups (Walters *et al.* 1988).

The dependency of the species on already existing clusters of cavity trees has strong implications in terms of defining the habitat for the species (Doerr *et al.* 1989). A cluster of cavity trees, even if inactive, has a high value in terms of potential nesting habitat for the species. Walters (1991) states that the “worst territories with an existing set of cavity trees may be sufficiently better than the best ones without cavities [.]”. Successful occupancy of artificial cavities by RCW supports this hypothesis (Doerr *et al.* 1989; Walters 1991, Walters *et al.* 1992; Rudolph *et al.* 1992; Carrie 1995, USDAFS, personal communication).

Throughout North Carolina Walters *et al.* (1988) studied for 5 years the composition of groups of red-cockaded woodpeckers. Fifty-nine percent of the observed groups were composed of a male and a female, only 30% by a breeding pair with at least one helper, and 11% by solitary males. From the groups containing helpers, just 5% had more than one helper. The maximum number of helpers observed was 3, and the helpers were almost exclusively males (98%). The composition of groups is variable from area to area, however. In Sam Houston National Forest 69.6% of the colonies have 2-3 roosting birds, 21.4% a single bird, and the remaining 9% from 4 to 7 roosting birds (Rudolph and Conner 1994).

Movements of Red-cockaded Woodpeckers in the Landscape

Movements of Red-cockaded Woodpeckers include three main types: foraging movements, defense movements, and dispersal movements. Birds can fly considerable distances every day in foraging and defense activities (Ligon 1970). In Florida, woodpeckers were observed approximately 1300 m away from their colony (Ligon 1970). In central Florida, on some occasions, groups were observed to fly up to 950 m away from their territory to intercept an intruding neighbor at the territorial boundary, but mean distances traveled were 277.1 m (sd=196.3m) (DeLotelle *et al.* 1987). Also in central Florida, birds were observed to fly up to 1200 m (mean=720 m) away from the roost tree (Nesbitt *et al.* 1978).

Dispersal of fledglings or adults to other colonies is an important characteristic of the species for maintaining demographic processes and genetic variability in the population (Walters 1988; Doerr *et al.* 1989). Walters *et al.* (1988) suggest that red-cockaded woodpeckers disperse in the direction of existing groups or existing clusters of cavity trees and not in the direction of unoccupied territories.

Movements of females from the time of fledgling to the subsequent breeding season was quantified by Walters *et al.* (1988) in North Carolina. At the age of one year, 31% of the fledgling females dispersed to other colonies, 1% remained in the original group, and 68% disappeared (mortality). Out of the fledgling females that dispersed, 92% became breeders. One breeding season after the females became breeders, 56% remained in the same group, 12% moved to different groups, and 31% disappeared. Walters *et al.* (1988) quantified distances that fledgling females dispersed: mean=4.7 Km, median=3.2 Km, and

maximum=31.5 Km Using the number of territories through which the dispersing birds passed as an indicator of effective dispersal distance, they stated that 29% of the fledgling females dispersed to a neighboring group and 24% moved three or more territories away from the original colony.

Adult females also disperse. Incest avoidance, loss of mate, and mate desertion are reasons for these movements (Walters *et al.* 1988). These distances were quantified by Walters *et al.* (1988). mean=2.1 Km, median=1.3 Km, and maximum 15.0 Km. Adult females disperse mainly to neighboring groups (61%), while those that pass through more than two territories are relatively scarce (8%).

Male dispersal follows two strategies: "dispersal after fledgling, as females do, or remaining as helpers until a breeding vacancy arises in the vicinity" (Walters *et al.* 1988). Fledgling males were found to disperse in just 13% of the cases in North Carolina. Higher proportions either die (57%) or remain as helpers in the natal group (27%) (Walters *et al.* 1988). Fledgling males dispersal distances were quantified by Walters *et al.* (1988). mean=5.4 Km, median=4.5, and maximum=21.1 Km.

Adult male breeders and helpers move reduced distances and usually only to neighboring groups. Helpers became breeders either when they inherited territories (90%) or when they dispersed (91%) (Walters *et al.* 1988). Breeders remained as breeders in the same territory until they disappeared (Walters *et al.* 1988). Solitary males, those that are associated with a territory but not with a group, can disperse considerable distances. Floaters are solitary males without a territory. Solitary males became breeders in 26% of the

cases studied by Walters *et al.* (1988). Eighteen percent moved to new territories, and most of these became breeders (Walters *et al.* 1988).

RED-COCKADED WOODPECKER HABITAT

In the area of study of this project, which is the Raven District of the Sam Houston National Forest, the forest stands are mainly comprised of loblolly pines (*Pinus taeda*) and shortleaf pines (*Pinus echinata*). The following review will be based primarily on the red-cockaded woodpecker's habitat requirements relative to stands dominated by such species. Longleaf pine (*Pinus palustris*) is the species preferred for cavity excavation, but RCW also use the other native pines of the southeastern United States (Lay and Russell 1970; Ligon *et al.* 1986, Doerr *et al.* 1989).

Nesting and Roosting Habitat

Clans of red-cockaded woodpeckers concentrate a majority of their activity in the trees they excavate for roosting and nesting cavities. These cavity trees and the group of trees that constitute the cluster are the center of activity for individuals and clans of red-cockaded woodpeckers. The availability of cavity trees can determine the distribution of birds, group size, attraction and retention of mates, and reproductive success (Ligon 1970).

Age

Red-cockaded woodpeckers require old-growth living pines for excavation of cavities for nesting and roosting (Conner and O'Halloran 1987; Hooper 1988; Rudolph and

Conner 1991, Conner *et al.* 1994b). In spite of the skepticism of Field and Williams (1985), more recent literature has indicated that the tree age is a main attribute in the selection of trees by RCW and in the definition of suitable habitat for the species (Hovis and Labisky 1985; Conner and O'Halloran 1987; DeLotelle and Epting 1988; Hooper 1988; Engstrom and Evans 1990; Conner and Rudolph 1991; Thomlinson 1993).

Using data collected during 1991 in the Sam Houston National Forest, Conner *et al.* (1994b) detected significant differences in age between active cavity trees and trees selected randomly. In the Angelina, Davy Crockett, and Sam Houston National Forests in East Texas, Rudolph and Conner (1991) found statistically significant differences in tree age between cavity trees and both non-cavity trees within clusters and trees randomly selected from the stands surrounding the clusters. These differences were detected for the species that dominate the mentioned national forests, i.e., loblolly, shortleaf, and longleaf pines. While tree age is one of the variables that account for the greatest differences between cavity and non-cavity trees in the Angelina National Forest of Texas (Conner and O'Halloran 1987), diameter at breast height and crown characteristics are other important variables.

Age of trees is important in the process of selection of cavity trees by RCW primarily because in young trees the heartwood available in the trunk is not large enough in size to allow the excavation of a complete cavity (Conner and O'Halloran 1987; Conner *et al.* 1994b). Conner and Rudolph (1994 cit. in Conner *et al.* 1994b) state that a 15 cm diameter of heartwood is sufficient to house a RCW cavity. Another aspect associated with

heartwood diameter is the proportion of heartwood to sapwood since the flow of resin from the sapwood can inactivate a cavity (Conner and O'Halloran 1987).

Older trees allow the construction of cavities at higher positions on the trunk because the height of adequate heartwood volume increases with age (Jackson and Jackson 1986; Conner and O'Halloran 1987; Rudolph and Conner 1991). Cavities located high in the trunk are distant from the understory, a limiting factor of RCW habitat (Jackson and Jackson 1986). The height of the cavity creates protection against predators (Conner and O'Halloran 1987) and fire damage (Conner and Locke 1979). Age is also important in the selection of cavity trees because older trees with larger diameters possess the properties that allow the formation of typical resin wells and plates (Jackson and Jackson 1986). Protection against predators can be more efficient in old trees because certain resin properties, such as slower resin crystallization, are maintained for a longer period of time (Conner and O'Halloran 1987).

Age is also related to the probability of infection by fungi causing heartwood decay, which facilitates the excavation of cavities by red-cockaded woodpeckers (Lay and Russell 1970; Ligon 1970; Conner and Locke 1982; Conner and O'Halloran 1987; Hooper 1988; Conner *et al.* 1994b). *Phellinus pini* is the most common fungus causing heartwood decay in pines, but others can also be responsible for this disease (Conner and Locke 1982). Loblolly and shortleaf pines have heartwood decaying fungi more often than longleaf pines (Conner and Locke 1982). Wahlenberg (1946, 1960 cit. in Conner and O'Halloran 1987) found that, for ages under 75 years, loblolly pines have a lower frequency of heartwood decaying fungus infection. Hepting (1971 cit. Jackson and Jackson 1986) states that

southern pines less than 60 years old are rarely infected by *Phellinus pini*. In South Carolina, Hooper (1988) found frequencies of heartwood decaying fungus in 97% of longleaf pines which were cavity trees over 100 years old and 86% in cavity trees less than 80 years. Non-cavity trees less than 80 years old contained heartwood decaying fungus in just 9% of the cases. In two national forests in Florida the same authors detected an occurrence rate of heartwood decaying fungus of 80% and 90% for trees older than 100 years, and 32% for trees younger than 80 years old.

Selection of cavity trees by RCW seems based on an individual tree's age more than on the stand's age (Conner and O'Halloran 1987; Rudolph and Conner 1991). Rudolph and Conner (1991) using data from three national forests concluded that in Texas, RCW selects cavity trees from the oldest available trees. Woodpeckers seem to select individual trees that exhibited suppression followed by release (Conner and O'Halloran 1987). As a consequence of suppression, trees drop their lower branches, boles became open, additional heartwood can be formed, and susceptibility to fungal heartrot increases (Conner and O'Halloran 1987). Hooper (1988) suggests that RCW use the trees that are easiest to excavate - those with the presence of decayed heartwood or rapid diameter growth. Growth rate impacts the selection of trees for cavity excavation. Species with rapid growth, besides reaching suitable sizes faster, also present wood characteristics that facilitate excavation (Jackson and Jackson 1988).

In the Francis Marion National Forest in South Carolina and the Noxubee National Wildlife Refuge in Mississippi, young trees were more abundant than the trees chosen for excavation by woodpeckers (Jackson *et al.* 1979). In the Francis Marion National Forest,

80% of the loblolly pine stands were less than 50 years old, but the mean age of trees with cavity initiation was 77.4 years old (Jackson *et al.* 1979).

Data from Florida and North Carolina suggest a threshold requirement of loblolly pine trees above 60 years in age for continuous stand occupancy (DeLotelle and Epting 1988). The presence of trees older than 90 years in the stand can increase RCW population density (DeLotelle and Epting 1988).

In South Carolina and Mississippi, loblolly pines where cavity initiation was not completed had a mean age of 75 years (Jackson *et al.* 1979). In the same study, loblolly pines with just one completed cavity averaged 80.6 years ($sd=11.06$). Rudolph and Conner (1991) provide evidence that the mean age of recently initiated trees does not differ from cavity trees.

The studies of Loeb *et al.* (1992) and Thomlinson (1993) present data regarding tree age for colonies and for the stands where the colonies are located. In the Piedmont of Georgia, Loeb *et al.* (1992), using circular plots of 0.01 acres for characterization of colonies, obtained a mean value of 87 years ($sd=1$ year) for stands having active colonies, while in the Sam Houston National Forest 72 years (range=51-103) was the mean age of stands where RCW colonies occurred (Thomlinson 1993). Data from the Continuous Inventory of Stand Condition (CISC) database (USDA Forest Service) was used in this work. This value was found to be significantly different from the age of stands having the same silvicultural conditions (loblolly and shortleaf sawtimber) but that were not colonized.

Diameter at the Breast Height

Diameter at the breast height (dbh) has an intimate relationship with tree age. Like age, dbh of cavity trees is significantly different from trees not selected for cavity excavation by RCW (Hovis and Labisky 1985; Conner and O'Halloran 1987; Hooper 1988; Engstrom and Evans 1990; Conner *et al.* 1994b). Mean values ranging from 40 cm to about 53 cm for loblolly and shortleaf pines were observed in national forests in Texas (Lay and Russell 1970; Conner and O'Halloran 1987; Conner and Rudolph 1989).

Basal Area

It is generally accepted that RCW require open and park-like pine stands for nesting and roosting habitat (Ligon *et al.* 1986; Conner and Rudolph 1989). Basal area and number of stems per unit area are measures of density that have been evaluated in RCW colonies in relation to various other components in the stand (Lay and Russell 1970; Conner and O'Halloran 1987; Conner and Rudolph 1989; Kalisz and Boettcher 1991; Loeb *et al.* 1992). I chose to include in this study these particular components in order to evaluate the importance of each in the definition of habitat suitability. Total basal area and total number of stems per unit area include all the individual trees, independent of species, and the position they occupy in the vertical structure of the stand. Overstory basal area and number of stems refers to the dominant pine species and is very often similar to the total values when hardwood midstory basal area is reduced. Midstory basal area and number of stems includes the individuals below the overstory and above the understory levels. Hardwood midstory is the part of the midstory composed just of hardwood species.

Total Basal Area

Total basal area of the stands where RCW establish colonies can be an indicator of the overall density in a stand. It is, however, a relatively limited variable in terms of the information it can provide about specific aspects of basal area which are more directly related to stand suitability for RCW. In the literature, several values are referred to as reflecting the mean conditions of colonies. For loblolly and shortleaf pine stands expect mean values for total basal area ranging from 11 m²/ha to 23 m²/ha (Conner and O'Halloran 1987; Conner and Rudolph 1989; Kalisz and Boettcher 1991; Loeb *et al.* 1992). Hooper *et al.* (1980 cit. in Kalisz and Boettcher 1991) recommended the basal area as ranging from 4.6 to 7.4 m²/ha in pine habitat. The typical range seems to be between 5 and 15 m²/ha (Hovis and Labinsky 1985; Conner and Rudolph 1989).

Loeb *et al.* (1992) found statistically significant differences in both total basal area and total number of stems per unit area between stands with active colonies and stands with inactive colonies. In different locations over the area of distribution of RCW, significant differences in total basal area between stands supporting colonies and stands selected randomly were also observed (Loeb *et al.* 1992; Conner and O'Halloran 1987).

Overstory Basal Area

Conner and Rudolph (1989) noticed high pine basal area in the colony as a factor that could contribute to the decline of RCW in the Angelina, Davy Crockett, and Sabine National Forests in eastern Texas. Although the pine basal area within the colonies was acceptable, 20 m away from each cavity tree it rose rapidly. Hovis and Labisky (1985)

found significant differences in overstory stem density between areas within a 200 m circle around colonies and areas between 200 and 400 m away from the center of the colonies. Areas close to colonies presented lower basal area (median=10.6 m²/ha, range 5.0-19.2 m²/ha) than areas distant from colonies (median=15.0 m²/ha, range=6.7-26.3 m²/ha). These differences were not, however, statistically significant. Conner and O'Halloran (1987) recommend for colonies pine basal area of approximately 9 m²/ha, the limit of the basal area interval (9-14 m²/ha) defined by Hooper *et al.* (1980 cit. in Conner and O'Halloran 1987).

Using mean stand measurements of basal area, Thomlinson (1993) showed hardwood sawtimber basal area influenced colony activity more than poletimber basal area. Comparing active and inactive colonies, the same author found sawtimber basal area to be the only timber variable to have a significant effect on the colony status.

Midstory Basal Area

Hardwood midstory is another of the major factors which determines nesting habitat suitability for RCW. It is generally accepted that midstory encroachment is one of the reasons for the reduction in RCW populations in the last decades as fires were excluded or reduced in frequency (Van Balen and Doerr 1978; Ligon 1986; Conner and Rudolph 1989; Thomlinson 1993).

When the hardwood midstory reaches the height of the cavities, RCW abandon these cavity trees (Loeb *et al.* 1992). This behavior is even stronger when the midstory blocks cavity access (Van Balen and Doerr 1978). Hardwood midstory increases the competition for cavity trees with red-bellied woodpeckers and flying squirrels (*Glaucomys*

volans), and increases the frequency of enlargement of RCW cavities by pileated woodpeckers (Conner and Rudolph 1989).

In two areas in North Carolina, Van Balen and Doerr (1978) found statistically significant differences between cavity trees and randomly selected trees in basal area and the total number of stems of hardwood understory (trees less than 14 m in high) within 0.01 ha. In the Apalachicola National Forest of Florida, significant differences in midstory stem density and midstory crown area between areas around the colony (within a 200 radius circle) and areas distant from the colony (defined between 200 and 400 m away from the center of the colonies) were observed (Hovis and Labisky 1985).

Colonies that became inactive after 1983 in the Angelina and Davy Crockett National Forests of Texas contained significantly higher hardwood midstory than colonies still active in 1987 (Conner and Rudolph 1989). Discriminant function and logistic regression analyses indicated that hardwood midstory was the determining factor in the inactivity of colonies from 1983 to 1987.

In the Piedmont of Georgia, Loeb *et al.* (1992), using areas of 0.01 acres (0.004 ha), found statistically significant differences between active and inactive colonies in terms of total hardwood basal area and midstory hardwood basal. Differences in the number of total hardwood stems per unit of area and midstory hardwood stems per unit of area were also observed, but were not statistically significant.

At the northern extreme of the distribution of the species, in the Daniel Boone National Forest in Kentucky, Kalisz and Boettcher (1991) did not find differences in hardwood live crown density at the cavity height (a measure of hardwood density) using

circular plots of 0.01 ha around cavity trees. The authors concluded that midstory encroachment was not the reason for abandonment of cavity trees in that area.

Conner and O'Halloran (1987), comparing stand conditions around active cavity trees and trees randomly selected, observed significant differences in basal area of midstory hardwoods and midstory height. Loeb *et al.* (1992) found statistically significant differences between active and inactive colonies in terms of pine midstory basal area, total midstory basal area (pine + hardwood), and total number of midstory stems per acre. More than just hardwood midstory, all midstory trees, independently of the species or vegetation type present, seems to affect the activity of RCW colonies. Data from Conner and O'Halloran (1987) support this idea. They found significant differences in both hardwood and pine midstory basal area of colony stands and stands selected at random. Using a logistic regression model based on midstory basal area Loeb *et al.* (1992) present a value of 30 ft²/ac (6.9 m²/ha) as the maximum limit for RCW habitat suitability.

Foraging Habitat

In addition to nesting and roosting habitat, red-cockaded woodpeckers use large areas for foraging activity. Foraging areas are called *home ranges* (Burt (1943 cit. in DeLotelle *et al.* 1987)) or *total observed ranges* (Hooper *et al.* 1982) and include all the foraging habitat of a clan. Occasionally, the birds forage within the colony areas (Nesbitt *et al.* 1987). Home ranges or total observed ranges include areas which are defended by the clans, designated as *territories* (Burt (1943 cit. in DeLotelle *et al.* 1987) or *home range* (Hooper *et al.* 1982). Territorial boundaries result from habitat limitations and the

territories of other groups (Ligon, 1970). The number of groups in a population is determined by the distribution of cavity tree clusters and the number of acceptable territories (Walters 1991). Defense of territories is a main activity of all individuals in groups (Ligon, 1970). Home ranges can cover from less than 50 ha to over 400 ha depending on habitat quality (Conner and Rudolph 1989)

In central Florida the mean size of home ranges of six groups of RCW was 150.0 ha (sd=32.9ha; range=116.2-198.8 ha) and territory was 116.1 ha (sd=27.5ha; range=92.7-154.9 ha) (DeLotelle *et al.* 1987). Also, in central Florida the mean home range observed for three clans based on three days' observations was 69.8 ha (max=91.4, min=58.4 ha) (Nesbitt *et al.* 1978). Porter and Labisky (1986) observed year-round home ranges for four clans of 129 ha (sd=31ha; max=157 ha; min=85 ha) in northern Florida.

In South Carolina, total observed ranges ranged from 34 to 225 ha but the mean total observed range was 86.9 ha (± 44.2) (Hooper *et al.* 1982). For two clans in South Carolina, Skorupa and McFarlane (1976) registered year round home ranges of 48.3 and 80.4 ha.

Foraging habitat can be extremely diversified. Ligon (1970) observed birds foraging mainly in longleaf pine trees but also in cypress (*Taxodium distichum*) and pecan trees (*Carya illinoensis*). In northern and central Florida, RCW foraging habitat includes stands of longleaf pine and other pine species (*Pinus elliottii* and *Pinus serotina*), hardwood stands, savannahs, swamps dominated by several species, and open areas such as pastures and recent timber clearcuts (Porter and Labisky 1986; Nesbitt *et al.* 1987; DeLotelle *et al.* 1987). The land use of the area studied by DeLotelle *et al.* (1987) was composed of pine

flatwoods (88.1%), cypress domes and bayheads (8.6%), and wet prairie and open areas (3.3%).

In central Florida woodpeckers spent 90% of their foraging time in longleaf pine stands and the remaining time in cypress stands (DeLotelle *et al.* 1987). Unlogged pine stands were used relatively intensively: 41% of home ranges and 59% of foraging observations (DeLotelle *et al.* 1987). Stand use was found to be correlated with pine stand size (DeLotelle *et al.* 1987).

In the areas where foraging behavior was observed, red-cockaded woodpeckers showed a high preference for live pine species (Hooper and Lennartz 1981; Porter and Labisky 1986; DeLotelle *et al.* 1987). Snags and live hardwoods were also extensively used as foraging habitat by red-cockaded woodpeckers (Conner *et al.* 1994a).

In central Florida, pine flatwoods were available in 71% of the area and used in 82% of the foraging time by red-cockaded woodpeckers (Nesbitt *et al.* 1978). In northern Florida longleaf pine was preferred by the woodpeckers in 99% of the registered observations, in spite of its availability being only 69% (Porter and Labisky 1986). Slash pine occupied 12% of the foraging habitat but was used in just 1% of the cases (Porter and Labisky 1986).

Hooper and Lennartz (1981) observed in coastal South Carolina that live pines (longleaf and shortleaf) were selected on average 163 times more frequently than hardwoods. Pines were selected 96% of the times the birds foraged when its availability was 71.3%. Hardwoods, with a 24.6% availability, and cypress, with 1.9% availability, respectively, accounted for 0.9% and 0.1% of selections for foraging.

Cypress was used in 12% of the foraging time of a clan located in an area where the availability of pine stands was more reduced than the other areas (Hooper and Lennartz 1981). Hardwood stands were not avoided, but there foraging was mainly in the existing pine trees (Hooper and Lennartz 1981). In northern Florida birds prefer stands with certain requirements of height and dbh. When they use these stands for foraging activity, they choose the individual trees that meet the preferred criteria (Porter and Labisky 1986)

In territories of central Florida, pine stands within territories were young, ranging from 17 to 53 years (DeLotelle *et al.* 1987) Old trees (110 years) were also found. Sensitivity analyzes revealed age to be more important than density in determining stand use (DeLotelle *et al.* 1987). Porter and Labisky (1986) observed in northern Florida that the stands preferred for foraging activity had a mean age of 72 years, but the stands used for foraging ranged in age from 17 to 60 years

The age of trees preferred for foraging is related to the bark's flaking off and the bark plate size, both of which increase the conditions needed for arthropods to hide and which allow the "scaling" foraging behavior of the woodpeckers (Jackson and Jackson 1986). Older trees also have an increased height and structural diversity favorable to the creation of better and more diverse foraging conditions than young trees do (Jackson and Jackson 1986) Age of the stands used for foraging also influences the home range size (Jackson and Jackson 1986). When foraging stands are large, isolation of colonies increases and is conducive to the inactivation of colonies (Jackson and Jackson 1986).

In South Carolina, foraged pine trees had dbh mean values of 29.5 cm for males and 29.8 cm for females (Hooper and Lennartz 1981). Here the woodpeckers preferred pines greater than 23 cm dbh and avoided pines less than 13 cm dbh (Hooper and Lennartz 1981)

Territories in central Florida presented mean values of pine basal area and numbers of pine stems of 267.6 ft²/ac (61.4 m²/ha) (range=204.6-355.8 ft²/ac) and 9768 stems above 6 cm in dbh (24,137 stems/ha), respectively (DeLotelle *et al.* 1987). In northern Florida, RCW choose stands for foraging with height above 20 m and dbh above 20 cm (Porter and Labisky 1986).

In the area analyzed by DeLotelle *et al.* (1987), territories occupied about 95% (mean) of the available habitat. Territory size was correlated with the area of suitable habitat within a 2000 m radius for each group of cavity trees (DeLotelle *et al.* 1987). Hooper *et al.* (1982) also found a relationship between home range size and variables reflecting habitat quality. This relationship was, however, relatively weak.

A high frequency of extraterritorial foraging and group interactions can be interpreted as an indicator of poor habitat quality. Porter and Labisky (1986) suggest that the foraging habitat composition influences the size of home ranges. Nesbit *et al.* (1983) in DeLotelle *et al.* 1987) contends that habitat quality is the most important factor in determining home range size. In central Florida territories and home ranges of RCW are larger than in South Carolina but contain less pine basal area (DeLotelle *et al.* 1987). Central Florida RCW groups use larger habitat areas in their territories as a result of poorer habitat quality than that in South Carolina (DeLotelle *et al.* 1987). In the area studied population density is a major constraint in group territory size (DeLotelle *et al.* 1987).

Foraging in small stems (down to 5 cm dbh (DeLotelle *et al.* 1983 cit in DeLotelle *et al.* (1987)) (21% use of 5-11 cm dbh class) and in cypress is interpreted as compensation behavior for poor quality habitat (DeLotelle *et al.* 1987). Also, in coastal South Carolina cypress use was higher when pine availability was reduced (Hooper and Lennartz 1981). In South Carolina RCW foraged in hardwoods during the winter in 10% of the cases (Skorupa and McFarlane 1976) These authors suggested a limitation in prey in pine trees during the winter season. The home ranges of the clans considered in this study were relatively small in size. Hooper *et al.* (1982) suggested that in South Carolina year-round range sizes are determined by the density of colonies that divide the available suitable foraging habitat.

Fragmentation and Connectivity of the Red-cockaded Woodpecker Habitat

Fragmentation of habitats is characterized by 4 components (1) general loss of habitat area, (2) decrease in the size of habitat patches, (3) increase in distance between patches, and (4) increase in resistance to dispersal movements of organisms (Opdam *et al.* 1995). McGarigal and McComb (1995) add to this set of components the change in the configuration of habitats resulting from fragmentation. The habitat configuration is especially important to animal species in terms of movement patterns, intraspecific and interspecific interactions among individuals, and juxtaposition of habitats (McGarigal and McComb 1995)

Red-cockaded woodpecker populations are affected by habitat fragmentation resulting from timber management of the southern pine forests of the United States, particularly prior to 1968-1973 (Rudolph and Conner 1994). Conner and Rudolph (1991)

found evidence of fragmentation effects on RCW group size due to habitat loss (foraging insufficiency, components (1) & (2) above) in small populations of isolated clusters. In large and dense populations such as in the Raven district of the Sam Houston National Forest, however, the effects were not similar. Isolation (component (3) above) and forest removal within 800 m around colonies were negatively correlated with cluster activity. Rudolph and Conner (1994) in the same area detected significant correlations between the size of areas with forest older than 60 years (component (2) above) and the number of colonies, the number of woodpeckers, and the number of woodpeckers per colony. The same variables were not correlated to the size of the area when below 60 years of age. Colony activity in the Raven district was also detected to be dependent on stand size in the work of Thomlinson (1993)

Fragmentation in terms of a decrease in movement conditions in the landscape (component (4) above) seems to be the main constraint on the maintenance of RCW populations (Rudolph and Conner 1994). In fact, demographic dynamics of the species are based on the movements of individuals, primarily females, among clusters (Walters 1988). Rudolph and Conner (1994) suggest that the distribution pattern of clusters of RCW in the Raven District is better explained by differential attrition of active clusters related to the extent of forest fragmentation. This pattern decreases the dispersal efficiency of fledgling females, which increases the difficulty of locating active clusters with vacant breeding positions by these females. As a consequence, colonies remain without a breeding female and group size decreases. The results observed can also be attributed to the lack of nesting trees.

In spite of the absence of specific data about the topic, it seems reasonable to think that RCW individuals prefer to move within forest stands, particularly within those more suitable either for nesting or foraging habitat (R.N. Conner and D.C. Rudolph 1995, USDAFS, personal communication). The absence of landscape conditions that allow movement of individuals will irreversibly interrupt the reproduction of groups where a female is not present.

Indications of a decrease in landscape conditions conducive to movement can be taken from the work of Thomlinson (1993) in the Raven District of the Sam Houston National Forest. Variables such as stand size, stand shape, patch configuration, patch tortuosity, distance between patches, connectivity, habitat types surrounding colonies, and corridors and barriers between colonies are related to this component of fragmentation. In the work of Thomlinson (1993) the results of the application of these variables seem to corroborate the hypotheses of Rudolph and Conner (1994).

Increased distances among patches with inactive colonies was detected by Thomlinson (1993) in the Raven District. Here, distances to the nearest colonies were significantly higher for inactive colonies than for active colonies: “72% of the active colonies and 53% of the inactive colonies were within a linear distance of 500 m. 32% of the inactive colonies were more than 1 Km away from the closest active colony, compared with only 7% of the active colonies” (Thomlinson 1993). Isolation, quantified using three different coefficients, was significantly higher for inactive colonies than for active colonies when radii of 4000 m and 1130 m were used (Thomlinson 1993). When a radius of 390 m was used, no significant differences were observed.

Variables associated with isolation and connectivity, the stand size and the stand shape, were revealed to be different between active and inactive colonies. Stands where active colonies are present are bigger than stands with inactive colonies (Thomlinson 1993). The values for the configuration and tortuosity indexes used by Thomlinson (1993) were also significantly different between active and inactive colonies.

Habitat types surrounding colonies is another factor related to forest fragmentation. Thomlinson (1993) found that stands with inactive colonies share their perimeter with open areas such as pastures and pastures plus water significantly more often than stands with active colonies.

Active and inactive colonies in the Raven district present differences in connectivity as expressed by the analysis of corridors and barriers made by Thomlinson (1993). Inactive colonies are more likely to have circuitous corridors or barriers between them, and active colonies are more likely to have direct corridors between them.

LANDSCAPE ECOLOGY AND GEOGRAPHIC INFORMATION SYSTEMS

Landscape ecology is an emergent field in ecology and land sciences defined as the “study of structure, function and change in a heterogeneous land area composed of interacting ecosystems” (Forman and Godron 1986). The structure of a landscape is the distribution of energy, materials, and species in relation to the sizes, shapes, numbers, kinds, and configurations of landscape elements or ecosystems (Forman and Godron 1986). Matrix, patches, and corridors are considered the essential structural elements of a

landscape. The measure of how connected corridors or matrix are in a landscape is designated by connectivity (Forman and Godron 1986).

Methods for quantification of landscape patterns were developed to compare different landscapes, to identify significant changes through time, and to relate landscape patterns to ecological function (Turner 1989). Landscape richness, evenness, patchiness, dominance, contagion, and diversity result from the application of Information Theory to Landscape Ecology (Turner 1989, Turner 1990, Li and Reynolds 1993). Landscape pattern complexity can be evaluated based on the quantification of shapes and boundaries using fractals (Turner 1989), and complexity of patch perimeter can be measured based on edge to area relationships (Turner 1990). Complete landscapes can also be evaluated in terms of fractal dimension (Milne 1988; Olsen *et al.* 1993). Contagion, nearest neighbor probability, and edge measurements are used to express the degree to which landscape elements are connected (Turner 1989; Turner 1990).

The relationship between landscape patterns and ecological processes has received particular attention by scientists in the last decade. Turner and Bratton (1987) studied disturbance phenomena such as fire and grazing in a heterogeneous landscape in Georgia. Animal movements at landscape levels have been analyzed based on Neutral Models and Percolation Theory (Gardner 1987 cit. in Turner 1989; Johnson *et al.* 1992) and MAP models (Models of Mobile Animal Populations) (Pulliam *et al.* 1995). Other approaches have been used in the analysis of ecological processes in heterogeneous landscapes involving several groups of animals affected by fragmentation processes. Population demography of the euro kangaroo was related to habitat fragmentation in Australia (Arnold

et al. 1993). Forest fragmentation at a landscape level was related to pairing success in ovenbirds in Québec, Canada (Villard *et al.* 1993). Thomlinson (1993) analyzed the red-cockaded woodpecker colony status in terms of spatial habitat characteristics in the Sam Houston National Forest in Texas. The influence of the forest structure on the abundance of breeding birds was studied in the Oregon Coast Range (McGarigal and McComb 1995)

Metapopulation theory has been used as a demographic model in ecological studies on a broader scale (Opdam 1991; Opdam *et al.* 1995; Arnold *et al.* 1993; Pulliam *et al.* 1995). Metapopulation theory emerged from the recognition that small populations are not independent of other populations in the surrounding habitat (Pulliam *et al.* 1995).

Landscape structure and pattern can be expressed in terms of heterogeneity, which is defined as the composition of parts of different types (Kolasa and Rollo 1991). Measured heterogeneity, the classical perspective of heterogeneity and expressed by patch diversity, patch size, shape, etc., is probably not the most appropriate approach in analyzing landscapes from the point of view of an entity of interest, since this perspective constitutes an oversimplification of the system and is independent of that entity (Kolasa and Rollo 1991).

Functional heterogeneity, on the other hand, is the heterogeneity directly related to an entity of interest - an individual, species, population, or community (Kolasa and Rollo 1991). In the case of a population observed at a landscape scale, functional heterogeneity represents how this population perceives and responds to heterogeneity (Kolasa and Rollo 1991). Coulson *et al.* (1994) forecast the epidemiology of pine beetles in a heterogeneous forest landscape of East Texas applying a methodology based on this concept.

The emergence of landscape ecology follows the development of technology capable of performing spatial and temporal analysis in large surface areas. Geographic Information Systems (GIS) are among these new technologies and are one of the most successfully used. Even though several kinds of spatial analyses had been made before the wide availability of GIS (Johnston 1990), the development of this tool creates promising perspectives for quantification and analysis of patterns and processes over extensive territories. GIS is a helpful tool in the study of change in landscape structure, the factors that control landscape pattern, the effect of landscape patterns on ecological processes, the relationship between measurements of landscape pattern and ecological function, the effect of landscape pattern in disturbance propagation, and prediction of landscape changes based on simulation models (Turner 1990).

In ecology the use of GIS has been concentrated on characterization and measurement of linear and areal features, intersection of georeferenced data, and proximity analyses (Johnston 1990). Commercial GIS packages, however, lack adequate capabilities for computing classical landscape structure measurements (Baker and Cai 1992), so specific programs have been developed for particular applications in landscape ecology (Turner 1990; Baker and Cai 1992; Gustafson and Parker 1992). SPAN, a grid-cell based spatial analysis program, was developed to quantify landscape patterns and changes, and to evaluate predictions of spatial simulation models (Turner 1990). SPAN measures the proportion of landscape occupied by each landscape category, size and perimeter of each patch, fractal dimension of patch perimeters, edges between each pair of categories, probabilities of adjacency between categories, and diversity, dominance, and contagion

indexes. Gustafson and Parker (1992) modified SPAN creating HISA (Habitat Island Spatial Analysis) to quantify spatial patterns of landcover types from TM (Thematic Mapper) satellite images.

Baker and Cai (1992) developed programs for GRASS GIS that measured landscape structure variables. Measured variables included distance, size, shape, fractal dimension, perimeters, diversity, texture, juxtaposition, and edges.

CHAPTER III

STUDY AREA

The current project was conducted on the Raven District of the Sam Houston National Forest (SHNF), an area located in Southeastern Texas (Figure 1), at the extreme western edge of the pine forests that follow the Atlantic and Gulf Coastal Plain physiographic provinces. Thomlinson (1993) provides a detailed description of the area of study. For this reason, only relevant aspects for this particular study will be mentioned.

FOREST STANDS IN THE RAVEN DISTRICT

The Raven District is the largest and most continuous forested area of the Sam Houston National Forest. With a total area of 66,000 ha, the Raven District includes 39,200 ha of forested area. The Raven district is located between longitude 95° 56' and 95° 22' West and latitude 30° 26' and 30° 45' in Montgomery and Walker Counties. The district is comprised of 79 compartments (administrative units with a average area of 520 ha in the SHNF (Rudolph and Conner 1994)) (Figure 2) Stand size averages 19.25 ha, ranging from 0.1 ha to 537 ha. Adjacent private land is typically pasture and short rotation pine plantations, habitats which are in general not suitable for RCW (Rudolph and Conner 1994).

The dominant forest species is loblolly pine, *Pinus taeda*, but some shortleaf pine, *Pinus echinata*, occurs (Figure 3; Appendix 1) Hardwoods are usually well-developed in the midstory of pine stands (Rudolph and Conner 1994). The forest stands are managed

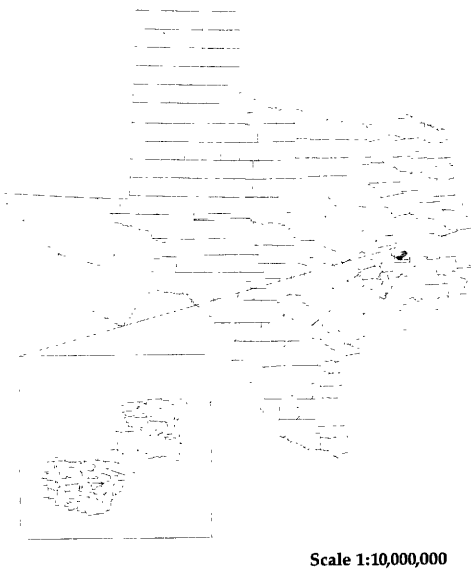
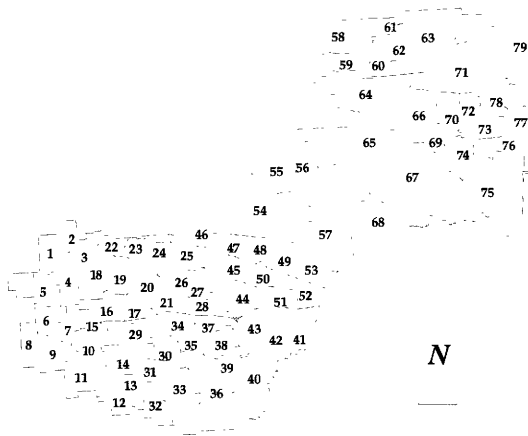


Figure 1 - Location of the Raven District of the Sam Houston National Forest.



Scale 1:325,000

Figure 2 - Compartments in the Raven District.

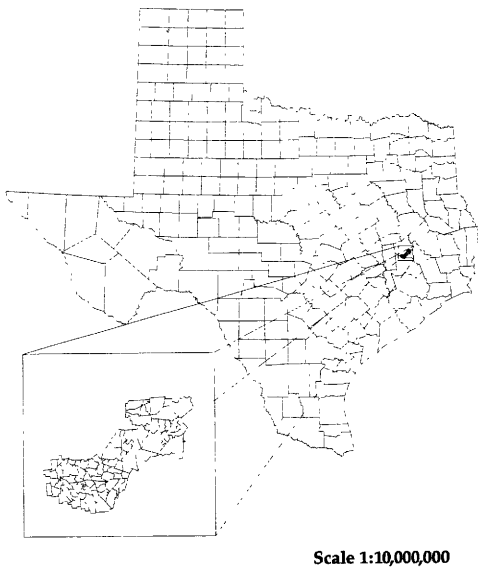
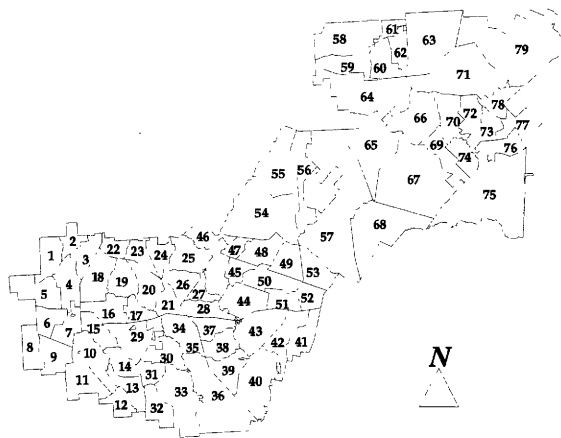
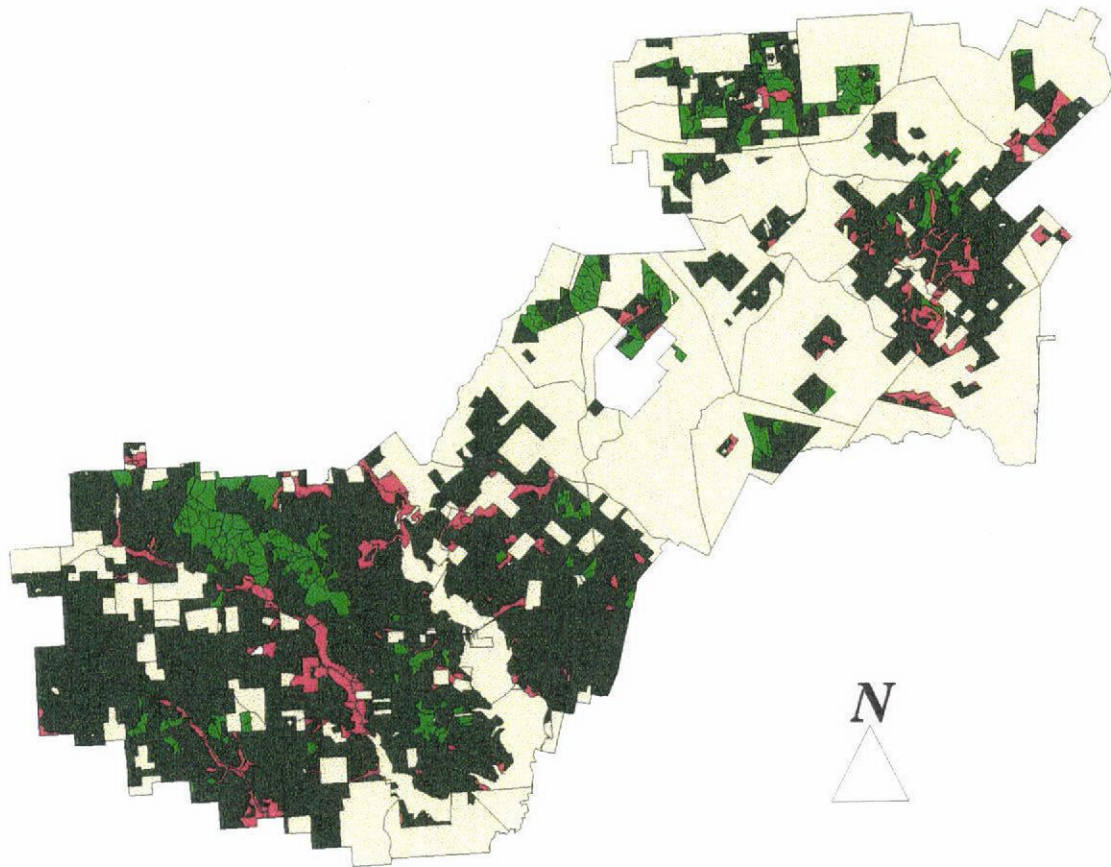


Figure 1 - Location of the Raven District of the Sam Houston National Forest.



Scale 1:325,000

Figure 2 - Compartments in the Raven District.



- Loblolly pine
- Shortleaf pine
- Other

Scale 1:325,000

Figure 3 - Forest Type Distribution in the Raven District.

using even-aged regeneration methods (Rudolph and Conner 1994). Until this year there had been no timber cuts in the Raven district since 1989 (Thomlinson 1993).

The loblolly and shortleaf pine stands in the district are generally young. About 87% of the area occupied by pine stands has an age below 80 years, and just 1% is above 100 years (Appendix 2). The stands are managed mainly for the growth of large sized materials. In 67% of the area, stands contain mature, immature, low quality, or sparse sawtimber (Appendix 3).

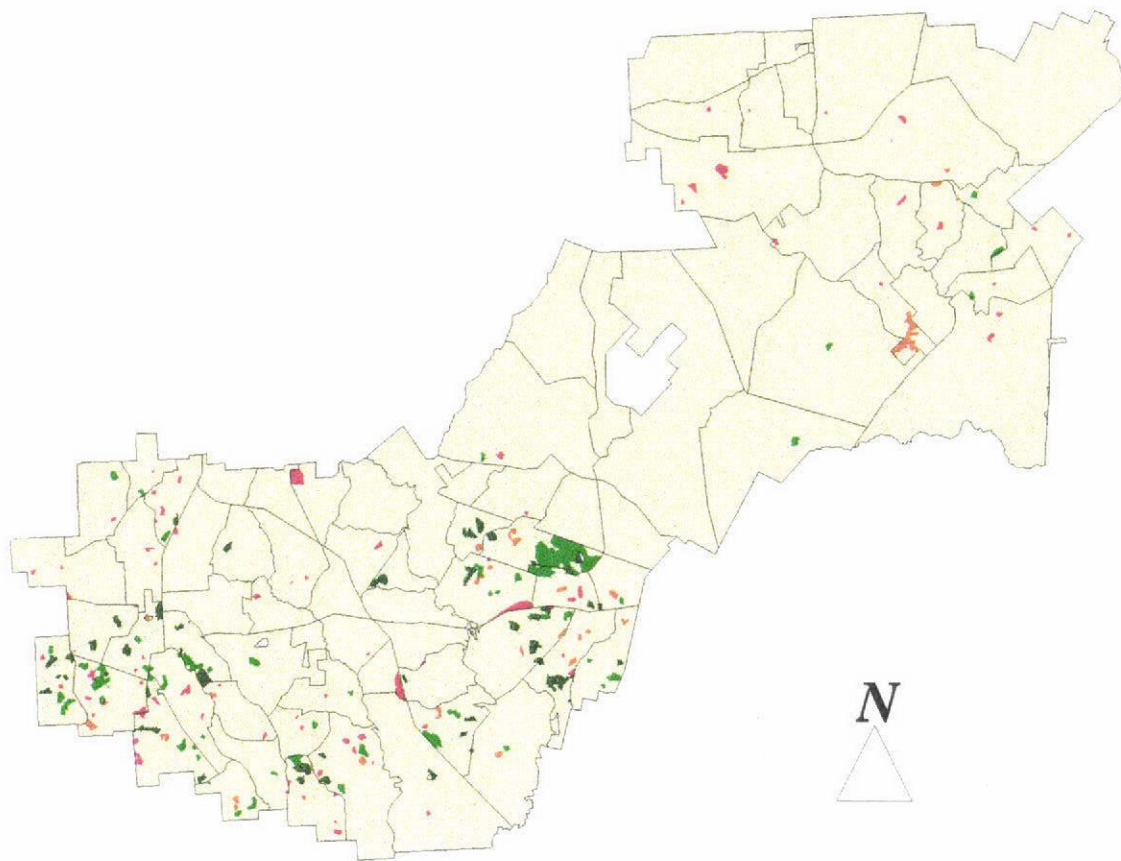
RED-COCKADED WOODPECKER IN THE RAVEN DISTRICT

The Raven District contains the majority of the population of red-cockaded woodpeckers in the Sam Houston National Forest and maintains one of the highest population densities of this species in the country (Rudolph and Conner 1994). The district contains 125 active colonies, with at least one active cavity tree, and 85 inactive colonies, colonies where no active cavity trees were found in the last survey. The area of forest per active colony is 314 ha. When considering solely pine forests, the area per active colony is 285 ha. Active colonies have, on average, 3.2 cavity trees, with the minimum and maximum number of cavity trees, respectively, 1 and 8. Active cavity trees are mostly natural cavity trees, but some artificial cavities are being used by red-cockaded woodpeckers.

The Forest Service uses Replacement and Recruitment Areas in the management of the RCW population in this area. Replacement Areas are areas with the required nesting and roosting habitat conditions located close to existing active colonies. The objective of this practice is to provide suitable habitat for a clan in the case of destruction of the actual

cluster of cavity trees. Recruitment Areas have the same habitat conditions but are located in unpopulated or low population density regions. They are used to attract new birds to these regions and in this way increase the number of active colonies and the overall population. Both types of areas are 10 acres in size. There are 208 replacement and 74 recruitment stands in the Raven District

In the Sam Houston National Forest 69.6% of the colonies have 2-3 roosting birds, 21.4% a single bird, and the remaining 9% from 4 to 7 roosting birds (Rudolph and Conner 1994). From our data, collected in 1994, there are 20% of the colonies with one active cavity tree, 43% with 2-3 active cavity trees and 37% with 4 or more active cavity trees. The distribution of colonies in the study area is shown in Figure 4.



- Inactive colony
- Active colony: 1 cavity tree
- Active colony: 2-3 cavity trees
- Active colony: 4 or more cavity trees

Scale 1:325,000

Figure 4 - Distribution of Active and Inactive Colonies in the Raven District.

CHAPTER IV

METHODOLOGY

MATERIAL

Arc/Info GIS software was used for spatial data representation, database management, habitat classification, and display. The functional heterogeneity analyses were conducted using FORTRAN programs on a UNIX platform. Additional software included Excel. The hardware used includes an Intergraph TD1 personal workstation, Sun Sparc workstations, and the SGI Power Challenge super computer located at the Texas A&M University.

DATA

In this project, I used data provided by the Raven District of the Sam Houston National Forest (SHNF), United States Department of Agriculture Forest Service (USDAFS). A GIS coverage for the area and a hard copy of data concerning red-cockaded woodpecker was provided by the district. A complementary data set from the Continuous Inventory of Stand Conditions (CISC) database was also provided.

THE GIS STANDS COVERAGE

A GIS coverage of the Raven District of the Sam Houston National Forest was obtained directly from the Raven District. This coverage includes 3383 polygons. Details

about this coverage are provided in Appendix 4, with additional information presented in the Study Area Chapter.

The GIS coverage includes lines relative to roads, 'quad' maps, and other linear features dividing the forest stands. For this reason the GIS coverage presents, in many cases, more than one polygon belonging to the same stand. I did not change this situation since a unique attribute existed that could group the polygons belonging to the same stand, and because the main analysis was done using raster format which was not affected by this delineation.

A large group of attributes were included in the table associated with the polygons of the graphic coverage. From this table I extracted the variables that would be used to perform the analyses. The attributes of interest in the project and the definitions as provided by USDAFS (1993) follow.

- **RAVSTAND#**: number of each polygon in the coverage. It is the attribute with unique values
- **AREA**: area of each polygon (ft^2). It is calculated automatically by the GIS.
- **COMP_NO**: compartment number
- **STAND_NO**: stand number "A stand is a community of trees possessing sufficient uniformity in composition, constitution, age, spatial arrangement or condition, to be distinguishable from adjacent communities, so forming a silvicultural or management entity"

- **LNCL**: land class. “Timber land suitability classification for National Forests land.

Two broad categories are considered: suitable and unsuitable for timber production”.

- **STCN**: stand condition “A classification of the woody growth occupying the stand that incorporates a broad evaluation of (1) the adequacy of stocking, (2) size of material, (3) thrift, (4) age, and (5) success in meeting planned product objectives”.

- **FRTY**: forest type. “Classification of the forest overstory cover type currently existing on the stand Forest type is based on one or more species of trees that comprise the main crown canopy (i.e. dominants and co-dominants)”. I am particularly interested in pine types defined as “stands in which 70% or more of the basal area of trees with dominant or co-dominant crowns are softwoods, the specific name represents the species comprising the plurality”.

- **AGYR**: age of the stand. “The calendar year of stand origin” (USDAFS 1993).

For simplification of the analysis, I created a new attribute **AGE** from the existing **AGYR** attribute. The **AGYR** variable includes the last three digits of the year of the stand origin The new variable **AGE** was defined as follows: $AGE = 995 - AGYR$

The stands table originally contained values for basal area of pine poletimber, pine sawtimber, hardwood poletimber, hardwood sawtimber, and diameter at the breast height of pine poletimber, pine sawtimber, hardwood poletimber, and hardwood sawtimber. I detected some inconsistencies in the values of these timber attributes, particularly the values

for pine poletimber and sawtimber basal area and diameter at breast height, relative to hardwood poletimber and sawtimber basal area and diameter at breast height. The CISC database was used to assess the values of these variables. The timber variables originally contained in the stands table were redefined and new attributes were created.

The final timber attributes that I considered in this project are listed below.

- **PNPOLE_BA**: pine poletimber basal area (ft^2/ac),
- **PNSAW_BA**: pine sawtimber basal area (ft^2/ac),
- **HWPOLE_BA**: hardwood poletimber basal area (ft^2/ac),
- **HWSAW_BA**: hardwood sawtimber basal area (ft^2/ac),
- **PN_BA**: pine basal area (ft^2/ac)= $\text{PNPOLE_BA} + \text{PNSAW_BA}$,
- **HW_BA**: hardwood basal area (ft^2/ac)= $\text{HWPOLE_BA} + \text{HWSAW_BA}$,
- **POLE_BA**: poletimber basal area (ft^2/ac)= $\text{PNPOLE_BA} + \text{HWPOLE_BA}$,
- **SAW_BA**: sawtimber basal area (ft^2/ac)= $\text{PNSAW_BA} + \text{HWSAW_BA}$,
- **PNPOLE_DBH**: pine poletimber diameter at the breast height (ft),
- **PNSAW_DBH**: pine sawtimber diameter at the breast height (ft),
- **HWPOLE_DBH**: hardwood poletimber diameter at the breast height (ft), and
- **HWSAW_DBH**: hardwood sawtimber diameter at the breast height (ft).

Although these timber attributes for stands in the Raven District of the Sam Houston National Forest are included in the stand table, many of the stands contain no data for these parameters. Initially I thought this was due to table updating problems. Using data from CISC, however, I realized that many stands were still missing data for these variables.

It was not possible, for this reason, to have a complete data set of timber variables for the entire area of interest.

Another problem detected in the GIS coverage was the noncoincidence between the number of stands in the coverage and the number in the CISC database: in the CISC database the number of stands was higher than in the GIS coverage. Besides the implications of this discrepancy in terms of final results, it created some problems in the next step of data preparation.

One last comment should be made about the meaning of the variables contained in the data set. The values attached to each stand refer to the mean conditions of these stands. The units of work, the stands, are by definition homogeneous areas. This purported homogeneity is most of the times illusory, however. Examining the CISC database, I found active colonies located in stands which were classified as 19 years old. This occurred because there are inclusions of mature trees in young stands. These inclusions are mentioned in the table field but are not defined as different stands in the CISC database. When the stand areas are large, the probability of heterogeneity increases. In such areas control over the mean values used to describe these large areas is very much reduced.

THE RED-COCKADED WOODPECKER TABLE

The Raven District of the Sam Houston National Forest provided their most recent data about the colonies in the area of interest. The data included location of active and inactive colonies and recruitment and replacement areas by compartment and stand number.

For each of these cases, information about the number of natural and artificial active or inactive cavities was also included.

RCW data location was established based on compartment and stand numbers according to the CISC database. This enumeration was not, however, entirely coincident with the enumeration followed in the GIS coverage. Stand numbers from the RCW data set in many cases didn't match the stand numbers in the coverage. The number of stands in the GIS coverage was in many cases less than the number of stands considered in the location of the RCW units. A description of the stands mentioned is given in the Appendix 5

Stand numbers for 15 active and 2 inactive colonies, as well as 29 replacement and 2 recruitment stands, were not included in the GIS coverage. I presumed that the variations were due to the differences in dates of construction/updating of the GIS coverage and the CISC database. The CISC database is continuously updated, and new divisions of the existing stands would have been included in that database. The GIS coverage was created in 1991 and has not been modified since. Thus, stands defined after this date are not included in the GIS coverage.

It was my decision to include the mentioned colonies, replacement, and recruitment areas in the analysis data set, even though I assumed that an error would result from such a procedure. The exclusion of these colonies from the data set would, however, generate higher errors than the error resulting from the location of the colonies in the compartments. The proportion of the units not included originally in the data set in relation to the total number of units of their respective type was 12% for active colonies, 3.5% for inactive colonies, 14% for replacement stands, and 2.7% for recruitment stands. Since the

compartment number was known for the “missing” stands and some cautions were used in the location of the units, it was expected that the errors resulting from the subsequent spatial analysis after including the stands will not be significant.

The location of colonies and recruitment and replacement stands was made following a procedure similar to that of selection of suitable nesting habitat for RCW (see below). In each compartment, the stands where forest type was loblolly or shortleaf pine, the age was above 50 years, and stand condition was 10 or 12, were selected. When hardwood basal area was included in the records, it was considered as a criteria for final placement of colonies as well. Stands with minimum values for total basal area and hardwood basal area were chosen. The values of 110 ft²/ac (25.3 m²/ha) for total basal area and of 20 ft²/ac (4.6 m²/ha) for hardwood basal area (Thomlinson 1993) were considered as maximum limits for the placement of these units. In the case of the active colonies these values were always respected. Six out of twenty nine replacement stands and one out of two recruitment stands had basal area above these values. Since many of the stands originally containing areas of these types had values above the values used as limits, the error introduced should not be very high. The location of replacement units was made considering also the location of existing colonies. In the GIS the selection of stands for placement of these units was made according to the proximity of the possible stands when more than one existed; i.e., the stands closer to the colonies were always chosen.

Stands in one compartment also presented inclusions of colonies located in stands of other compartments. Inclusions were excluded when their area was below 5 acres, since their small size would bias the composition of the stands where the inclusions existed

The RCW table created includes the following attributes:

- **RAVSTAND#**: the unique attribute that will be used to link the RCW table and the stands table,
- **ACCOL**: active colonies,
- **INCOL**: inactive colonies,
- **RP**: replacement stands,
- **RC**: recruitment stands,
- **ACNT**: active natural cavity trees,
- **ACAT**: active artificial cavity trees,
- **ACTO**: total active cavity trees,
- **INNT**: inactive natural cavity trees,
- **INAT**: inactive artificial cavity trees, and
- **INTO**: total inactive cavity trees.

The RCW table was created as a text file in Excel software, imported into the Arc/Info system, and joined to the stands table at the “Tables” prompt of Arc/Info. Using the “polygrid” command in Arc/Info, the final GIS coverage was converted from vector format into several raster format layers for some of the attributes described previously. The grid format is more suitable for the kind of analysis performed in this project. The cell size of 328 x 328 ft (100 x 100 m=1 ha) was chosen for the conversion. Smaller cell sizes were avoided because some information would be lost during the conversion and also because considerable additional time would be required during the analysis process. In the GIS

coverage there are 44 stands with areas below 1 ha (2% of the total number of stands) and 14 with area below 0.5 ha (0.7 % of the total number of stands)

RED-COCKADED WOODPECKER HABITAT SUITABILITY CLASSIFICATION

In this step, the area of study was classified in terms of habitat suitability for the RCW using the concept of functional heterogeneity. The types of habitat required by the species - nesting, roosting, and foraging - were considered. The areas resulting from this process were hierarchically preferred by the woodpeckers independent of their accessibility in spatial terms. Spatial availability of the preferred stands was assessed by the application of the functional heterogeneity indices to the cover that includes additional information about location and group size of RCW colonies.

I followed a general assumption according to which foraging insufficiency does not affect RCW in the area of study (Rudolph and Conner 1994, Conner and Rudolph 1995, USDAFS, personal communication). The main implication of this assumption is that the distribution and spatial dynamics of the species is dependent only on the nesting and roosting habitat quality, habitat used by birds for movements, the location of sources for birds movements, and the distribution and configuration of these units.

In the definition and classification of the RCW habitat I considered five different approaches. The necessity for the creation of five different approaches derives from the lack of data for timber variables in many of the stands in the database. The delineation of the conditions following five different approaches define the most likely characterizations of the forest pattern in the Raven District. The establishment of these approaches also simulate a

set of conditions where two types of fragmentation could be considered. Approach 1 intends to establish the best possible scenario. Approaches 2 and 3 represent fragmentation in terms of decreases in just nesting and roosting habitat. The other type of fragmentation, in terms of absolute loss of areas of roosting, nesting, and foraging habitat, is expressed by approaches 4 and 5. Approach 5 constitutes the worst-case scenario. Approaches 1, 2, and 3 constitute a gradient of fragmentation of the first type. Approaches 1, 4, and 5 constitute a gradient of the other type. An overall gradient of fragmentation can also be considered from 1 to 5. Analyzing these several situations, the effect of fragmentation on the population in the area of study can be considered.

Approach 1 - Definition and classification of the red cockaded woodpecker habitat based on forest type, age, stand condition, and cavity trees assumed that the timber parameters, particularly basal area of hardwoods, can be managed in order to create suitable nesting and roosting habitat for RCW. All habitat of pine forest above a certain age and following a certain growth pattern is suitable for RCW if hardwood control is applied to those areas. A summary of the criteria followed in this classification system is given in Appendix 9.

The dependency of the species on already existing cavity trees has strong implications in terms of the definition of the suitable habitat for the species. A cluster of cavity trees, even if inactive, has a high value in terms of potential nesting habitat for the species (Walters 1991). For this reason, I considered the presence of active or inactive clusters within a stand as the most important component for the definition of habitat suitability. A similar approach was used by Probst and Hayes (1987) when they defined

suitable habitat for Kirtland's Warblers as areas that had been used by the species for at least 3 years.

Habitat suitability classification consisted of eight different classes ranging from 0 to 7. The stands where active or inactive clusters of trees are present were classified with the highest suitability habitat value: active clusters were assigned a value of 7; inactive clusters were assigned a value of 6. From the data available it was not possible to distinguish among inactive clusters abandoned for more or less than 2 years, so it was assumed that all of them could be colonized by RCW. Replacement and recruitment stands were considered to have suitable conditions for nesting and roosting habitat since they are managed for that purpose. These areas were classified as class 5 habitats.

The next classes of habitat suitability were based on age of the stands given that the forest type was loblolly or shortleaf pine and stand condition was mature or immature sawtimber. Thomlinson (1993) found all active colonies in mature or immature sawtimber in 54 compartments of the Raven District of the SHNF. The data provide evidence of a similar conclusion for the entire district. The only colonies that did not follow this pattern occur in stands where inclusions of mature sawtimber are present. The youngest stand with active colonies in the area studied by Thomlinson (1993) was 51 years old. In the data set of this project the minimum age of stands having active colonies was 54 years old. I considered, however, the age of 60 years as the limit of suitability of pine stands for red cockaded woodpeckers since in the data set only two colonies were located in stands with ages below 60 years. Stands with ages ranging from 60 to 80 years were assigned the lowest value of suitability, and were classified with a value of 2; stands 80 to 100 years old were classified

with a value of 3, and stands with ages above 100 were classified with a suitability value of 4.

Finally, the stands not suitable for nesting and roosting but suitable for foraging habitat were include in the suitability classification. This habitat represents conditions favorable for movement of individual birds. It was assumed that RCW individuals prefer to move within pine forest stands. There is reluctance to cross open areas by the birds when they do not know what is on the other side of the open area (Conner and Rudolph 1995, USDAFS, personal communication).

Occasionally, red-cockaded woodpeckers use hardwood stands and open areas but exhibit higher preference for live pine species (Ligon 1970; Nesbitt *et al.* 1987; DeLotelle *et al.* 1987; Hooper and Lennartz 1981; Conner *et al.* 1994b), where avoidance of pines less than 13 cm dbh and preference for pines greater than 23 cm dbh has been observed (Hooper and Lennartz 1981). In territories in central Florida, pine stands containing longleaf pine were young, ranging from 17 to 53 years (DeLotelle *et al.* 1987). This is the only reference to age of pines in territories of RCW other than to the age of actual clusters of cavity trees. Longleaf pine grows more slowly than the pine species present in the area of study, so for this reason this class of suitability was limited by the age of 17 years. The last class of habitat suitability was then defined by the stands of loblolly and shortleaf pine with ages above 16 years.

Approach 2 - Definition and classification of the red cockaded woodpecker habitat was based on forest type, age, stand condition, cavity trees, and timber variables. Using the

data available for the stands concerning total basal area and hardwood basal area, restrictions were created relative to approach 1 (Appendix 10)

The classification was based on the schema defined in approach 1, but basal area was now included as an additional criterion. Total basal area above 110 ft²/ac (25.3 m²/ha) and hardwood basal area above 20 ft²/ac (4.6 m²/ha) for forest stands in the Raven District of the Sam Houston National Forest appear to be restrictive in terms of habitat suitability (Thomlinson 1993) All the areas missing data in the database (with total and hardwood basal area simultaneously equal to zero) were considered suitable for nesting and roosting habitat. The areas with total and hardwood basal area above the limiting values mentioned were considered as foraging habitat (suitability class 1).

Approach 3 - Definition and classification of the red cockaded woodpecker habitat was based on forest type, age, stand condition, cavity trees, and timber variables. Stands missing data concerning timber variables (total and hardwood basal area simultaneously equal to zero) were considered as foraging habitat (suitability class 1). In the previous approach, the stands without basal area data were considered as nesting and roosting habitat. This classification system is explained in Appendix 11.

Approach 4 - This approach differs from the second approach by excluding those stands that do not match the timber variable conditions. All stands with total and hardwood basal area above 110 ft²/ac (25.3 m²/ha) and 20 ft²/ac (4.6 m²/ha), respectively were not considered suitable for any activity of RCW (Appendix 12)

Approach 5 - This was the most restrictive approach followed. If a stand had no information concerning basal area it was excluded from the RCW habitat. Appendix 13 describes the classification followed in this case.

Maps of habitat suitability for the five cases described were created in raster format, using the existing raster layers of stand condition, forest type, age, active colonies, inactive colonies, total basal area, and hardwood basal area. These maps are the result of the application of queries in the 'docell' block in 'Grid' prompt of Arc/Info based on the layers mentioned above.

COMBINATION OF HABITAT SUITABILITY AND RED-COCKADED WOODPECKER INFORMATION

In this step additional information about the behavior of the red-cockaded woodpecker was incorporated into the previously created habitat suitability maps. Some information about the species was already included in the habitat maps because the existence of cavity trees was a main criteria in the suitability classification process. The additional RCW variable used was clan size

The number of active cavity trees in each stand provided an indication of group size. I assume here that large groups had more potential for movement of birds, particularly fledgling females, than small groups. This assumption is in accordance with indications provided by the research conducted about bird movements (Lennartz and Harlow 1979, Conner and Rudolph 1989; Conner and Rudolph 1995, USDAFS, personal communication).

Three classes for group size were considered (Table 1). The lowest class considered, class 0, included the colonies with 1 cavity tree. The potential for dispersal is the smallest for this class. Class 1 included colonies with two or three cavity trees. The last class, 2, included the colonies with four or more cavity trees. This class should have the highest potential for dispersal.

Table 1 - Classes of RCW Group Size.

Class	Number of Cavity Trees
0	1
1	2 - 3
2	≥4

A raster layer was created to include the information concerning group size. Final habitat/RCW maps were obtained by summing each of the five habitat suitability grid layers with the group size layer. In this way a classification system based on ten classes was obtained. Each functional heterogeneity class value is a function of the habitat conditions, location of RCW colonies, and potential for dispersal in each forest stand. A stand of class 9, for example, represents the “best” habitat conditions and contains a RCW colony where the group size is maximum. The 5 final habitat/RCW grids will constitute the matrices to submit to the algorithms which calculate the functional heterogeneity indexes

THE FUNCTIONAL HETEROGENEITY INDICES

Functional heterogeneity, defined by Kolasa and Rollo (1991) as the way an organism perceives and responds to its environment, can be a useful concept in defining connected landscape units because it integrates the landscape structure and the demographic processes of animals. In order to evaluate the functional heterogeneity of the landscape of interest, I used the indices of functional heterogeneity created and adapted by Coulson *et al.* (1994). These indices are sensitive to different aspects of the landscape: **Angular Moment of Inertia** is sensitive to the dispersion of landscape elements; **Connectivity** is sensitive to connectedness of the landscape elements, and **Spatial Interaction** is sensitive to the fragmentation of the highest valued, or most important, landscape element (Coulson *et al.* 1994). In addition to these indexes I used the **Weighted Connectivity Index**, which considers the value of the matrix cells in the determination of connectivity (Coulson *et al.* 1994). The weighted connectivity index is necessary because the connectivity index is not able to distinguish between a situation of homogeneity of the input matrix due to 0 values and a homogeneity due to the highest values in the same matrix.

Angular Moment of Inertia (AMI)

This *AMI* index measures variation in the dispersion of matrix elements in relation to a centroid. This centroid is obtained for each matrix by weighing the coordinates i and j with the value of the corresponding cells (a_{ij}). The centroid is defined by the following equations.

$$X_o = \frac{(\sum_j \sum_i (a_{ij})) * j}{\sum_i \sum_j a_{ij}} \quad Y_o = \frac{(\sum_i \sum_j (a_{ij})) * i}{\sum_i \sum_j a_{ij}}$$

Within each matrix, dispersion is measured by subtracting from the i and j coordinates of each element the X_o and Y_o components of the centroid. The squared ($j-X_o$) and ($i-Y_o$) distances are summed and multiplied by the value of the cell. The value of the index is the result of the sum of these operations for all the cells in the matrix. A final factor considering all the a_{ij} values is later added.

$$AMI = \sum_{ij} (((j - X_o)^2 + (i - Y_o)^2) * a_{ij}) + \frac{\sum_{ij} a_{ij}}{12}$$

Connectivity (H)

The Connectivity index is based on the number of adjacent cells with the same value (runs) evaluated in columns, rows, and both diagonals. A given run has a value, $S(i)$, which is a function of its extent, L . It is calculated as follows

$$S(i) = L * \frac{(L+1)}{2}$$

The total run values (T) in a matrix are calculated as the sum of all the runs for all the values in the matrix, where i is a particular value and n is the number of different values in the matrix.

$$T = \sum_1^n S(i)$$

The minimum T possible is obtained when a $N \times N$ matrix is absolutely heterogeneous, i.e., all the runs have a value of 1.

$$T_{\min} = 2(N^2 + \frac{N^2}{2^{-2}})$$

The maximum sum of run values will be obtained for a homogeneous $N \times N$ matrix where only one element value is found. The k value ranges from 1 to N

$$T_{\max} = N^2(N+1) + 2(\frac{\sum k(k+1)}{2^{-2}}) - N \frac{(N+1)}{2^{-2}}$$

The connectivity index (H) is calculated as the relative difference of the total run value of the matrix and the minimum possible total run value (T_{\min})

$$H = \frac{T - T_{\min}}{T_{\max} - T_{\min}} * 100$$

This value is independent of the values of the cells that constitute the measured runs.

Weighted Connectivity (WH)

The weighted connectivity index was derived from H by weighting the run values with the value of the cell considered in the run.

$$WH = \sum i(\sum S(i))$$

Spatial Interaction (SI)

This index is based on Newton's Law of Attraction Between Masses, and it is sensitive to the fragmentation of the most valuable element type in the matrix. It is calculated based on the value of all the possible pairs of different values in the matrix (m_k , m_l), the distances between them (r_{kl}), and the maximum value in the matrix (t) It is calculated as follows

$$SI = \frac{\sum_{k,l} \frac{(m_k * m_l)}{r_{kl}^2}}{t^2 * \sum_{k,l} \frac{1}{r_{kl}^2}}$$

THE APPLICATION OF THE FUNCTIONAL HETEROGENEITY INDICES

These indices were calculated using a moving window function. In this function, the values of the functional heterogeneity indices are calculated for each cell in the matrix using the values of a constant number of cells, or submatrix, in the neighboring region of each cell. This submatrix used for the calculation of the value for each cell is determined by the window size.

To determine the window size to use in this project, mean dispersal distances of RCW individuals were considered, and two window sizes were tested: 4.1 x 4.1 Km (41 x 41 cells) and 2.1 x 2.1 Km (21x 21 cells). The first distance represents the distances flown by fledgling females, the most important group in terms of dispersal movements among red-cockaded woodpeckers and the most important group in terms of maintenance of RCW populations. Since distances flown by RCW in the area of study were unknown, the flight distances measured by Walters *et al.* (1988) in North Carolina were used, where the mean dispersal distance of fledgling females was 4.7 Km and the median was 3.2 Km. The second distance, 2.1 Km, includes the movements of adult females (mean=2.1 Km, median=1.3 Km), also important for maintaining RCW populations. Male dispersal distances were not completely considered in the chosen window size. The median flight distances by fledgling male birds in North Carolina was 4.5 Km. The 4.1 x 4.1 Km window thus included an

important part, though not complete, portion of the males that disperse. The distance of 4.1 Km seemed to be a reasonable distance to use in this work since it included the majority of the movements of RCW individuals. The use of two window sizes met the objective of testing the behavior of the indices when the window size changed.

The habitat/RCW grids were converted to ASCII files in Arc/Info and used as inputs for the calculation of the functional heterogeneity indices. FORTRAN programs written by Dr. Eugene Pulley (1995, Texas A&M University, personal communication) and first used in the study of the relationship between bark beetles and forest pattern (Coulson *et al.* 1994) were adapted to the grid size and window sizes used in this project. These programs run in a UNIX environment. Due to the extension of the input matrices and the calculations included in the algorithms, the Sun Sparc workstations were not able to run the programs in an acceptable period of time, when the 41 x 41 cell window size was used, one program took five days to run in a workstation. The SGI Power Challenge super computer was used to run the remaining matrices. The programs generated ASCII files which were converted to Grid files in Arc/Info and visualized using that software. The new grids were smaller in size than the input matrices due to the loss of one half of the window size within the matrix.

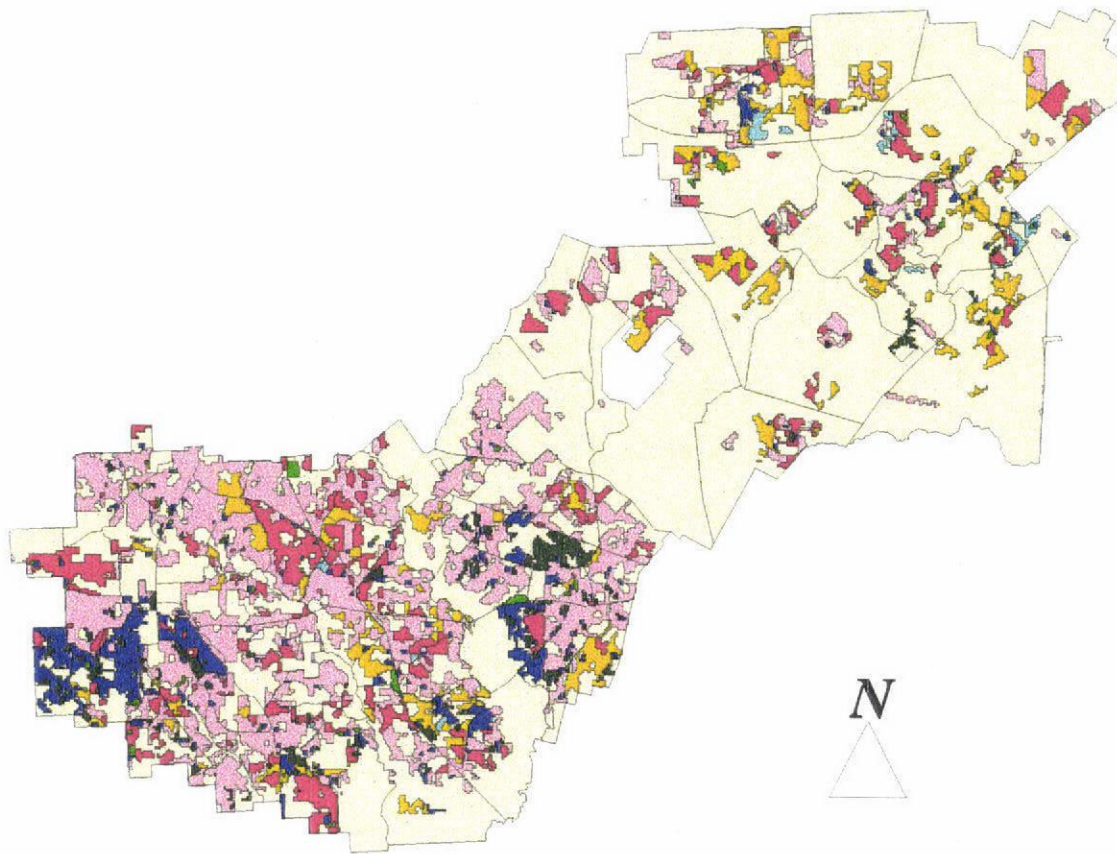
CHAPTER V

RESULTS

The present chapter includes some of the intermediate results of the successive steps followed in the methodology: habitat maps, habitat/RCW maps, and the final maps resulting from the application of the functional heterogeneity indices. The large number of maps generated during the analysis process for the five approaches, four indices, and two window sizes upon which the work was based, and the impossibility of including all of them in this thesis, made necessary a selection of some of these maps. The maps shown here are the most representative of the overall results obtained. For simplification and convenience of the presentation of the results, the area of study was divided in two regions: the southwestern and the northeastern regions.

HABITAT SUITABILITY MAPS

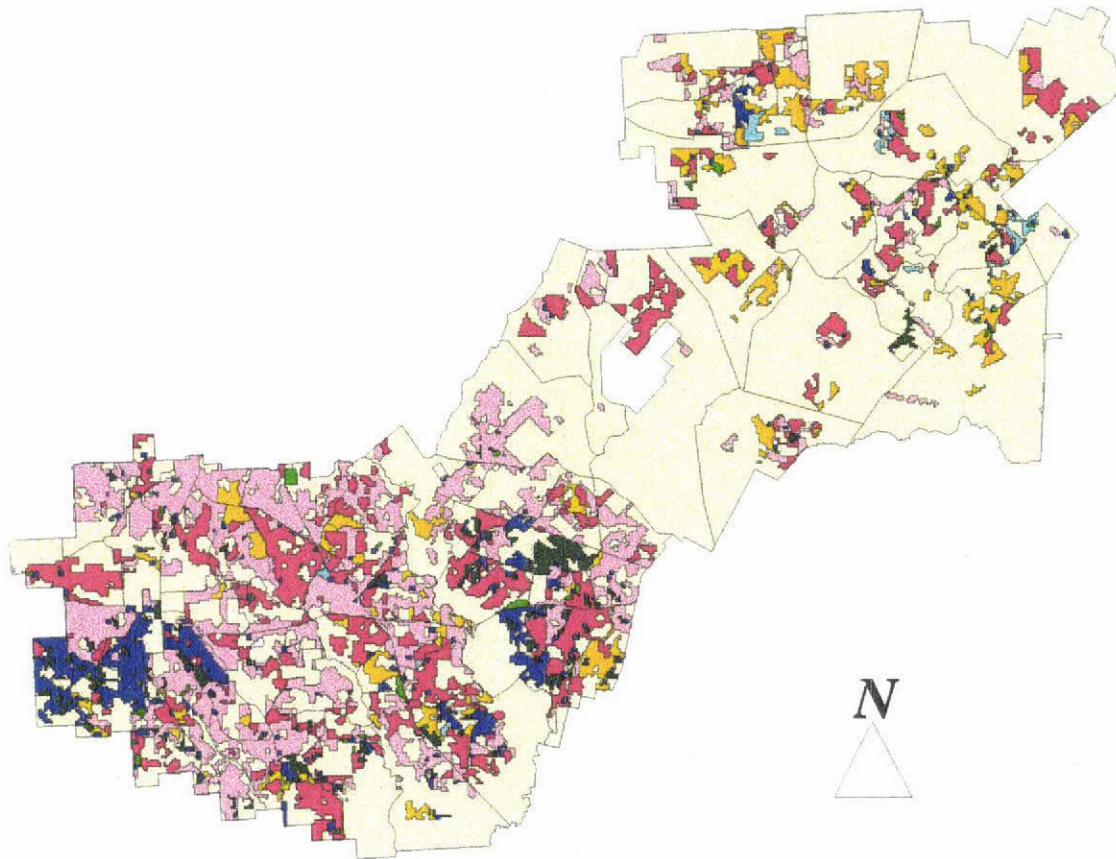
Figures 5 to 9 present the habitat suitability maps created following the criteria defined for the five approaches (see methodology). The areas of classes 5, 6, and 7 are constant over the five maps since they include colonies and replacement and recruitment stands. The variation in foraging habitat can be seen in maps for approaches 1, 4, and 5 (Figures 5, 8, and 9). Variations in the loss of areas of any kind of habitat from approaches 1 to 3 can be seen in Figures 5 to 7. Table 2 presents the areas occupied by each suitability class in the various maps.



- 0 unsuitable habitat
- 1 foraging habitat
- 2 age from 60 to 80 years
- 3 age from 80 to 100 years
- 4 age > 100 years
- 5 replacement or recruitment stands
- 6 inactive colonies
- 7 active colonies

Scale 1:325,000

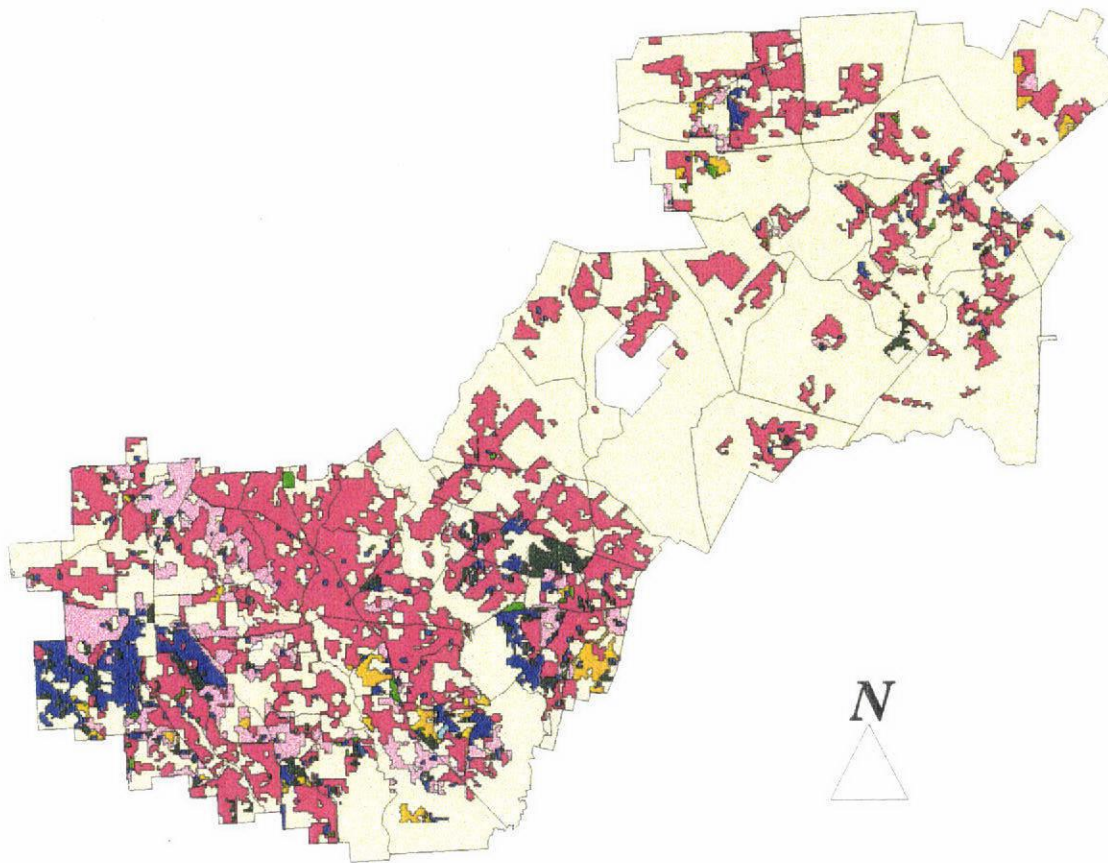
Figure 5 - Habitat Suitability Map for Approach 1. Raven District of the SHNF, 1995.



- 0 unsuitable habitat
- 1 foraging habitat
- 2 age from 60 to 80 years
- 3 age from 80 to 100 years
- 4 age > 100 years
- 5 replacement or recruitment stands
- 6 inactive colonies
- 7 active colonies

Scale 1:325,000

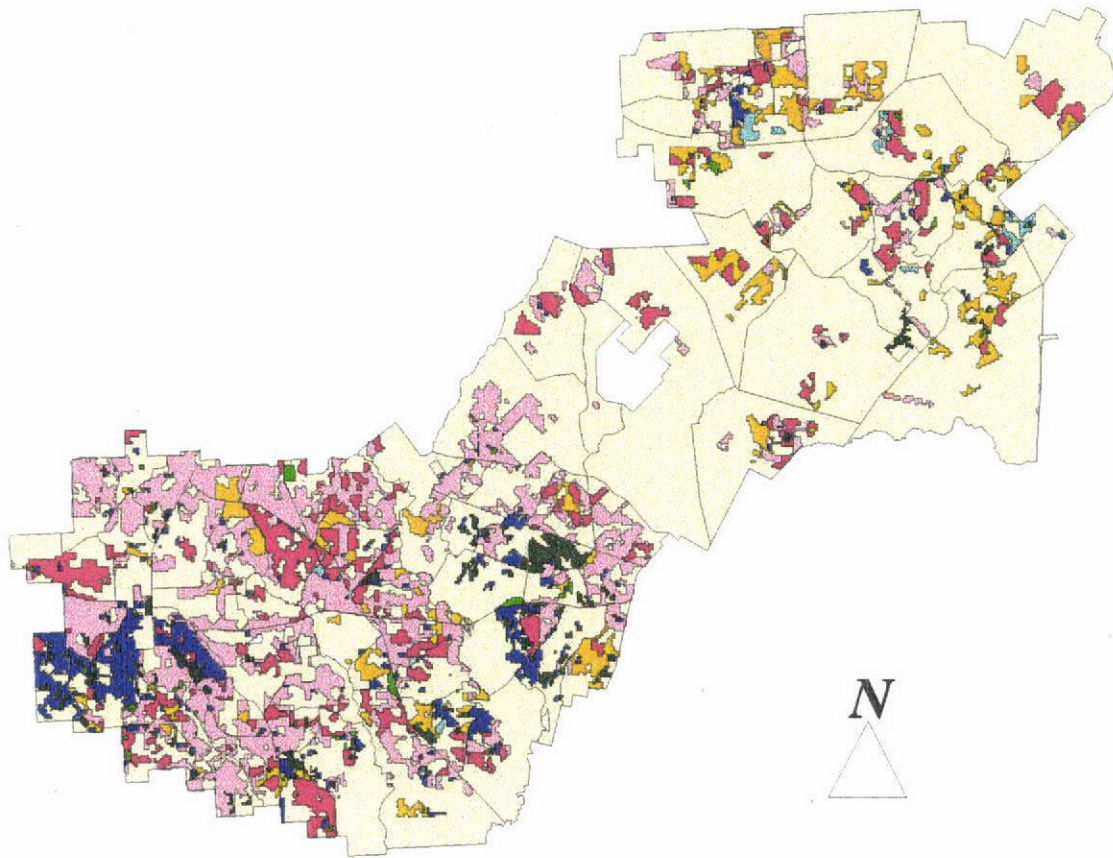
Figure 6 - Habitat Suitability Map for Approach 2. Raven District of the SHNF, 1995.



- 0 unsuitable habitat
- 1 foraging habitat
- 2 age from 60 to 80 years
- 3 age from 80 to 100 years
- 4 age > 100 years
- 5 replacement or recruitment stands
- 6 inactive colonies
- 7 active colonies

Scale 1:325,000

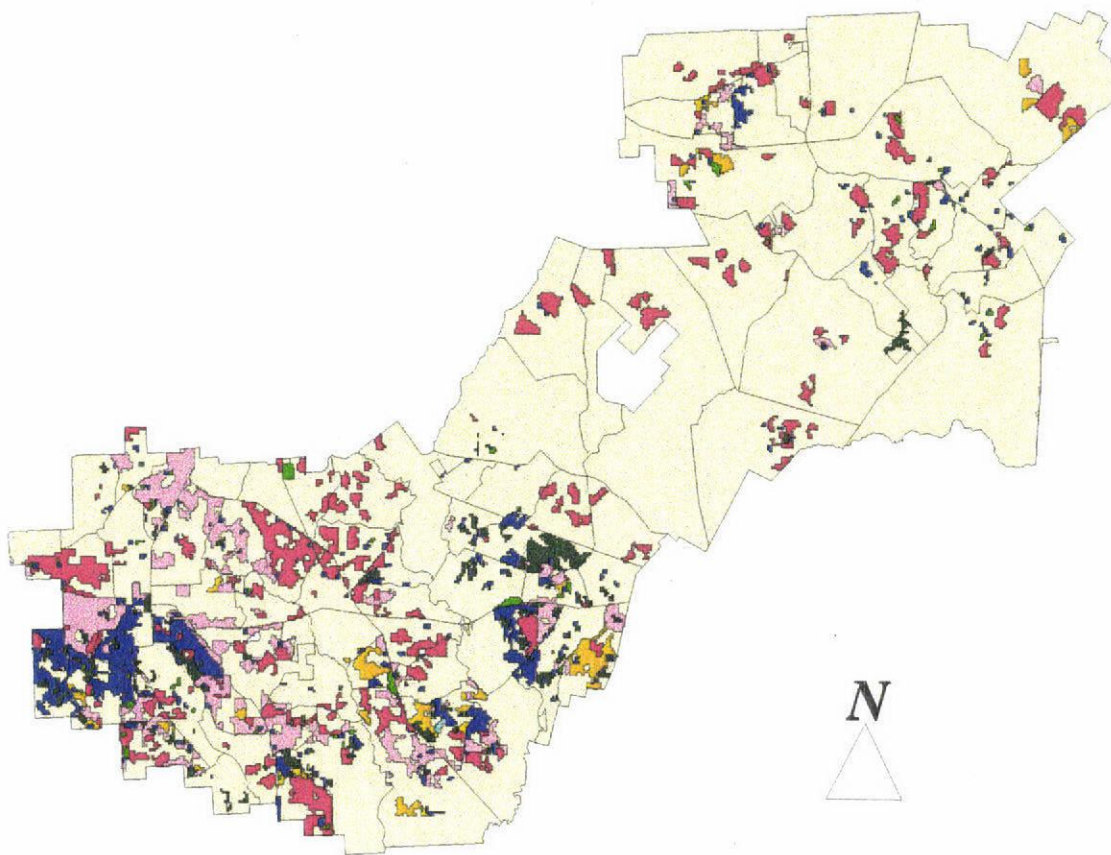
Figure 7 - Habitat Suitability Map for Approach 3. Raven District of the SHNF, 1995.



- 0 unsuitable habitat
- 1 foraging habitat
- 2 age from 60 to 80 years
- 3 age from 80 to 100 years
- 4 age > 100 years
- 5 replacement or recruitment stands
- 6 inactive colonies
- 7 active colonies

Scale 1:325,000

Figure 8 - Habitat Suitability Map for Approach 4. Raven District of the SHNF, 1995.



- 0 unsuitable habitat
- 1 foraging habitat
- 2 age from 60 to 80 years
- 3 age from 80 to 100 years
- 4 age > 100 years
- 5 replacement or recruitment stands
- 6 inactive colonies
- 7 active colonies

Scale 1:325,000

Figure 9 - Habitat Suitability Map for Approach 5. Raven District of the SHNF, 1995.

Table 2 - Distribution of Area by Habitat Suitability Class and Approach Followed.

Class	Area Occupied (number of cells)				
	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
0	324142	324142	324142	327173	337509
1	5270	8301	18637	5270	5270
2	13253	10802	3428	10802	3428
3	4155	3584	894	3584	894
4	297	288	16	288	16
5	2701	2701	2701	2701	2701
6	349	349	349	349	349
7	1313	1313	1313	1313	1313

Note the reduction in area of habitat classes 2, 3, and 4 occurring from the first to the third approach and from the first to the fifth approaches, and a corresponding increment in foraging habitat (class 1) and not suitable habitat (class 0). The areas changing in class are not uniformly distributed over the study area. When the areas with no information are considered as foraging or nonsuitable habitat (approaches 3 and 5), there is a major concentration of the resulting classes (1 and 0) in the central and east portions of the southwestern region and overall in the northeastern region.

HABITAT/RCW MAPS

No maps of this category are shown here since they do not illustrate substantial differences from the habitat maps. The only difference is the subdivision of the class 7 in the habitat maps into three classes: 7, 8, and 9. After the split of the 1313 cells representing active colonies into the three new classes, the area occupied by each one is 217 cells for the class 7, 617 cells for the class 8, and 479 for the class 9.

FUNCTIONAL HETEROGENEITY INDICES MAPS

21 x 21 Window Size

Due to the large range in values contained in the outputs, and to the difficulty of distinction among different areas, classes for each index were created. The procedures followed are summarized in Table 3. The zero values are not considered as belonging to any class. I attempted to create the maximum number of classes that could reduce the diversity of values and at the same time more easily distinguish among different portions of the area.

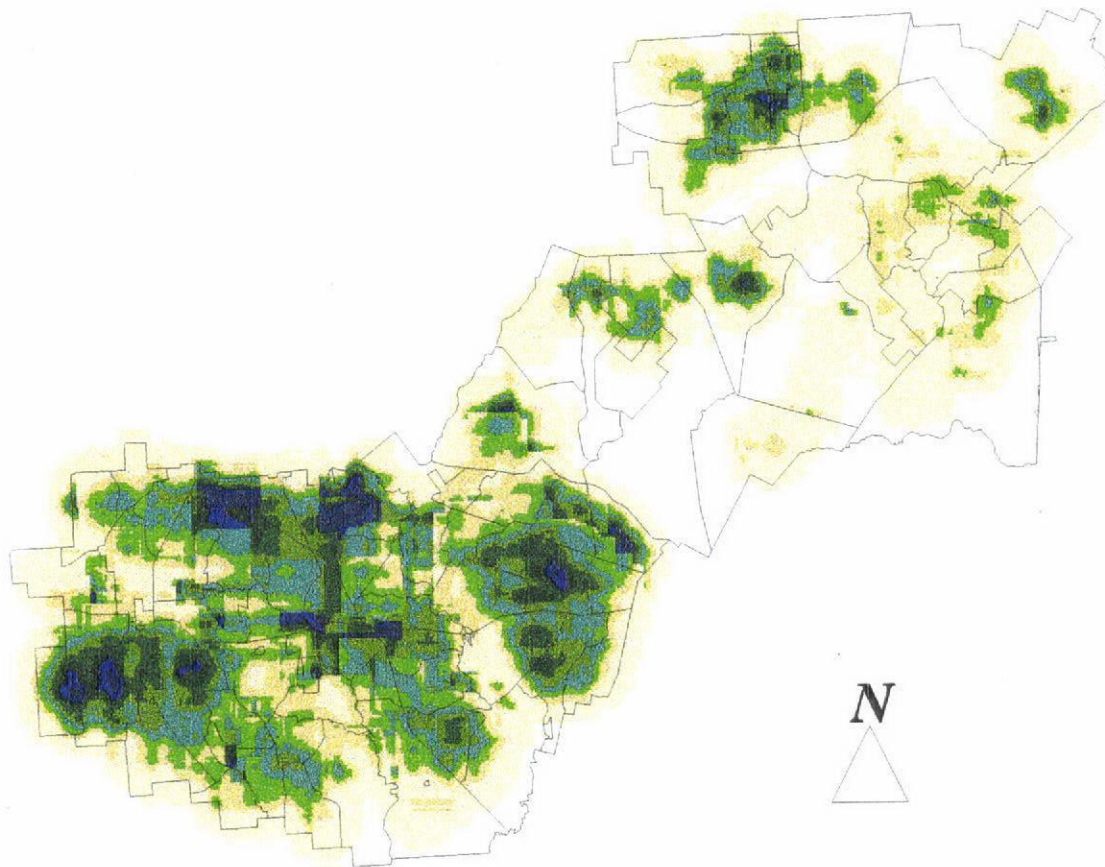
Not all the 40 maps generated in this phase of the work are included in this document. The maps resulting from the application of the indices to approaches 1, 2, and 4 are usually very similar and for that reason maps from approaches 2 and 4 will not be shown. The description of the output maps will be made in a sequential way, following the fragmentation gradient established from approaches 1 to 5.

Table 3 - Ranges and Classification of the Outputs of the Functional Heterogeneity Indices;
21 x 21 Window Size.

Index	Range of the Results					No of	Interval	Highest
						Classes	Width	Class
	App. 1	App. 2	App. 3	App. 4	App. 5			
<i>AMI</i>	0-70	0-67	0-92	0-67	0-50	10	5	>45
<i>H</i>	12-100	12-100	12-100	12-100	12-100	10	10	90-100
<i>WH</i>	0-44	0-38	0-77	0-37	0-26	7	5	>30
<i>SI</i>	0-56	0-53	0-88	0-53	0-38	7	5	>30

Angular Moment of Inertia (*AMI*)

In the output relative to approach 1 (Figure 10), five main areas of the highest *AMI* classes can be observed within the southwestern region: one in the west (compartments 6, 7, 8, 9, 10, 14, and 15), another in the east (compartments 42, 43, 50, 51, and 52), two in the north (compartments 18, 22, 23, 24, and 25 with some small portions in compartments 19 and 20), and the last in the center (compartments 24 and 25 crossing compartments 17, 21, and 34 in the southern direction) (for location of compartments see Figure 2). The northern and central areas differ from the others by their polygonal and regular shape. The two other areas are round in shape and include typical concentric zones of increasing *AMI* class values. In the northeastern region of the district, different units can be visualized within which small areas of relatively high *AMI* values are observed. The four areas are



Class	Range
0	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	31-35
8	36-40
9	41-45
10	>45

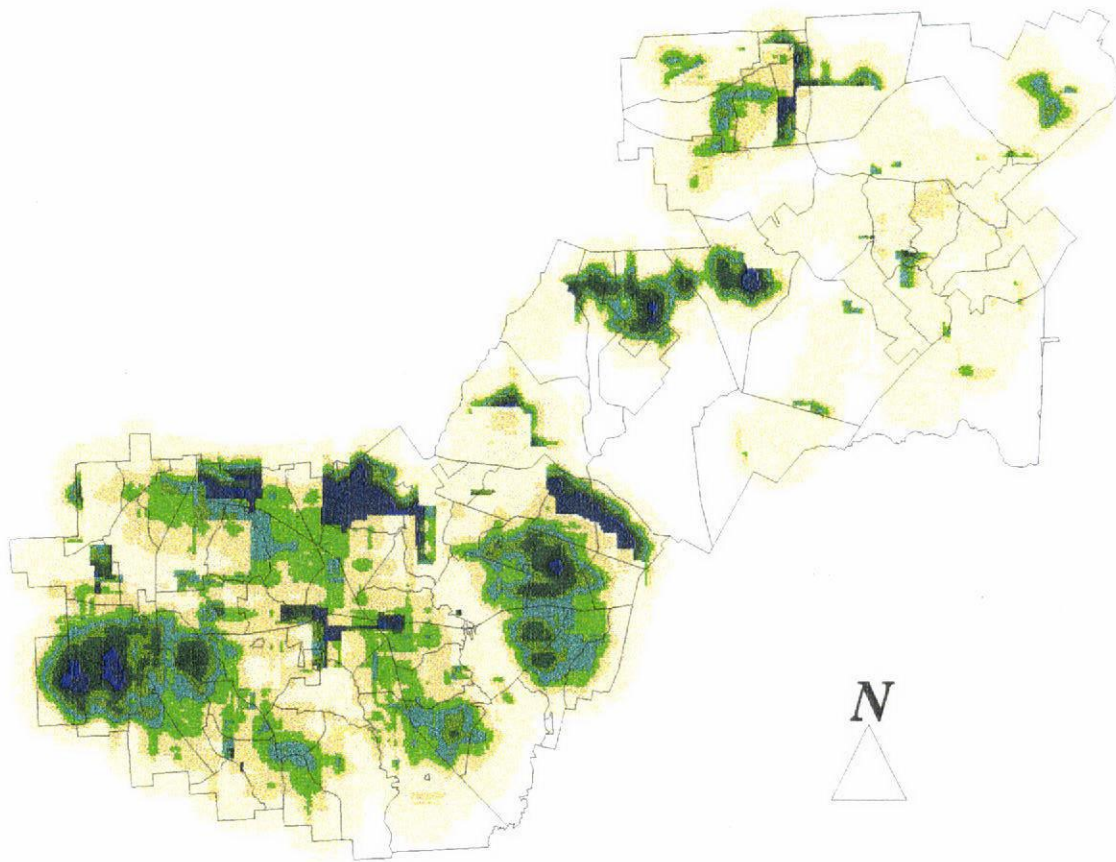
Scale 1:325,000

Figure 10 - AMI; Approach 1; 21 x 21 Window Size. Raven District of the SHNF, 1995.

located in compartments 59, 60, 61, and 62; the center of compartment 65; compartment 56; and compartment 79. The results for approach 2 are similar to those in Figure 10. The third approach generated a different set of results (Figure 11). There is a decrease in the values of the central and northern portions in the southwestern region. In this same region, the eastern portion is separated from the rest by a narrow strip containing *AMI* class values of 1 and 2. In the northeastern region a shift in importance can be observed between the northern and eastern portions relative to the previous approaches. Approach 4 generated an output similar to the two first outputs. There is, however, a decrease in cells of class 7 and above and an increase in cells of classes 1 and 2. Approach 5 output (Figure 12) shows a higher abundance of cells of the lowest *AMI* values (classes 0, 1, 2, and 3). Two of the areas of highest values detected before are now isolated within the area of study (compartments 6, 7, 8, 9, 10, 14, and 15 and compartments 50, 51, and 43), though they maintain their characteristic shapes and most of their extension. Northern and central areas have, in this case, low *AMI* values and an opening (0 value area) appears in the center of this portion of the district. The northeastern region is now more isolated from the southeastern region. Within this last area, smaller areas with medium *AMI* values are reduced and the spots of areas with higher values are more isolated among them.

Connectivity (*H*)

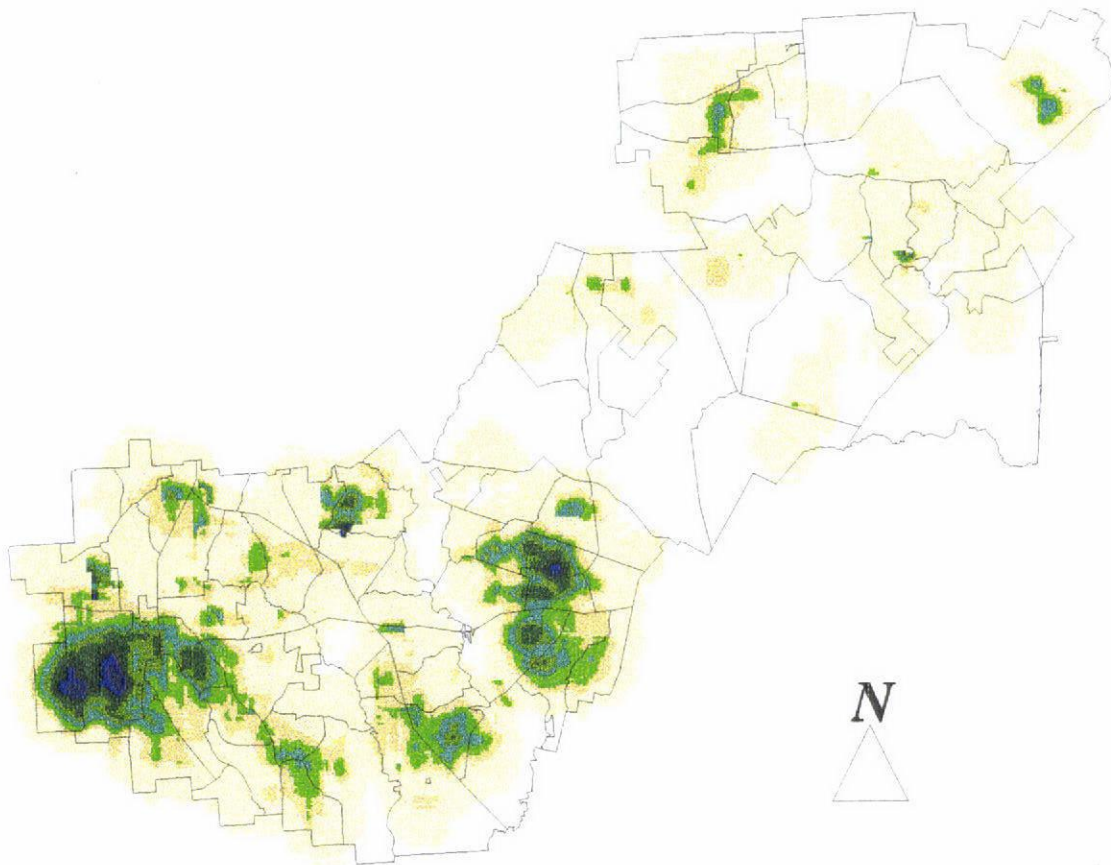
In the output resulting from approach 1 (Figure 13) the area is dominated by class 3 cells. Large continuous areas of class 2 exist, however. The areas where absolute connectivity is higher (equal or above 6) are located in the southwestern region: west



Class	Range
	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	31-35
8	36-40
9	41-45
10	>45

Scale 1:325,000

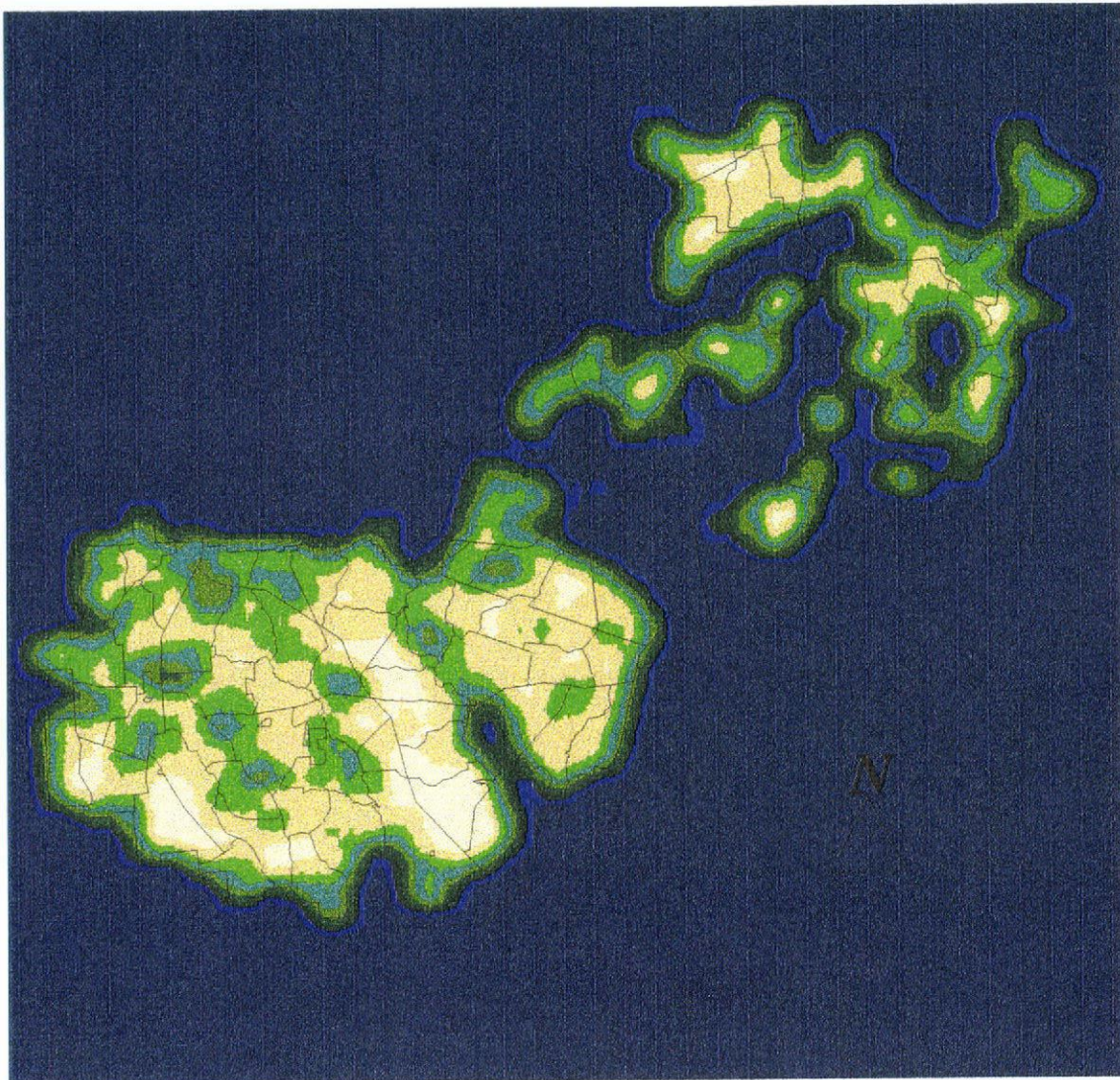
Figure 11 - AMI; Approach 3; 21 x 21 Window Size. Raven District of the SHNF, 1995.



Class	Range
0	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	31-35
8	36-40
9	41-45
10	>45

Scale 1:325,000

Figure 12 - AMI; Approach 5; 21 x 21 Window Size. Raven District of the SHNF, 1995.



Class	Range
0	0
1	1-10
2	11-20
3	21-30
4	31-40
5	41-50
6	51-60
7	61-70
8	71-80
9	81-90
10	91-100

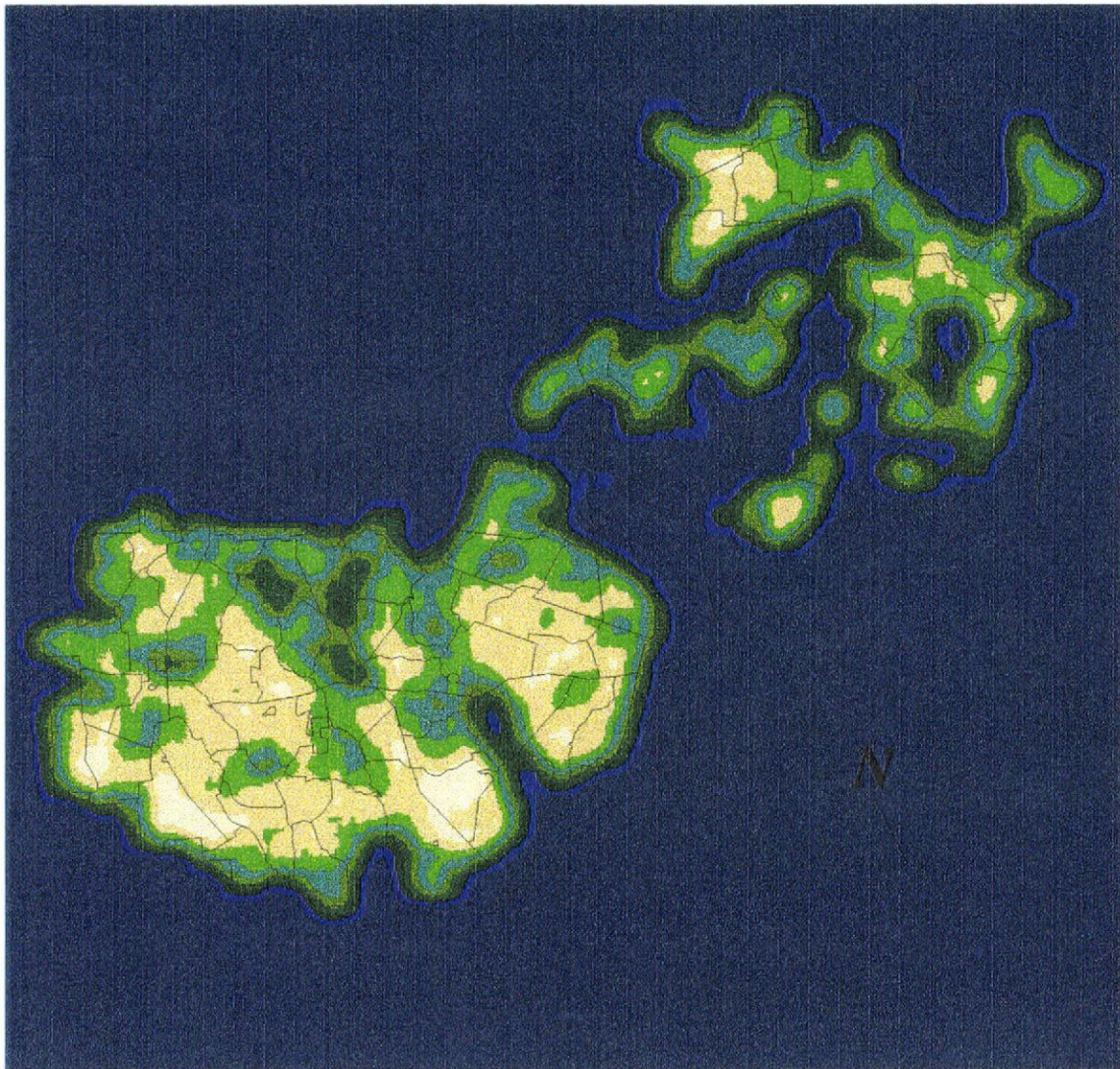
Scale 1:325,000

Figure 13 - *H*; Approach 1; 21 x 21 Window Size. Raven District of the SHNF, 1995.

(junction of compartments 4, 16, 18), north (compartments 18 and 22), and northeast (compartments 48 and 46). Small areas of class 6 can be observed in compartment 29. The northeastern region presents areas with connectivity below 6 except for areas affected by the zero values outside of the study area. For the second approach, there are small differences in the results. The areas previously detected in the north are very reduced now, and the small area in compartment 29 disappeared. In the third situation (Figure 14), the southwestern region presents three large areas with values above 6. They are located in compartments 20 and 23, compartments 24, 25, and 26; and compartment 21. In the output for approach 4 the northeastern region exhibits areas separated from its core. Values inside the small areas are low. The southwestern region shows a central area of class 8 (compartment 34). The northern, western, and one of the northern areas of class 6 detected in previous approaches are maintained. A large area of class 10 is shown at the center of the southwestern region in the fifth approach (Figure 15). The western area increases in size. The eastern portion of the region is separated from the rest. In the northeastern region, very small and isolated areas can now be observed. They are high in value because of the edge effect in the calculation of the index values.

Weighted Connectivity (*WH*)

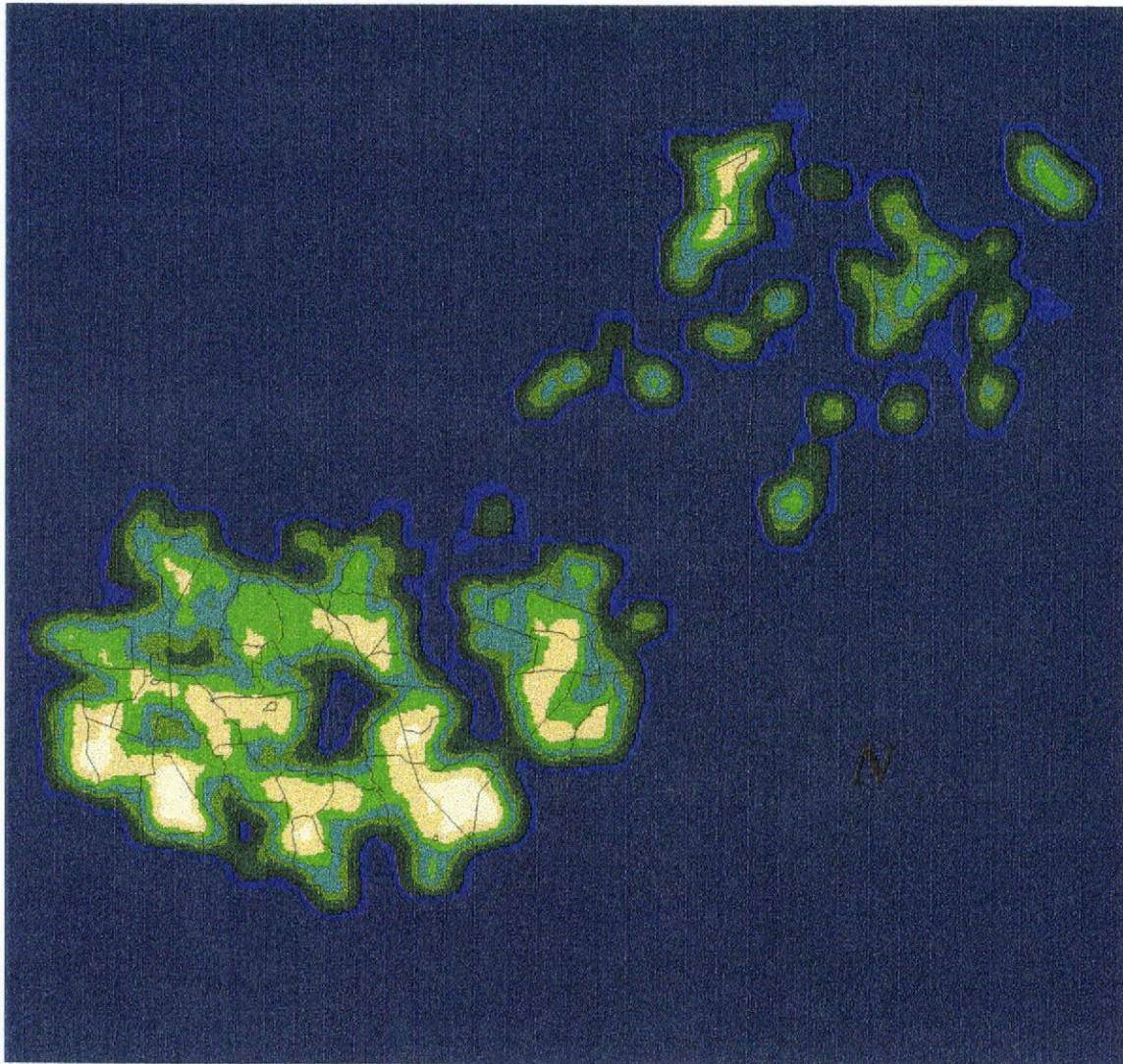
Within the area of study the dominant values in the output of approach 1 (Figure 16) belong to the lowest class considered (class 1). The northeastern region of the district presents small patches with low connectivity classes (2 and 3). In the southwestern region, four areas of higher connectivity can be observed. The western area (compartments 7, 9,



Class	Range
0	0
1	1-10
2	11-20
3	21-30
4	31-40
5	41-50
6	51-60
7	61-70
8	71-80
9	81-90
10	91-100

Scale 1:325,000

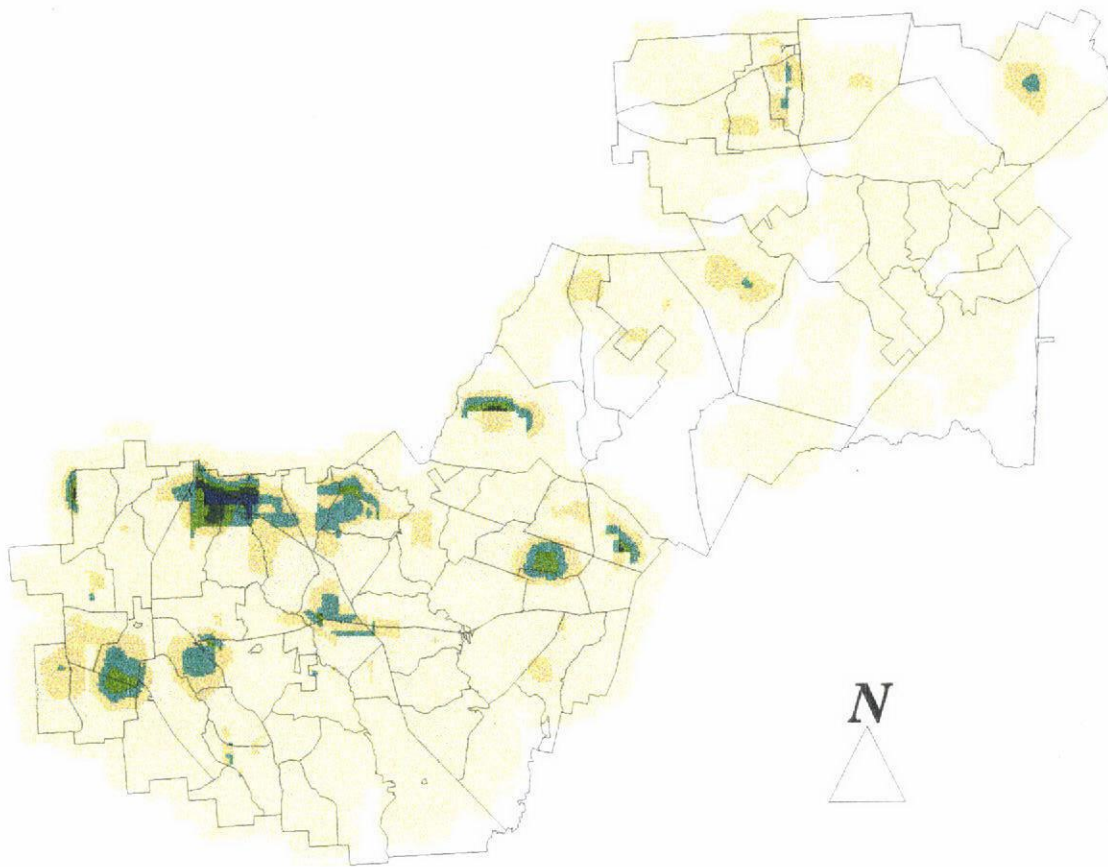
Figure 14 - H; Approach 3; 21 x 21 Window Size. Raven District of the SHNF, 1995.



Class	Range
	0
1	1-10
2	11-20
3	21-30
4	31-40
5	41-50
6	51-60
7	61-70
8	71-80
9	81-90
10	91-100

Scale 1:325,000

Figure 15 - *H*; Approach 5; 21 x 21 Window Size. Raven District of the SHNF, 1995.



Class	Range
0	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	> 30

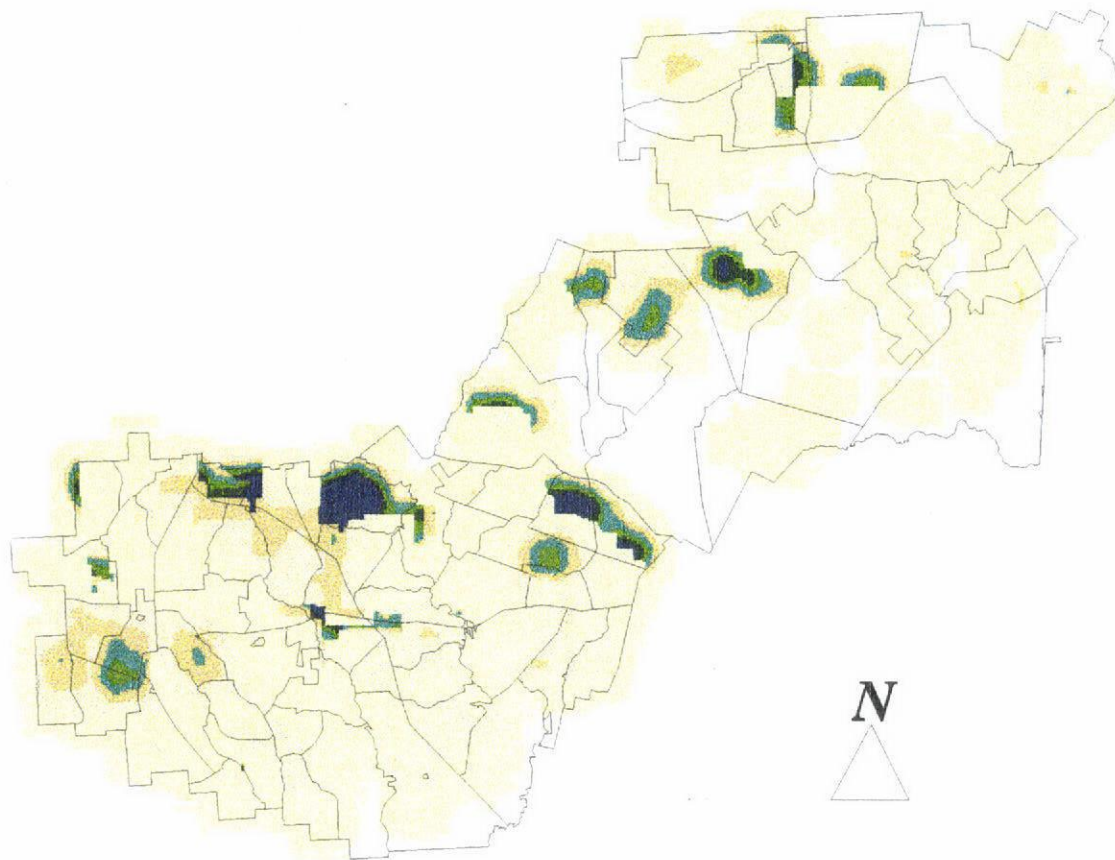
Scale 1:325,000

Figure 16 - *WH*; Approach 1; 21 x 21 Window Size. Raven District of the SHNF, 1995.

and 15) and the eastern area (compartments 50, 51, and 53) do not reach the highest connectivity class. The highest values are observed in the northern area (compartments 18, 19, 22, 23, 24, and 25). This area is connected to the central area (compartments 21, and 34) by a class 2 area. The second approach results in an overall light reduction of class 2 areas around the spots described previously. In the output of the third approach (Figure 17) the areas of class 1 are more abundant. Larger areas with the highest connectivity value (class 7) not observed before can now be detected in compartments 25, 49, and 23. In the results from approach 4, there is an increase of the areas with class 1 values. For the last output (Figure 18), the results show a matrix of class 1 cells, where “islands” of relatively high connectivity (up to 5) are found in compartment 50 and compartments 7,9, and 10. The overall result is more fragmented. The northeastern region is divided into several small islands of weakly connected areas. The southwestern region presents an opening in the center and the eastern portion which is practically separated from the rest.

Spatial Interaction (*SI*)

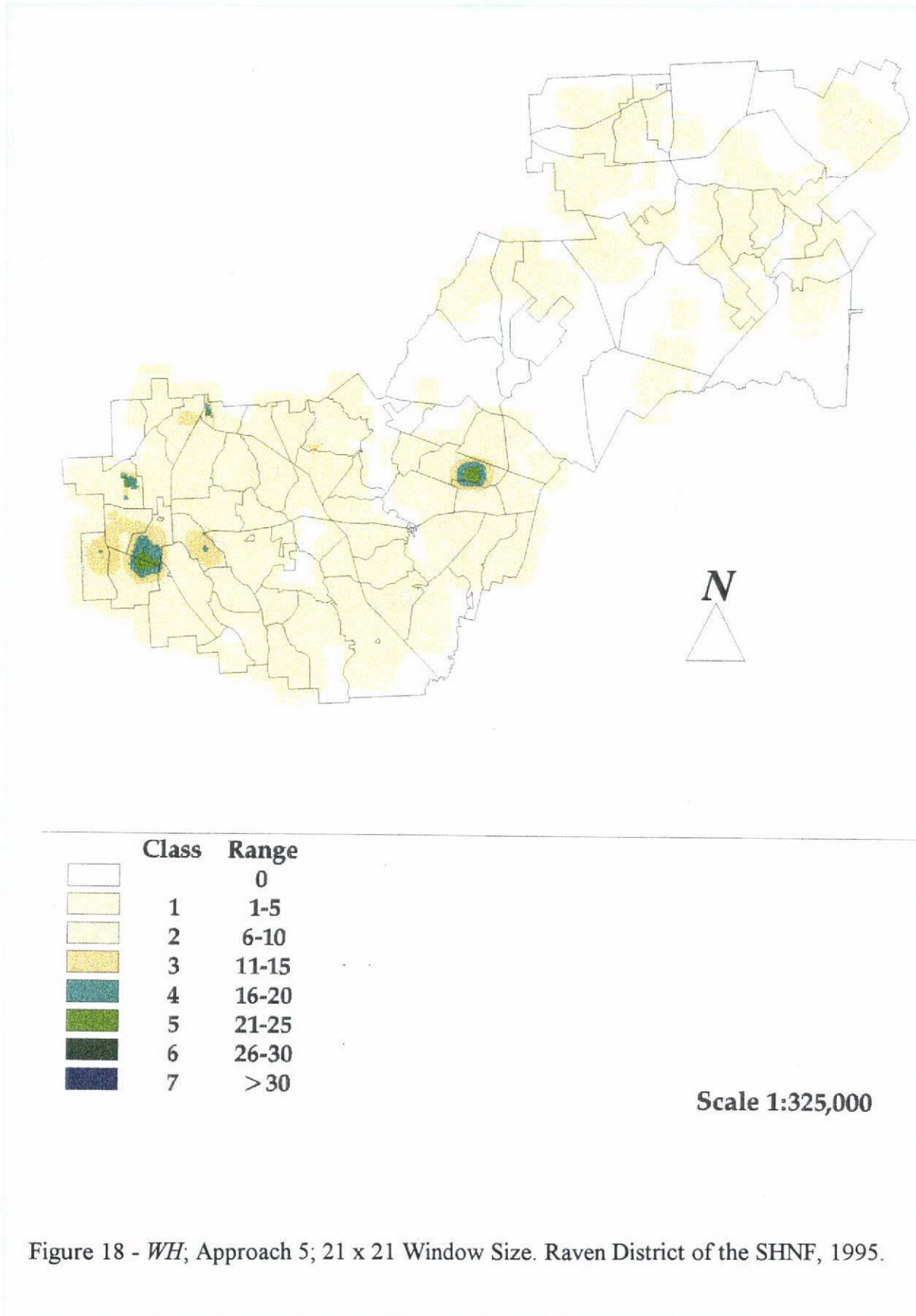
In the output of approach 1 (Figure 19) areas with index class values equal or above 5 can be found mainly in the southwestern region: north (compartments 22, 23, 24, 25, and small portions of 18 and 19), center (compartments 34 and small portions of 17, 21, 28, and 37), west (compartments 7, 9, 10, and 15), east (compartments 50 and small portions of 49 and 51), and northeast (compartment 54). The western area is the only one where the maximum class level, 7, is not reached. Differences of shapes, similar to those observed for the *AMI* outputs can be seen between the western and eastern areas and the northern and

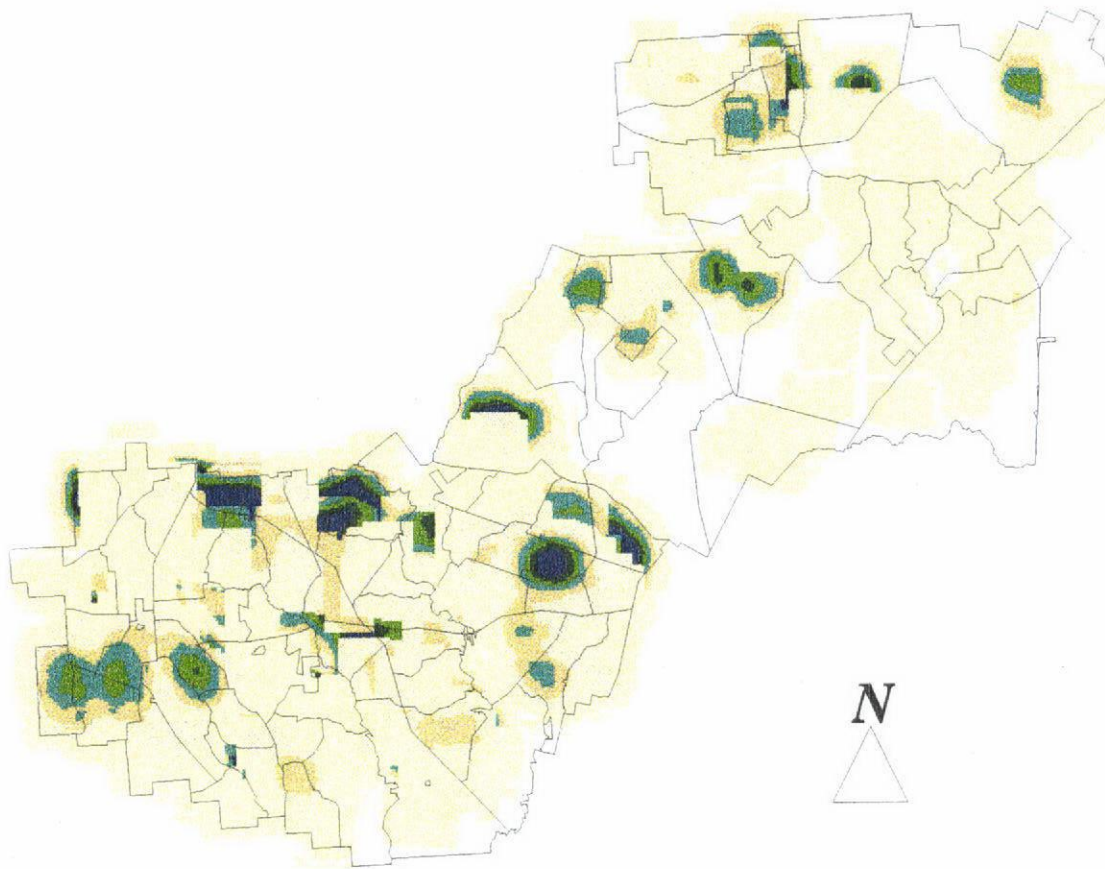


Class	Range
	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	> 30

Scale 1:325,000

Figure 17 - *WH*; Approach 3; 21 x 21 Window Size. Raven District of the SHNF, 1995.





Class	Range
	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	> 30

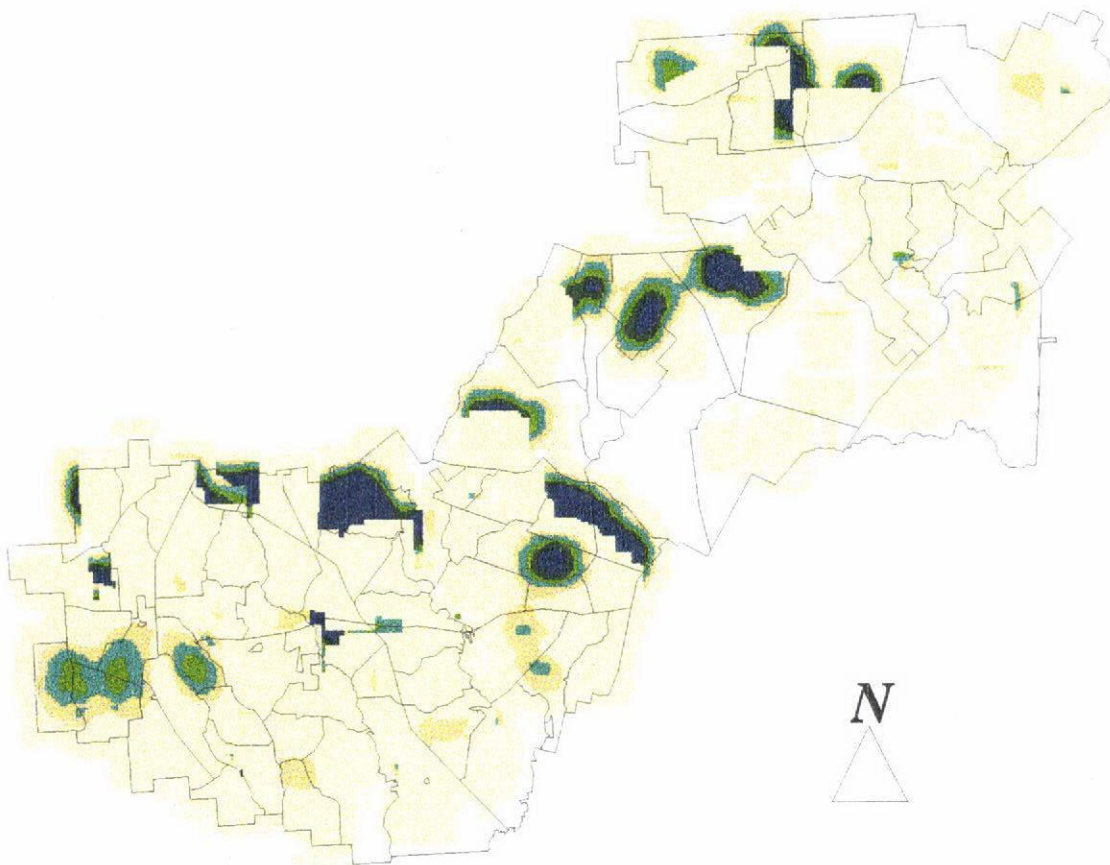
Scale 1:325,000


Figure 19 - *SI*, Approach 1; 21 x 21 Window Size. Raven District of the SHNF, 1995.

central areas. In the northeastern part of the study area, only in a very reduced extension, the maximum value is reached. Zones with SI values equal to or above 5 can be found in the northern (compartment 62), northeastern (compartment 79) and western (compartment 65) areas of this region. The output of the second approach is identical to the previous one. The results of the third approach (Figure 20) show large areas of the higher class values found in the southwestern region (compartments 22, 23, 24, 25, and 32; compartments 7, 9, 10, and 15; compartments 49 and 53) and in the northern and western areas of the northeastern region (62, 56, 57, and 65). The matrix is dominated by class 1 areas with islands of higher SI values in the zones mentioned. Small differences are found between the results of the fourth approach and the results of the first approach. There is a slight reduction in class 2 and class 3 cells, and the northern zone in the northeastern region lost the high class areas. The spot in compartments 56, 57 and 65 was also lost. For the last approach (Figure 21), the results show the northeastern and southwestern regions completely independent, i.e., no interaction. Class 1 areas are still more dominant over all the area of study. The only areas where it is now possible to locate zones of SI equal to or above 5 are in the southwestern region (compartments 6, 7, 8, 9, 10, 15, and 50).

41 x 41 Window Size

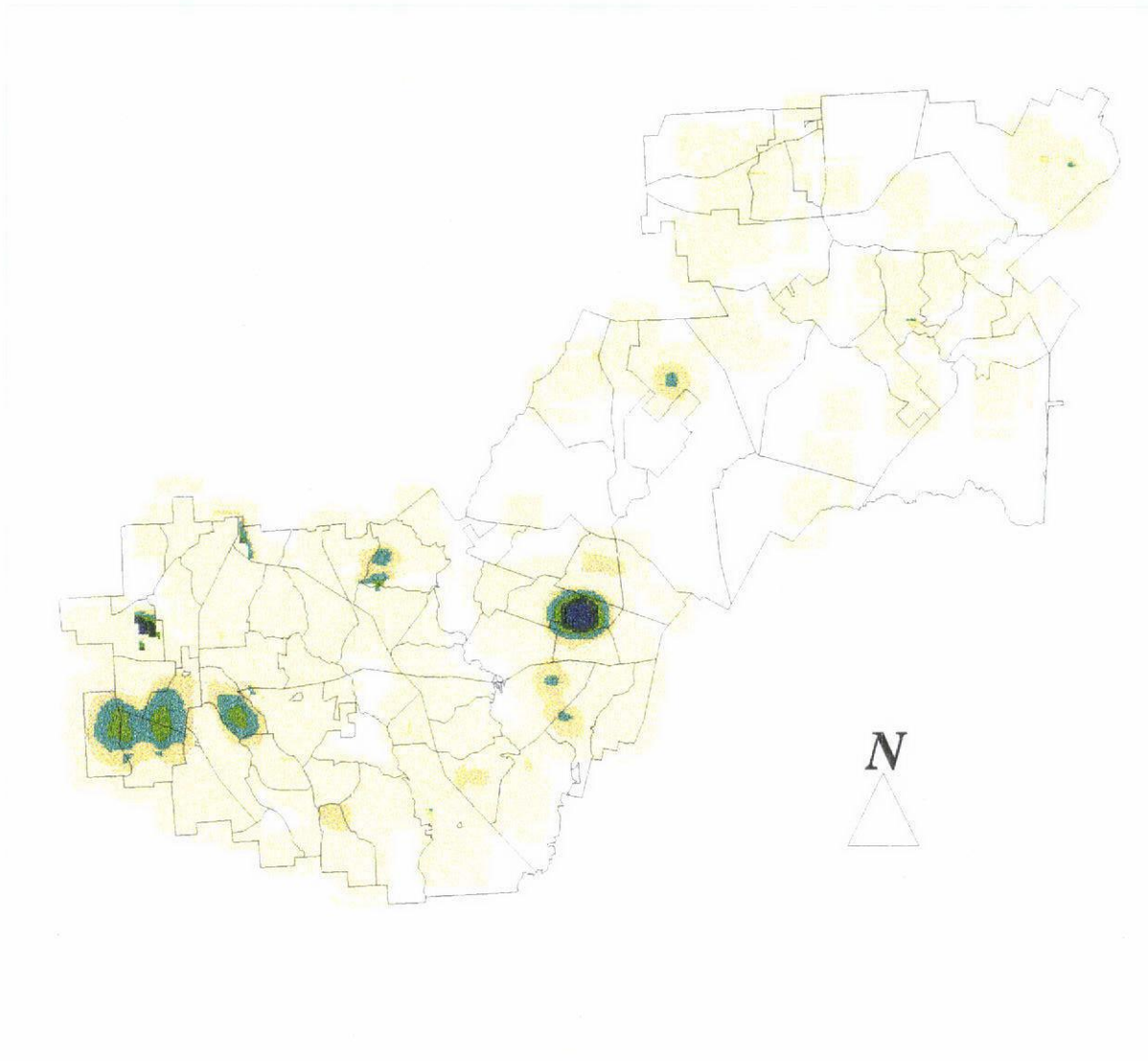
The classification system used for the 21 x 21 window size is kept except for the WH index. The values obtained for this index reach a maximum of 23 in approach 3, and in the other cases never higher than 12. The same classes are used here to make comparisons between the results of both window sizes possible. All the functional heterogeneity indices,



	Class	Range
		0
	1	1-5
	2	6-10
	3	11-15
	4	16-20
	5	21-25
	6	26-30
	7	> 30

Scale 1:325,000

Figure 20 - *SI*; Approach 3; 21 x 21 Window Size. Raven District of the SHNF, 1995.



Class	Range
0	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	>30

Scale 1:325,000

Figure 21 - *SI*; Approach 5; 21 x 21 Window Size. Raven District of the SHNF, 1995.

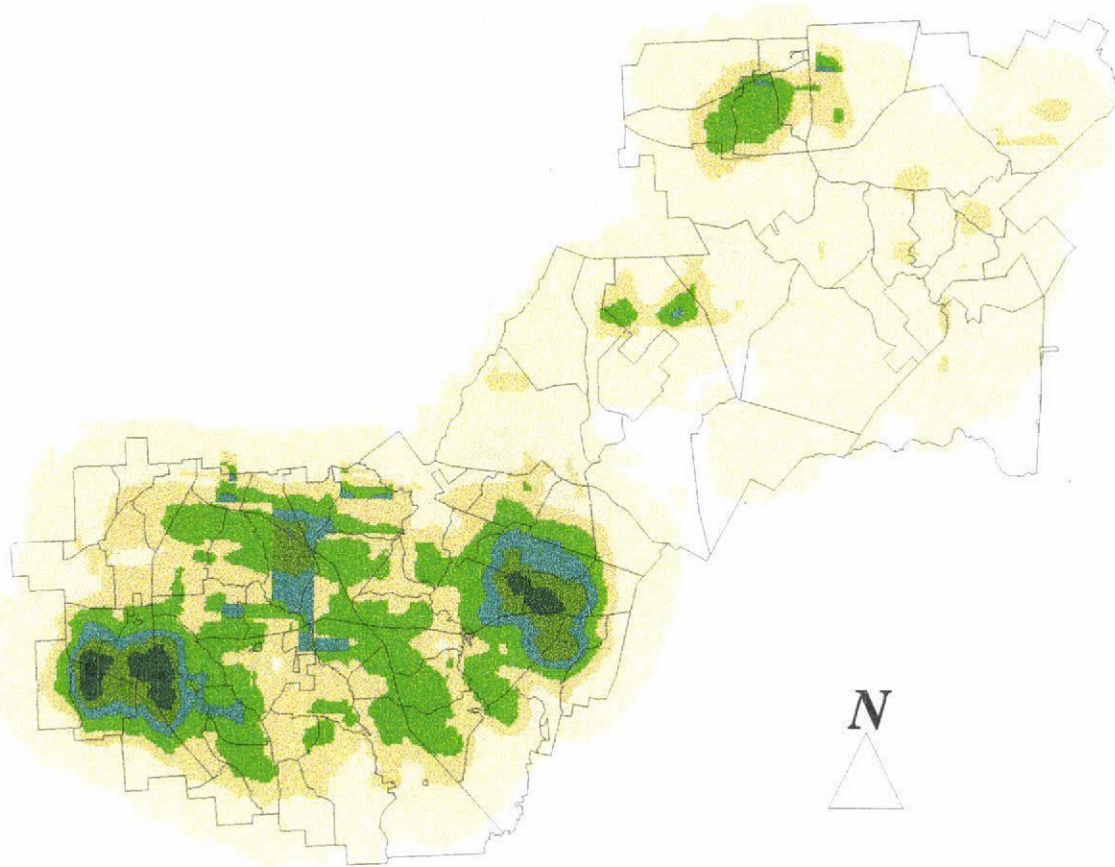
except for H due to the particular way it is calculated, produced more reduced ranges of values when the larger window size was used. Table 4 shows the ranges of the outputs.

Table 4 - Ranges of the Outputs of the Functional Heterogeneity Indices; 41 x 41 Window Size.

Index	Range of the Results				
	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
<i>AMI</i>	0-37	0-37	0-40	0-37	0-37
<i>H</i>	9-100	10-100	10-100	11-100	12-100
<i>WH</i>	0-12	0-11	0-23	0-11	0-9
<i>SI</i>	0-22	0-21	0-43	0-21	0-18

Angular Moment of Inertia (*AMI*)

The maximum class value obtained in the output relative to approach 1 is 8 (Figure 22). The areas with higher values in the southwestern region are located in the west (compartments 7, 9, and 10 with small portions in 6, 11, and 15), the east (compartments 51 and small portions in 42, 43, 44, and 50), and the north (20 and 23). This last area differs from the previous by its regular shape and by the maximum value reached, 7. There is also a diagonal of class 4 in the center of this region. Class values 3 and 4 are dominant. The northeastern region presents the maximum value of 5 in very reduced spots. Two is the dominant value here. The second approach results in a reduction in the areas of highest class value, especially in the eastern area of the southwestern region where class 8 is no



Class	Range
0	0
1	1-5
2	6-10
3	11-15
4	16-20
5	21-25
6	26-30
7	31-35
8	36-40
9	41-45
10	>45

Scale 1:325,000

Figure 22 - AMI; Approach 1; 41 x 41 Window Size. Raven District of the SHNF, 1995.

longer present. Approach 3 (Figure 23) maintains the eastern and western areas of the southwest almost completely. A new area with high class value appears in the southwestern portion of the northeastern region in the upper part of compartment 57. The output of the fourth approach is very similar to that obtained by the second approach. The results of the last approach (Figure 24) reveal that in the overall study area just the eastern and western areas defined by the results of the first approach are maintained. The rest of the area now has class values of 1, 2, and 3

Connectivity (*H*)

In the output of approach 1, class 2 represents the dominant connectivity in the interior of the area of study, where the effect of the outside zero values is no longer a factor. There is no differentiation of areas of high connectivity classes. The same happens relative to the second and third approaches. In this last, however, an area of class 5 surrounded by an extensive area of class 4 can be observed in the northern part of the southwestern region. Approach 4 also results in an output identical to the previous approaches. Class 3 is now more extensive. In the results for the last approach there is a division of the study area into two independent regions. Within the southwestern region there is an evident separation of the eastern part and a hole appears in the center. Class 3 values are the most important.

Weighted Connectivity (*WH*)

The maps relative to this index and window size are given in absolute values of the

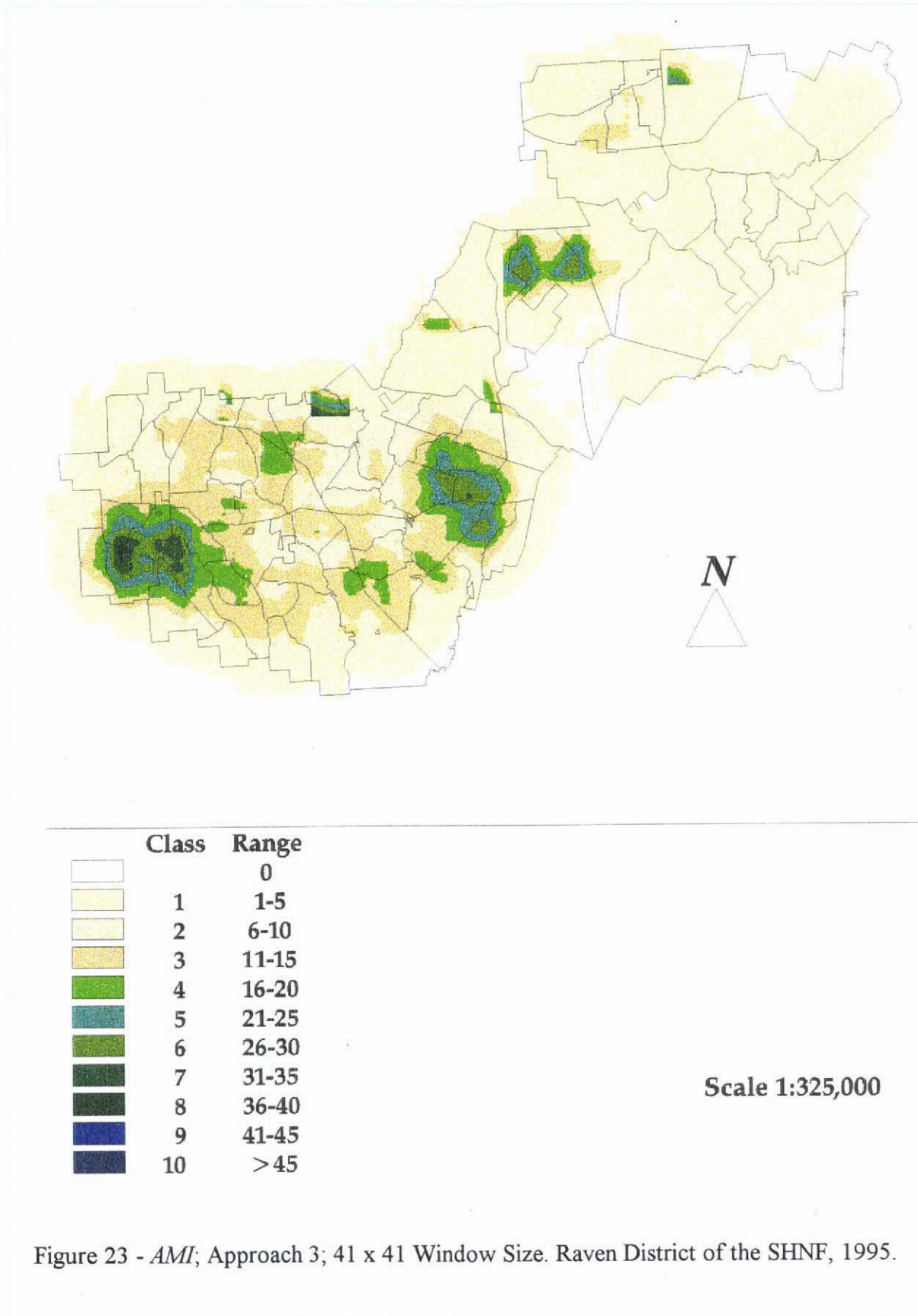


Figure 23 - AMI; Approach 3; 41 x 41 Window Size. Raven District of the SHNF, 1995.

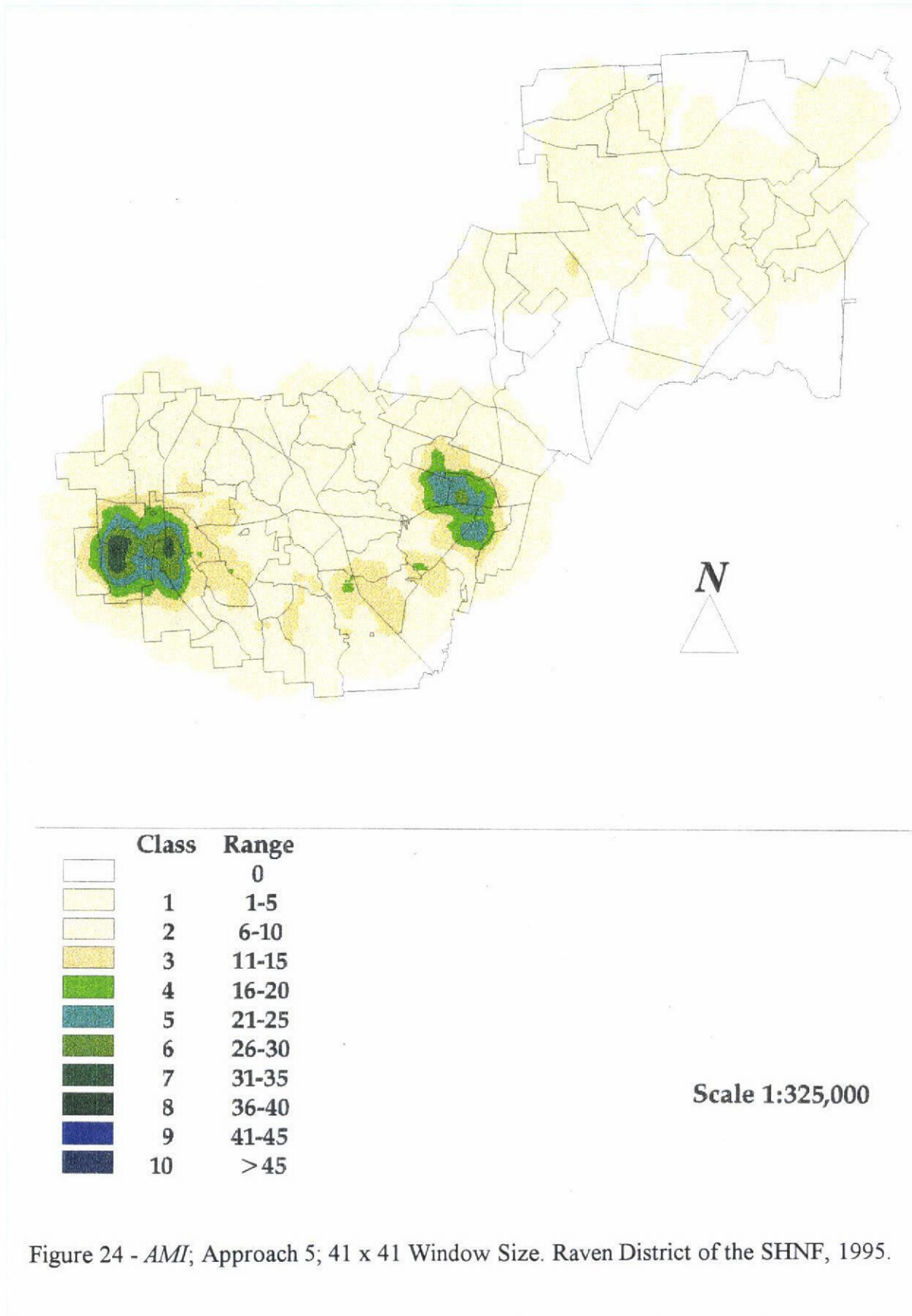
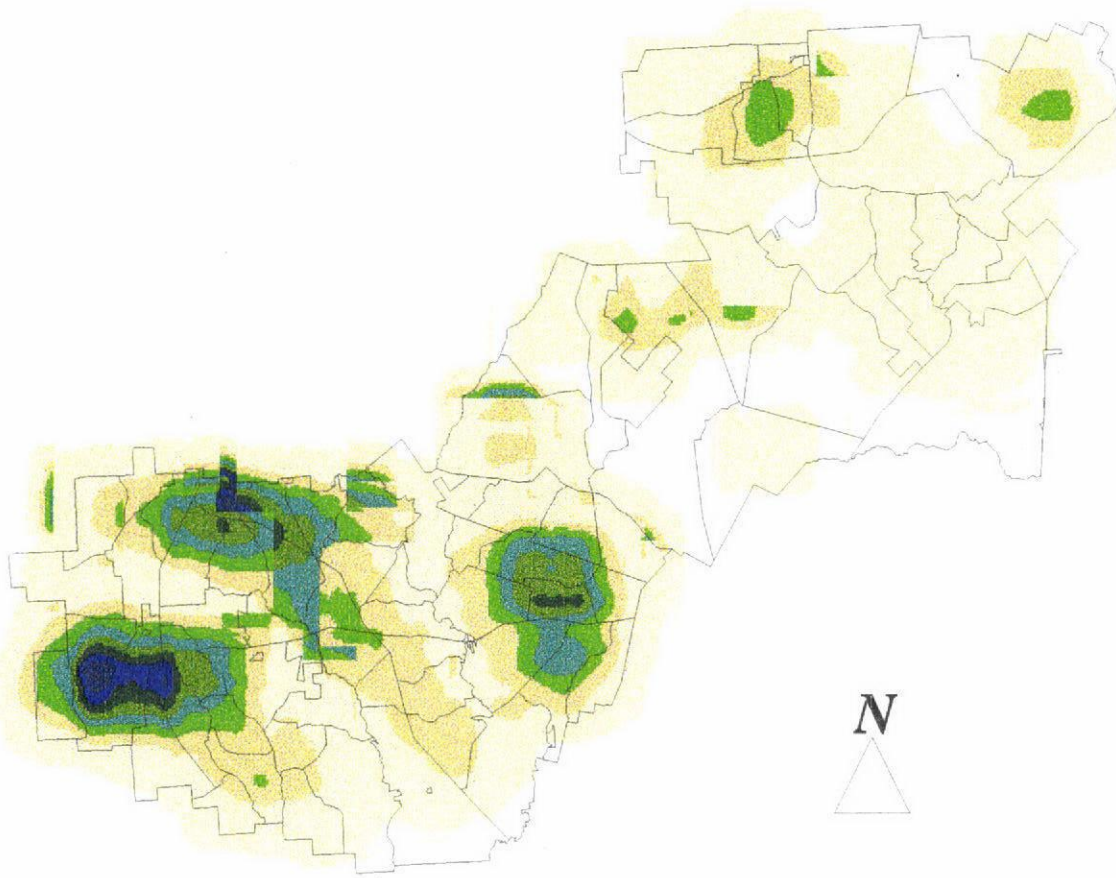
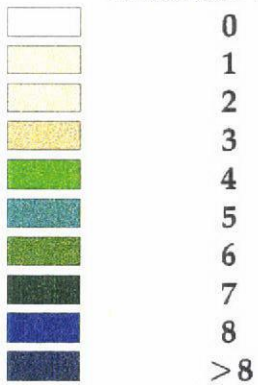


Figure 24 - AMI; Approach 5; 41 x 41 Window Size. Raven District of the SHNF, 1995.

index because of the reduced range in values of the results when the 41 x 41 window size was used. The areas presenting higher values in the output for the southwestern region resulting from the first approach (Figure 25) are in the west (compartments 6, 7, 9, and 10), the east (compartment 51) and the north (compartments 19, 22, and 23). The rest of the region is composed of cells with 2 and 3 values. In the northeastern region the maximum value reached is 4. The second output shows a small decrease in cell values but is essentially the same as the previous one. The output of approach 3 (Figure 26) shows a more extensive area of high connectivity values in the northern area of the southwestern region. In the northeastern region an area with higher values (compartments 57 and 65) can now be seen. The results of the fourth approach are still very similar to 1 and 2. The last results, approach 5 (Figure 27), present the area of study formed by isolated fragments of the lowest value cells. Some areas with higher values can be observed as the intact western and eastern areas detected before in the southwestern region.

Spatial Interaction (*SI*)

The overall area is dominated by class 1 values in the results of approach 1 (Figure 28). Two areas with class values up to 4 can, however, be observed. They are located in the east and west of the Southwestern region, in compartments 6, 7, 9, and 10, and in compartments 50 and 51, respectively. The second outputs are similar to the first. For approach 3 (Figure 29), an area of class 7 is observed in the northeast of the southwestern region in the compartment 25, and an area of class 4 is observed in the southwest of the

**Absolute Value**

Scale 1:325,000

Figure 25 - *WH*, Approach 1; 41 x 41 Window Size. Raven District of the SHNF, 1995.

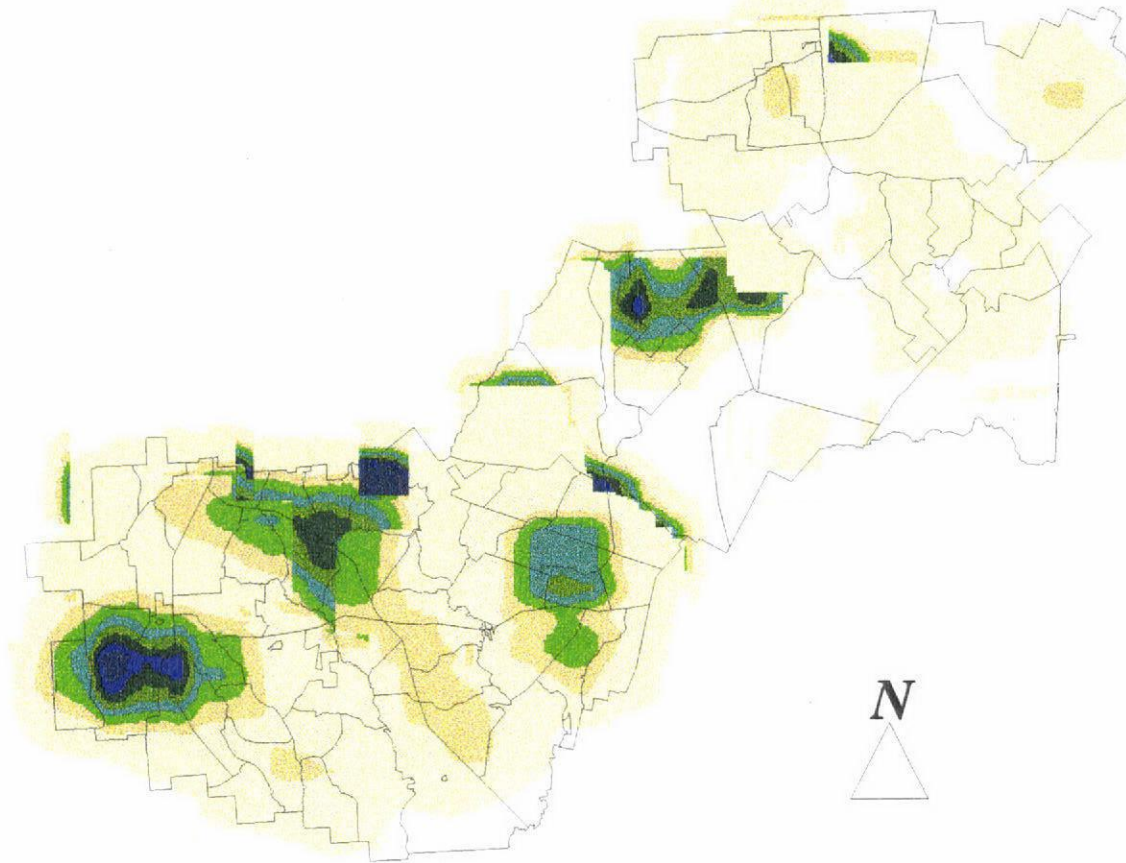
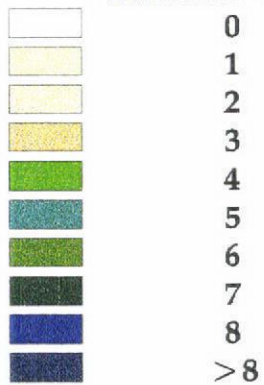
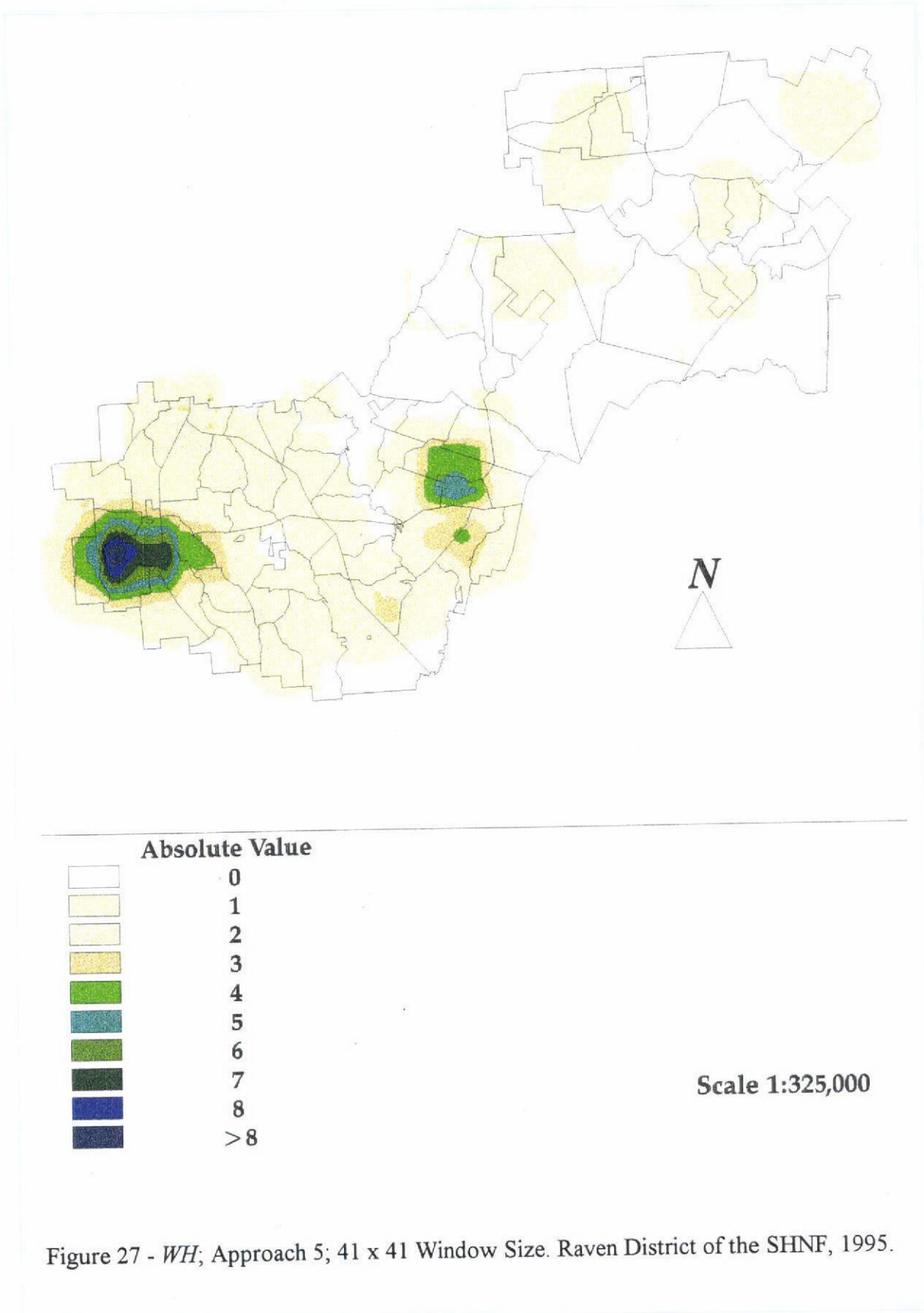
**Absolute Value****Scale 1:325,000**

Figure 26 - *WH*; Approach 3; 41 x 41 Window Size. Raven District of the SHNF, 1995.



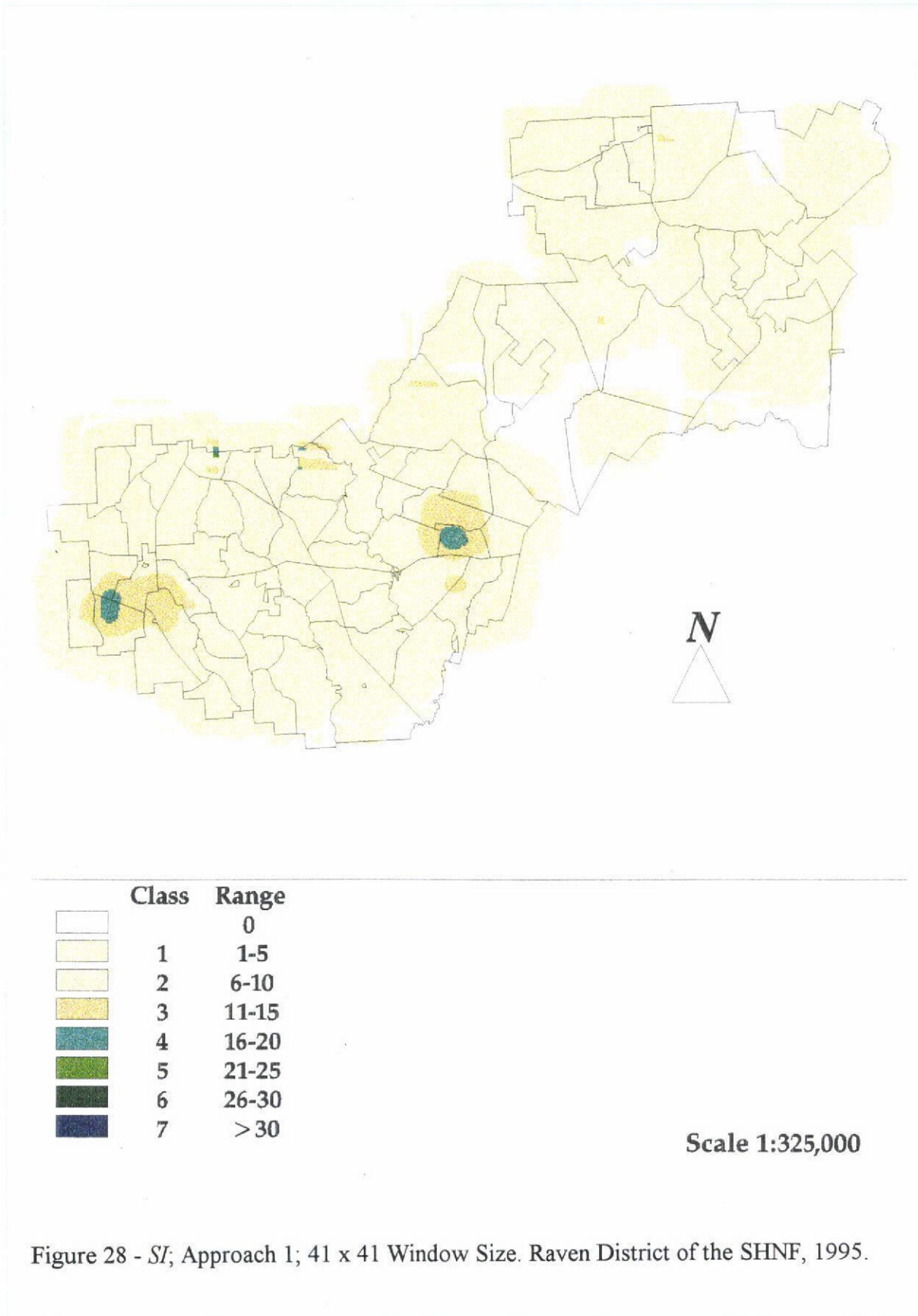


Figure 28 - *SI*; Approach 1; 41 x 41 Window Size. Raven District of the SHNF, 1995.

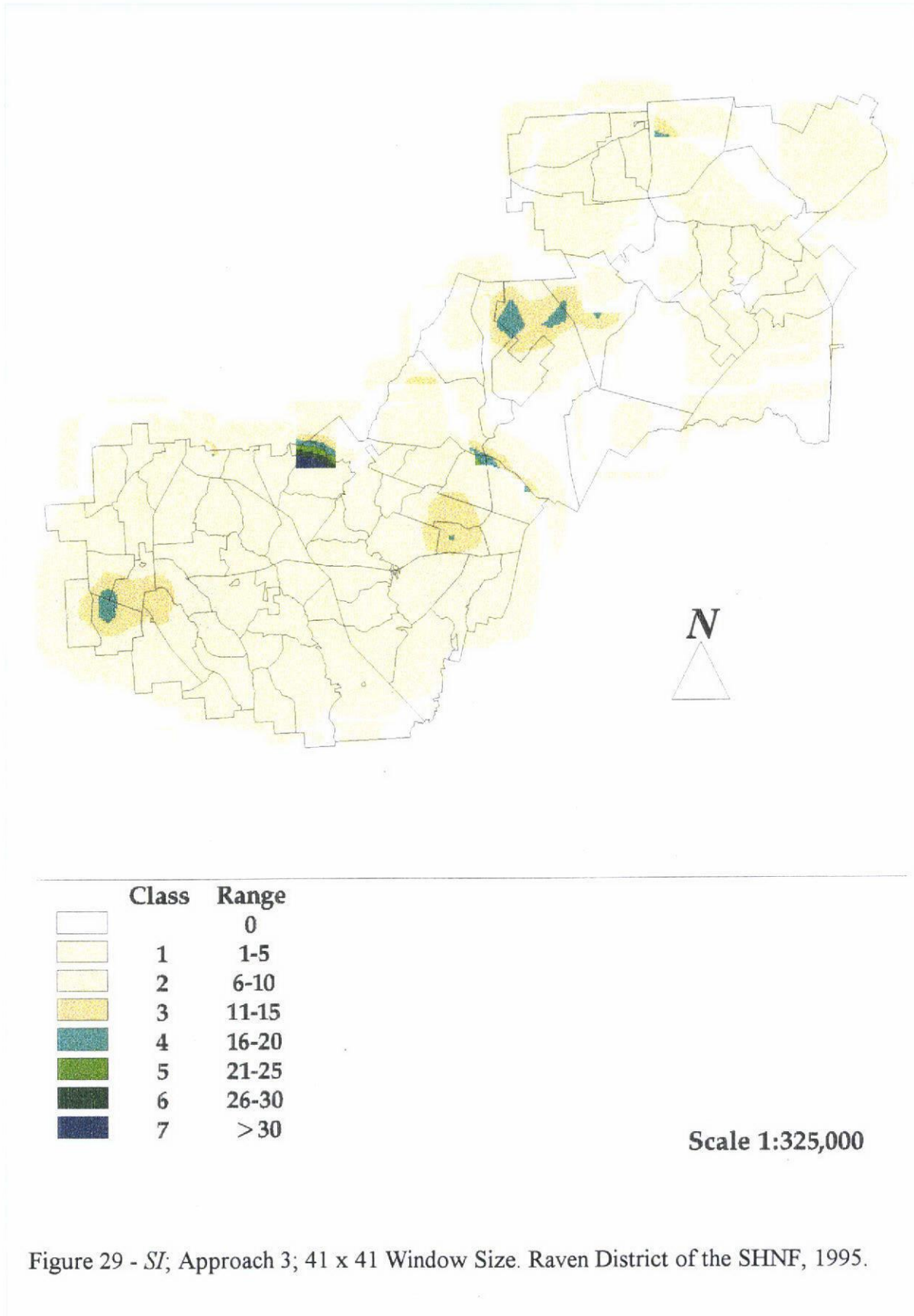


Figure 29 - *SI*; Approach 3; 41 x 41 Window Size. Raven District of the SHNF, 1995.

northeastern region in compartments 57 and 65. In the results of approach 5 (Figure 30) the western and eastern areas are smaller, have lower SI values, and are more isolated. The remaining area is comprised of class 1 values.

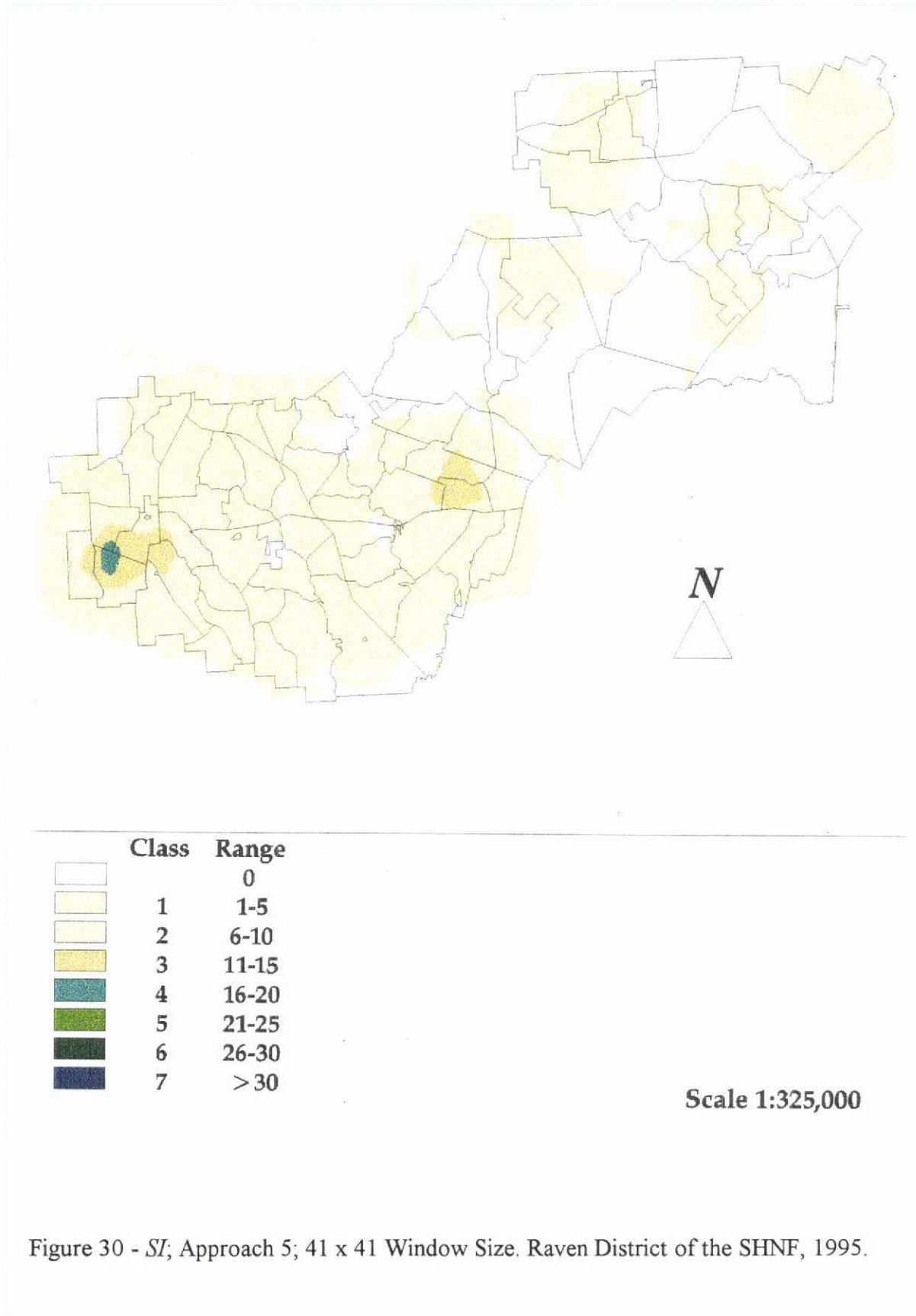


Figure 30 - *SI*; Approach 5; 41 x 41 Window Size. Raven District of the SHNF, 1995.

CHAPTER VI

DISCUSSION

THE MEANING OF THE APPROACHES

The complete conditions of the stands included in the area were not known at the beginning of the project. For this reason analysis of the actual landscape pattern and RCW - process relationship in the area of study was not possible. The conditions included in the five approaches define the most likely situation for the forest pattern in the Raven District. This procedure could have implications in terms of the abundance, density, dispersion, and configuration of different landscape elements and could result in different patterns of fragmentation expressed by isolation and connectivity.

The Raven District already exhibits some degree of fragmentation, particularly in the northeastern region where forest stands are considerably separated from each other. The establishment of the five approaches also simulated a set of conditions where 2 types of fragmentation could be examined. One type was fragmentation in terms of a decrease in nesting and roosting habitat (approaches 2 and 3 where the areas not suitable for these activities were considered as foraging habitat) and the second type in terms of absolute loss of areas for roosting, nesting, and foraging habitat (approaches 4 and 5 where areas not suitable were simply excluded from the habitat). Approaches 1, 2, and 3 constitute a gradient of fragmentation of the first type. Approaches 1, 4 and 5 constitute a gradient of the second type. An overall gradient of fragmentation can also be considered from 1 to 5.

The first approach would constitute the best possible scenario for the area since all loblolly and shortleaf stands of mature or immature sawtimber older than 16 years were considered suitable. Approach 5 constitutes the worst possible scenario in that the abundance of suitable stands is much reduced. I believe that approaches 2 and 3 best represent the true conditions existing in the study area, since the situations defined by approaches 4 and 5 are unlikely. If this assumption is true, the set of conditions defined by the third approach constitutes the worst possible actual scenario for the Raven District. By allowing the inclusion of the areas not suitable for nesting and roosting in at least suitability class 1 in the habitat maps, approaches 2 and 3 allow the maintenance of some conditions in the landscape for movement of birds.

The sequence of the approaches 1, 4, and 5 primarily test a set of conditions that, although they don't currently exist, might occur in the future if disturbance factors are intensified. These conditions would occur if a strong disturbance like fire or hurricanes affected the area.

The implications of the spatial pattern in terms of the RCW population maintenance were analyzed from these two points of view in this project. Simulating the effects of fragmentation on this bird population is possible, independently of the conditions existing at this moment, to forecast how the population can be affected by the factors that presently configure the forest pattern.

THE MEANING OF THE INDICES

Angular Moment of Inertia (*AMI*)

The location of the centroid is a function of the values of the cells present in a matrix and their position. A centroid will be placed closer to the most valuable and more abundant cells in a matrix. The presence of valuable cells in the matrix and distances of each cell to the centroid increase the *AMI* result. The abundance of a specific cell type will affect the position of the centroid and the result of the multiplication of the differences by the cell value. Two matrices with the same abundance of high valued cells have different *AMI* values according to their distances relative to the centroid. Zero values for the *AMI* index are obtained only when all the cells in a matrix have zero values. Higher values will occur where cells with higher values are abundant and are distant from the centroid. A matrix homogeneously composed of the highest values will present the highest *AMI* result.

I was not able to distinguish between high *AMI* values which were due to abundance of high values in the matrix and those which were due to distances from the centroid. This dispersion of landscape elements occurs within a range defined by the size of the window used, and should not be understood as synonymous with isolation. This dispersion would express potential connectivity conditions in a landscape since it would create a set of vertices of a hypothetical network. This network, however, would only work if intermediary suitable conditions exist between the points.

The cells with higher habitat/RCW values are those where active colonies are found. Active colonies actually define the 3 most important class values in the Habitat/RCW maps.

Using a 21 x 21 or 41 x 41 cell window, the cells with higher values are those where, considering the neighboring square area, active RCW colonies present a high density and the surrounding landscape has at least a reasonable suitability value.

As mentioned before, the areas detected by this index imply a high potential for landscape connectivity within the spatial limits defined by the window size. Connectivity is not, however, dependent only on the abundance of suitable patches, though this is an important part of it. Other indices will more appropriately assess this aspect.

Connectivity (*H*)

The values of this index depend on the T value for each matrix since the T min and T max are constant when the matrix size is constant. The maximum value for the index, 100, occurs when the T value equals the T max. This happens when all the cells in the matrix have the same value. The minimum value for the index, 0, occurs when T equals T min. This happens when all the cells in a landscape have different values. Matrices composed of long vertical, horizontal, and diagonal runs of cells will result in large values of H . Long runs in this way indicate connectivity in the element types present in the landscape independently of the element type.

The Connectivity index is probably the least useful index for achieving the objectives proposed in this project. This index behaves in a different way relative to the other indices used in this study. Since its calculation is based only on the runs of cells with the same value, independently of those values, the maximum values will be reached outside the area of study where the matrix is continuously filled by zero values. When the moving window

starts operating with values from the study area, the index values start decreasing until the outside area is no longer included in the moving window calculations. After this point the index indicates only the connectivity within the area of study.

Considering a sub-matrix size of 21 x 21 or 41 x 41 cells, a given value in the output grid will represent numerically the connectivity expressed by the extent of horizontally, vertically, and diagonally contiguous cell values within that range. There is little ecological meaning for the resulting value because it is unknown what cells constitute the runs. It is possible to obtain a "good" (high) value of connectivity in a landscape, even when that connectivity is based on landscape elements that are not favorable to the organism of interest.

Weighted Connectivity (*WH*)

This index detects the connectivity of the most valuable classes present in the matrix since the values of the elements that constitute the runs are used as a weighting factor of those runs. The value of the *WH* is dependent on both the extent of the runs and the value of the cells that are contiguous in the vertical, the horizontal, and the diagonals of a matrix. Higher values result when long vertical, horizontal, and diagonal runs of high values are present. Lower values result from short runs of low value cells.

The window size used reflects the connectivity conditions existing within a certain limited area. The areas detected by the index will indicate the areas where there is continuous, high connectivity of the most valuable elements in the matrix.

Spatial interaction (SI)

Zero values result from a matrix where all the elements are 0. In such a situation m_k and m_l will be zero and the index value is necessarily zero. Small values occur when there is high abundance of elements with low values in the matrix, these elements are not close together, and there is a high value present in the matrix. High values for the SI index occur when there is high abundance of high values close to each other, and when the highest value is equal to m_k or m_l . Considering that there is always a high value t in the matrix, the SI values depend on the values of the cells, m_k and m_l , and the distance between them.

A high value of the SI index indicates a high abundance of valuable cells within the matrix close together. The areas where the most important stands are present (better habitat and higher group size) and where they are closer together should have higher values.

THE MEANING OF THE WINDOW SIZE

The 41 x 41 window size is indicative of the movement conditions for fledgling females and the majority of fledgling males. Fledgling females constitute the most important group in terms of dispersal movements among red-cockaded woodpecker groups and in terms of maintenance of RCW populations. This window creates a limited area within which the several indices are applied successively. The results for each particular cell of the outputs will indicate the conditions existing within this range considering the landscape conditions and the RCW population conditions. The areas detected by the application of the indices are those where adult females would be able to find landscape conditions allowing movement from colony to colony. These conditions are measured by the indices used in this

project. The 21 x 21 window size represents mainly the movement conditions of adult females. The results of the indices can in this way indicate the areas that are more likely to be used by this group of birds in movements between colonies. It might be considered also the distance used by fledgling females or males if a small group of colonies is surrounded by unfavorable habitat conditions. In such a situation the movements of the birds would be confined to a smaller area represented by this reduced window size.

ANALYSIS OF THE RESULTS

In this section several components of this study will be discussed. the window size, the gradient of fragmentation defined by the 5 approaches used, the 4 indices, and the relations between them. The actual landscape pattern/RCW scenario that I believe exists in the Raven District of the Sam Houston National Forest likely is included between the conditions defined by approaches 2 and 3. For this reason, in this section I will analyze in particular the results relative to approaches 1 to 3. The other approaches will be analyzed in more detail for the considerations relative to fragmentation.

The Areas Detected by the Indices

Angular Moment of Inertia (*AMI*)

For the 21 x 21 cell and 41 x 41 cells window sizes and the first three approaches (Figures 10, 11, 22, and 23), the *AMI* index detected higher class areas located in the west, in the east, and in the north of the southwestern region. A central area was also detected,

and more marked with the 21 x 21 window size. These areas correspond to areas of the input habitat/RCW matrices with different characteristics. The northern area is dominated by cells of the classes 2 (youngest suitable nesting and roosting habitat) and 3 (medium age nesting and roosting habitat), with many small areas of class 5 (recruitment and replacement stands) and a few small areas of class 6 (inactive colonies). The west area is dominated by habitat/RCW class 5 with some additional extensive areas with values 1 (foraging habitat) and 2. There are, however, also many areas of classes 8 (colony with 2 or 3 cavity trees) and 9 (colony with 4 or more cavity trees) and class 6 areas as well. The east area presents a similar situation to the west area in terms of abundance and distribution of cells with the highest values (5, 6, 7, 8, and 9). A large central area of class 8 and another of class 5 are present in the east area.

These 3 areas, although different in terms of matrix dominance, abundance, and configuration of the several landscape element types, obtain similar *AMI* values. The importance of the areas for RCW is quite different, however. The north area, although its *AMI* results are high, includes no active colonies. This means that even though this area has conditions comparable to other areas where woodpeckers exist, it is not used by RCW because there are no cavities present. Despite this fact, the *AMI* index indicated this area as an important area for the RCW.

Connectivity (*H*)

The results of the application of this index with the 41 x 41 window size did not indicate particular areas of the region as distinct from the rest. The areas of high values in

the output from the 21 x 21 window size (Figures 13 to 15) for this index are coincident with empty areas (holes of zero values) in the input matrix or with continuous areas of class 1, 2, or 3.

Stands with colonies do not seem to influence the results of the application of the *H* index since the colonies, active or inactive, are located in areas of the lowest connectivity classes (2, 3, and 4). The reduced size of the stands compared to the window size is probably one reason this occurs. Another obvious factor is that the calculations don't consider the values of the cells. This index might, however, eventually be useful in the definition of areas considered important for a particular group of birds and in the definition of absolute connectivity of a landscape for comparative purposes

Weighted Connectivity (*WH*)

Both 21 x 21 and 41 x 41 window sizes (Figures 16, 17, 25, and 26) indicate basically the same high value areas in the output grids despite the important differences in values obtained and the spatial dimensions and shapes of the highlighted areas for the two window sizes. There is, however, a quantitative difference in the input values. In the west and east areas the values in the Habitat/RCW matrix are quite elevated, mostly classes 5 and 8. The east area is located over a large area of class 8. In the north region the same cannot be observed. In that area, cells of the classes 2 and 3 are dominant with many small areas of class 5.

Spatial Interaction (*SI*)

The areas of the District generating the highest *SI* values (Figures 19, 20, 28, and 29) are areas with different habitat conditions. For the first approach, the north areas are over an extensive class 2 area with some smaller areas of class 3 and 1. The east and west areas are the same as for other indices. In the northeastern region the area to the north is over a class 3 area with some class 4 and 5 areas, while the area to the west is mainly over habitat of class 3. For the 41 x 41 window size only the areas located to the east and west have high index values, and their extent and absolute value are more reduced than for the smaller window size.

The Areas Indicated by the Overall Results

There is a general tendency for the indices to identify the same areas of the landscape as those having the highest values, independently of the window size or the approach used in the analysis. The extent, the absolute values obtained, and the exact location of these areas change from approach to approach and between window sizes, but they are almost always located around the same group of compartments. These areas are located in the north, in the west, and in the east of the southwestern region. A central area of more reduced size is many times also detected in this region. The northeastern region is more difficult to describe since the areas of high values are not as constant. There are, however, areas in the west and north of this region which are detected especially in the third approach using the Angular Moment of Inertia, Weighted Connectivity, and Spatial Interaction Indices for both window sizes.

The conditions that generate the same high index values are quite different from area to area, as described before. Some examples of several conditions that produce high values for the different indices were given in the previous section. The areas of high index values always have a reasonable abundance of groups of cells of at least class 5 located within larger areas of classes 1, 2, and 3 values. Among the areas with higher *AMI* values, the one presenting the least high values in the habitat/RCW input is the northern location where there is a relatively high abundance of class 5 cells. This would indicate that high values for this index could be obtained when there is, within sub matrices of 21 x 21 or 41 x 41 cells, a density of suitable habitat at least equal to that observed in the northern part of the southwestern region. The Connectivity index indicates areas of high cell contiguity. These areas don't have any relationship to the presence of cells of the high habitat/RCW classes. The Weighted Connectivity and Spatial Interaction indices seem to express the presence of high values of the input matrix but have some tendency to include areas of relatively high density of the most valuable input values. Using the 21 x 21 window size in the analysis, the areas detected by both indices seem quite similar. When the window size is changed to 41 x 41 cells, however, the northern area of the southwestern region loses relative importance for both indices. This last window size (41 x 41) seems in this way to be a better indicator of the presence and density of the most valuable landscape elements.

Fragmentation

Fragmentation in the terms defined previously indicates how RCW populations would change in response to loss of habitat (nesting and roosting habitat, or any kind of

habitat). It is expected that the areas that are able to “survive” the effects of fragmentation can also be indicated as those with the best chance for maintenance. This means that the areas that present high values for the indices considered would provide the most favorable conditions for the species in spite of the degree of fragmentation created (which was quite intense in the fifth approach)

Fragmentation increases the abundance of the lowest values in the habitat/RCW input grids (1 or zero according to the type of fragmentation considered). This will considerably reduce the values obtained for the various indices, except Connectivity, since all these indices are sensitive to the presence of zero values in the input matrices

The fragmentation considered in terms of shifting the habitat class of roosting and nesting habitat, as described by the sequence of outputs relative to approaches 1 to 3, does not seem to interfere considerably, in terms of spatial conditions, with the maintenance of the actual pattern of the RCW population distribution in the Raven District. The areas more important for the RCW in the less fragmented situation, approach 1, are generally maintained in the third approach. Actually, a decrease in nesting and roosting habitat should not affect the existing and occupied nesting and roosting habitat; the spatial conditions among these areas change categories but the conditions required for movement still exist in the foraging habitat. Thus an increase in foraging areas would not reduce movement conditions for the landscape. The northern area of the southwestern region loses some importance from approach 1 to 3 in terms of *AMI* for both window sizes, whereas other areas become more important. The same doesn't occur for the other indices. Weighted Connectivity and Spatial Interaction indices generate even more extensive areas in the same

region. Spatial Interaction, based on the 41 x 41 window size, decreases the importance of the east area when this fragmentation increases

Fragmentation in terms of absolute loss of habitat as incorporated in approaches 1, 4, and 5 reveals that some modification would occur at the level of the landscape, but some of the areas detected in the approach 1 are still maintained. Actually, few changes in location of the areas with higher values for the indices were observed. The main change, for this gradient of fragmentation, was the loss of importance of the northern area in the southwestern region based on the fifth approach

Other major changes observed are related to the overall area of study. From the outputs relative to the sequence of approaches 1, 4, and 5, the following changes were evident:

- isolation of the northeastern region of the district in relation to the southwestern region by areas containing no suitable conditions (indices values equal to zero);
- isolation within the northeastern region; there was a fragmentation of the area into very small islands with values slightly above zero,
- isolation within the southwestern region; the eastern region becomes separated from the rest of the region by a strip of zero values. A hole corresponding to an extensive area of zero values in the input grid, is observed in the center of the region.

It seems that the western and eastern areas of the southwestern region are independent of the changes created by this fragmentation. If the Raven District is subject to fragmentation of RCW habitat following the pattern considered (approaches 1, 4, and 5), the main nucleus of RCW populations would be maintained in the area. Active colonies

located outside the areas defined by the indices, however, will have a tendency to disappear since there are no conditions suitable for contact with other colonies. Inactive colonies located outside of these same high-value areas also will not be recolonized

Differences Between Window Sizes

Most of the areas mentioned before were detected using both window sizes. Some differences, however, can be perceived between the outputs resulting from the use of the two window sizes. The magnitude of the output values is considerably lower for the 41 x 41 window size except for the Connectivity Index. The most important revelation from the application of the 41 x 41 window size is the potential reduction in the relative importance of the areas located at the north of the southwestern region by the *AMI*, *WH*, and *SI* indices. Other differences include the size and shape of the detected areas. In the 41 x 41 cell size analysis the areas were generally larger and more uniform. Because of this, the number of areas indicated by the indices based on this window size were fewer in number.

The 41 x 41 window size is the most important in ecological terms because it encompasses movements of all the sex-age categories within a RCW population. The areas detected by the application of the indices deserve special attention in the analysis of the relationship between pattern and dispersal processes, and logically more emphasis will be given to the results obtained using this scale

The areas detected by the *AMI*, *WH*, and *SI* indices for the five approaches have some points in common. Given the uniformity of the results of the Connectivity index, it will be excluded from this discussion. The first point in common between results is that the

western and eastern areas of the southwest region have particular importance over the rest of the areas because of their predominance when any of the several approaches are used. The northern areas are especially detected by the Weighted Connectivity index for the approaches 1 to 3. This area is, however, also present in the results of the other two indices for at least one approach. In the northeastern region the northern and western portions, in spite of their reduced dimensions, also have some importance.

From the reasons pointed out, it is possible to indicate the areas located in the west and east of the southwest region as those that possess the most important actual conditions for the species. Also, these conditions would be enough to maintain the present groups of colonies in case of increasing fragmentation as defined by the gradient ranging from approach 1 to approach 5. According to the values of the indices, these areas provide the best conditions in terms of presence of birds, presence of cavity trees, presence of nesting and roosting habitat, presence of foraging habitat, and density, connectivity, and interaction of the areas with these favorable characteristics. The northern area is also an important area when approaches 1 to 3 are used. It presents a relatively high abundance of suitable habitat areas, but it has no cavities and birds. Since the values obtained by the indices in that particular area are comparable to the values obtained for the other areas mentioned, this area seems able to support a group of active colonies.

Another observation is that the groups of colonies mentioned (west, east, and north locations) are apparently isolated, with no contact between them. Since the window size does not include all the possible distances that birds can fly, this hypothesis is not strongly supported. Male birds fly longer distances and can maintain some links between the existing

groups of colonies. They are not, however, as important as females are for the maintenance of populations, and females are not able in most cases to fly the distances needed for maintaining contact between groups of colonies in this region.

The Metapopulation Theory as Related to the Raven District Red-cockaded Woodpecker Population

The results suggest that the population of red-cockaded woodpeckers of the Raven District is not a population in the classical sense, but instead is a population composed of a set of sub-populations which are relatively or totally isolated from each other. The metapopulation model thus might apply to the present population distribution. To be considered as a metapopulation, a population must possess certain other characteristics. The first is the independence of the sub-populations' dynamics (Haila 1990 cit. in Simberloff 1995). The second is specific extinction-recolonization dynamics followed by a metapopulation (Opdam 1991). Independence of sub-population dynamics is likely to occur in the Raven District since the nucleus of populations detected seem to be isolated from each other. The distances between them and the landscape conditions are not very favorable to dispersal movements between them, as expressed by the indices. Extinction in RCW populations would occur in groups where there is not renewal of females in the colonies when breeding females disappear (Walters *et al.* 1988). Areas from the northeastern region where only inactive colonies exist are likely to be the result of such a process.

Recolonization occurs in colonies as a natural demographic process of abandonment and reoccupation of colonies (Doerr *et al.* 1989, Walters *et al.* 1988; Walters 1991), but at

the scale considered in this study there is no indication of such a process. It is difficult to consider extinction-recolonization dynamics in a species so dependent on cavity trees. It does not seem probable that woodpeckers can recolonize an area of available territory when cavity trees are absent. It is theoretically admissible to consider the existence of cavity trees in areas where woodpeckers have recently become extinct. It is difficult, however, to find extinction factors that could provoke a fast extinction of a population without a decrease in the habitat quality of the area. The factors that might be associated with extinction of local populations of woodpeckers (change of landscape conditions for dispersal movement, hardwood encroachment, intensive disturbance such as fire, bark beetles, or hurricanes) all create conditions unfavorable to the presence of RCW clans. Demographic stochasticity and predation would cause population extinction only if a population was stressed by any of the factors mentioned above and if the population was reduced in size. For all these reasons, natural recolonization by RCW is unlikely. This is, from my point of view, the condition that does not allow the classification of this RCW population in the Raven District as a metapopulation.

Final Considerations

All the indices detected basically the same areas as more important than others according to the conditions they were measuring. The reasons for this result are unknown since the model was not validated. It is possible, however, to speculate based on the results obtained. The areas detected by the indices are coincident with the major aggregations of active colonies. This does not occur in every case, but the major concentrations of active

colonies are indicated by the indices. The indices indicated also areas that have no colonies but do contain recruitment stands and suitable habitat conditions and thus present high final values. The fact that the same areas were detected by all the indices in several approaches can be explained by two hypotheses: (1) the areas detected contain simultaneously the conditions evaluated by the indices allowing the dispersal movements of the birds, and for that reason the birds occupy the best areas in terms of the conditions defined, or (2) the indication of these areas was only a consequence of the way the habitat and habitat/RCW inputs were established, or the way in which the indices were calculated, thus high values were assigned to particular areas. Given the high coincidence of the areas detected by the indices and the areas of higher density of active colonies, it seems that the indices are an effective way to indicate the best set of conditions associated with both the woodpeckers and the forest pattern. The areas of high index values that were obtained for areas without active colonies are indicative of the limits at which the indices can operate; i.e. they are able to detect areas with favorable conditions for the species even when the species is not present. The northern area of the southwestern region is the primary example of that ability, and in fact this area is indicated with more strength than some areas containing active colonies. Concentrations of active colonies that were not detected by the indices are mainly located in the compartment 39, group of compartments 1, 2, 3, and 4, compartments 13, 31, 32, and 33, and compartments 67, 69, and 74. These groups are relatively small in number. The indices present medium-low values for these areas, but are very low when approach 5 is used. It is possible that the indices are not able to detect small and isolated groups like these, or, alternatively, these groups are located in areas of poor landscape

conditions for the species, or they are small in size and isolated from other groups of colonies by unsuitable habitat and might disappear in the next years

Eventual Limitations of the Study

The first subject of comment is the spatial and ecological unit of work followed in this study, the forest stand. These areas were used as landscape elements with the meaning of the traditional ecotopes: homogeneous units of the landscape mosaic. This homogeneity is, however, unlikely. From the comments made in the methodology chapter one can question the validity of the forest stands as homogeneous land units when so much heterogeneity is included. Variables such as age and timber variables are expressed by a single value, the mean, for an area that can be as large as 537 ha. It was found that a stand can include several conditions within its limits. It was detected, for example, that some stands present inclusions older than the overall stand conditions and not described by the mean value. Even if they were considered in the mean, the mean value would describe conditions that in fact do not exist in the stands. This problem is extensive and affects all the attributes used in the classification of the RCW habitat. The solution to this problem would be the reevaluation of the Raven District, creating homogeneous areas and thereby reducing the variability of the variables describing the land units. Such a procedure was not viable for this study.

Another problem related to the units is the variability in size that the stands represent. Since the stand and not an area around the exact location of the colonies was used in this study, it is possible that small stands with large RCW groups would be less

important based upon the calculated indices than large areas of a lower habitat/RCW class. I am not able, however, to quantify the magnitude of such an error in this project. The solution previously mentioned (i.e., reclassification of the land units) could have solved this problem in part, but additional corrections would also be necessary. The most logical approach would be the consideration of the geographic location of the colonies in the study area. Again, the investment in time that this procedure would require made it impossible to pursue.

I employed the dispersal distances measured in North Carolina by Walters *et al.* (1988) for the establishment of the window sizes to apply in the Raven District. The habitat of the RCW population where these distances were evaluated is not necessarily similar to the habitat of the RCW population in the East Texas. Patch size, distances between suitable habitat areas, and configuration of the habitat are all conditions that can influence the distances flown by red-cockaded woodpeckers in an area. The population density and group size are population attributes that can also influence the dispersal distances

CHAPTER VII

CONCLUSIONS

Based on the results of the study developed for the Raven District of the Sam Houston National Forest, some conclusions can be presented.

(1) The functional heterogeneity indices seem to be an effective way to detect areas of the forest most important for the maintenance of red-cockaded woodpecker populations. These areas are those presenting the best demographic, habitat, and landscape conditions for the species.

(2) The Connectivity index is not a useful index for achieving the objectives proposed in this study since its results are not related to the distribution of the RCW colonies or the most valuable habitat conditions

(3) Angular Moment of Inertia, Weighted Connectivity, and Spatial Interaction indices indicate the same areas of the Raven District as those which are more important for the birds given actual distribution, group size, habitat conditions, and landscape conditions. These areas are listed below.

- the western and eastern areas of the southwestern region, which had the highest values for the *AMI*, *WH*, and *SI* for all the approaches and for both 21 x 21 and 41 x 41 window sizes, and
- the northern and central areas of the southwestern region, with high values for approaches 1 to 3 and for the 21 x 21 window size

(4) Fragmentation of the kind expressed by approaches 1 to 3 does not seem to interfere considerably in the maintenance of spatial conditions within the areas detected as most important for the species.

(5) Fragmentation of the kind expressed by approaches 1, 4, and 5, seems to allow the maintenance of the main centers of RCW

CHAPTER VIII

RECOMMENDATIONS FOR THE CONSERVATION OF THE RED-COCKADED WOODPECKER IN THE RAVEN DISTRICT

Although this population cannot be considered a true metapopulation, some of the characteristics of the metapopulation model can be used to understand the population dynamics and, especially, to provide some recommendations for the conservation of the species in the area. The metapopulation model of Boorman and Levitt (1973 cit in Simberloff 1995) is based on a central, long-lived population which is responsible for the re-establishment by immigration of peripheral areas where extinction occurs. The existing centers of red-cockaded woodpeckers presenting the most favorable conditions can be considered as sources for future expansion of the population towards currently vacant areas which provide conditions to support red-cockaded woodpeckers, such as the northern area of the southwestern region.

RCW can not, however, colonize areas where cavity trees are absent. Given the successful results in the use of artificial cavities (Walters 1991; Walters *et al* 1992), it seems that the installation of these cavities could allow the creation of the missing conditions in the areas which have all the remaining habitat and landscape conditions. In this way, the expansion of the actual population centers to the remainder of the Raven District would be possible

Recolonization of the mentioned areas can be accomplished following two strategies, either independently or combined. One would be the creation of suitable conditions between the existing centers and the areas able to support active colonies. The other would be the reintroduction of pairs of birds directly in the new territories. The creation of intermediary areas of suitable conditions between the occupied and the unoccupied areas of the Raven District would include the continuation of the creation and maintenance of replacement and recruitment stands that the Forest Service currently uses for the conservation of the species. Additionally, these areas should contain artificial cavities. In this way a progressive reoccupation of territories can be carried out from the actual centers in the direction of the northern area. This strategy would be responsible for the creation of an overall network, allowing movements and contacts between woodpeckers in colonies in different locations.

The reintroduction of woodpeckers in the areas containing the best conditions for supporting red-cockaded woodpeckers is interesting because it would make the process of recolonization faster, creating new sources of birds in the center of the unoccupied territories. This process has already been used with success (Rudolph *et al.* 1992). These new centers of dispersal, in conjunction with the network of nesting and roosting habitat, would create the most efficient strategy for the conservation of the species in the Raven District.

Particular groups of active colonies were not detected by the indices. The colonies located in the compartments 1, 2, 3, and 4 are isolated from the western area of the southwestern region by a large area of unsuitable habitat. These colonies are, however,

close to the northern areas. It is possible to connect this sub-population with the northern group after the recolonization of these areas by new groups of red-cockaded woodpeckers.

The group located at compartment 39 seems isolated as well. In this case connections to the east or west areas are unlikely since this group is surrounded by large water surfaces except to the north. The expansion of this group in that direction seems to be the only option to its conservation, based on the actual forest pattern.

The group of colonies located in compartments 13, 31, 32, and 33 seems to be relatively close to the western concentration of the southwestern region of the District, although it does not seem to be functionally connected to it. The linkage of this group to the groups in the west area could create conditions for its maintenance.

The group of colonies located in compartments 67, 69, and 74, in the northeast region seems to be absolutely isolated from the rest of the population and is likely to become extinct very soon. The maintenance of active colonies in the northeastern region of the District seems more complicated due to the existing fragmentation in the area. The maintenance of this group should be analyzed in much more detail and at a larger scale, according to the debility of this sub-population.

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APPENDICES

APPENDIX I
FOREST TYPES IN THE RAVEN DISTRICT

Forest Type ¹	Area occupied (ha)	Relative Area (%)
Loblolly Pine	30920	79.34
Shortleaf Pine	4672	11.99
White Oak-Northern Red Oak-Hickory	855	2.19
Sweet Gum-Nuttall Oak-Willow	752	1.93
Loblolly Pine-Hardwood	719	1.84
Sugarberry-American Elm-Green Ash	572	1.47
Bottomland Hardwood-Yellow Pine	110	0.28
White Oak-Black Oak-Yellow Pine	79	0.20
Slash Pine	74	0.19
Laurel Oak-Willow Oak	62	0.16
Post Oak-Black Oak	53	0.14
Undrained flatwoods - Savannahs	50	0.13
Sycamore-Pecan-American Elm	29	0.07
Southern Red Oak-Yellow Pine	15	0.04
River Birch-Sycamore	7	0.02
White Oak	5	0.01
Total	38973	100

¹ - Definitions follow the CISC database manual

APPENDIX 2**LOBLOLLY AND SHORTLEAF PINE STANDS AREA DISTRIBUTION BY AGE
CLASS**

Age	Area Occupied (ha)	Relative Area (%)
0-20	9269	26.0
21-40	2699	7.6
41-60	2225	6.3
61-80	16722	47.0
81-100	4333	12.2
>100	344	1.0
Total	35592	100

APPENDIX 3
STAND CONDITION IN THE RAVEN DISTRICT

Stand Condition	Area Occupied (ha)	Relative Area (%)
Mature sawtimber	12799	32.8
Immature sawtimber	12583	32.3
Seedlings & saplings adequately stocked	5404	13.9
In regeneration	4633	11.9
Immature poletimber	2713	7.0
Low quality sawtimber	454	1.2
Sparse sawtimber	228	0.6
Low quality poletimber	76	0.2
Non-stocked	56	0.1
Sparse poletimber	17	0.04
Seedlings & saplings inadequately stocked	14	0.04
Total	38977	100

APPENDIX 4
GIS COVERAGE

Projection: State Plane

FIPS Zone: 4203

Spheroid: Clarke 1866

Datum: NAD27

Units: Feet

Xmin=3401899.750

Xmax=3600376.0

Ymin=285782.219

Ymax=475880.719

APPENDIX 5
ACTIVE COLONIES WITH STAND NUMBER NOT INCLUDED IN THE GIS
COVERAGE

Compartment Number	Original Stand Number	Stand Number After Placement	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
7	15	17	96	4
8	25	12	103	13
9	52	11	106	9
15	23	3	92	4
15	22	6	89	4
30	26	25	0	0
32	33	1	94	4
39	32	21	0	0
39	50	9	94	12
42	30	16	108	17
50	15	3	0	0
50	33	7	0	0
51	25	2	107	5
69	21	12	0	0
72	23	25	93	13

APPENDIX 6
INACTIVE COLONIES WITH STAND NUMBER NOT INCLUDED IN THE GIS
COVERAGE

Compartment Number	Stand Number (Original)	Stand Number (After Placement)	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
35	18	7	110	11
44	9	17	120	20

APPENDIX 7

REPLACEMENT STANDS WITH STAND NUMBER NOT INCLUDED IN THE GIS
COVERAGE

Compartment Number	Stand Number (Original)	Stand Number (After Placement)	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
2	15	16	124	16
7	6	4	94	5
7	19	4	94	5
8	24	1	102	15
8	24	1	102	15
8	26	1	102	15
9	47	8	114	15
9	53	4	114	15
15	11	7	92	4
15	27	7	92	4
27	8	12	0	0
32	28	25	105	5
32	35	2	100	6
35	17	9	104	10
35	10	6	82	3
36	49	44	0	0
36	39	19	82	1
39	55	14	95	10

APPENDIX 7

Continued

Compartment Number	Stand Number (Original)	Stand Number (After Placement)	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
39	56	26	108	9
40	24	8	122	20
42	37	14	130	21
43	25	11	103	11
43	26	1	124	18
50	25	22	0	0
50	34	30	0	0
51	27	7	109	4
69	23	16	128	27
72	31	21	106	11
75	44	28	0	0

APPENDIX 8**RECRUITMENT STANDS WITH STAND NUMBER NOT INCLUDED IN THE GIS
COVERAGE**

Compartment Number	Stand Number (Original)	Stand Number (After Placement)	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
12	25	14	0	0
60	33	5	0	0

APPENDIX 9
CRITERIA FOLLOWED IN THE RCW HABITAT SUITABILITY CLASSIFICATION;
APPROACH 1

Class	Forest Type	Stand Condition	Age (years)	Cavity Trees
0	other than loblolly or shortleaf pine	other than mature or immature sawtimber	<17	no
1	loblolly or shortleaf pine	any	17-59	no
2	loblolly or shortleaf pine	mature or immature sawtimber	60-79	no
3	loblolly or shortleaf pine	mature or immature sawtimber	80-99	no
4	loblolly or shortleaf pine	mature or immature sawtimber	≥ 100	no
5	loblolly or shortleaf pine	mature or immature sawtimber	> 50	no
6	-	-	-	inactive
7	-	-	-	active

APPENDIX 10

CRITERIA FOLLOWED IN THE RCW HABITAT SUITABILITY CLASSIFICATION;
APPROACH 2

Class	Forest Type	Stand Condition	Stand Age	Cavity Trees	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
0	other than loblolly or shortleaf pine	other than mature or immature sawtimber	< 17	no	any	any
1	loblolly or shortleaf pine	any	17-59 ≥ 60	no no	any >110	any >20
2	loblolly or shortleaf pine	mature or immature sawtimber	60-79	no	< 110	< 20
3	loblolly or shortleaf pine	mature or immature sawtimber	80-99	no	< 110	< 20
4	loblolly or shortleaf pine	mature or immature sawtimber	≥ 100	no	< 110	< 20
5	loblolly or shortleaf pine	mature or immature sawtimber	>50	no	-	-
6	loblolly or shortleaf pine	mature or immature sawtimber	-	inactive	-	-
7	loblolly or shortleaf pine	mature or immature sawtimber	-	active	-	-

APPENDIX 11
CRITERIA FOLLOWED IN THE RCW HABITAT SUITABILITY CLASSIFICATION;
APPROACH 3

Class	Forest Type	Stand Condition	Stand Age	Cavity Trees	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
0	other than loblolly or shortleaf pine	other than mature or immature sawtimber	< 17	no	any	any
1	loblolly or shortleaf pine	any any	17-59 ≥ 60	no no	any =0 or >110	any =0 or >20
2	loblolly or shortleaf pine	mature or immature sawtimber	60-79	no	0-109	0-19
3	loblolly or shortleaf pine	mature or immature sawtimber	80-99	no	0-109	0-19
4	loblolly or shortleaf pine	mature or immature sawtimber	≥ 100	no	0-109	0-19
5	loblolly or shortleaf pine	mature or immature sawtimber	>50	no	-	-
6	loblolly or shortleaf pine	mature or immature sawtimber	-	inactive	-	-
7	loblolly or shortleaf pine	mature or immature sawtimber	-	active	-	-

APPENDIX 12

CRITERIA FOLLOWED IN THE RCW HABITAT SUITABILITY CLASSIFICATION;

APPROACH 4

Class	Forest Type	Stand Condition	Stand Age	Cavity Trees	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
0	other than loblolly or shortleaf pine	other than mature or immature sawtimber	< 17	no	any	any
1	loblolly or shortleaf pine	any	17-59	no	any	any
2	loblolly or shortleaf pine	mature or immature sawtimber	60-79	no	< 110	< 20
3	loblolly or shortleaf pine	mature or immature sawtimber	80-99	no	< 110	< 20
4	loblolly or shortleaf pine	mature or immature sawtimber	≥ 100	no	< 110	< 20
5	loblolly or shortleaf pine	mature or immature sawtimber	>50	no	-	-
6	loblolly or shortleaf pine	mature or immature sawtimber	-	inactive	-	-
7	loblolly or shortleaf pine	mature or immature sawtimber	-	active	-	-

APPENDIX 13

CRITERIA FOLLOWED IN THE RCW HABITAT SUITABILITY CLASSIFICATION;

APPROACH 5

Class	Forest Type	Stand Condition	Stand Age	Cavity Trees	Total Basal Area (ft ² /ac)	Hardwood Basal Area (ft ² /ac)
0	other than loblolly or shortleaf pine	other than mature or immature sawtimber	< 17	no	any	any
1	loblolly or shortleaf pine	any	17-59	no	any	any
2	loblolly or shortleaf pine	mature or immature sawtimber	60-79	no	1-109	1-19
3	loblolly or shortleaf pine	mature or immature sawtimber	80-99	no	1-109	1-19
4	loblolly or shortleaf pine	mature or immature sawtimber	≥ 100	no	1-109	1-19
5	loblolly or shortleaf pine	mature or immature sawtimber	>50	no	-	-
6	loblolly or shortleaf pine	mature or immature sawtimber	-	inactive	-	-
7	loblolly or shortleaf pine	mature or immature sawtimber	-	active	-	-

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