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A DECISION SUPPORT SYSTEM
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By

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ABSTRACT

A DECISION SUPPORT SYSTEM FOR WHITE-TAILED DEER MANAGEMENT

By

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Effective management of white-tailed deer *(Odocoileus virginianus)* can be enhanced by the integration of wildlife science, modern technology, and wildlife managers' expertise. The goal of this research was to integrate the population modeling, landscape structure analyses, and socioeconomic considerations into a decision support system for deer management in the Upper Peninsula (UP) of Michigan.

This research consists of three interrelated studies. The first study was a deer management options model (DeerMOM) designed to assess the effects of harvest options on deer population size, sex and age structure. The simulation results indicated that a high rate of buck harvest (similar to the current harvest practices) resulted in high deer numbers with a low percentage of antlered bucks. Moderate harvest of both sexes would control population growth and increase the percentage of antlered bucks. Quality deer management objectives could be reached only by lowering buck harvest rates while simultaneously increasing doe harvest.

The second study was a landscape structure analysis of deer habitat in the UP. Using 1991 Landsat Thematic Mapper imagery, the landscape was classified into 30-, 21-, 8-, and 4-class of patches. Each of the 15 counties in the UP was treated as a landscape and its landscape metrics were calculated using these four classification schemes. The analysis indicated that deer density had significant positive relationships with edge density, patch density, and landscape shape index even when different schemes were used. There were no significant positive relationships with patch diversity indices, contagion and interspersion indices. These findings suggest that edges and spatial heterogeneity play important roles in determining deer spatial distribution at landscape scales.

The third study was a knowledge-based system for deer management (DeerKBS). The main task of deer management was divided into 3 major sub-tasks: assessments of population status, habitat conditions, and cultural carrying capacity. Each sub-task was represented by a decision tree that related a decision with relevant attributes; and each sub-task was developed and tested separately. DeerKBS was able to capture and retain wildlife managers' expertise and to standardize decision-making procedures, and could be an effective communication tool for presenting the decision-making process to stakeholders.

Dedicated to my wife Hong Zhang for her love and support, and my daughter Daisy for her delightful diversions

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Chapter 1

INTRODUCTION

The graceful and elusive white-tailed deer (*Odocoileus virginianus*) is a symbol of wildlife in North America, which reminds us of the importance of the relationship between humans and nature. Because of their economic, ecological, and aesthetic values, white-tailed deer are one of the most studied and generally enjoyed large game species (Halls 1984, Rue 1989).

The population dynamics and spatial distribution changes of white-tailed deer exemplify the interaction between wildlife and human development. From near extirpation in North America at the end of the nineteenth century, white-tailed deer have rebounded almost over their entire distribution area (McCabe and McCabe 1984, Langenau 1994). This rebound may be attributed to the deer's strong adaptability to diverse habitats and wildlife managers' continuous management efforts (Halls 1984, Ozaga et al. 1994).

The rebounding population provides more opportunities for hunting and recreation, but also causes serious socioeconomic and ecological concerns, such as deer-vehicle accidents (Allen and McCullough 1976, Conover et al. 1995), crop damage (Matschke et al. 1984, Braun 1996), disease transmission (Schmitt et al. 1997, Wilson and Childs 1997), negative impacts on biodiversity (DeCalesta 1994), changing succession trajectories (Ross et al. 1970, Alverson et al. 1988) and impacting forest regeneration (Tilghman 1989, Mladenoff and Strearns 1993). Given the conflicting interests surrounding deer, it is essential to establish management goals that consider the needs of different stakeholders as well as the integrity of the ecosystem. Based on the established goals, deer managers then can determine the appropriate measures needed to achieve their specific objectives.

To better manage deer populations and their habitats, many field observations and experiments have been carried out to collect data and information about deer biology (Eberhardt 1960, Verme 1969), population ecology (Hayne 1984, Dusek et al. 1989, Nixon et al.1991), movement and habitat (Verme 1973, Larson et al. 1978, Nelson 1984), relationship with weather (Verme 1968, Drolet 1976, Mech et al. 1987), and effects of management (Crawford 1984, Creed et al.1984, Euler 1984). Through these studies, knowledge about deer populations and habitats and management expertise have been accumulated in wildlife science and management.

However, deer managers are facing more challenges than ever before. First, society demands that deer be managed to meet a wide range of goals. Public involvement in deer management is an indispensable component in the decision-making process. So people management is becoming important to address socioeconomic issues (Kellert 1994). Second, the management paradigm is shifting from traditional small-scale, single species management to ecosystem management. Deer management needs to be integrated with the management of multiple natural resources system and biodiversity conservation programs (NRC 1995, Swanson 1997), and to greatly expand the scale on which ecosystems are analyzed and managed (Crow and Gustafson 1997). Third, ecosystem management emphasizes sustainability and large-scale management, recognizes humans as an ecosystem component, and acknowledges “that current knowledge and paradigms of ecosystem functions are provisional, incomplete, and subject to change” (Christensen et al. 1996). Expertise in ecosystem management is even scarcer and more valuable if it exists (Ludwig et al. 1993, Giles 1998).

Computer modeling can help wildlife managers understand wildlife population dynamics and choose a better alternative to reach their objectives (Walters and Gross 1972, McCullough 1979, Starfield 1997). Empirical models such as “stock-recruitment” models are constructed through empirical data fitting instead of mechanistic functions (McCullough 1979). The drawback of empirical models is their lack of description of population sex and age structure. Mechanistic models, such as those based on POP-II (Bartholow 1986, Bender and Roloff 1996) and its predecessor ONEPOP (Walters and Gross 1972, Meddin and Anderson 1979) track animals through each annual cycle. These "accounting" models require detailed data, including pre- and post-harvest season natural mortality, harvest and wounding loss, age-specific vulnerability, and age-specific reproductive rates (Bartholow 1986). Both empirical and mechanistic modeling approaches have their advantages and disadvantages. The empirical models incorporate the expertise of wildlife managers, but neither address some underlying mechanisms nor provide crucial information needed for deer management. The mechanistic models, on the other hand, provide more scientific reasoning and explanation but require much more data.

Deer are an abundant herbivore and habitat generalist that have unique roles in ecological processes because they are often a key species in the ecosystem (Alverson et al. 1988, DeCalesta 1994). Understanding landscape structure and its relationship with deer distribution is important in ecological research and natural resources management (Turner 1989, Gustafson 1998).

A traditional approach to studying the responses of deer to their environmental changes is habitat analysis of isolated patches at fine scales. Based on deer's physiological and nutritional requirements, carrying capacity in a study area is estimated (Wallmo et al. 1977). A more coarse-scale analysis is the quantification of necessary habitat elements such as food, cover, water, and space (Bender and Haufler 1990, Virgós and Tellería 1998). One of the most comprehensive deer habitat models may be the habitat suitability index (HSI) models developed by Short (1986) for use in the Gulf of Mexico and south Atlantic coastal plain. These HSI models include 4 models. Model I estimates the carrying capacity of habitats during autumn-winter based on the energy requirements of deer during these seasons. Model II and Model III are derived from Model I. Model II determines the quantities of suitable forage and Model III provides general estimates of habitat quality on an evaluation area. Model IV predicts the probable presence or absence of deer on an evaluation area. The uniqueness of these models is that they take direct measurements of available energy and forage quantity as indicators of habitat quality. Stauffer (1990) evaluated the inputs and assumptions of those models. Banker (1994) did a field test on Quantico Marine Corps Base, Virginia, and made some changes and improvements for these HSI models. The obvious limitation of this approach is that it requires intensive field samplings.

Other attempts are made to link deer age-specific birth rates with forage nitrogen yield (Meddin and Anderson 1979), to link deer population with northern forest vegetation (Cooperrider 1974) and with an aspen-type (*Populus spp.*) forest (Mello 1983, Campa 1989). An individual-based modeling approach was also used to study the effects of nutrition, variation in predation pressure, bonding interruption, and variation of birth cover quality on deer population dynamics (German 1992). The model results indicated that predation and nutrition are the most important regulating factors and the size of the deer herd could be increased by reducing the number of predators and by improving birthing cover.

The models based on these habitat analyses have limited applications in management because of intensive data requirements and/or low accuracy in prediction (Morrison et al. 1992). New developments in remote sensing (RS), global positioning system (GPS) and geographical information systems (GISs), provide valuable tools to obtain, update, integrate, synthesize, and analyze temporal and spatial data (Coulson et al. 1987, 1991, Ormsby et al. 1987, Elston and Buckland 1993, Mladenoff 1994, Chang 1995). Linking GIS with resource databases enables the generation and evaluation of multiple-use management options (Brown et al. 1994, Mallawaarachchi et al. 1996).

Deer have relatively large and often seasonally migratory home ranges (Verme 1973, Nelson and Mech 1984, Van Deelen et al. 1998), requiring the understanding of landscapes in addition to isolated patches of habitat. Field observations often indicate that deer densities differ dramatically even though two areas have seemingly similar habitats (Morrison et al. 1992). This implies that there exists a landscape level of habitat characteristics that influence deer spatial distribution.

With more data accumulating from research and new technology, the complexity of decision making increases because it involves more issues and needs to offer more alternatives. Complexity makes it difficult for wildlife stewards to have all the relevant information and knowledge (Starfield and Bleloch 1986). However, decisions must be made, even with uncertainties and conflicting goals and without complete data and scientific consensus (Ludwig et al. 1993, Ehrlich and Daily 1993). This requires deer managers to take a new approach to address the problem. The application of artificial intelligence (AI) in natural resources management offers great potentials for aiding and improving decision making (Coulson et al. 1987, 1991, Covington et al. 1988, Davis et al. 1989).

Knowledge-based systems (KBSs), a branch of artificial intelligence (AI), can be used to help wildlife managers take advantage of the accumulated data and information to make more informed decisions. Generally speaking, KBSs are computer systems that use human knowledge to solve problems that normally would require human intelligence. They differ from other AI programs in their performance, domain-specific problem-solving strategies, and their justification for conclusions (Edwards 1991). They differ from conventional software programs in their symbolic representation, symbolic inference, and heuristic search (Hayes-Roth et al. 1983).

KBSs for natural resource management have been developed since the beginning of KBSs research. The first successful KBS application in natural resource management is Prospector for mineral exploration in the late 1970s (Duda et al. 1979). Most of the early applications are limited to the interpretation and diagnosis task of geological and mineral problems. Production rules are the predominant type of knowledge representation scheme. Since the late 1980s, KBSs have expanded applications to management of forests, water resources, and ecosystems. Bremdal (1997) reviewed 27 KBSs for the management of natural resources. Among them, only one is for wildlife (whale) visual identification.

A new direction of KBSs for natural resource management is to integrate simulation models, GIS, and database management to provide a framework tool for decision-making. The ecosystem management decision support system (EMDS), which was developed by the USDA Forest Service Pacific Northwest Research, integrates GIS and knowledge-based reasoning technologies (Reynolds 1999).

With the development of KBSs, natural resource managers and ecological modelers have begun to recognize their potentials to understand, manage, and model natural resource systems and to integrate landscape data and knowledge from diverse scientific disciplines into natural resource management (Starfield and Bleloch 1986, Coulson et al.1987, 1991, Schmoldt and Rauscher 1996, Giles

1998). In fact, a few attempts with AI or KBSs techniques have been made to study moose-forest interactions (Saarenmaa et al. 1988) and deer movements in a heterogeneous habitat (Folse et al. 1989), to help resource agencies and managers use computer models (Ritchie 1989), and to assess qualitative information and infer logically valid conclusions (Davis et al. 1989).

Effective management of deer and other wildlife species can be enhanced by integration of wildlife science, modern technology, and wildlife managers' expertise. The goal of this research was to integrate deer population modeling, landscape level habitat analysis, and socioeconomic considerations into a decision support system for white-tailed deer management. Through this research, I provided the wildlife community with tools to evaluate population dynamics under different management options, to assess habitat conditions on landscape scales, and to make informed decisions using knowledge-based system. My research was done using the data from the Upper Peninsula (UP) of Michigan.

Specific objectives of this research were to:

1. Assess the effects of management alternatives on deer population size, sex and age structure by constructing a population model;
2. Identify the relationships between landscape structure and deer spatial distribution; and
3. Provide a unifying framework for deer decision-making with a knowledge-based deer management system

Chapter 2

WHITE-TAILED DEER MANAGEMENT OPTIONS MODEL (DeerMOM): DESIGN, QUANTIFICATION, AND APPLICATION

The white-tailed deer is one of the most important game species in North America. This species provides opportunities for hunting and recreation, but also cause serious socioeconomic and ecological concerns, such as deer-vehicle accidents, crop damage, and impacting forest regeneration (Caughley 1981, McShea et al. 1997). Given the conflicting interests surrounding deer, it is essential to establish management goals that consider the needs of different stakeholders as well as the integrity of the ecosystem. Based on the established goals, deer managers then can determine the appropriate measures needed to achieve their specific objectives. Harvesting is a primary option for population manipulation.

Deer management requires instruments that can assess the effects of harvesting options on deer population size and structure. Computer modeling can help wildlife managers to understand deer population dynamics and choose a better alternative to reach their objectives (Walters and Gross 1972, McCullough 1979, Starfield 1997). Good models incorporate essential information and allow for evaluation of the consequences of different management options.

There are basically two approaches to modeling deer population dynamics. One approach is to build empirical models such as "stock-recruitment" models.

The stock-recruitment models are constructed through empirical data fitting instead of mechanistic functions (McCullough 1979). The use of empirical models is limited because they do not describe population sex and age structure, which are important parameters to deer managers. The other approach is to build mechanistic models, such as a density-dependent matrix harvest model (Jensen 1996) and models based on POP-II (Bartholow 1986, Bender and Roloff 1996) and its predecessor ONEPOP (Walters and Gross 1972, Meddin and Anderson 1979). The matrix model considers age-specific mortality and fecundity, but does not describe sex structure. POP-II and its predecessor track animals through each annual cycle. These "accounting" models require detailed data, including pre- and post-harvest season natural mortality, harvest and wounding loss, age-specific vulnerability, and age-specific reproductive rates (Bartholow 1986). Both modeling approaches have their advantages and disadvantages. The empirical models incorporate the expertise of wildlife managers but do not address some underlying mechanisms and do not provide crucial information needed for deer management. On the other hand, the mechanistic models provide more scientific reasoning and explanation but require much more data.

I developed a hybrid (mechanistic and empirical) model, DeerMOM, to evaluate the effects of deer management options on population size, sex and age structure. Mechanisms in DeerMOM are similar to those in POP-II, but DeerMOM also incorporates management empiricism. The model takes advantage of the data available from field studies, yet it is not limited by data incompleteness. DeerMOM is designed to simulate deer populations in different locations but was parameterized and tested for the deer population in the Upper Peninsula (UP), Michigan. The objectives of this study are to introduce the design of the model and the quantification of the model parameters, and to demonstrate its application in deer management under the specific constraints of management goals in the UP of Michigan.

2.1 Methods

2.1.1 Model Design

I followed 3 principles to design the model: simplicity, accuracy, and management orientation. These principles were incorporated into the process of model design, construction, validation, and simulation. They are also interconnected and not separable.

2.1.1.1 Simplicity

The model should be structured as simply as possible. The deer populations in most areas are heavily hunted, which reduce their life expectancy relative to slightly exploited deer populations (Burgoyne 1981). I grouped deer into 3 age classes: fawn (<12 months), yearling (13-24 months), and adult (>24 months) to simplify model structure. This classification is widely accepted and adopted by deer managers (McCullough 1979). I divided mortality into harvest mortality and natural mortality (e.g. vehicle accidents, starvation, predation) and used annual mortality instead of seasonal mortality to ease data collection and model application.

2.1.1.2 Accuracy

The model should simulate and predict population dynamics as accurately as possible. Knowledge of age and sex composition of the deer population is essential for deer managers to establish their management objectives. Since male deer are polygamous, only female deer numbers have a substantial impact on changes in population size. However, the percentage of bucks in the population is of special interest to deer hunters and consequently deer managers. In the model, I simulated the dynamics of males and females separately. I used age- and sex-specific natural mortality and harvest mortality. In addition, I differentiated their reproductive rates and fetal sex ratios by age class for female deer.

2.1.1.3 Management orientation

The final principle was to develop a model that is management oriented. Management goals could be used as criteria to evaluate harvest strategies under defined time frames. A user could set goals and run the model to determine which harvest scenarios would achieve the management goals during a predefined time period. Specific management goals include maximum sustained yield, trophy management, and quality deer management. A user could also change the model structure by adding or removing some components, or by modifying parameter values. However, the model should be user friendly and have a graphical user interface to assist users in learning and using the model. In addition, model results should be easily transferred to other software programs for further data analysis. Finally, the model should accommodate users with different levels of expertise in modeling and mathematics.

To fulfil the above-mentioned requirements, I used Stella® to develop DeerMOM. Stella® is a multi-level, hierarchical environment for constructing models (High Performance Systems 1997) which allows DeerMOM to have a 3-level hierarchical structure. The first level is a user interface, where novice users can change parameter values by using sliders or numerical pads. Moreover, the user can also inspect simulation results using tables and graphs as well as export them to other programs through dynamic data exchange. At the second level, a more advanced user can access the model structure in order to modify the model structure and manipulate parameter values. Finally, an expert user can access the third level to review the mathematical equations and to learn the model mechanisms in detail.

2.1.2 Model Structure

DeerMOM consists of 5 interconnected sectors: Female, Male, Birth/Death, Harvest, and Population (Figure 2.1). DeerMOM operates on an annual cycle that starts on October 1 and ends on September 30 of the following year.

2.1.2.1 Female Sector

Females were grouped into 3 age classes: fawn, yearling, and adult as previously mentioned. For each annual cycle, surviving newborn females enter the female fawn group, and similarly surviving fawns recruit to the female yearling group, surviving yearlings to the female adult group. Adult females that

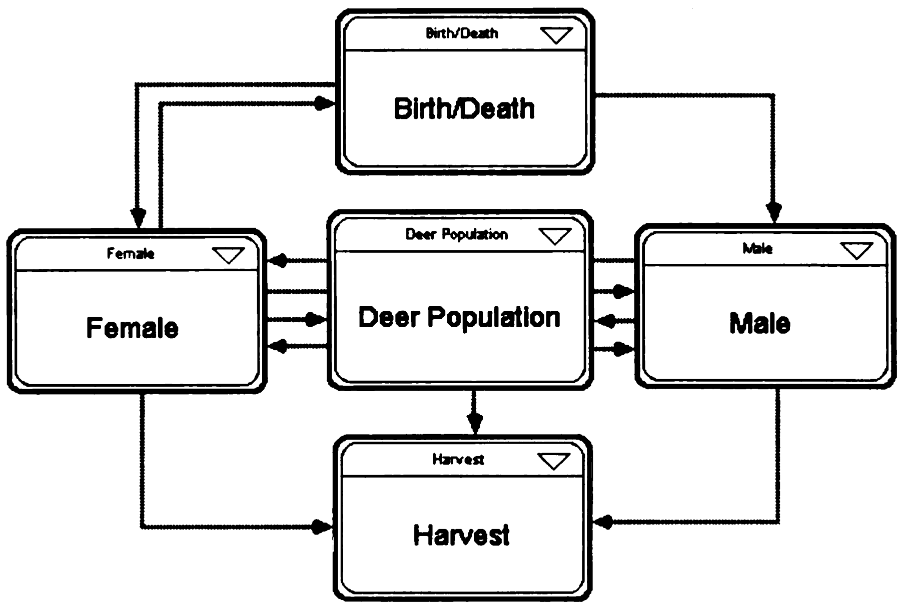


Figure 2.1. Part of the user interface in DeerMOM showing the five interrelated sectors.

survive hunting season and natural mortality remain in the adult age class. Natural mortality for each age class was density- and harvest-dependent and influenced by winter severity.

2.1.2.2 Male Sector

The male sector had the same model structure as the female sector, but parameter values were quantified differently. For example, the harvest rate for male adults was different from that for female adults. As with females, all mortality rates were age- and sex-specific.

2.1.2.3 Birth/Death Sector

Changes in deer population size and structure depend on the dynamics of both births and deaths. I assumed that immigration and emigration would not affect age and sex structure of the population. Thus, any addition to the population comes from the offspring of female fawns, yearlings, and adults. To estimate newborn females and males, I used female number in spring, reproductive rate, and sex ratio for each age class. The spring female number in each age class was estimated by subtracting harvest and natural mortality from the previous fall female number in each age class. Deaths were a result of harvest mortality and natural mortality. Mortality rates were age- and sex-specific.

2.1.2.4 Harvest Sector

I included all harvest-related information in this sector. Specifically the sector contained age and sex composition of harvest, total harvest, percentage of antlered bucks and antlerless deer in the harvest.

2.1.2.5 Population Sector

I included population initialization, management goals, and all data related to age and sex distribution of deer in this sector. The population was initialized by size, sex ratio, and percentage of deer in each age class. This sector also extended the female and male sectors by deriving population statistics of interest. Specifically, it contained numbers and sex ratios for each age class, numbers of females and males, total population size, sex ratio, density, and percentage of antlered bucks in the population.

2.1.3 Quantification of the Model

The most important parameters for DeerMOM included age-specific reproductive rates, fetal sex ratios, and neonatal mortality; age- and sex-specific natural mortality, and harvest mortality. DeerMOM was parameterized to represent the deer population in the UP of Michigan. As winter weather conditions greatly influence the population dynamics in the UP, winter severity indices (WSIs), which measure air chill and snow hazard (Verme 1968), were incorporated into the model. Data for estimating model parameters were obtained from the Michigan Department of Natural Resources (MDNR) and recent field studies (Van Deelen et al. 1997).

2.1.3.1 Reproductive rates

Reproductive rates were defined as average fetuses per female based on spring surveys (Friedrich and Schmitt 1988, Verme 1989). From March to May, the MDNR personnel conducted necropsies of female deer that died from vehicle collisions and other accidents. Female deer were aged and their fetuses were counted if they were pregnant. Based on these data, reproductive rates were calculated for fawns, yearlings, and adults. The MDNR discontinued these surveys in the UP after 1988. In DeerMOM, I used the data from the MDNR spring surveys from 1973 to 1988 (Friedrich and Schmitt 1988) because these data provided an adequate sample for analytical purposes. Reproductive rate ranges were 0-0.14, 0.8-1.55, 1.67-2.13 with an average of 0.05 (0.01, SE), 1.30 (0.05), and 1.84 (0.05) for female fawns, yearlings, and adults, respectively.

As reproductive rates showed a great annual variability, regression analyses and F-tests were used to detect whether or not the variability was associated with population size. The estimates for population size were provided by the MDNR based on POP-II model (MDNR 1996). No significant relationship was detected between population and the reproductive rates of yearlings ($F_{1, 14}$ = 0.399, P = 0.538) or of adults ($F_{1, 14}$ = 0.036, P = 0.852) from 1973 to 1988. However, there was a significant decrease for fawn reproductive rates as population size increased ($F_{1,14}$ = 7.891, P = 0.014). These findings were consistent with the reproductive patterns found in southern Michigan (Verme 1989). Even so, as fawn deer had very low reproductive rates (0.05) in the UP, changes in fawn reproductive rates had a minimal impact on the entire population.

Regression analyses were also used to detect the relationships between age-specific reproductive rates. The results showed that reproductive rates for fawns and for yearling were positively associated with reproductive rates for adults (P = 0.014, P = 0.054, respectively). To account for the annual variability of reproductive rates, a uniform random function of 95% confidence intervals of the mean (from 1.78 to 1.90) was used to estimate the reproductive rates for female adults. The estimates of reproductive rates for fawns and for yearling were derived from regression equations $Y_1 = 0.2145X - 0.3472$ ($R^2 = 0.36$, $F_{1,14} = 7.969$, P = 0.014), $Y_2 = 0.9221X - 0.3945$ ($R^2 = 0.24$, $F_{1,14} = 4.407$, P = 0.054), where Y_1 is the reproductive rate for fawns, Y_2 is the reproductive rates for yearling, X is the reproductive rate for adults.

2.1.3.2 Fetal sex ratio

Sex ratio was defined as the percentage of males in each age class. Fetal sex ratio was the percentage of newborn males in offspring. Verme's (1983) data were used to determine the fetal sex ratio. The fetal sex ratios for female fawns, yearlings, and adults were 62.5%, 52.6%, and 50.6%, respectively.

2.1.3.3 Mortality

Causes of mortality were classified as harvest mortality and natural mortality. The harvest mortality was estimated from the MDNR harvest survey (Verme 1989) data from 1989 to 1996. The natural mortality was based on a radio-collared deer study in the UP from 1992-1994, where the deer population was exposed to hunting (Van Deelen et al. 1997). I partitioned the natural mortality into 3 additive parts: base mortality, winter mortality, and harvest compensatory mortality (HCM). The base mortality was the mortality when the population density was low (< 5 deer/km^2) and winter weather was very mild.

Base mortality may be largely due to vehicle accidents or old age. The winter mortality was mainly due to malnutrition during severe winter conditions. Cumulative WSIs, which summed the weekly WSIs from December to April, were used to relate winter severity to deer winter mortality. The cumulative WSIs in the UP ranged from 65.7 in 1987 to 147.7 in 1979, with an average of 105.4 from 1969 to 1996. To estimate winter mortality, I scaled the difference between the actual WSI and the lowest WSI in the UP (65.7) by a different adjustment factor for fawns, yearlings, and adults. HCM was a function of deer density and harvest mortality. Harvest mortality was assumed to be compensatory to density-dependent mortality (DDM). In other words, DDM would be lower under a higher harvest rate. HCM was mainly a result of predation, diseases, and other unknown causes.

I used a 2-step procedure to calculate HCM. The first step was to calculate DDM, assuming that there was no harvest. If deer density was < 5 deer/km^2, DDM(age) was assumed to be 0 for all age classes. Five deer/km^2 was used as the minimum density(D_{min}) because DDM(age) could be negligible when deer density was < 5 deer/km^2 in the UP. When deer density was between 5 deer/km^2 and 35 deer/km^2, it was assumed that there was a linear relationship between DDM(age) for each age class and deer density (Figure 2.2). If deer density was > 35 deer/km^2, the maximum DDM (DDM_{max}(age)) was assumed to be 0.5, 0.3, and 0.1 for fawns, yearlings, and adults, respectively. Thirty-five deer/km^2 was used as the maximum density(D_{max}) for DDM because it could be the biological carrying capacity (BCC) in Michigan (McCullough 1979). In mathematical terms,

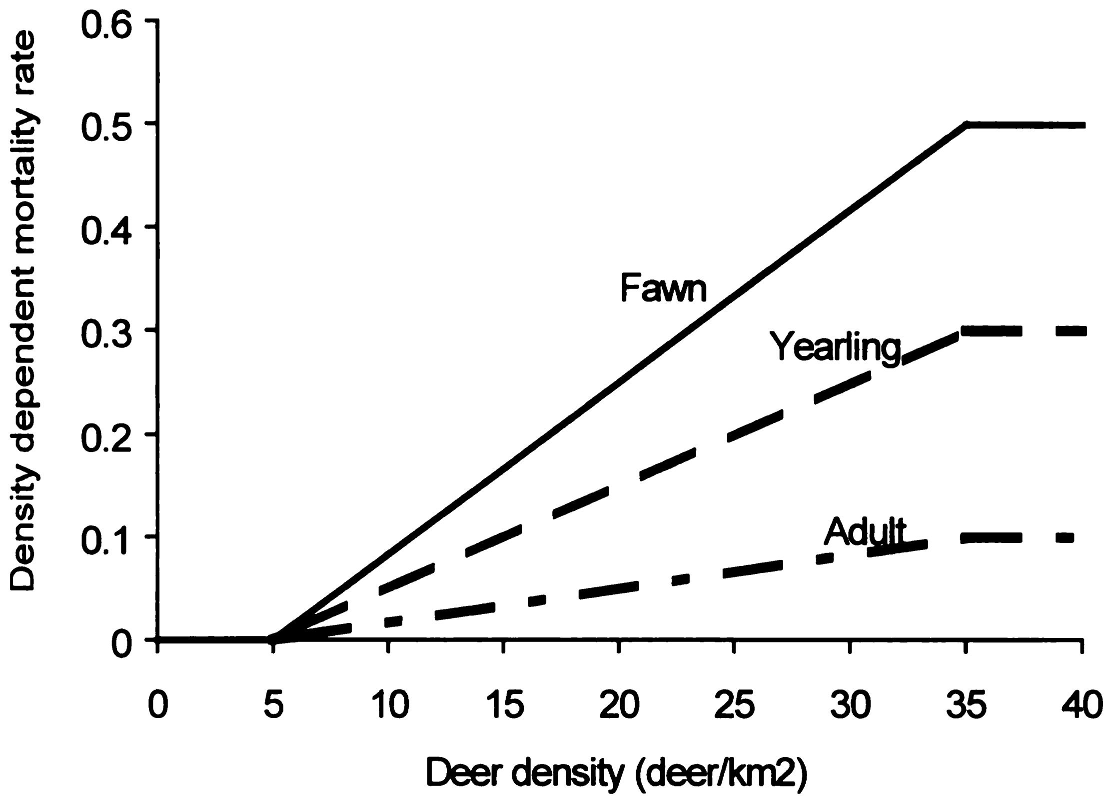


Figure 2.2. Relationship between age-specific density-dependent mortality and deer density, assuming that there was no harvest.

for a deer population with density D, age-specific DDM can be expressed as equation 1:

$$\mathrm{DDM(age)} = \begin{cases} 0 & (\text{if } D \le 5) \\ (\mathrm{D - Dmin}) * \mathrm{DDMmax(age)} / (\mathrm{Dmax - Dmin}) & (\text{if } 5 < D < 35) \\ \mathrm{DDMmax(age)} & (\text{if } D \ge 35) \end{cases} \quad (1)$$

The second step to calculate HCM was to consider the compensatory effect of harvest and to estimate adjusted DDM. Because deer harvest might mitigate DDM, I then adjusted DDM by a factor of (1 - harvest rate(HR)) for each respective age class. In mathematical terms, age specific HCM can be expressed as equation 2:

$$\mathrm{HCM(age)} = (1 - \mathrm{HR(age)}) * \mathrm{DDM(age)} \quad (2)$$

Take male yearling as an example. If the deer population density was 15 deer/km^2 and the harvest rate for male yearlings was 50%, then the DDM for male yearlings would be (15-5)*0.3/(35-5) = 0.1 (from Equation 1), and the HCM was (1-0.5) * 0.1 = 0.05 (from Equation 2).

To summarize, the calculation of annual natural mortality can be expressed as equation 3:

$$\mathrm{NM(age)} = \mathrm{BM(age)} + (\mathrm{WSI} - \mathrm{LWSI}) * \mathrm{SF(age)} + \mathrm{HCM(age)} \quad (3)$$

Where NM is natural mortality, BM is base mortality, WSI is winter severity index, LWSI is the lowest winter severity index, and SF is a scale factor that converts WSIs to winter mortality.

2.1.3.4 Neonatal mortality

Winter weather has a significant impact on fetal development during late gestation and thus influences natal survival (Verme 1977). Because of this impact, I partitioned neonatal mortality into 2 parts: base neonatal mortality and neonatal mortality due to winter severity. Base neonatal mortality was the mortality when winter weather was very mild (low WSI). Based on Verme's data (1977), I used the following equation to estimate neonatal mortality:

$$NnM = BNnM + (WSI - LWSI) * SF \quad (4)$$

Where NnM is the neonatal mortality, BNnM is the base neonatal mortality, and other variables are defined in previous equations.

2.1.4 Model Initialization

The 1989 fall population in the UP of Michigan was used to initialize DeerMOM. Population size was estimated from pellet group surveys. Sex ratio and age distribution were based on MDNR deer checking station data (Hill and Rabe 1989).

2.1.5 Model Testing

DeerMOM was run 50 times to simulate deer population from 1989 to 1996 using a one-year time step. The model was run only 50 times because the variability of the population size was small. Annual harvest data and WSIs from the MDNR were used in these simulations. The 1989-1996 fall population estimates from annual pellet group surveys (Hill 1996) were used to verify simulation results from DeerMOM. Paired t-tests were used to compare population estimates (1990-1996) from the pellet group surveys and DeerMOM simulations. After the model was verified, the 1996 fall population estimate, harvest data during 1996-1997 hunting season, and WSI for the winter of 1996-1997 were used to predict the 1997 fall population.

2.1.6 Simulation Scenarios

I ran 50 simulations of 35 representative management scenarios resulting from the combinations of 7 buck harvest rates and 5 doe harvest rates. Buck harvest rates ranged from 10% to 70% with 10% intervals and doe harvest rates ranged from 5% to 25% with 5% intervals. Based on the deer checking station data, the harvest rates for female and male fawns were assumed to be 5%. I simulated deer population dynamics from 1989 to 1996 using actual WSIs. These scenarios were evaluated by whether they could reach the management goals by 1996. The management goals included a quantity goal (372,500 deer in the fall) and a quality goal (35% antlered bucks) (MDNR 1993).

I chose the optimal scenario, defined as the scenario that could most closely achieve both goals by 1996, to project the 1996 deer population for the next 5 years (from 1997 to 2001) under different weather conditions (mild, moderate, harsh, and random). WSIs were set at 80, 100, and 120 for mild, moderate, and harsh winters, respectively. WSIs were assumed to be constant for 5 consecutive years, except when WSI was a random function, where the WSIs were uniformly distributed random numbers between 80 and 120.

2.2 Results

DeerMOM simulated deer population well and there was no significant difference (t= 1.24, df = 6, P =0.26) between the population estimates from DeerMOM and those from pellet group surveys (Figure 2.3). DeerMOM predicted that the average of 1997 fall population was 528,307, 11.5% higher than the MDNR estimate of 474,000 deer (H. R. Hill, MDNR, personal communication).

When buck harvest rate was 50%, which was similar to current buck harvest rate, harvesting more does reduced the population size dramatically (Figure 2.4a) but only slightly increased the percentage of antlered buck. Thus, the quality goal was not reached (Figure 2.4b).

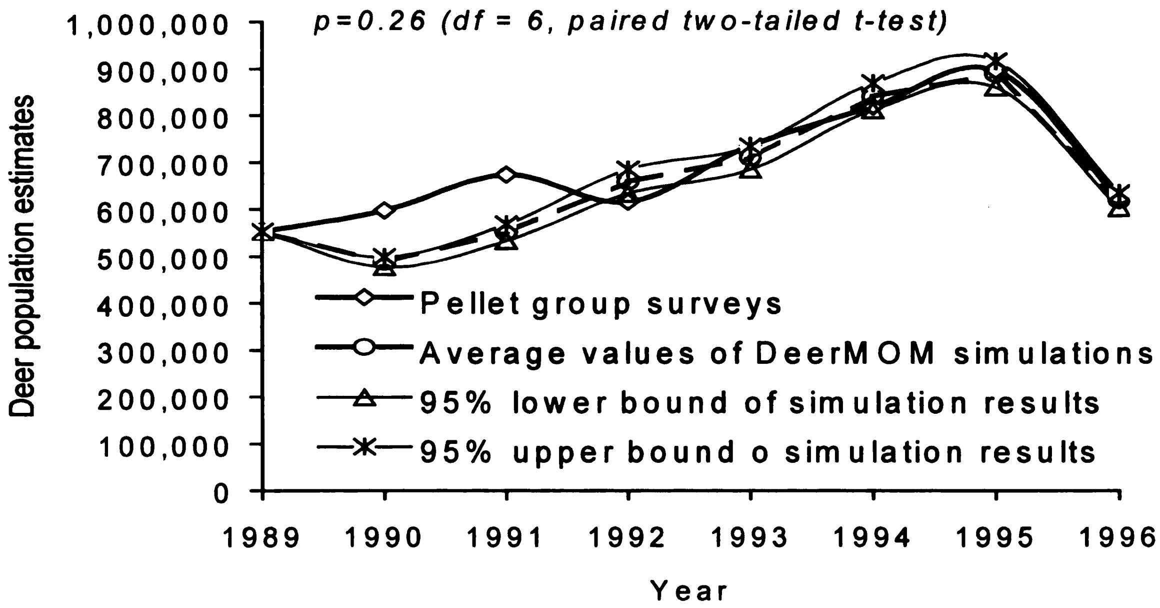


Figure 2.3. Comparison between population estimates from DeerMOM simulations and from pellet group surveys.

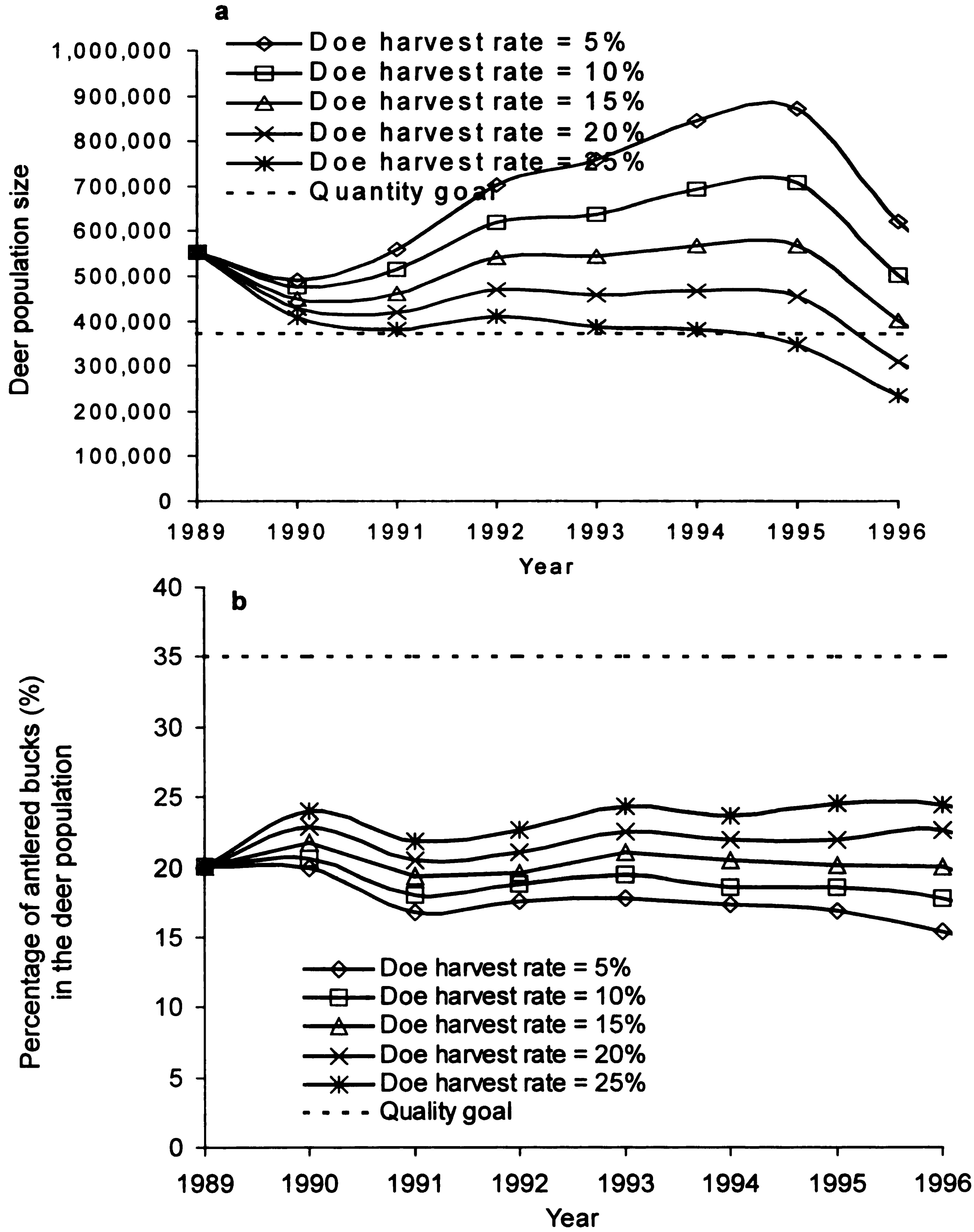


Figure 2.4 (a) Population dynamics under different doe harvest rates when 50% of bucks were harvested. (b) Dynamics of percentage of antlered bucks under different doe harvest rates when 50% of bucks were harvested.

When doe harvest rates remained constant, decreasing buck harvest rates did not change deer population sizes markedly (Figure 2.5a) but increased the percentage of antlered bucks greatly (Figure 2.5b). The best scenario in terms of management goals was the harvest of 20% of both bucks and does. It brought the population down to the quantity goal level (Figure 2.5a) and increased the percentage of antlered bucks near the quality goal level (Figure 2.5b).

Winter severity had a dramatic impact on the population. When 20% of bucks and does were harvested, it took 5 years to reach the quantity goal under moderate (WSIs = 100) winters (Figure 2.6a). When winter conditions were continuously harsh (WSIs = 120), deer population decreased rapidly. When the winter conditions were mild (WSIs =80), the population remained stable (Figure 2.6a). However, regardless of WSI, the percentage of antlered bucks increased to the goal level (Figure 2.6b) if 20% of bucks and does were harvested.

Winter weather conditions were important in determining appropriate harvest rates for achieving the quantity goal. Under harsh winters, it was necessary to lower the harvest rate from 20% to 5% (Figure 2.7a). Under mild winters, however, the harvest rate should be increased from 20% to 30% (Figure 2.7a) to reach the quantity goal. Both harsh and mild winter conditions allowed deer to reach the quality goal level under either 5% or 30% harvest rates if harvest rates were the same for both female and male deer (Figure 2.7b).

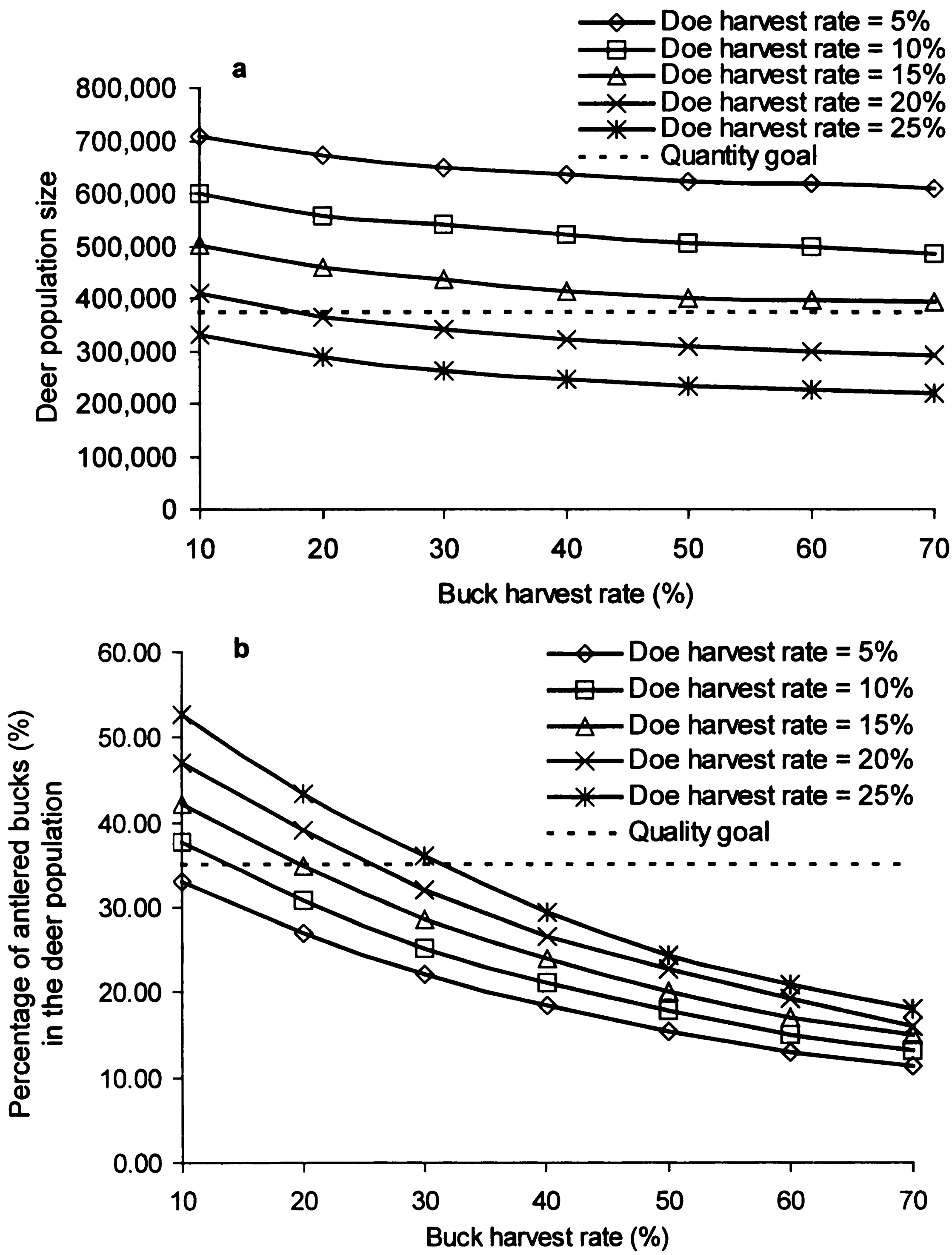


Figure 2.5 (a) Population size in 1996 under different management scenarios. (b) Percentage of antlered bucks in 1996 under different management scenarios.

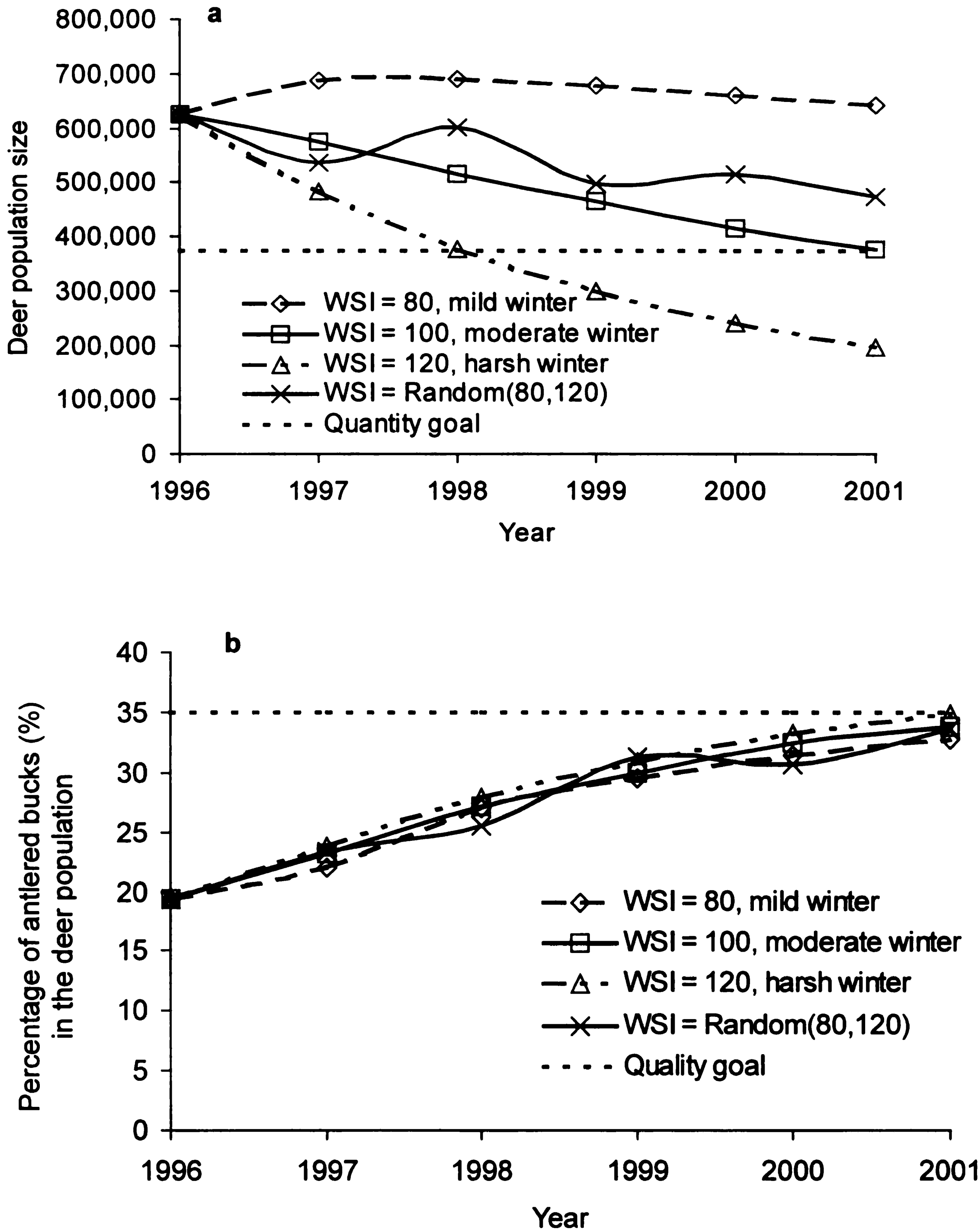


Figure 2.6 (a) Effect of winter severity on population dynamics (Buck and doe harvest rates = 20%). (b) Effect of winter severity on dynamics of the percentage of antlered bucks (Buck and doe harvest rates = 20%).

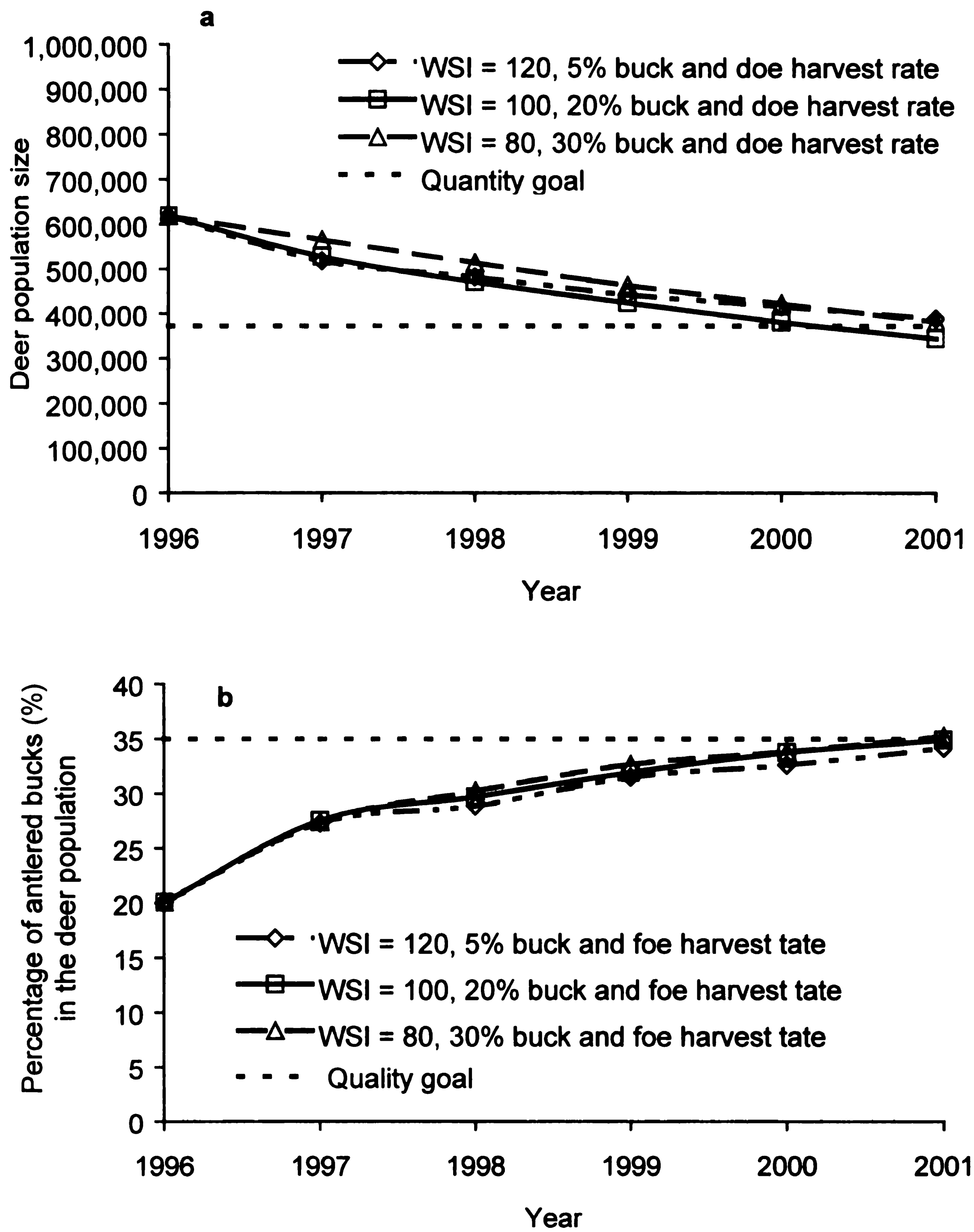


Figure 2.7 (a) Deer population dynamics in response to low harvest rates under harsh winters (WSIs=120) and high harvest rates under mild winters (WSIs=80). (b) Percentage of antlered bucks in response to low harvest rates under harsh winters (WSIs=120) and high harvest rates under mild winters (WSIs=80).

2.3 Discussion

2.3.1 Model structure

In this study, I tried to balance model simplicity, accuracy, and generality (Levins 1966) in order that the model is accessible to the wildlife management community. I minimized data requirements for the model but still offered vital population information, which is crucial for deer management decision processes. The model structure could be easily modified to include new information once it is available. For example, if there are field data available for neonatal mortality, the empirical function can be easily replaced with actual data.

2.3.2 Quantification of parameters

Quantification of model parameters is usually the most challenging step in systems modeling. I felt comfortable with age-specific reproductive rates because good historical data existed. There is controversy about how maternal age and nutritional conditions affect offspring sex ratios (Harder 1980, Verme 1983, Burke and Birch 1995). Because of this controversy, I used Verme's (1983) data as they were based on research on deer in the UP. However, I did not incorporate yearly variation in fetal sex ratios because the data were not available.

I took an empirical approach to estimate natural mortality and neonatal mortality. Because harsh winter weather accounted for most of the deer mortality in winters, winter mortality was linked with WSIs. This approach might oversimplify the relationship between deer mortality and weather conditions, however, simulations suggested these estimates are reasonable.

To apply DeerMOM to other deer populations, model parameter values should be changed to reflect the biological and ecological characteristics of those populations (Euler and Morris 1984, Gavin et al. 1984, Dusek et al. 1989). The most important changes might be the estimates of natural mortality and neonatal mortality. Winter severity might not play such an important role in regulating deer population in warmer geographical areas as it did in the UP.

2.3.3 Current management practices

Although the MDNR tended to adapt ad hoc regulations in the UP because of the unpredictability of harsh winters, they realized that more consistent proactive management regulations should and could be implemented in the field. The winters of 1995-1996 and 1996-1997 were harsh and greatly decreased the UP deer population by up to 50% (Urbain 1997). Nevertheless, the deer population in the UP remains higher than the goal level. The MDNR continues to issue antlerless deer permits to reduce the deer population (Urbain 1997). Some local experiments, such as Hiawatha Sportsmans Club's 1996 resolutions, are carried out to harvest more antlerless deer and to restrain buck harvest (T. R. Minzey, MDNR, personal communication). However, no such statewide effort has been implemented to discourage the harvest of antlered bucks. Under current management practices, the quality goal can not be reached (Van Deelen et al. 1997).

2.3.4 Harvest recommendations

The recommendations are mainly based on ecological considerations.

Which option is the best to implement in management practices also depends on acceptability of a specific management option by stakeholders. However, the advantages of DeerMOM is that it offers options that a wildlife manager can assess their outcomes before the specific harvest scenario is implemented, thus it offers a logical and defensible rationale for wildlife decision making (Starfield 1997).

The recommendation of harvesting 20% of both bucks and does is based on then existing population size, management goals, winter severity conditions, and the time frame previously defined. Accordingly, the 20% harvest rates should not be interpreted as a general guideline to other populations. However, the model reveals that doe harvest is a more effective way to manage population size and buck harvest is a more effective way to manage the percentage of antlered bucks. This finding has important implications in quality deer management. To reach both the quantity and the quality goals, managers must balance both buck and doe harvest rates. Contrary to wildlife manager's intuitive viewpoint that simply increasing doe harvest would increase the percentage of antlered buck to the goal level (McCullough 1979), the simulations show that the quality goal cannot be reached without also decreasing buck harvest simultaneously. In other words, the quality goal can only be achieved by restricting the buck harvest and increasing the doe harvest.

Chapter 3

LANDSCAPE STRUCTURE AND SPATIAL DISTRIBUTION OF WHITE-TAILED DEER

Understanding landscape structure and its underlying ecological consequences is a central theme in ecological research and natural resource management (Turner 1989). Quantifying landscape structure has been important in landscape analyses and has received considerable attentions in landscape ecology (Gustafson 1998). Many attempts have been made to link landscape attributes with spatial pattern of endangered species and common birds and small mammals (Andrén 1994, Flather and Sauer 1996, Bayne and Hobson 1998). However, few have studied the relationship between landscape structure and spatial pattern of abundant species, particularly large herbivores such as white-tailed deer at landscape scales. These abundant herbivores are usually habitat generalists and have unique roles in ecological processes because they are often key species in the ecosystem.

In this study, I examined the relationship between landscape structure and the spatial pattern of white-tailed deer, a habitat generalist and a keystone species in many ecosystems in North America (Alverson 1988, Campa 1989, DeCalesta 1994). The importance of the study lies not only in that deer are the most valuable game species, but also in that their spatial dynamics in the past 100 years reveals well its response to spatial and temporal landscape changes (McCabe and McCabe 1984). Almost extirpated due to overexploitation in the end of the nineteenth century, white-tailed deer have rebounded and expanded in most areas due to landscape changes and wildlife management since the beginning of the twentieth century.

A traditional approach to studying the responses of deer to environmental changes is habitat analysis of isolated patches at two levels. The first level of analysis, at a fine scale, deals with the physiological and energetic requirements of the organism, such as Short's (1986) deer energetics model. The second level of analysis, at a coarse-scale, is the quantification of necessary habitat elements such as food, cover, water, and space (Bender and Haufler 1990, Virgós and Tellería 1998). The assumption for these studies is that a positive relationship exists between the amount of necessary habitat elements and relative deer abundance. It is assumed that investigators, with good estimates of habitat components, can predict deer abundance in a defined area by evaluating the habitat suitability.

The models based on these habitat analyses have limited applications in management because of intensive data requirements and/or low accuracy in prediction (Morrison et al. 1992, Van Deelen 1995). Deer have relatively large and often seasonally migratory home ranges (Verme 1973, Nelson and Mech 1984, Van Deelen et al. 1998); these characteristics require wildlife managers to understand deer's landscapes in addition to isolated patches of habitat (Hanley 1996). Field observations often indicate that deer densities differ dramatically even though two areas have a similar habitat suitability index (HSI, a combined measurement of habitat quantity and quality) (Morrison et al. 1992, Van Deelen

1995). This may imply that there exists a higher level of habitat properties that influence deer spatial pattern. I hypothesized that the deer spatial distribution is related to spatial characteristics of habitat patches at landscape level. The spatial characteristics at the landscape level include spatial attributes of patch, area, edge, and shape. To test this hypothesis, I quantified landscape attributes and then linked these attributes with deer spatial distribution. The first objective of this study was to determine which landscape attributes have good associations with deer spatial distribution.

Many field observations and empirical studies at local scales have indicated that deer prefer edges to interior areas (Leopold 1933, Verme 1965, Krefting and Phillips 1970). It is a widely accepted principle in deer management that increasing habitat edge would improve deer habitat conditions, thus would increase deer population size. However, it is not clear whether this principle will hold at landscape scales. The second objective of this study was to determine whether deer show edge preference at landscape scales.

The investigation included all 15 counties in the Upper Peninsula (UP) of Michigan, which comprise a total area of 43,070 km^2 (Figure 3.1). County areas range from 1,368 km^2 to 4,836 km^2, with an average of 2,871 km^2. Physical and biotic characteristics of the UP are described in detail by Albert et al. (1986). The eastern UP has a cool lacustrine climate, low elevation, and flat, glacial lake plain topography with poorly drained soils composed of sand and clay. The forests of this region mainly comprise northern conifers and northern hardwoods. Northern conifers, such as white spruce (*Picea glauca*), balsam fir (*Abies balsamea*), and northern white-cedar *(Thuja occidentalis),* are prevalent in swamp areas while northern hardwoods are in well-drained moraine ridges. The western UP has a continental climate, high elevations, and plateau topography with well-drained soils. Northern hardwoods are dominant over most areas, whereas white cedar is less common than in eastern UP. Commercial lumbering and fire have reduced hemlock (*Tsuga canadensis*), white pines (*Pinus strobus*) and red pines *(Pinus resinosa*) over the entire UP (Albert et al. 1986).

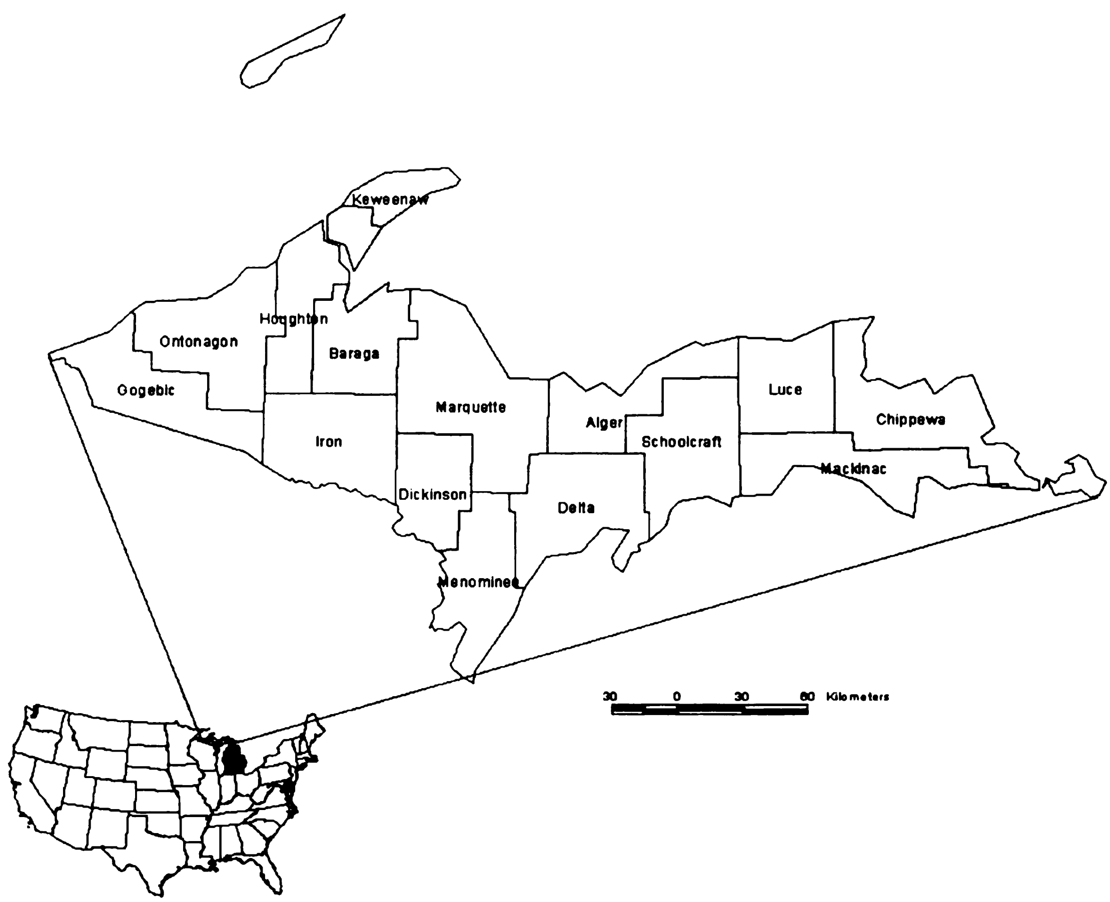


Figure 3.1. Map of the study area showing the names and locations of all 15 counties in the Upper Peninsula of Michigan.

3.1 Methods

3.1.1 Image acquisition, processing, and classification

The Michigan Department of Natural Resources (MDNR) inventoried deer habitat in the UP using Landsat Thematic Mapper (TM) imagery in the growing season of 1991 (Maclean 1994). A hybrid unsupervised-supervised approach was applied to classify the imagery (Lillesand and Kiefer 1994). Each of the 15 counties had a separate image with a grain size of 929 m^2 (100 x 100 feet). These images were first classified into 21 classes according to the MDNR deer habitat classification scheme (Table 3.1). Each of these classes was considered as a separate class of habitat patch type. The coniferous classes in the 21-class scheme were further differentiated (by pine species or crown closures) and resulted in a total of 30 classes of patch type. Aerial photos and ground truthing were used to assess the accuracy of these classifications. The overall accuracy of the 30-class classification scheme is 81%. On the other hand, the 21 classes were re-coded into 8 and 4 classes to more reflect deer manager's perceptions of deer habitat (food, water, space, and shelter) (Table 3.1, Figure 3.2).

3.1.2 Quantification of landscape structure

There are many metrics to quantify landscape composition and configuration. I used FRAGSTATS (McGarigal and Marks 1994) to compute metrics that measure area, patch, edge, shape, core area, diversity, interspersion and contagion for each landscape. For a given landscape, FRAGSTATS (raster version) accepts image file as input, and calculates about 60 landscape statistics

Table 3.1. Four-level hierarchical classification schemes.

30-class scheme		21-class scheme		8-class scheme		4-class scheme	
Patch type	Class #	Patch type	Class #	Patch type	Class #	Patch type	Class #
Urban	1	Urban	1	Non-vegetative	1	Non-vegetative	1
Non-vegetative	2	Non-vegetative	2				
Ag*/cropland	3	Ag/cropland	3	Ag/cropland	2	Nonforest	2
Herbaceous openland	4	Herbaceous openland	4	Herbaceous openland	3		
Shrubland	5	Shrubland	5	Shrubland	4		
Northern hardwood	6	Northern hardwood	6	Hardwood	5	Forest	3
Oak	7	Oak	7				
Aspen/birch	8	Aspen/birch	8				
Lowland hardwoods	9	Lowland hardwoods	9				
Dry hdwd**/conifer mix	10	Dry hdwd/conifer mix	10				
Wet hdwd/conifer mix	11	Wet hdwd/conifer mix	11				
Wetlands	12	Wetlands	12	Wetland	6		
Water	13	Water	13	Water	7	Water	4
Red pine	14	Pines	14	Softwood	8	Forest	3
Jack pine	15						
White pine	16						

Other (mixed) pine	17						
Tamarack	18	Tamarack	15				
Hemlock:<70% CC ***	19	Hemlock	16				
Hemlock:>70% CC	20						
Black spruce:<70% CC	21	Black spruce	17				
Black spruce:>70% CC	22						
White spruce:<70% CC	23	White spruce	18				
White spruce:>70% CC	24						
Balsam fir: <70% CC	25	Balsam fir	19				
Balsam fir:>70% CC	26						
White cedar:<70% CC	27	White cedar	20				
White cedar:>70% CC	28						
Mixed conifer:<70% CC	29	Mixed conifer	21				
Mixed conifer:>70% CC	30						

* Ag: Agricultural land, ** Hdwd: Hardwood, *** CC: Crown Closure

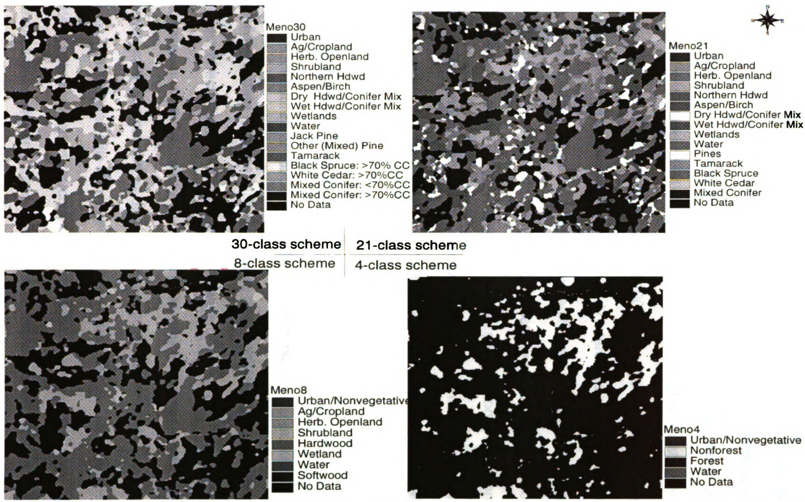


Figure 3.2. Example of landscape patterns under 4 classification schemes. The image was part of Menominee landscape with an extent of 300 x 300 cells (83.61 km^2).

at 3 levels: patch-, class-, and landscape-level. Patch-level metrics represent information for each single patch, whereas, class-level metrics represent the spatial patterns of a single patch type within a landscape and landscape-level metrics represent the spatial pattern of all patch types within an entire landscape (McGarigal and Marks 1994). Based on the assumption of an existing deer HSI model (Bender and Haufler 1990), I used 100 m as edge width to calculate indices related to core areas. I was particularly interested in the indices for diversity and interspersion because it was traditionally believed that there was a good association between diversity and deer density at local scales (Leopold 1933, Compton et al. 1988). Therefore, I calculated Shannon's, Simpson's, modified Simpson's diversity index and evenness index, interspersion index, and contagion index (for more details on these indices, see McGarigal and Marks 1994).

3.1.3 Deer density measures

To measure the spatial distribution of white-tailed deer populations, I used the following data from the MDNR: harvest, deer-vehicle accidents, and reported kills from check stations. The harvest data were obtained by sampling about 10% of licensed hunters by mail surveys. The deer-vehicle accidents were the reported collisions caused by deer, which are compiled by the Michigan State Police. The reported kills from check stations were collected through deer hunters' voluntary reports to check stations in hunting seasons. These three measures are commonly used indices of deer population sizes (Jahn 1959, Allen and McCullough 1976, Verme 1989). As none of these indices provide an absolute deer number, I presented these three population indices for comparison. The deer data used in this study were for each county in 1991, in order to coincide with the 1991 TM imagery. All the data were standardized by the county area to the measures of deer harvest, deer-vehicle accidents, and reported kills per 100 km^2 (Table 3.2).

3.1.4 Relationships between deer density and landscape metrics

As the primary interest was the relationship between landscape structure and deer spatial pattern, I used class- and landscape-level indices to perform statistical analysis. I used each of the deer density measures as a response variable and each of the landscape metrics as an explanatory variable to do regression analyses (Cody and Smith 1997). I tested for significance of the relationships using F ratios. The statistical analyses were performed using SAS statistical software (SAS Institute Inc. 1998). I examined the residuals from the linear regression model to determine whether the linear model was appropriate. If not, a nonlinear model was applied. As many of the metrics represent the same information about the spatial pattern of patch types or landscape, they are inherently redundant. To avoid this problem, I presented only those metrics representing unique aspects of landscape structure and with highest associations with deer density measures.

Table 3.2. White-tailed deer density measures (number/100 km^2) (1991 data, provided by MDNR).

County	Deer harvest	Deer-vehicle accidents	Reported kills
Alger	73.4	7.9	5.4
Baraga	142.9	11.2	18.9
Chippewa	69.5	10.2	4.9
Delta	359.1	31.3	15.2
Dickinson	579.2	37.5	28.5
Gogebic	158.3	5.9	13.5
Houghton	92.7	6.3	9.1
Iron	417.0	19.1	30.2
Keweenaw	19.3	1.2	2.0
Luce	84.9	5.5	5.4
Mackinac	127.4	15.6	6.4
Marquette	208.5	12.2	17.1
Menominee	695.0	41.4	35.2
Ontonagon	181.5	11.6	14.8
Schoolcraft	131.3	6.6	5.5

To identify the relationships between deer density measures and landscape metrics and to determine the effects of different measures of deer density, I analyzed the associations between three deer density measures and landscape-level indices calculated using the 30-class classification scheme. To determine whether these associations would hold under other three classification schemes (4-, 8-, and 21-class), I did analyses using the landscape index that showed the highest association with deer density under the 30-class scheme. Finally, I analyzed the associations between deer spatial measure(s) and class-level indices under 4 different classification schemes to determine which class' spatial pattern would have the highest associations with deer density.

Ideally, ecological units such as ecoregions (Albert et al. 1986) instead of political boundaries such as county boundaries should be used to relate deer spatial pattern with landscape structure. This boundary limitation in this study is due to the fact that deer data were collected at a county level. Data regarding deer spatial distribution across landscapes in ecological units are not available for meaningful statistical analysis.

3.2 Results

Landscape structures differed among the 15 counties in the UP. Most counties had 20 to 23 patch types, while Keweenaw had only 15 patch types. The single largest patch, measured as the percent of the total landscape area in a county, ranged from 1% in Dickenson to 40% in Gogebic with an average of 18.6% (±12.2%, SD). The mean patch size ranged from 6.8 ha in Dickenson to 16.0 ha in Keweenaw with an average of 11.9 ha (± 3.1, SD). Other metrics showed similar variations among landscapes (Table 3.3). For example, Dickinson had the highest patch density, whereas Keweenaw had the lowest patch density.

The regression analyses demonstrated a significant positive relationship between deer harvest and patch density (Figure 3.3a), edge density (Figure 3.3b), and landscape shape index (Figure 3.3c). However, deer harvest showed a negative relationship with mean patch size (r=-0.84, p=0.0001) and all three core area indices: mean core area per patch (r=-0.84, p=0.0001), mean area per disjunct core (r=-0.78, p=0.006), and total core area index (r=-0.89, p=0.0001, Figure 3.3d). Patch density and mean patch size represented the same landscape attribute because both were derived from the total landscape area and the number of patches. All the core area indices, which were computed from patch size, patch shape, and edge width, described similar landscape attributes. To avoid redundancy, I chose patch density and total core area index to do further analysis because they are more ecologically meaningful and easier to measure.

Like the deer harvest, deer-vehicle accidents and reported kills showed similar positive relationships with patch density (Figure 3.4a, Figure 3.4b), edge density, and landscape shape index (Figure 3.5). Similarly, both deer-vehicle accidents and reported kills had a negative relationship with total core area index (Figure 3.5). However, among the three deer density measures, deer harvest showed the highest degree of association with patch density, edge density, landscape shape index and core area index; while the reported kills had the lowest association (Figure 3.5).

Table 3.3. Landscape metrics for the counties in the Upper Peninsula under 30-class scheme. PD = patch density (number of patches /100 ha), ED = edge density (m/ha, sum of lengths (m) of all edge segments per ha), LSI= landscape shape index (ratio of the sum of landscape boundary and all patch edge segments to total landscape area), TCAI = total core area index (percentage of the landscape that is core area), SHDI = Shannon's diversity index (a combined measure of richness and evenness), IJI = interspersion & juxtaposition index (%, observed interspersion over the maximum possible interspersion for the given number of patch types), and CONTAG = contagion index (%, observed contagion over the maximum possible contagion for the given number of patch types).

County	PD	ED	LSI	TCAI	SHDI	IJI	CONTAG
Alger	7.1	47.5	63.2	54.7	1.8	70.2	63.9
Baraga	6.3	50.7	65.5	51.0	1.7	63.5	64.4
Chippewa	7.5	57.1	101.9	45.3	2.4	76.2	52.5
Delta	10.7	67.0	104.5	40.1	2.3	73.8	53.0
Dickinson	14.7	84.9	96.3	26.8	2.2	71.2	53.2
Gogebic	7.8	57.9	82.3	45.0	1.7	62.3	64.9
Houghton	6.8	51.3	70.2	51.0	1.8	64.5	64.4
Iron	10.7	74.1	105.4	34.8	1.9	62.1	60.9
Keweenaw	6.3	48.7	42.6	52.4	1.9	68.4	58.5
Luce	7.7	59.0	74.3	43.4	2.2	68.6	57.4
Mackinac	7.5	55.6	83.1	46.9	2.3	72.2	55.9
Marquette	11.3	66.9	120.1	41.3	2.1	71.8	58.0
Menominee	14.6	86.0	115.6	25.3	2.3	72.6	51.1
Ontonagon	6.9	56.9	85.3	45.3	1.7	54.5	65.4
Schoolcraft	10.0	68.5	100.0	36.6	2.2	69.9	54.0
Mean	9.0	62.1	87.4	42.7	2.0	68.1	58.5
SD	2.8	12.2	21.6	8.8	0.2	5.5	5.0

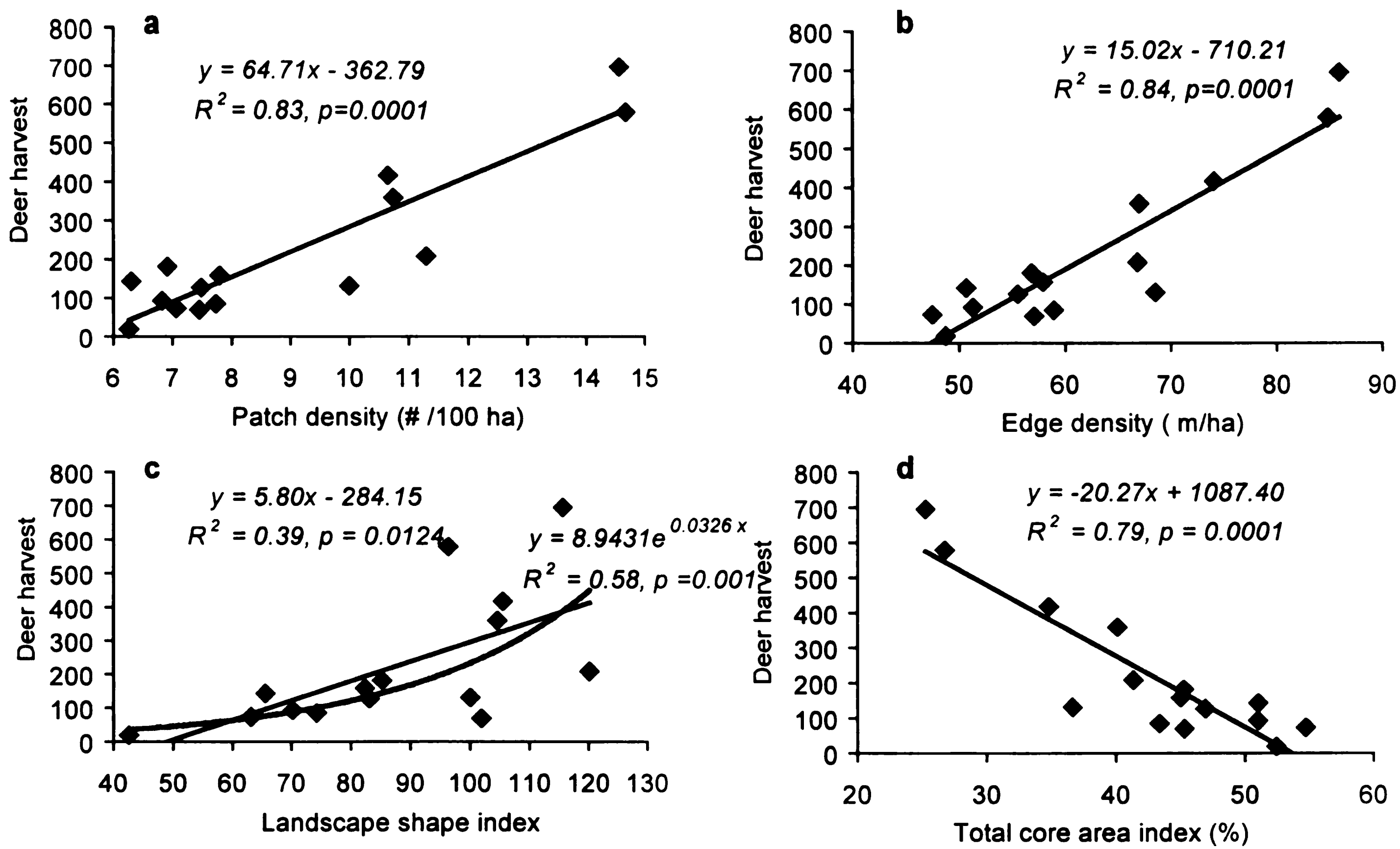
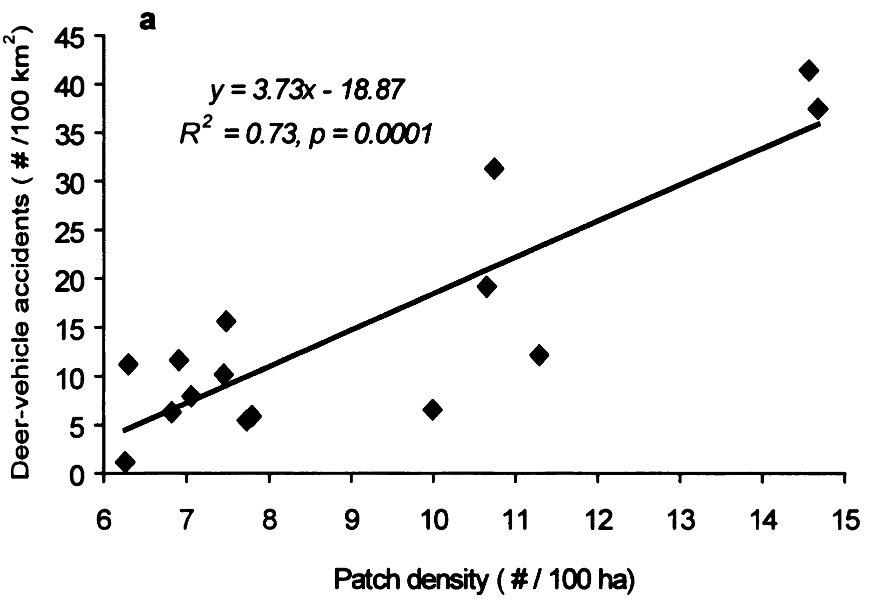


Figure 3.3. Relationship between deer harvest (number of harvested deer per 100 km^2) and (a) patch density (number of patches per 100 ha), (b) edge density (sum of lengths (m) of all edge segments per ha), (c) landscape shape index (ratio of the sum of landscape boundary and all patch edge segments to total landscape area), and (d) total core area index (percentage of the landscape that is core area).



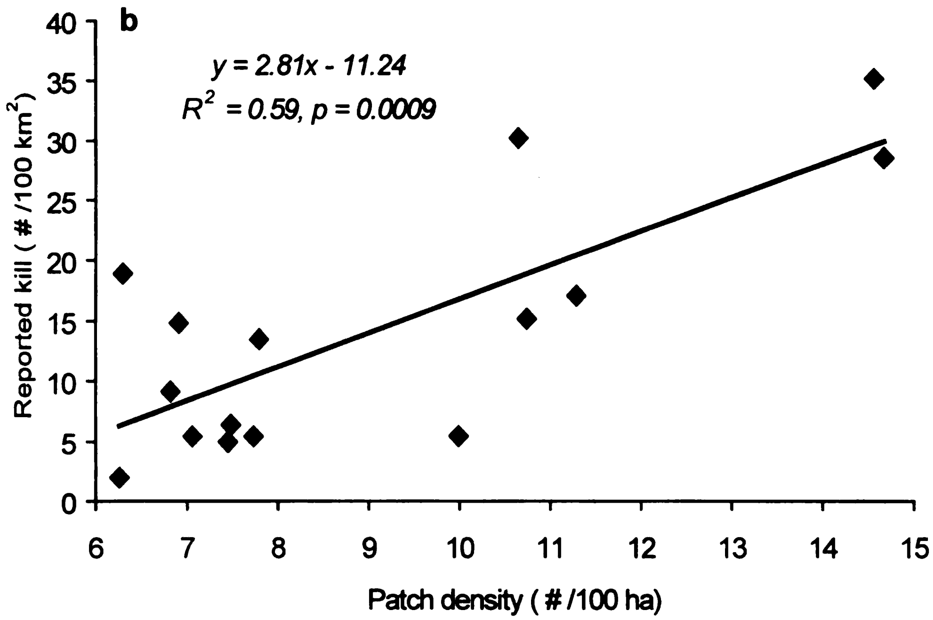


Figure 3.4. (a) Relationship between deer-vehicle accidents and patch density (number of patches per 100 ha). (b) Relationship between reported kills and patch density (number of patches per 100 ha).

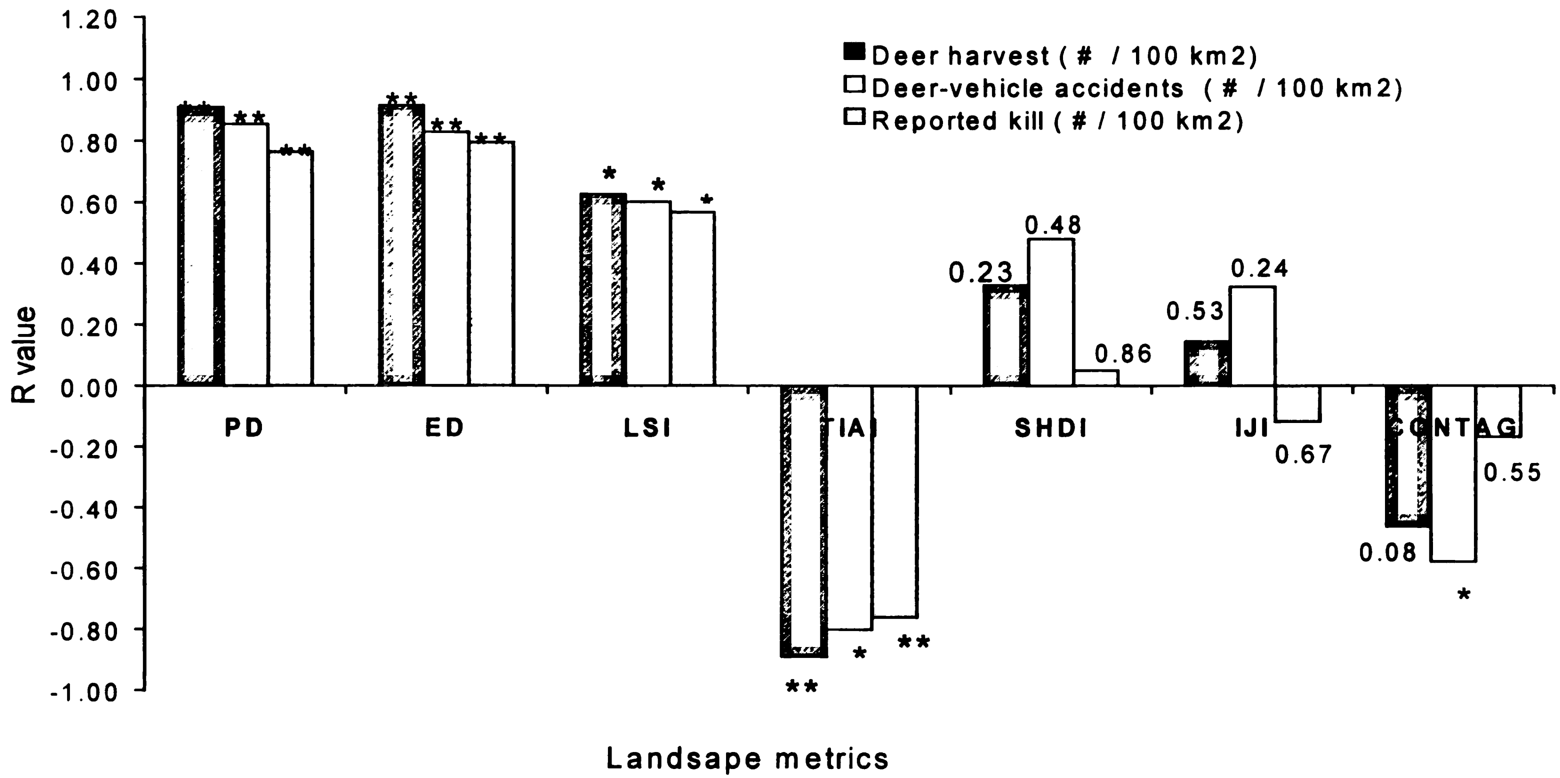


Figure 3.5. Relationships between deer density measures and landscape metrics. * = $p < 0.05$, ** = $p < 0.01$, PD = patch density (number of patches per 100 ha), ED = edge density (sum of lengths (m) of all edge segments per ha), LSI = landscape shape index (ratio of the sum of landscape boundary and all patch edge segments to total landscape area), TIAI = total core area index (percentage of the landscape that is core area), SHDI = Shannon's diversity index (a combined measure of richness and evenness), IJI = interspersion and juxtaposition index (%, observed interspersion over the maximum possible interspersion for the given number of patch types), and CONTAG = contagion index (%, observed contagion over the maximum possible contagion for the given number of patch types).

The deer density measures displayed no significant relationships with landscape metrics for diversity and interspersion (Figure 3.5). However, to the contagion index, deer-vehicle accidents showed a negative relationship (p=0.02), deer harvest data displayed a marginal negative relationship (p=0.08), whereas reported kills had no relationship (p=0.55) (Figure 3.5).

Among all landscape-level metrics, edge density showed the highest associations with deer density measures under the 30-class scheme (Figure 3.3, Figure 3.5). So I chose landscape-level edge density to examine its behavior under 4 classification schemes. Edge density varied across the landscapes in the UP (Table 3.4). Under all 4 classification schemes, Menominee and Dickinson had the highest and second highest edge density, respectively. Keweenaw had the lowest edge density under the 4- and 8-class schemes and second lowest under the other two schemes, while Alger had the lowest edge density under both the 21- and 30-class schemes, and Luce and Ontonagn had the second lowest edge density under the 4- and 8-class schemes, respectively.

For the same landscape, edge density showed a logarithmic increase as class number increased from 4 to 21, however, the increases leveled off when the class numbers increased from 21 to 30 (Figure 3.6). For different landscapes, the patterns of increase in edge density behaved differently across landscapes. For example, edge density of the Iron county landscape ranked the third highest under the 30- and 21-class schemes, but the rank fell to the tenth under the 8-class scheme and the sixth under the 4-class scheme.

Table 3.4. Landscape-level edge densities (sum of lengths (m) of all edge segments per ha) under 4 classification schemes.

County	30-class	21-class	8-class	4-class
Alger	47.5	46.9	29.7	14.3
Baraga	50.7	50.4	24.9	12.4
Chippewa	57.1	56	40.1	18
Delta	67	65.8	47.7	22.6
Dickinson	84.9	84.8	60.7	36.2
Gogebic	57.9	57.9	35.8	15
Houghton	51.3	51.1	26.6	16.5
Iron	74.1	73.6	34.3	18.4
Keweenaw	48.7	48	21.7	9.6
Luce	59	56.9	39.3	12.3
Mackinac	55.6	54.1	36.7	14.3
Marquette	66.9	66.4	44.7	26.1
Menominee	86	85.9	64.2	37.3
Ontonagn	56.9	56.8	22.4	13.8
Schoolcraft	68.5	67.3	50	20.2
Mean	62.1	61.5	38.6	19.1
SD	12.2	12.3	13.1	8.3

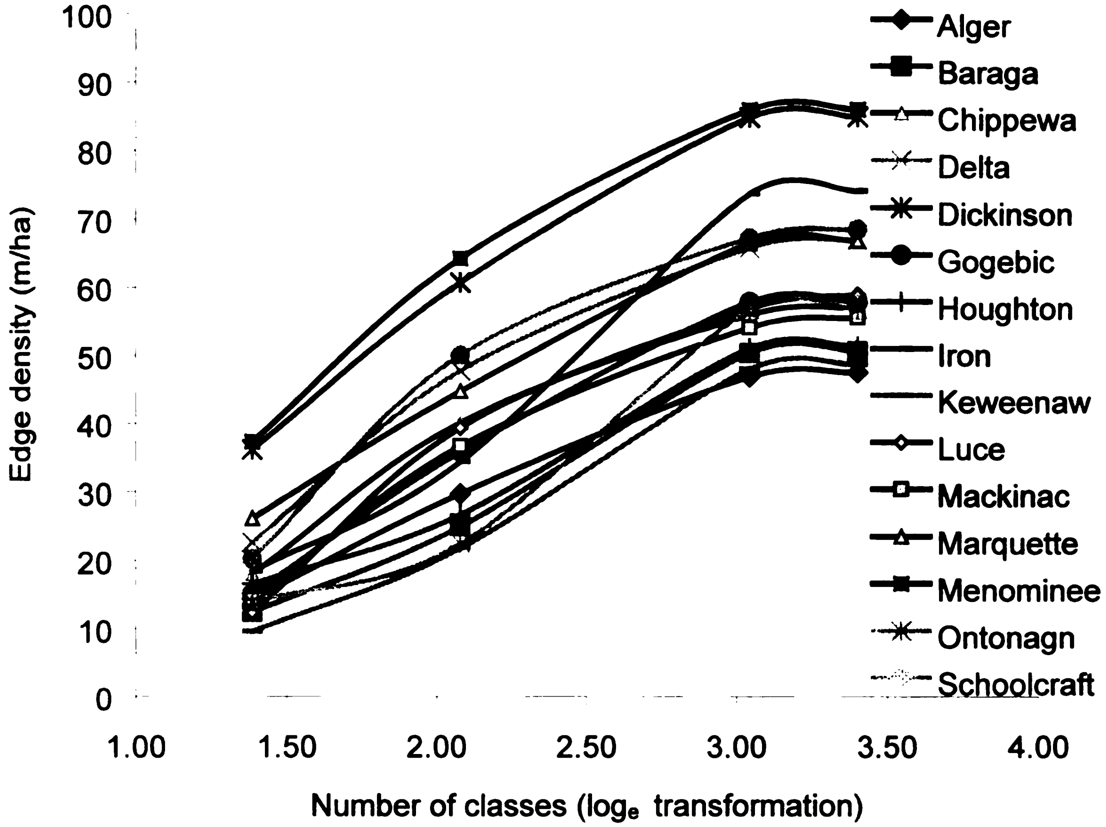


Figure 3.6. Sensitivity of edge density (sum of lengths (m) of all edge segments per ha) to changes in classification schemes.

As three deer density measures showed similar associations with landscape metrics and deer harvest showed the highest associations with deer density measures under the 30-class scheme, I further analyzed the relationships between deer harvest and landscapes-level edge density under the other three classification schemes. There was a significant linear relationship between deer harvest and landscape-level edge density. However, the degree of associations between them varied as classification schemes changed (Figure 3.7). The order of associations was 21-, 30-, 4-, and 8- class scheme, from the highest to the lowest.

The edge density of tamarack, agricultural land/cropland, and herbaceous openland had the highest associations with deer density under 21- and 30-class schemes as these 3 classes remained in the same classes under these two classification schemes (Table 3.1, Figure 3.8). Under 8-class scheme, the edge density of agricultural land/cropland and hardwood showed a strong association with deer density measure. Under the 4-class scheme, the edge density of forests and non-forests showed strong associations with deer density measure as both forests and non-forests shared the most edges in the UP where the areas of non-vegetative and water were minimal.

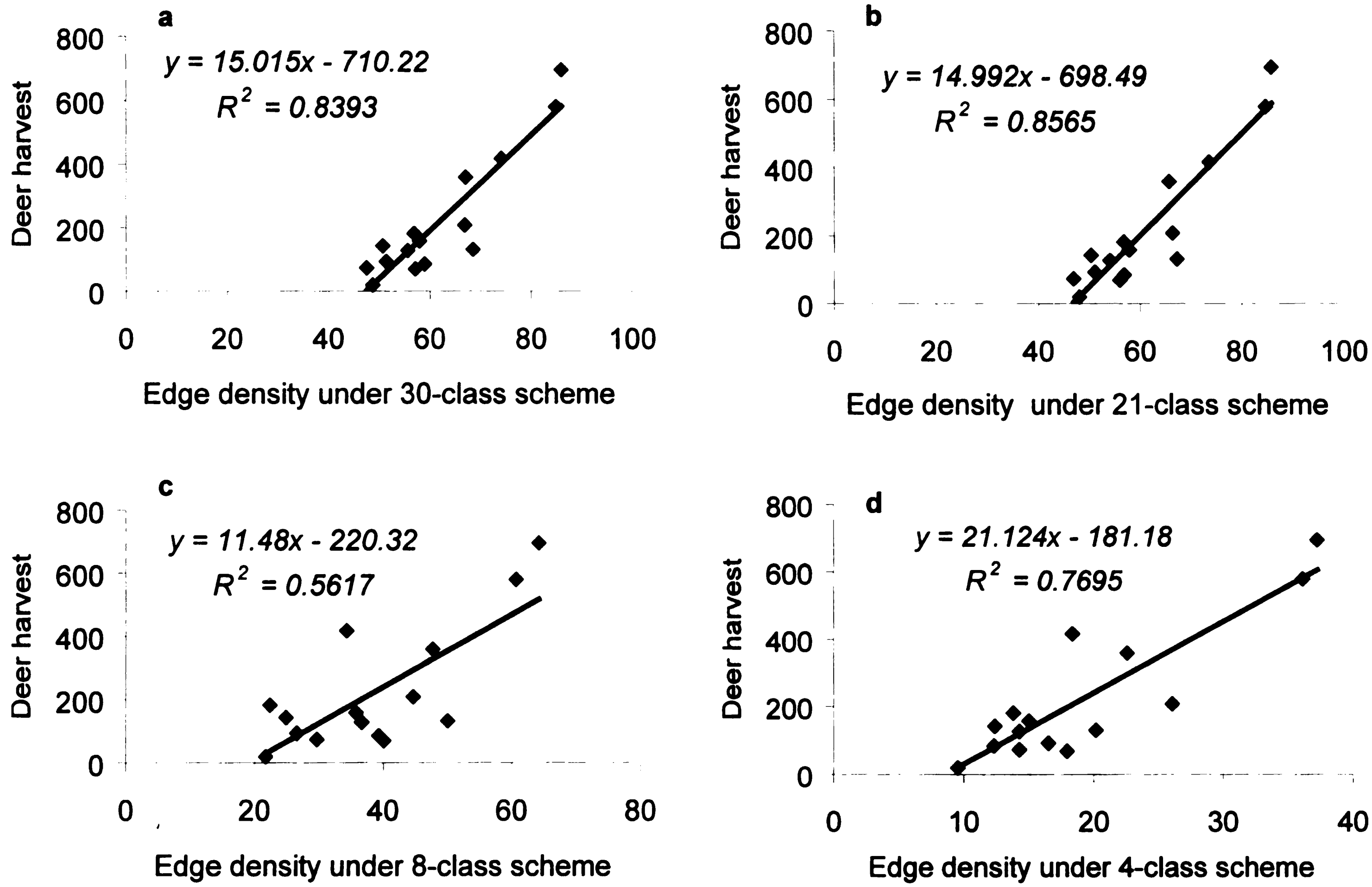


Figure 3.7. Relationship between deer harvest (number /100 km^2) and edge densities (sum of lengths (m) of all edge segments per ha) under 4 classification schemes.

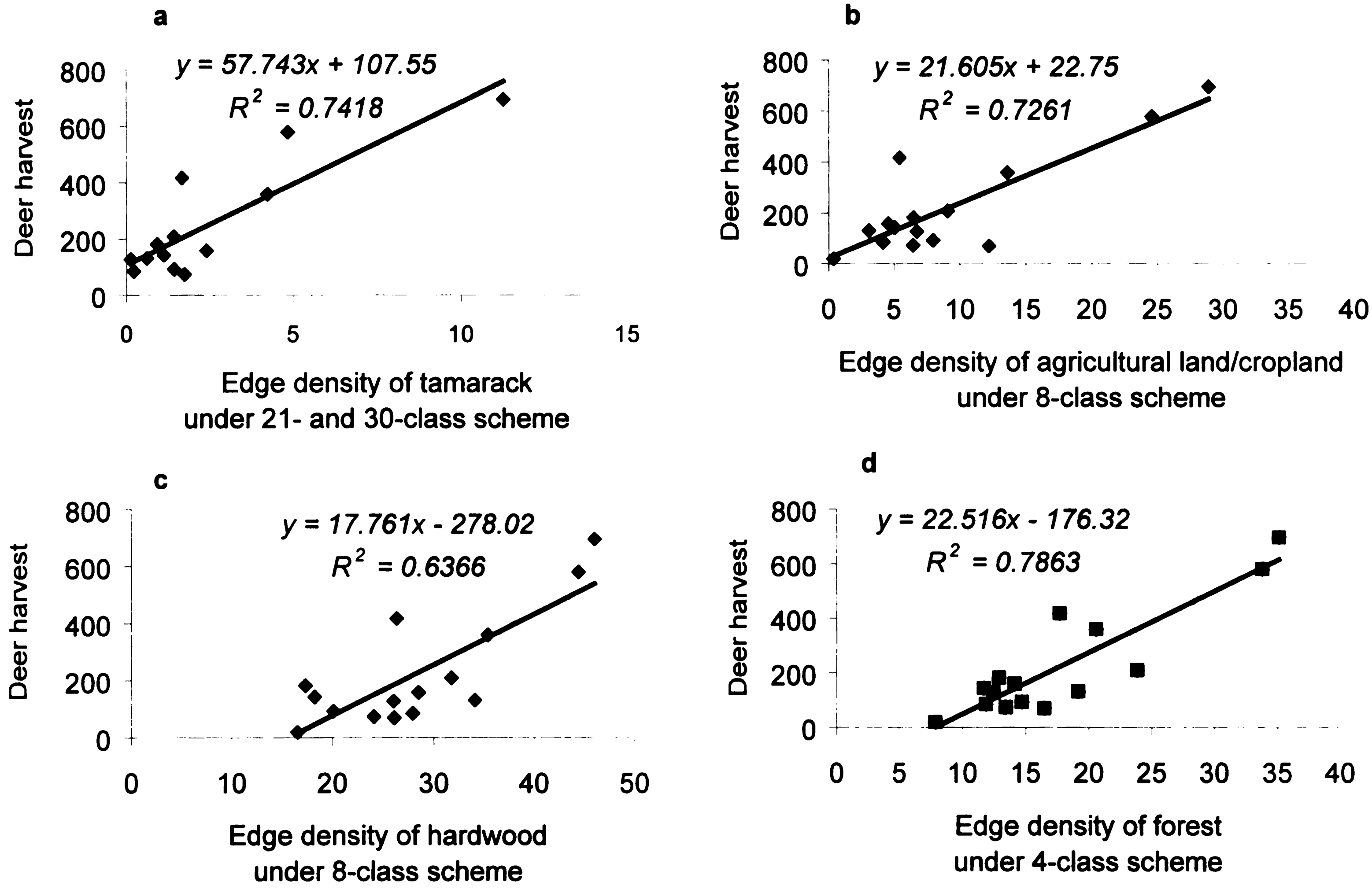


Figure 3.8. Highest associations between deer harvest (number /100 km^2) and edge density (sum of lengths (m) of all edge segments per ha) of single class under 4 classification schemes.

3.3 Discussion

Quantifying the relationships between landscape structure and ecological consequences is a primary focus of landscape ecology (Turner 1989, Dunning et al. 1992). The study revealed that the spatial pattern of patches had a strong association with deer density, measured by deer harvest, deer vehicle accidents, and reported kills. Furthermore, this study demonstrated significant relationships between deer density measures and several landscape metrics (Figure 3.3 and Figure 3.5). Among these metrics, patch density and edge density are good heterogeneity indices, while landscape shape index measures the complexity of patch shape (Li and Reynolds 1994). These findings suggest that spatial heterogeneity plays an important role in characterizing the spatial distribution of white-tailed deer at landscape scales.

The regression analyses also indicated that a single landscape index such as patch density (R^2=0.83) and edge density (R^2=0.84) can explain more than 80% of variations of deer density measures. This suggests that these linear regression models may be applied to predict the spatial pattern of deer distribution at a landscape level. These models may also apply to other areas if the same resolution of imagery and the same habitat classification system are used. However, further studies are necessary to examine whether and how these findings can be applied to identify deer concentrated areas within a landscape. A crucial issue is how to scale down and to sample a landscape in order to detect the areas with specified landscape attributes such as high edge density or patch density in a landscape. Because many landscape indices are not independent but inherently interrelated, I did not perform multiple regression analysis.

Deer density measures showed a negative relationship with total core area index (Figure 3.3d). However, it should be emphasized that the total core area index was obtained using an arbitrary edge width. Therefore, I recommend using patch density, edge density, or landscape shape index to describe the landscape structure for white-tailed deer. These indices showed strong relationships to deer spatial distribution, are not dependent on the arbitrary edge width, are more ecologically meaningful, and are easier to measure.

Landscape diversity, measured by Shannon's and Simpson's diversity index and evenness index, could not characterize deer spatial distribution. Similar findings are reported by other studies (Compton et al. 1988). The lack of any significant relationships between deer density measures and diversity and interspersion indices might result from inappropriate loss of information of diversity metrics. All of these diversity indices are basically dependent on the patch richness (number of patch types in a landscape) and evenness (proportion for each patch type). Although proportion for each patch type may differ, most landscapes have similar patch richness. Thus the indices might fail to measure the diversity of the landscape, and could not characterize the spatial pattern of deer distribution.

The landscapes containing well interspersed patches, as indicated by a lower contagion value, tended to have a high density of deer vehicle accidents.

This correlation is consistent with traditional observations that the areas with large and contiguous patches have few deer vehicle accidents, while the areas with small and dispersed patches have more deer vehicle accidents (Allen and McCullough 1976, Bashore et al. 1986).

Depending on classification schemes, deer showed discriminating preference to edges. The edge density of tamarack had a higher association than other coniferous species had with deer density measured by deer harvest under 21- and 30-class schemes. The edge density of hardwood and agricultural land had higher associations than softwood and wetland had.

Applying the study results from one scale to another scale is a challenging issue in landscape ecology (Turner et al. 1989). Previous observations have indicated that deer prefer edges at local scales probably because the edges provide browse and are close to good shelter (Leopold 1933, Verme 1965, Krefting and Phillips 1970). This study showed that edges played a significant role in deer distribution at landscape scales as well. Thus, I concluded deer show edge preference at large as well as small scales. This suggests that deer may be scale-independent regarding habitat selection. However, it is unclear how edges at local scales and at landscape scales interact to affect deer spatial distribution. Both empirical and theoretical studies at multiple scales are warranted to explore the effects of edge distances, areas, and configurations on deer spatial distribution across heterogeneous landscapes.

Chapter 4

A KNOWLEDGE-BASED SYSTEM FOR WHITE-TAILED DEER MANAGEMENT (DeerKBS)

Wildlife management is a blend of science and art. The previous two chapters emphasize the importance of the scientific investigations of deer population and their habitats. DeerMOM is developed to evaluate different management options to see how harvest scenarios would affect the population dynamics (Chapter 2). Deer managers can use this model to select the best scenario in order to reach their objectives in a defined area during a specific time frame (Xie et al. 1999). The spatial analyses are performed to evaluate habitat conditions on landscape scales to see which landscape attributes would be more associated with deer distribution than others (Chapter 3). Based on these analyses, wildlife managers can plan and manipulate landscapes either to improve habitat conditions in order to increase deer population or to deteriorate habitat conditions in order to decrease crop damage and/or deer-vehicle accidents.

What makes wildlife management as a practice differ from wildlife science as a discipline is the importance of art in management. Some argue that "too much of wildlife management is today still more of an art than a science" (Walker 1998). To make effective management, wildlife managers need to employ expertise to balance the delicate relationships among all relevant factors to address an array of complex issues. For example, wildlife stakeholders such as hunters, farmers, and environment conservationists are demanding more involvement in the process of management decision making. Global changes, rapid species endangerment and extinction awake the public, and many government agencies make biodiversity conservation mandatory in any natural resources management (NRC 1995, Swanson 1997). As more and more problems emerge from the humans shortsightedness or mismanagement, the management paradigm is shifting from small scale, single species management to large-scale adaptive ecosystem management (Walters 1986, Crow and Gustafson 1997). Although this new paradigm sounds promising in solving the problems caused by traditional management systems, decision-making risk is exponentially increasing with the increase in management scales. Experience and expertise are scarce or not available. Mismanagement may result in ecological and economic disasters.

New technologies offer promises to overcome some difficulties for adaptive ecosystem management. Global positioning systems (GPS), remote sensing (RS), and geographic information systems (GIS) can be utilized to collect and store huge amounts of spatial and temporal data of wildlife species and their environment (Franklin 1994). Database management tools, such as data mining and data warehousing, offer the capacity of finding patterns from historical data, thus transforming a deluge of data into valuable information, and then from information to useful knowledge (Singh 1997).

In science, it is a principle to let data speak out. In management, however, data do not make decisions, only humans do. The overwhelming amount of data and information can help wildlife managers better understand the system, but also add another dimension of complexity to the decision making processes. Complexity makes it difficult for stewards of the wildlife to have all the relevant information and knowledge (Starfield and Bleloch 1986). However, decisions must be made, even with conflicting goals and scientific uncertainties but without complete data or scientific consensus (Ludwig et al. 1993, Ehrlich and Daily 1993). It is the wisdom of wildlife managers who apply the accumulated data, information, and knowledge from researches and from the technologies to their decision-making processes.

Knowledge-based systems (KBSs), a branch of artificial intelligence (AI), can be used to help wildlife managers take advantage of the accumulated data and information to make more informed decisions. Generally speaking, KBSs are computer systems that use human knowledge to solve problems that normally would require human intelligence (Edwards 1991). KBSs differ from other AI programs in their performance, domain-specific problem-solving strategies, and their justification for conclusions. KBSs differ from conventional software programs in their symbolic representation, symbolic inference, and heuristic search (Hayes-Roth et al. 1983).

KBSs for natural resource management have been studied since the beginning of KBS research. The first successful KBS application on natural resources is Prospector for mineral exploration in the late 1970s (Duda et al. 1979). Most of the early applications are limited to interpretation and diagnosis task of geological and mineral problems. Production rules are the predominant type of knowledge representation schemes. Since the late 1980s, KBSs have expanded applications to management for forestry, water resources, and ecosystems. The book written by Schmoldt and Rauscher (1996) may be the first one that systematically introduces the concepts of AI, KBS, and knowledge engineering life cycle to and integrates them into the system development for natural resource management. The authors introduced the whole life cycle of the development of a Red Pine Forest Management Advisory System (RP-FMAS) using Prolog in which predicate logic was selected for knowledge representation. A nice feature for this system is that it uses hypertext so that the system can be used as an alternative to a manual. Bremdal (1997) reviewed 27 KBSs for management of natural resources. Among them, 11 systems are for geological exploration and mineral analysis, 6 for ecosystem management, 5 for forestry management, 4 for water resources management, and only 1 for wildlife taxonomy (whale visual identification).

A noticeable trend in KBS development is the integration of system modeling, database management, and GIS into a decision support system to provide a framework tool for decision making. The Ecosystem Management Decision Support System (EMDS), which is developed by the USDA Forest Service Pacific Northwest Research Center, integrates GIS and knowledge based reasoning technologies. It uses NetWeaver engine for knowledge-based reasoning and object- and fuzzy logic-based networks for the knowledge representation (Reynolds 1999).

In this study, I constructed a deer knowledge-based system (DeerKBS) that concerns white-tailed deer management in the Upper Peninsula (UP) of

Michigan. The major objectives of this study were three-fold: to provide a unifying decision-making framework for deer management, to help users identify their management issues and make appropriate decisions, and to standardize the management procedures and use the system as a communication and educational tool.

4.1 System Components of DeerKBS

The main components of a KBS include knowledge base, reasoning engine, and user interface. As a database is a collection of data, a knowledge base is a collection of knowledge. There are many different ways to represent knowledge, such as rules (Newell and Simon 1973, Shortliffe 1976, Davis et al. 1977, McDermott 1982), frames (Minsky 1975), scripts (Schank and Abelson 1977), objects (Goldberg and Robson 1983), and networks (Quinlan 1986). In DeerKBS, I use rule-based knowledge representation because it has some desirable properties for system development. For example, each rule represents a "chunk" of knowledge for a specific domain (Duda and Gaschnig 1981). The rules' properties of uniformity (rules have the same structure) and modularity (rules are grouped) also make the development and maintenance easier (Schmoldt and Rauscher 1996). In practice, wildlife managers utilize their "rules of thumb" in their decision making. It is relatively easy to ask experts to express their thoughts out as rules, to code their thinking processes into rules, and to ask the user to test the rules.

Reasoning engine is a set of reasoning methods that determine the mechanisms by which the system makes decisions based on knowledge stored in the knowledge base. Decision making or problem solving, in terms of artificial intelligence, is a process of search for a solution (a state) from a collection of solutions (a state space). Two mechanisms are involved in this process: inference and control. In DeerKBS, a decision tree search is used as inference that generates new assertions. A decision tree is a hierarchical structure with each node (a branching point in a tree) determining which lower node will be searched, and each leaf (terminal point) representing a solution. The nice property of a decision tree is that the tree structure offers the control strategy and the nodes allow for inferences (Quinlan 1986). Both backward chaining and forward chaining are used in DeerKBS as control methods that determine how the system seeks solutions. Forward chaining is a data-driven search strategy, whereas backward chaining is a goal-driven search strategy. The last component of KBS is the user interface. In DeerKBS, graphical user interface (GUI) is used to ease the system usage.

4.2 System Development of DeerKBS: An Overview

A traditional life cycle for software engineering follows a waterfall model (Boehm 1976) that includes 5 major phases: specification, design, implementation, testing, and maintenance. The model requires that complete specifications and assessment criteria for each phase can be provided before system design and implementation, so the overall development remain linear. A knowledge engineering life cycle usually follows a spiral model (Boehm 1988) that has similar components with the waterfall model but is characterized by iterative design and prototyping. One of the widely used spiral models in KBSs is the life cycle model proposed by Buchanan et al. (1983) that includes the following 5 iterative steps:

1. Identification: identify problem characteristics
2. Conceptualization: find concepts representing knowledge
3. Formalization: design structure organizing knowledge
4. Implementation: formulate rules embodying knowledge, and
5. Testing: validate rules organizing knowledge

In Buchanan's model (1983), knowledge acquisition is an ongoing central activity across different development stages and the system development is cyclic processes. A variant of this model (Awad 1996), which focus on structured tasks, includes the following stages:

1. Problem identification (system requirements and knowledge analysis)
2. Selection of KBS tools
3. Representation (knowledge acquisition, prototype, verification and validation)
4. Implementation, and
5. Operation and maintenance.

The development of DeerKBS roughly follows this model. The first phase is domain problem identification that leads to the system requirements and problem definition. Once the problem is defined, a KBS tool is determined based on system requirements. Then the concern of the development focuses on knowledge acquisition, prototyping, and validation. Following this phase are system implementation, operation, and maintenance.

4.3 Domain Problem Definition

Deer management is the management of deer population, habitat, and people (Giles 1978, Decker et al.1992). It usually takes a long time for a deer manager to gain enough experience to effectively manage deer population and habitats and to gain support from all stakeholders. Moreover, as government agencies encourage employees to retire early, many experienced wildlife managers have retired, or will retire soon. Retaining their valuable expertise is important for management agencies to prevent loss of institutional expertise and to provide more consistent decisions.

Problem defining is the process that identifies the scope, requirements, and objectives of the problem-solving system. Before I define the problem, some background for deer management is necessary to understand the problem. Although it is often difficult to make distinctive judgments about how many deer are best in an area, deer managers make their judgment based on their own observations and experience. The areas with few deer usually have insufficient or low quality deer habitat. These areas can be selected for deer habitat improvement if more deer are desirable. Hunting recommendations can be restrictive to antlerless deer harvest and thus to increase deer population size. For those areas with too many deer (in terms of habitat and social carrying capacity), hunting recommendations can be harvesting more antlerless deer. In the areas with adequate population, hunting antlerless deer can control the population as deer population in Michigan has potential to increase at a rate of 20-40 percent each year (McCullough 1979, Xie et al. 1999).

Deer managers often establish deer objectives at hierarchical management levels (deer management unit (DMU), district, region, and state) based on their assessments of deer population, habitat status, and stakeholders' attitudes. The long-range objective in Michigan is a fall population of 1.3 million deer, 35% of which should be antlered bucks (MDNR 1993). Each year, deer managers recommend to have more, fewer or the same number of deer for each management level compared with that in the previous years. These recommendations are based on the following considerations and assessments (Langenau 1994, Ozaga et al. 1994):

- Deer status: including deer population density and the percentage of antlered bucks in the population.
- Habitat status: including habitat quantity and quality
- Cultural carrying capacity (CCC): the range of population levels acceptable to all stakeholders such as deer hunters, farmers, and other interest groups (Minnis 1996)
- Environment conditions: winter conditions measured by winter severity index (Verme 1965)

DeerKBS divides the whole task of decision-making for deer management into a few small subtasks. Each subtask can be further divided into sub-subtasks.

If DeerKBS is viewed as an intelligent agent, an application performing some tasks for the user (Prerau et al. 1997), then each sub-task can be assigned to a subagent that is an expert who makes his or her own decisions in a specific field. For example, the subagent for deer population management can be an expert or a panel of experts who specialize in deer population evaluation and decide whether the population is good, too high, or too low. The outcomes of DeerKBS can be a suite of recommendations for hunting, habitat modification, and education based on all the inputs from one or many panels of experts. This study will focus on recommendations for deer hunting. One major objective of DeerKBS is to provide a general KBS framework for deer management, although the knowledge base is built based on deer management in the UP of Michigan. DeerKBS is intended for use by wildlife managers, researchers, and educators.

4.4 Selection of KBS tool: XpertRule KBS

XpertRule KBS (Attar Software Limited 1996) was chosen for DeerKBS development. XpertRule KBS is a shell tool for the graphical development and maintenance of knowledge-based applications. An XpertRule application is constructed graphically as a hierarchy of chained tasks under Windows environment. A task can consist of a decision tree representing a flow chart controlling procedures, dialogs, reports or other tasks. Complex knowledge can be structured into a hierarchy of chained tasks.

4.5 Knowledge Representation

Knowledge engineering is the process that centers on the process of transforming the expert knowledge and expertise to a knowledge base. This process can be further divided into 3 processes: knowledge structuring, knowledge acquisition, and knowledge validation.

4.5.1 Knowledge structuring

Knowledge structuring is the process of transferring the problem-solving conceptual model into a structure hierarchy of decision-making tasks that relate the management alternatives with all the considerations. In DeerKBS, I identified 8 attributes that are related to 4 sub-tasks: assessment of population, habitat, CCC, and weather. These attributes are: (1) deer population size, (2) buck percentage in the population, (3) deer habitat quantity, (4) deer habitat quality, (5) deer population size expected by deer hunters, (6) deer population size expected by farmers, (7) deer population size expected by other interest groups, and (8) winter severity index.

The outcomes of assessment for deer population size are low, good, or high. The outcomes of assessment for other attributes are listed in Table 4.1. Once assessment for each attribute is finished, further assessment for some attributes can be performed to obtain a higher level assessment. For example, habitat quantity can be lack, average, or abundant; and habitat quality can be poor, medium, or high. The outcomes for overall habitat are assessed as poor, moderate, or excellent (Table 4.1).

Table 4.1. Attributes in DeerKBS and their assessment outcomes

Attributes	Outcomes	Outcomes at a higher level
Deer population size	low, good, high	
Buck percentage	low, average, high	
Habitat quantity	lack, average, abundant	poor, moderate, excellent
Habitat quality	poor, medium, high	
Hunters expectation	fewer, same, more	fewer, same, more
Farmers expectation	fewer, same, more	
General public expectation	fewer, same, more	
Winter severity index	favorable, average, harsh	

4.5.2 Knowledge acquisition

Knowledge acquisition is the process of acquiring the knowledge of the individual tasks from expert and literature. I acquired knowledge from experts by interviewing deer managers and biologists and from documentation by searching literature and the Michigan Department of Natural Resources (MDNR) reports. The knowledge was represented as a decision rule. For example,

Rule I:

IF population density is high, and
habitat condition is moderate or poor, and
social carrying capacity is fewer deer
THEN recommend harvesting more deer

As deer managers gave only some typical management scenarios, I used these typical scenarios as examples (referred to as example table) to generate all the possible combinations of attributes (referred to as truth table). Based on these tables, decision trees were generated by induction. If the information or knowledge was not available to generate the rules, I made some educated guesses.

4.5.3 Knowledge Validation

Testing knowledge base involves examining the correctness and completeness of the overall knowledge base. Tests were performed at two levels. The first level was the validation of each individual decision rule. I present the attributes for each rule to deer managers and then compare the decisions from them and from DeerKBS. The second level was the validation of all rules to eliminate redundant and conflicting rules. The decision tree that XpertRule induced from example table could detect conflicting rules visually, so the completeness of knowledge base could be guaranteed. During the development of DeerKBS, I also demonstrated the system to deer biologists and wildlife managers in the Wildlife Division at MDNR, compared the decision results from them and from DeerKBS, and requested their suggestions for system improvement.

4.6 System Implementation

DeerKBS was developed using XpertRule KBS under Microsoft Windows® environment. The deer management decision making task was structured into 4 sub-tasks: assessment of population, habitat, CCC, and weather. Once these subtasks were finished successfully, decisions were made to give pertinent harvest recommendations. These recommendations were further refined by considering buck percentage in deer population.

4.6.1 Subtask for assessing population

Population assessment is the first task that deer biologists and managers need to deal with. Generally speaking, population assessment can be divided into two subtasks: assessment of population size and assessment of population structure. Population size and structure are vital parameters in deer management because they are bases for decision-making. DeerMOM can be used to project population size and structure under different harvesting scenarios (Chapter 2). Although many efforts are made to estimate the absolute number of deer in the wild, many biologists and wildlife managers emphasize the importance of relative abundance of deer. Management decisions are often made based on the population size relative to biological carrying capacity (BCC), CCC, and the trends of deer population changes, rather than the absolute number of deer population (Hayne 1984).

On the basis of McCullough's (1979) long-term study in George Reserve of Michigan, the maximum carrying capacity was estimated to be 35 deer/km^2 (90 deer/mi^2), and the optimum carrying capacity to be 19 deer/km^2 (50 deer/mi^2). On some farmlands in Wisconsin, the carrying capacity was estimated to be 40 deer/km^2 (McCafferey 1989). The management objective for population size in the UP of Michigan is 372,500 in the fall, or at an average density of 9 deer/km^2 (23 deer/mi^2) (MDNR 1993). In DeerKBS, deer population density is classified as high if it is above 35 deer/mi^2, low if below 20 deer/mi^2, and good if between 20 and 35 deer/mi^2 (Figure 4.1). For users' convenience, I used square miles rather than square kilometers as area unit.

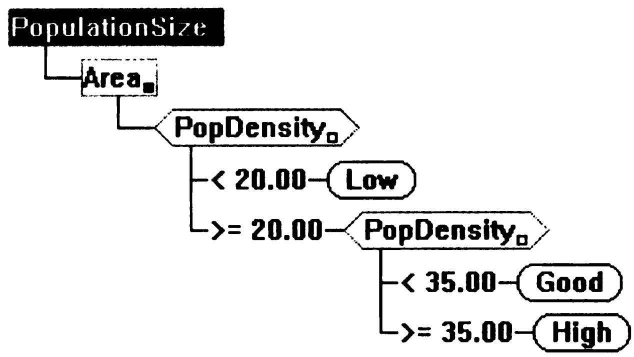


Figure 4.1. Subtask for population size assessment, where PopulationSize represents population size, and PopDensity represents population density.

Population structure is the other aspect of population assessment. As the deer population increases, there are more hunting opportunities for deer hunters and more recreational opportunities for the public. However, the cost of abundant deer is high in some areas. Relatively high deer population have unacceptable economic impact on the society caused by crop damages (Allen and McCullough 1976, Conover and Decker 1991) and deer-vehicle accidents (Conover et al. 1995), disease transmission (Wilson and Childs 1997) and ecological impact on the ecosystem caused by influencing forest regeneration (Alverson et al 1988). To improve the quality of deer hunting and to minimize the negative impact of high deer densities, deer management in Michigan is aiming at producing more bucks but fewer deer. One of the objectives in quality deer management in Michigan is to have a 35% of antlered bucks in deer population. In DeerKBS, the percentage of antlered buck (or buck ratio) was classified as high if it is above 35, low if below 20, average if between 20 and 35 (Figure 4.2).

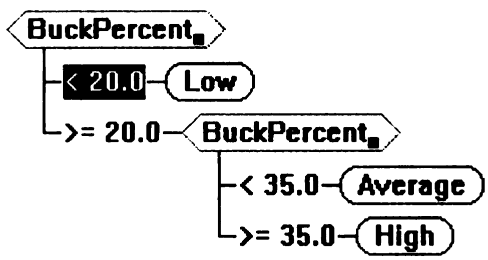


Figure 4.2. Subtask for antlered buck percentage assessment, where BuckPercent represents the percentage of antlered buck in deer population.

4.6.2 Subtask for assessing habitat

There are many approaches to assess deer habitat. The spatial analysis of the deer distribution across the UP is an approach to assessing deer habitat at the landscape level (county scale). Using a single landscape index such as edge density can quickly assess the overall habitat condition at large scales. If management recommendations need to be made at the landscape level, the landscape analysis can give an assessment of overall habitat using some landscape metrics. However, deer biologists and deer managers often assess the habitat in a much smaller scale (Krefting and Phillips 1970, Ozaga et al. 1994, Braun 1996) by following habitat assessment procedures and habitat suitability index (HSI) (Short 1986, Bender and Haufler 1990). In DeerKBS, only high level evaluations of habitat quantity and habitat quality were considered. Habitat quantity was evaluated as lack, average, or abundant. Habitat quality was evaluated as poor, medium, or high. Overall habitat was evaluated as poor, medium, or excellent (Figure 4.3). For example,

Rule II:
IF habitat quantity is abundant, and
habitat quality is high or medium
THEN overall habitat is excellent

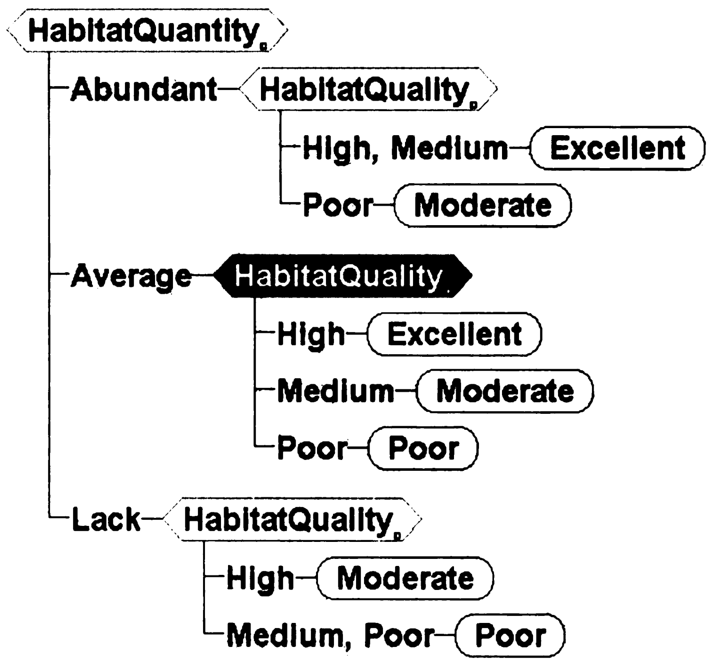


Figure 4.3. Subtask for habitat assessment, where HabitatQuantity represents habitat quantity, HabitatQuality represents habitat quality; Abundant, Average, and Lack are the outcomes of habitat quantity assessment; High, Medium, and Poor are the outcomes of habitat quality assessment; Poor, Moderate, and Excellent are the outcomes of habitat assessment.

4.6.3 Subtask for assessing Cultural Carrying Capacity

Cultural carrying capacity is the wildlife population level that is acceptable to people (Decker and Purdy 1988, Minnis 1996). Measuring public attitudes has been the subject of considerable interest by managers (Arthur and Wilson 1979). While objectives based on BCC are an ecological consideration made mainly by biologists, objectives based on CCC are a more popular decision guided by wildlife managers (Strickland et al. 1994). Usually, the population objectives imposed by CCC are well below those imposed by BCC. For example, on some farmlands in Wisconsin, CCC is about 12 deer/km^2, while BCC is about 40 deer/km^2 (McCafferery 1989). As expected, CCC is highly subject to how much weight the decision-makers put on each stockholder' preferences. In a region where deer hunters are well organized, they often exert greater influence than other groups do in the decision-making processes. On the other hand, in a region where farmers are well organized, they may have more impact than other groups in shaping the deer management decisions. In DeerKBS, deer hunters, farmers, and other interest groups (therefore other public) were considered to be the major stakeholders. The expected deer population size for each group was evaluated to have more, to have the same, or to have fewer deer. Once the assessment for each stakeholder was finished, the overall CCC was evaluated to have more, the same, or fewer deer compared with the previous years (Figure 4.4). For example,

Rule III:
IF deer hunters expect to have more, and
farmers expect to have fewer, and
other public expect to have fewer
THEN overall of CCC is to have the same number of deer

In this rule, more weight was put on the expectation of deer hunters and less weight on the expectation of farmers and the other public. In other words, not every stakeholder was given the same consideration. In this example,

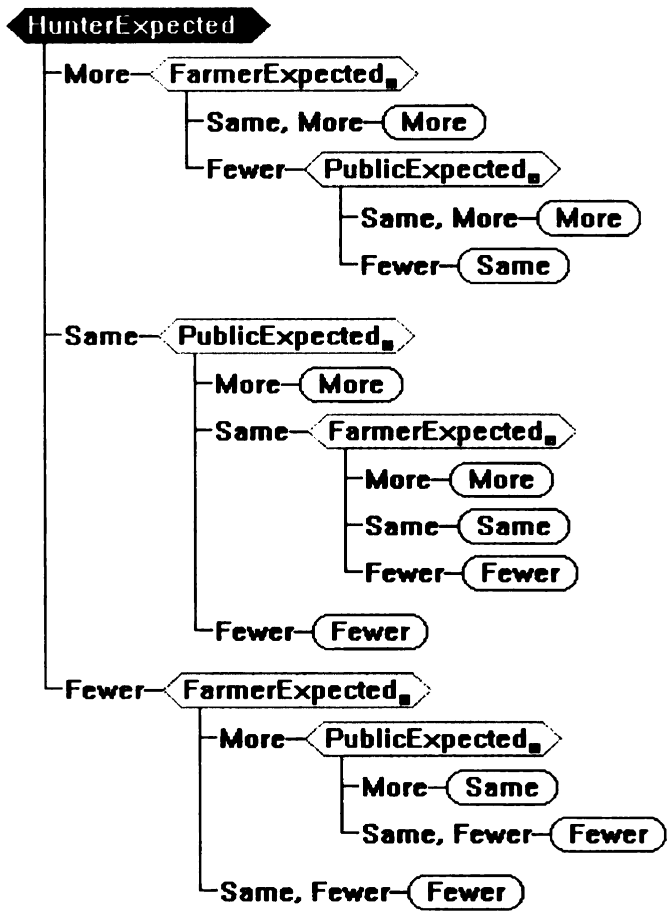


Figure 4.4. Subtask for CCC assessment, HunterExpected, FarmerExpected, and PublicExpected represents the expectation for deer numbers by hunters, farmers, and the other interest groups. Fewer, Same, and More are the outcomes of CCC assessments.

if equal weight was given to each stakeholder, the outcome should favor the groups who expected fewer deer because two groups expected fewer deer and only one group expected more deer. These rules could be easily changed to reflect the reality in the decision-making process specific to different management units and management objectives.

4.6.4 Subtask for assessing weather

There are many environmental variables that influence deer population dynamics by affecting their movement and food availability. Winter conditions are considered to be a critical factor that impacts deer natural mortality and productivity (Verme 1969). DeerMOM incorporates winter conditions into the model and can be used to project the population dynamics under different winter conditions measured by WSI (Chapter 2). Historically, WSI in the UP ranged from about 50 to 150 with an average of approximately 100. In DeerKBS, weather condition is evaluated as favorable if WSI is below 80, harsh if above 120, and average if between 80 and 120 (Figure 4.5).

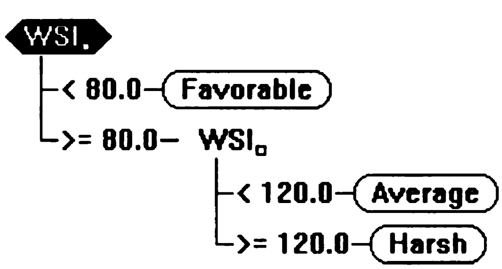


Figure 4.5. Subtask for winter weather assessment, Favorable, Average, and Harsh are the outcome of the assessment of winter conditions.

4.6.5 Decision tree and task for decision making

Putting all the information together, a decision tree was generated as partly shown in Figure 4.6. The tree structure offers the control strategy and the nodes allow for inferences. Each node, represented as a hexagon in Figure 4.6, determines which lower node will be searched. Each leaf, represented as ellipse in Figure 4.6, indicates a solution. For example, if population density (node PopulationDensity) is high, the search will evaluate habitat (node Habitat). If habitat is poor, then recommendation is made to harvest more deer (leaf More). If habitat is excellent, then CCC (node CulturalCarryingCapacity) is further considered, and harvest recommendations (leaf Same or More) are made based on the outcome of CCC evaluations.

An emerging feature in the decision tree is that not all decision outcomes follow the same path, as demonstrated in the aforementioned example and in Figure 4.6. This feature simulates some decision-making processes in wildlife management. For example, if population density is high and deer habitat is poor, wildlife managers may recommend harvesting more deer without considering CCC for the purpose of long-term deer sustainability.

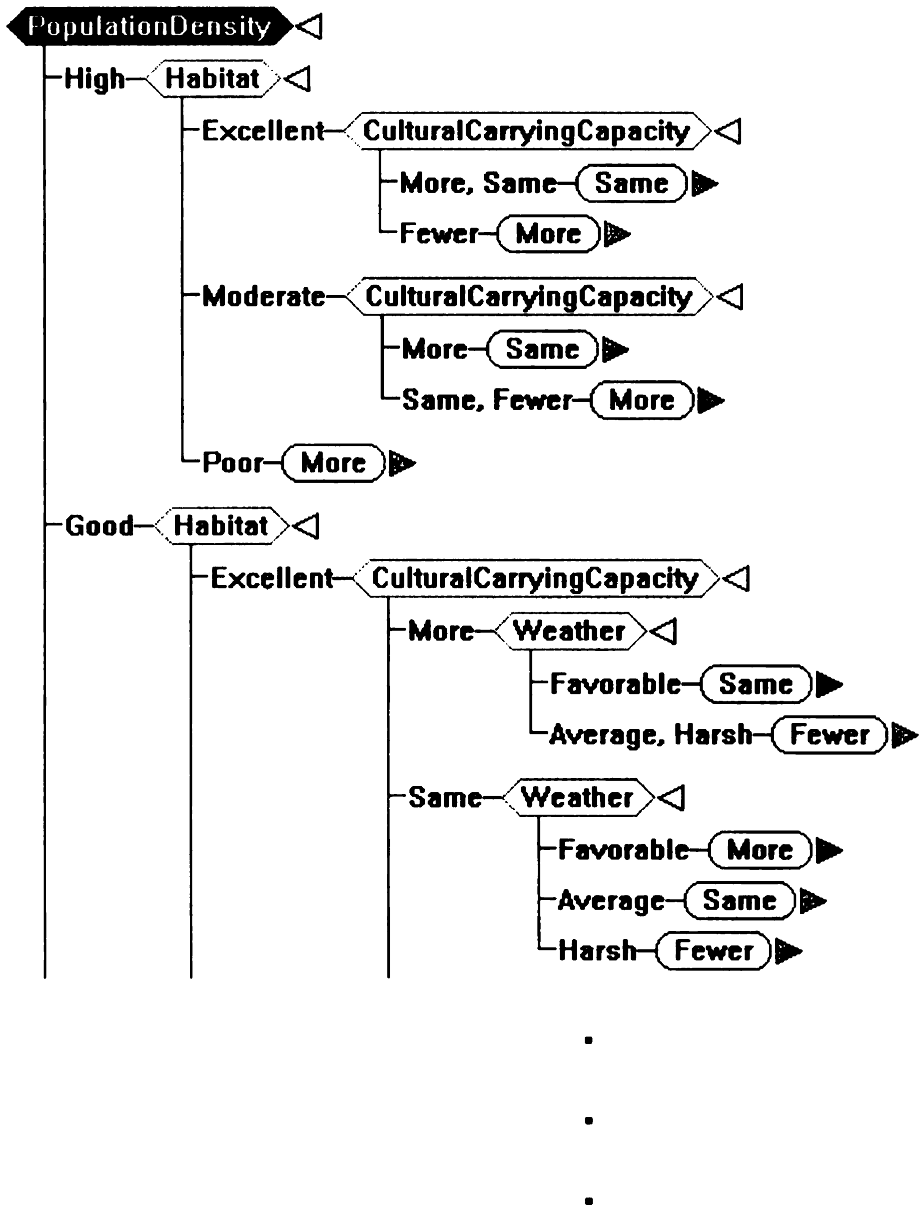


Figure 4.6. Part of a decision tree showing how a preliminary recommendation was made based on the outcomes of assessments of deer density, habitat conditions, cultural carrying capacity, and weather conditions. Note that hexagon represents node and ellipse represents leaf (outcome). Left-pointed triangles represent backward chaining, and right-pointed ones represent forward chaining.

4.6.6 Decision procedure

Once every attribute has been evaluated, each sub-task in a specific sub-domain has its evaluation outcome. Population density assessment can have an outcome of low, good, or high. Habitat assessment results in an overall outcome of poor, moderate, or excellent. CCC evaluation results in an outcome of more, fewer, or the same. Weather evaluation results in an outcome of favorable, average, or harsh. Now it is up to deer managers to make decisions based on their expertise and knowledge. As Ed Langenau (1991) stated, "Wildlife managers assess deer populations and public attitudes to establish deer herd objectives at a local level. Annual recommendations are made to have more, fewer, or the same number of deer within each DMU". Obviously, these recommendations are made in the context of previous years' deer management practices. All harvest quotas are compared with the previous years' quotas. Then they recommend the hunting licensee quotas for antlered bucks and antlerless deer at each DMU based on their experience in previous years and the management agency's policies and mission.

In DeerKBS, preliminary recommendations are made based on all the outcomes of assessments of population density, habitat conditions, CCC, and weather conditions (backward chaining process). DeerKBS then refines its management recommendations by considering the buck ratios in deer population (forward chaining process) (Figure 4. 7). For example,

Rule IV:
IF preliminary recommendation is to harvest more deer, and buck ratio is low
THEN recommend harvesting more antlerless but fewer bucks

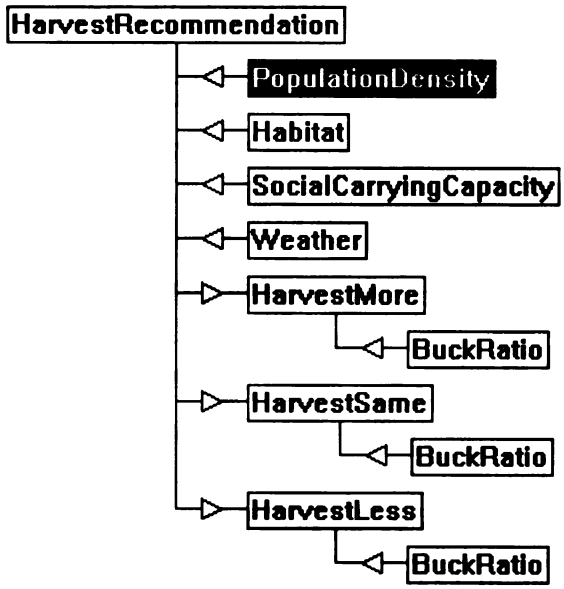


Figure 4.7. Diagram of a decision-making procedure. HarvestRecommendation represents the preliminary harvest recommendations that were made based on the assessments of population density, habitat, CCC, and weather. The recommendations were further refined by considering antlered buck percentage in deer population. Note that left-pointed triangles represent backward chaining, and right-pointed ones represent forward chaining.

4.7 Operation and Delivery of DeerKBS

DeerKBS works under Microsoft Windows® environment using XpertRule. Background data, information and images were incorporated into the user interface (Figure 4.8). Explanation mechanism, which is built in the XpertRule KBS, keeps track of the decision process. The user can use this feature to understand how DeerKBS works. DeerKBS can be modified through example tables or decision trees. System inputs include attributes of deer population size, size of interest area, evaluation results for habitat quantity and quality, evaluation

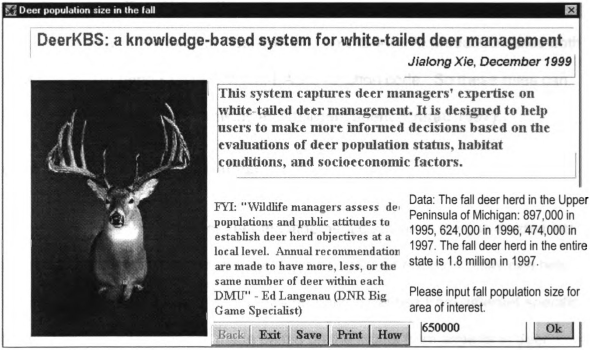


Figure 4.8. Graphic user interface of DeerKBS showing that background information and images are incorporated into the user interface. Explanation is provided by clicking the "How" button.

results of expected deer population size for deer hunters, farmers, and other interest groups, percentage of antlered buck, and WSI. Through dialogs, users input numbers for numerical attributes or select a choice from a list of values for logical attributes. System output is a set of harvest recommendations based on the assessment of all the attributes. The output can be printed out or saved into a file. A demonstration of the operation is included in Appendix B.

The system can be delivered to end users as a binary file with or without password protected. End users can use XpertRun - the XpertRule KBS run time program from Attar Software Limited - to run DeerKBS. The end users can use DeerKBS but cannot change the system's structure or knowledge base without a fully copyrighted XpertRule KBS system.

The knowledge base in DeerKBS can be exported to production rules both as a text file (Appendix C) or a Visual BASIC function code. So these rules can be embedded in other programs as an intelligent agent (Prerau 1997).

4.8 Conclusions and Discussions

In DeerKBS, the task of deer management decision making is divided into an array of decision-making subtasks. These structured decision tasks can help decision-makers better utilize the knowledge and expertise from different specific fields. The final decisions are made based on the inputs from experts in deer population, habitat, and human dimensions. Thus the decisions are more informative, democratic (Schmoldt and Rauscher 1996), reliable, and effective than a decision made by a single specialist.

The "top down" technique used in building DeerKBS offers the flexibility to include more information once it is available. For some sub-tasks such as habitat assessment, only the highest level attributes are included because the data for lower levels are not available. If there is more detailed information available, another level of details can be easily incorporated into the system. For example, if I have sampled a specific area and can estimate the biomass for each species of food, I can calculate the total amounts of biomass of food and convert the amounts to a relative assessment of habitat quantity. I can also estimate how much of the biomass is preferred food for deer and then evaluate the habitat quality. If HSI is available for a specific area, a decision tree can be added to convert the numerical HSI to qualitative assessment of habitat. Landscape metrics such as edge density in the landscape analysis as demonstrated in Chapter 3 can also be converted to qualitative assessment of habitat. This feature is important in deer management because wildlife managers have to make decisions even without complete data and scientific consensus. Very often, they resort to their judgment, intuition, and experience to make decisions (Starfield and Bleloch 1986).

Communication between policy makers and stakeholders is important to achieve management objectives effectively (Kellert 1994). However, deer managers lack an instrument to effectively communicate with other stakeholders. DeerMOM can be used to demonstrate how management options and winter weather conditions influence population size and structure (Chapter 2). But very often, stakeholders want to be involved in the decision-making process.

DeerKBS provides a framework of the decision-making process for deer management. Major ecological and socioeconomic factors are considered in this system. The user can easily identify the management issues related to deer harvest, habitat management, and different interest groups. As DeerKBS provides a platform (common vocabulary) for all stakeholders, it can be an effective communication tool for deer managers to present their decision-making processes to other stakeholders and improve their accountability. With this tool, deer managers can also exchange their decision-making processes with their peers so that wildlife management can enhance collaboration among managers, scientists, and interested stakeholders (Franklin 1994).

DeerKBS can be used for other purposes. For educators, it can be an educational tool to help students understand the complexity of wildlife management and the decision-making processes of wildlife management. For wildlife management agencies, DeerKBS can be an effective tool to standardize the management decision procedures. When this system was demonstrated to the wildlife biologists and managers at the Wildlife Division of the MDNR, it was considered as a pioneer study to standardize the diverse management decision processes happening in field offices of the MDNR (Dale Rabe, MDNR, personal communication).

Though DeerKBS has the potential in many aspects of deer management, there are some limitations. First, the knowledge base in DeerKBS is based on interviews with deer managers, literature, and some educated guesses. The validity of its knowledge base is not fully tested. This is mainly due to the difficulty of knowledge engineering. The process of transferring the expert knowledge into a knowledge base is still the bottleneck for developing a KBS. Since the 1980s, research efforts have been targeted to tackling this problem. Based on knowledge-level hypothesis (Newell 1982, Sticklen 1989), some new approaches such as heuristic classification, generic task (Chandrasekaran 1993), and role limiting methods (McDermott 1988) are proposed to bridge the gap between expert knowledge and representation constructs. Founded on these hypotheses and approaches, system shells such as CSRL (Bylander and Mittal 1985) and KADS (Breuker and Wielinga 1989) are developed. These tools may have broad applications, but they are still more research-oriented and not commercially available.

In this system, XpertRule KBS shell is used because it is an application-oriented tool for KBS application development and maintenance (Attar Software Limited 1996). XpertRule is a useful tool for rapid application design and prototype. Its graphic user interface and decision tree are easy to learn and use and helpful to communicate with wildlife managers. However, no matter how technologies are advanced, the difficulty of eliciting the expertise and knowledge from experts is not yet overcome. In DeerKBS, interviews and written documents are two major knowledge sources. Although there are many interview techniques (Guida and Tasso 1994) to stimulate the expression of knowledge and expertise, most of these techniques are time-consuming and not efficient and require rich personal experience. So DeerKBS relies much on written documents and my educated guesses. The problem with this technique is that the knowledge elicited must be verified by some appropriate ways (Guida and Tasso 1994), preferably by deer managers. However, many wildlife managers are often reluctant to share their decision-making processes. Like other KBS applications, validity of recommendations from DeerKBS is dependent on the validity of the decision rules in the knowledge base. The decision rules are difficult to validate, as the rules are not universal. Each manager has his or her own "rules of thumb" in practice, making cross-examination more difficult.

In DeerKBS, eight attributes are considered in the process of decision-making. If each attribute has 5 discrete values, there are 390625 (5^8) combinations. To avoid this kind of combinatorial exploration, 2 methods are used in DeerKBS. First, the main task is structured into 4 subtasks. Second, for logic attributes, only three discrete values (e.g., low, good, or high for population density) are used. So the total combinations are reduced to 81 (3^4). To further reduce the possible outcomes (or number of rules), some attributes are ignored on purpose, as demonstrated in the example presented in section 4.6.5. and in Figure 4.6.

The rules in the knowledge base need to be modified to reflect the management reality in a specified area and under a specified time frame. For example, winters in southern Michigan are much warmer than in the UP, so the evaluation criteria for winter conditions should be changed. Moreover, DeerKBS has no capacity to learn, so it is not so intelligent (Schank 1987) and cannot replace deer managers. Nevertheless, DeerKBS can be an assistant or educational tool to deer managers because it integrates all relevant information into the decision-making process and provides a unifying decision-making framework for deer management.

Chapter 5

SUMMARY

Effective management of white-tailed deer should integrate wildlife science, modern technology, and wildlife managers' expertise into the management decision processes. This research combined deer population modeling, landscape structure analyses, and socioeconomic considerations into the decision support system for deer management in the Upper Peninsula (UP) of Michigan.

DeerMOM is a computer simulation model designed to assess the effects of management options on population size, sex and age structure of white-tailed deer. In this model, deer were grouped into three age classes: fawn, yearling, and adult. Reproductive rates and fetal sex ratios were age-specific, while natural and harvest mortality rates were both age- and sex-specific. DeerMOM was parameterized to represent the deer population in the Upper Peninsula (UP) of Michigan. Effects of winter severity were incorporated into the model. Population estimates derived from annual pellet group surveys were used to validate the model. Different management options were evaluated using two criteria: a quantity goal (number of deer) and a quality goal (percentage of antlered bucks in the deer population).

Simulation results from DeerMOM indicated that current management practices (with a high rate of buck harvest) resulted in high deer numbers with a low percentage of antlered bucks. Under the condition of high buck harvest rate, increasing doe harvest did not achieve both the quantity and the quality goals simultaneously. Moderate harvest of both sexes would control population growth and increase the percentage of antlered bucks. The simulations also showed that winter weather conditions and doe harvest shaped deer population trends but buck harvest determined the percentage of antlered bucks. Although increasing doe harvest was an effective method to control deer population, its effect on buck ratio was limited. On the contrary, lowering buck harvest would increase buck ratio and would have minimal impact on population size. These findings indicate that quality deer management objectives could be reached only by lowering buck harvest rates while simultaneously increasing the doe harvest. The best option for achieving both the quantity and the quality goals was moderate harvest of bucks and does without sex bias.

Deer population size and deer spatial distribution across landscapes are determined not only by harvest, but also by landscape attributes. To evaluate how deer spatial pattern is associated with landscape attributes, the spatial structure of landscapes in the UP was quantified. Each of the 15 counties in the UP was treated as a landscape. Using 1991 Landsat Thematic Mapper imagery, the landscape was classified into 30-, 21-, 8-, and 4-classes of patches and its landscape metrics was calculated. Deer harvest, deer-vehicle accidents, and reported kills were used to measure deer density, and related to landscape metrics in each landscape.

Deer spatial distribution showed significant positive relationships with patch density, edge density, and landscape shape index, but had a significant negative relationship with total core area index. There were no significant positive relationships with patch diversity indices, contagion, or interspersion indices. These findings suggest that spatial heterogeneity plays an important role in the spatial distribution of white-tailed deer at landscape scales. Although it is well known that deer prefer edges at local scales, this study shows that edges are also important to deer distribution at landscape scales, indicating deer habitat-selection may be scale-independent. To increase deer population size, one should consider deer habitat characteristics and aim at increasing patch density and edge density. On the contrary, to control crop damage and deer-vehicle accidents, a reverse approach may be used to decrease spatial heterogeneity.

Recognizing that wildlife managers are facing many challenges (e.g., more stakeholders involvement) and decisions must be made with conflicting goals and without complete data, I designed a knowledge-based system for white-tailed deer management (DeerKBS) to help the user make informed decisions. This system was an attempt to capture and retain wildlife manager expertise and knowledge, and to standardize decision-making procedures for management. A "top down" technique was used to divide the main task of deer management into 3 major sub-tasks: population status evaluation, habitat condition evaluation, and social carrying capacity evaluation. Each sub-task was represented by a decision tree, which related a decision with relevant attributes. Each sub-task was developed and tested separately.

The development of DeerKBS indicated that structured decision tasks could help deer managers better organize their knowledge and expertise. The “top-down” technique offers the flexibility to include more information once it is available. DeerKBS can be an effective communication tool for presenting the decision-making process to various stakeholders. It can also be used as an educational tool to help students understand the complexity of management decision-making process. However, like any other KBSs, the validity of recommendations is dependent on the decision rules in the knowledge base.

APPENDIX A

DeerMOM USER'S GUIDE

This guide is developed using HTML. Included here is the main page that has links to the detailed information for model background and model components.

DeerMOM User's Guide (Main page)

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1. Introduction

DeerMOM is a computer simulation model designed to assess the effects of management options on population size, sex and age structure of white-tailed deer (*Odocoileus virginianus*). In this model, I grouped deer into three age classes: fawn, yearling, and adult. Reproductive rates and fetal sex ratios were age-specific, while natural and harvest mortality rates were both age- and sex-specific. DeerMOM was parameterized to represent the deer population in the Upper Peninsula of Michigan. Effects of winter severity were incorporated into the model. Population estimates derived from annual pellet group surveys were used to validate the model in the Upper Peninsula. The model was developed in Stella ® for Windows.

2. Model Design

I followed 3 principles to design the model: simplicity, accuracy, and management orientation:

- ***Simplicity:*** I grouped deer into 3 age classes: fawn (<12 months), yearling (13-24 months), and adult (24 months or older) to simplify the model structure. I divided mortality into harvest mortality and natural mortality (e.g., vehicle accidents, starvation, predation). I used annual mortality instead of seasonal mortality to simplify data collection and model application.
- ***Accuracy:*** I simulated the dynamics of males and females separately. I used age- and sex-specific natural mortality and harvest mortality. In addition, I differentiated their reproductive rates and fetal sex ratios by age class for female deer.
- ***Management orientation:*** Management goals could be used as criteria to evaluate harvest strategies under defined time frames. A user could also change the model structure by adding or removing some components, or by modifying parameter values.

3. Model Structure

Model hierarchical structure

Stella is a multi-level, hierarchical environment for constructing models (High Performance Systems, 1997) which allows DeerMOM to have a 3-level hierarchical structure. ***The first level is a user interface***, where novice users can change parameter values by using sliders. Moreover, the user can also inspect simulation results using tables and graphs as well as export them to other programs through dynamic data exchange. ***In the second level, a more advanced user can access the model structure*** in order to modify the structure and manipulate parameter values. Finally, an expert user can access the ***third level to review the mathematical equations*** and to learn the model mechanisms in detail.

Model components

DeerMOM consists of 5 interconnected sectors: Female, Male, Birth/Death, Harvest, and Population. DeerMOM operates on an annual cycle that starts on October 1 and ends on September 30 of the following year.

- **Female Sector:** Females are grouped into 3 age classes: fawn, yearling, and adult as previously mentioned. For each annual cycle, surviving newborn females enter the female fawn group, and similarly surviving fawns recruit to the female yearling group, surviving yearlings to the female adult group. Adult females that survive the hunting season and natural mortality remain in the adult age class. Natural mortality for each age class is density- and harvest-dependent and influenced by winter severity.
- **Male Sector:** The male sector had the same model structure as the female sector, but parameter values were quantified differently.

- **Birth/Death Sector:** Changes in the deer population size and structure depend on the dynamics of both births and deaths. I assumed that immigration and emigration would not affect age and sex structure of the population. Thus, any addition to the population comes from the offspring of female fawns, yearlings, and adults. To estimate newborn females and males, I used female number in spring, reproductive rate, and sex ratio for each age class. The spring female number in each age class was estimated by subtracting harvest and natural mortality from the previous fall female number in each age class. Deaths were a result of harvest mortality and natural mortality. Mortality rates were age- and sex-specific.
- **Harvest Sector:** I included all harvest-related information in this sector. Specifically the sector contained age and sex composition of harvest, total harvest, percentage of antlered bucks and antlerless deer in the harvest.
- **Population Sector:** I included population initialization, management goals, and all data related to age and sex distribution of deer in this sector. The population was initialized by size, sex ratio, and percentage of deer number in each age class. This sector also extended the female and male sectors by deriving population statistics of interest.

4. Quantification of the Model

The most important parameters for DeerMOM included age-specific reproductive rates, fetal sex ratios, neonatal mortality, age- and sex-specific natural mortality, and harvest mortality.

- **Reproductive rates:** defined as average fetuses per female. To see how I quantified the reproductive rates in the UP, please follow this link.
- **Fetal sex ratio:** defined as the percentage of males in each age class. Fetal sex ratio was the percentage of newborn males in offspring. To see Verme's (1983) data, follow this link.
- **Mortality:** Causes of mortality were classified as harvest mortality and natural mortality. To see how I quantified the mortality rates in the UP, follow this link.
- **Neonatal mortality:** Winter weather has a significant impact on fetal development during late gestation and thus influences natal survival (Verme, 1977). Because of this impact, I partitioned neonatal mortality into 2 parts: base neonatal mortality and neonatal mortality due to winter severity. Base neonatal mortality was the mortality when winter weather was very mild (low WSI). To see how I quantified the neonatal mortality rates in the UP, follow this link.

5. Model Initialization

The model should be initialized by population size and age- and sex-distribution. To see how I initialized the population in the UP, follow this link.

6. System Requirements

Operating system: Microsoft Windows® 95/98

Stella ® Research Version 5 for Microsoft Windows®

7. Get Started Quickly

To open Stella: Click Start-- Programs-- Stella5 (or Stella 5.11)-- Stella. The program should be in Model mode.

To open file: From the menu, click File-- Close Model. Then click File-- Open, choose the Drive, Folder, and then the File name. Wait for loading the file DeerMOM.stm.

To change parameter values: Click Control Panel button, then click on Initialization or Mortality button to change parameter values for initial popuation and harvest .

To run the model: From the menu, click Run-- Time Specs to change your time setting. Make sure that time step is set at one year. Then click Run-- Run.

To check the results: Click "Simulation Results" button to see the model simulation results in figures, tables, or numerical displays.

8. More Information about the Model

APPENDIX B

DEERKBS INTERFACE

The following figures are the screenshots of DeerKBS.

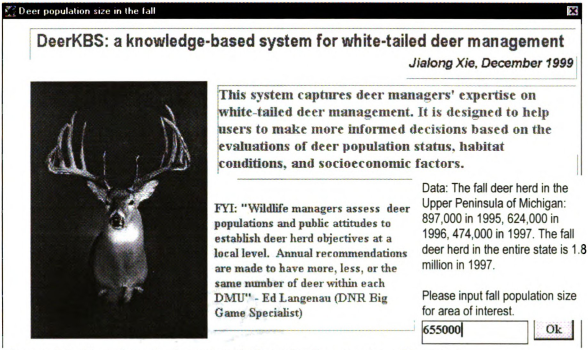

Figure B1: User inputs deer population size in an area of interest.

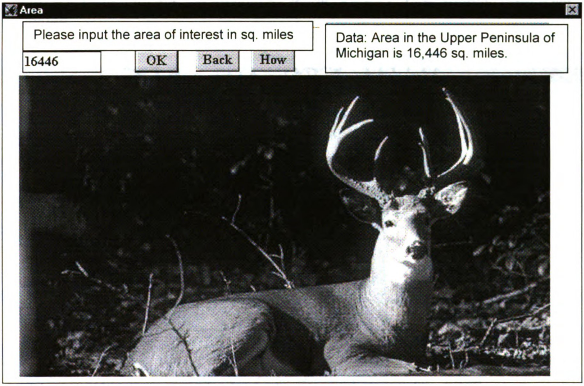

Figure B2: User inputs the area of interest in square miles.

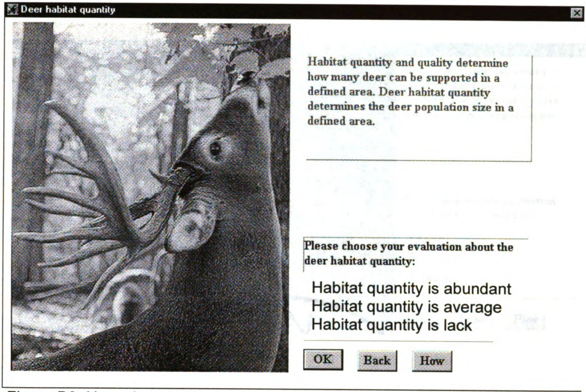

Figure B3: User chooses the evaluation result of deer habitat quantity from a list of values.

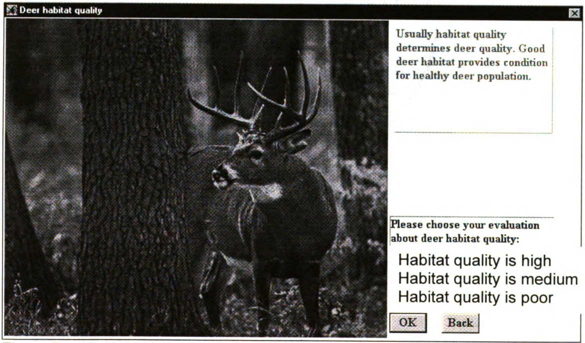

Figure B4: User chooses the evaluation result of habitat quality from a list of values.

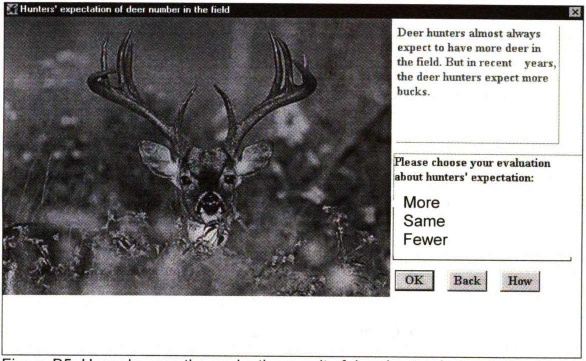

Figure B5: User chooses the evaluation result of deer hunters' expectation from a list of values.

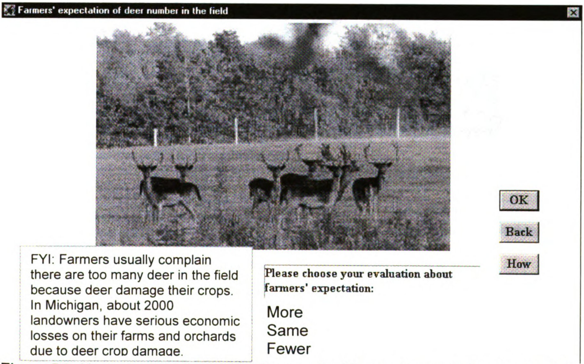

Figure B6: User chooses the evaluation result of farmers' expectation from a list of values.

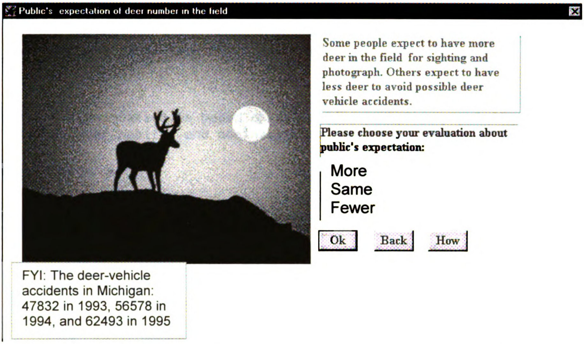

Figure B7: User chooses the evaluation result of other general public's expectation from a list of values.

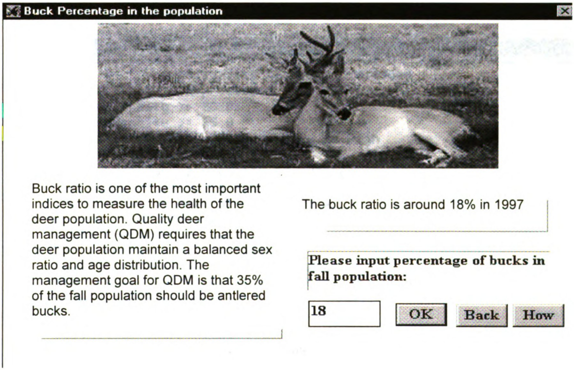

Figure B8: User inputs the percentage of antlered bucks in the fall population.

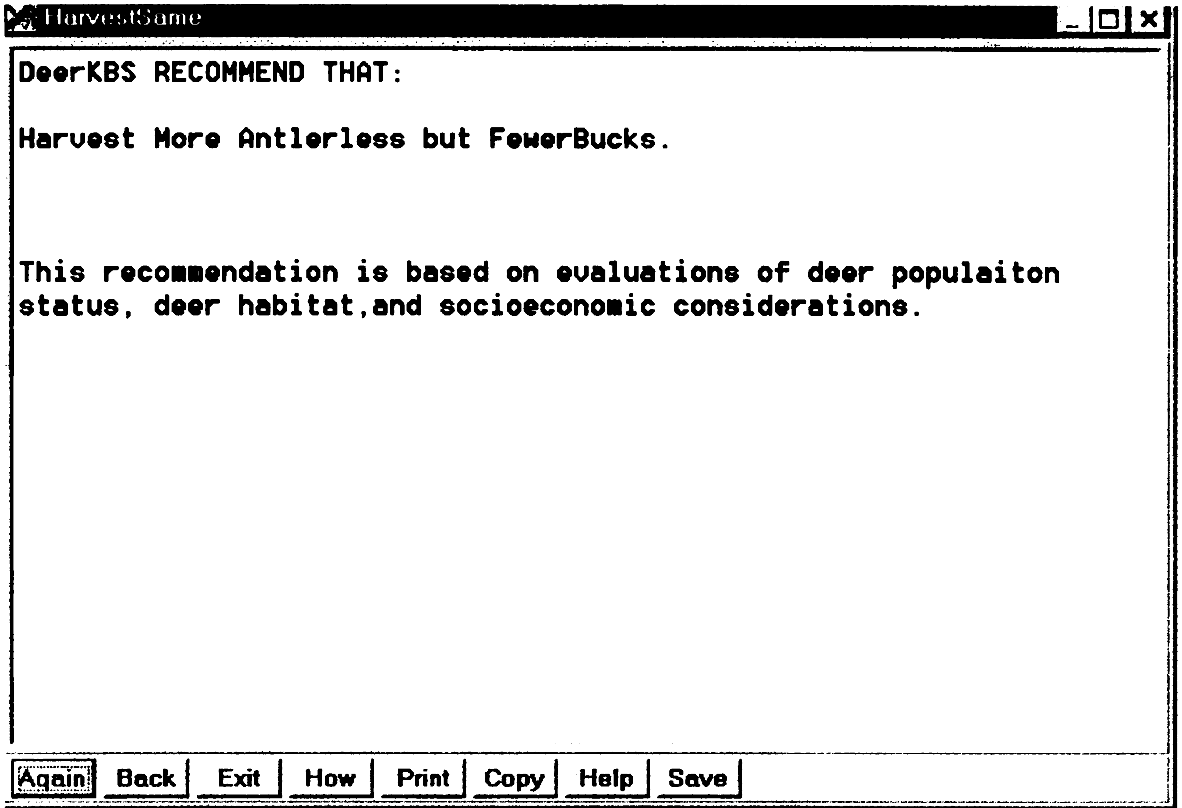

Figure B9: DeerKBS makes harvest recommendations.

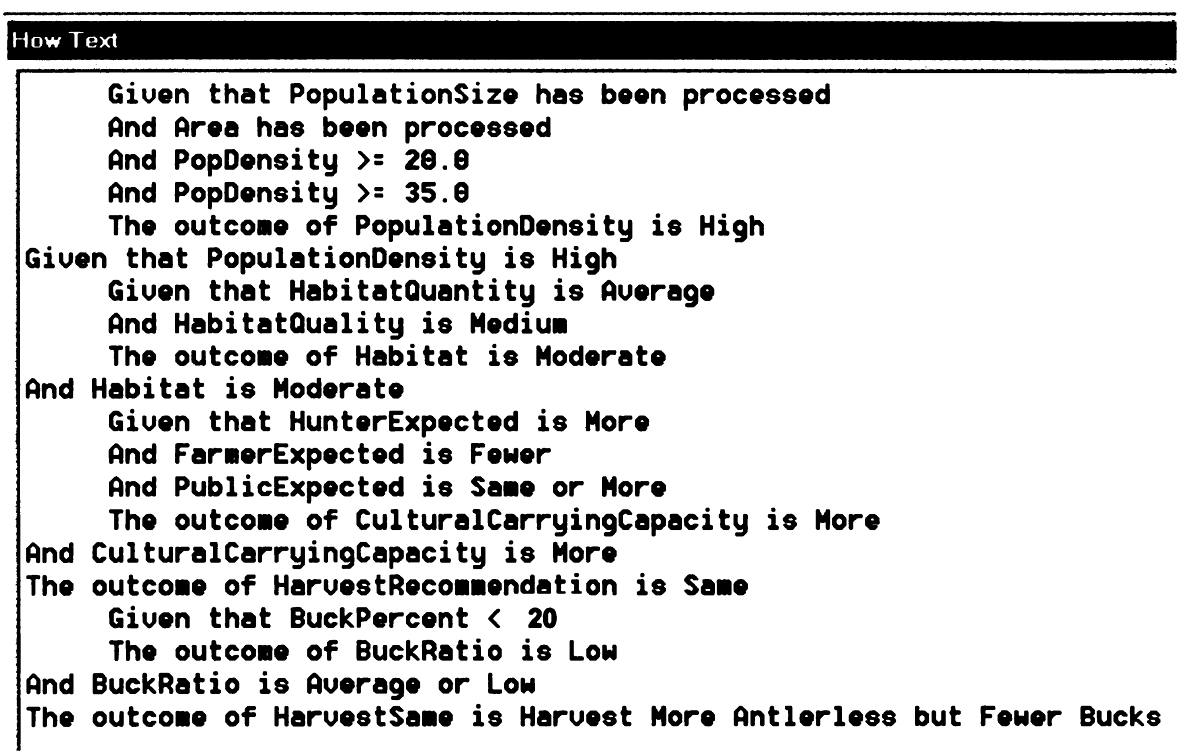

Figure B10: DeerKBS provides explanations by tracking the decision process.

APPENDIX C

DECISION RULES IN DeerKBS

Population Density:

If population density < 20.00
Then Population Density is Low

If population density >= 20.00
And population density < 35.00
Then population density is Good

If population density >= 35.00
Then population density is High

Buck Ratio:

If buck ratio < 20.0
Then buck ratio is Low

If buck ratio >= 20.0
And buck ratio < 35.0
Then buck ratio is Average

If buck ratio >= 35.0
Then buck ratio is High

Habitat:

If habitat quantity is Abundant
And habitat quality is High or Medium
Then habitat is Excellent

If habitat quantity is Abundant
And habitat quality is Poor
Then habitat is Moderate

If habitat quantity is Average
And habitat quality is High
Then habitat is Excellent

If habitat quantity is Average
And habitat quality is Medium
Then habitat is Moderate

If habitat quantity is Average
And habitat quality is Poor
Then habitat is Poor

If habitat quantity is Lack
And habitat quality is High
Then habitat is Moderate

If habitat quantity is Lack
And habitat quality is Medium or Poor
Then habitat is Poor

Cultural Carrying Capacity:

If hunters' expectation is More
And farmers' expectation is More or Same
Then cultural carrying capacity is More

If hunters' expectation is More
And farmers' expectation is Fewer
And other interest groups' expectation is More or Same
Then cultural carrying capacity is More

If hunters' expectation is More
And farmers' expectation is Fewer
And other interest groups' expectation is Fewer
Then cultural carrying capacity is Same

If hunters' expectation is Same
And other interest groups' expectation is More
Then cultural carrying capacity is More

If hunters' expectation is Same
And other interest groups' expectation is Same
And farmers' expectation is More
Then cultural carrying capacity is More

If hunters' expectation is Same
And other interest groups' expectation is Same
And farmers' expectation is Same
Then cultural carrying capacity is Same

If hunters' expectation is Same
And other interest groups' expectation is Same
And farmers' expectation is Fewer
Then cultural carrying capacity is Fewer

If hunters' expectation is Same
And other interest groups' expectation is Fewer
Then cultural carrying capacity is Fewer

If hunters' expectation is Fewer
And farmers' expectation is More
And other interest groups' expectation is More
Then cultural carrying capacity is Same

If hunters' expectation is Fewer
And farmers' expectation is More
And other interest groups' expectation is Same or Fewer
Then cultural carrying capacity is Fewer

If hunters' expectation is Fewer
And farmers' expectation is Same or Fewer
Then cultural carrying capacity is Fewer

Weather Conditions:

If WSI < 80.0
Then Weather is Favorable

If WSI >= 80.0
And WSI < 120.0
Then Weather is Average

If WSI >= 120.0
Then Weather is Harsh

Preliminary Harvest Recommendations:

If Population density is High
And habitat is Excellent
And cultural carrying capacity is More or Same
Then Preliminary harvest recommendation is Same

If Population density is High
And habitat is Excellent

And cultural carrying capacity is Fewer
Then Preliminary harvest recommendation is More

If Population density is High
And habitat is Moderate
And cultural carrying capacity is More
Then Preliminary harvest recommendation is Same

If Population density is High
And habitat is Moderate
And cultural carrying capacity is Same or Fewer
Then Preliminary harvest recommendation is More

If Population density is High
And habitat is Poor
Then Preliminary harvest recommendation is More

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is More
And Weather is Favorable
Then Preliminary harvest recommendation is Same

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is More
And Weather is Average or Harsh
Then Preliminary harvest recommendation is Fewer

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is Same
And Weather is Favorable
Then Preliminary harvest recommendation is More

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is Same
And Weather is Average
Then Preliminary harvest recommendation is Same

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is Same
And Weather is Harsh
Then Preliminary harvest recommendation is Fewer

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is Fewer
And Weather is Favorable or Average
Then Preliminary harvest recommendation is More

If Population density is Good
And habitat is Excellent
And cultural carrying capacity is Fewer
And Weather is Harsh
Then Preliminary harvest recommendation is Same

If Population density is Good
And habitat is Moderate
And cultural carrying capacity is More or Same or Fewer
And Weather is Favorable or Average
Then Preliminary harvest recommendation is More

If Population density is Good
And habitat is Moderate
And cultural carrying capacity is More or Same or Fewer
And Weather is Harsh
Then Preliminary harvest recommendation is Same

If Population density is Good
And habitat is Poor
And cultural carrying capacity is More or Fewer
And Weather is Favorable or Average
Then Preliminary harvest recommendation is More

If Population density is Good
And habitat is Poor
And cultural carrying capacity is More or Fewer
And Weather is Harsh
Then Preliminary harvest recommendation is Same

If Population density is Good
And habitat is Poor
And cultural carrying capacity is Same
And Weather is Favorable
Then Preliminary harvest recommendation is More

If Population density is Good
And habitat is Poor
And cultural carrying capacity is Same

And Weather is Average or Harsh
Then Preliminary harvest recommendation is Same

If Population density is Low
And habitat is Excellent or Moderate
Then Preliminary harvest recommendation is Fewer

If Population density is Low
And habitat is Poor
Then Preliminary harvest recommendation is Same

Further Harvest Recommendations:

If buck ratio is High
And harvest recommendation is More
Then further recommendation is Harvest More Antlerless and More Bucks.

If buck ratio is Average
And harvest recommendation is More
Then further recommendation is Harvest More Antlerless and Same Bucks.

If buck ratio is Low
And harvest recommendation is More
Then further recommendation is Harvest More Antlerless but Fewer Bucks.

If buck ratio is High
And harvest recommendation is Same
Then further recommendation is Harvest Same Antlerless and Bucks.

If buck ratio is Average or Low
And harvest recommendation is Same
Then further recommendation is Harvest More Antlerless but Fewer Bucks.

If buck ratio is High or Average
And harvest recommendation is Less
Then further recommendation is Harvest Fewer Antlerless but Same Bucks

If buck ratio is Low
And harvest recommendation is Less
Then further recommendation is Harvest Fewer Antlerless and Bucks.

REFERENCES

REFERENCES

Albert, D. A., S. R. Denton, and B. V. Barnes.1986. Regional landscape ecosystem of Michigan. School of Natural Resources, University of Michigan. Ann Arbor, MI. 32pp.

Allen, R. E. and D. R. McCullough. 1976. Deer-car accidents in southern Michigan. Journal of Wildlife Management 40:317-325.

Alverson, W. S., D. M. Waller, and S. L. Solheim. 1988. Forests too deer:edge effects in northern Wisconsin. Conservation Biology 2:248-258.

Andrén, H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat:a review. Oikos 71:355-366.

Arthur, L.M. and W. R. Wilson. 1979. Assessing the demand for wildlife resources:a first step. Wildlife Society Bulletin 7(1):30-34.

Attar Software Limited. 1996. XpertRule User Guide. Lancashire, United Kingdom.

Awad, E. M. 1996. Building expert systems. West Publishing Co.

Banker, M. E. 1994. Modeling white-tailed deer habitat quality and vegetation response to succession and management. M.S. Thesis. Virginia Tech University. Blacksburg, Virginia. 147pp.

Bartholow, J. 1986. POP-II system documentation. Fossil Creek Software, Ft. Collins, CO.

Bashore, T. L., W. M. Tzilkowski, and E. D. Bellis.1986. Analysis of deer-vehicle collision sites in Pennsylvania. Journal of Wildlife Management 49:769-774.

Bayne, E. M., and K. A. Hobson. 1998. The effects of habitat fragmentation by forestry and agriculture on the abundance of small mammals in the southern boreal mixedwood forest. Canadian Journal of Zoology 76:62-69.

Bender L. C. and J. B. Haufler.1990. A white-tailed deer HSI for the upper Great Lakes Region. Unpublished report. Department of Fisheries and Wildlife, Michigan State University. East Lansing, MI.

Bender, L. C. and G. J. Roloff, 1996. Modeling deer harvest alternatives in Indiana. Transactions of the Illinois State Academy of Science 89:63-71.

Boehm, B. W. 1976. Software engineering. IEEE Transactions on Computers C-25 (12):1226-1241.

_____. 1988. A spiral model of software development and enhancement. Computer 21(5):61-72.

Braun, K. F.1996. Ecological factors influencing white-tailed deer damage to agricultural crops in northern Lower Michigan. M.S.Thesis. Michigan State University. East Lansing, MI.

Bremdal, B. A. 1997. Expert system for management of natural resources. Pages 30:1-47. *in* J. Liebowitz, ed. The Handbook of Applied Expert Systems. CRC Press LLC.

Breuker, J. and B. Wielinga. 1989. Models of expertise in knowledge acquisition. Pages 265-295 *in* G. Guida and C. Tasso, eds. Topics in expert systems design: methodologies and tools. North Holland Publishing Company, Amsterdam.

Brown, S., H. Schreier, W. A. Thompson, and I. Vertinksy. 1994. Linking multiple accounts with GIS as decision support system to resolve forestry/wildlife conflicts. Journal of Environmental Management 42:349-364.

Buchnanm, B. G., D. Barstow, R. Bechtal, J. Bennett, W. Clancy, C. Kulikowski, T. Mitchell, and D. A. Waterman. 1983. Constructing an expert system. Pages 127-167. *in* F. Hayses -Roth, D. A. Waterman, and D. B. Lenat, eds. Building expert system. Addison-Wesley Publishers. Reading, MA.

Burgoyne, G. Jr, 1981. Observations on a heavily exploited deer population. Pages 403-413 *in* C. W. Fowler. ed.. Dynamics of Large Mammal Populations. John Wiley & Sons. Inc.

Burke, R. L. and J. M. Birch, 1995. White-tailed deer vary offspring sex-ratio according to maternal condition and age. Ecological Research 10:351-357.

Bylander, T. and S. Mittal. 1985. CSRL:a language for classificatory problem solving and uncertainty handling. AI Magazine 7(3):66-77.

Bylander, T., T. R. Johnson, and A. Goel. 1991. Structured matchingL a task-specific technique for making decisions. Knowledge Acquisition 3:1-20

Campa, H. III. 1989. Effects of deer and elk browsing on aspen regeneration and nutritional qualities in Michigan. Ph.D. Dissertation. Michigan State University. East Lansing, MI.

Caughley G .1981. Overpopulation. Pages 7-20 *in* P. A. Jewell, and S. Holt. eds. Problems in management of locally abundant wild mammals. Academic Press, NY.

Chandrasekaran, B. and T. R. Johnson. 1993. Generic tasks and task structure:history, critique, and new directions. Pages 232-272 *in* J. M. David, J. P. Krivien, and R. Simmons, eds. Second generation expert system. Springer-Verag. Berlin.

Chang, K., D. L. Verbyla, and J. J. Yeo. 1995. Spatial analysis of habitat selection by Sitka black-tailed deer in southeast Alaska, USA. Environmental Management 19(4):579-589.

Christensen N. L., A. M. Bartuska, J. H. Brown, S. Carpenter, C. DAntonio, R. Francis, J. F. Franklin, J. A. MacMahon, R. F. Noss, D. J. Parsons, C. H. Peterson, and M. G. Turner. 1996. The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. Ecological Applications 6(3):665-691.

Clancy, W. J. 1983. The epistemology of a rule-based expert system - a framework for explanation. Artificial Intelligence 20:215-251.

Cody R. P. and J. K. Smith.1997. Applied statistics and the SAS programming language. 4th edition. Prentice-Hall, Inc. Upper Saddle River, NJ.

Compton B. B., R. J. Mackie, and G. L. Dusek. 1988. Factors influencing distribution of white-tailed deer in riparian habitats. Journal of Wildlife Management 52:544-548.

Conover, M. R. and D. J. Decker. 1991. Wildlife damage to crops:perceptions of agricultural and wildlife professionals in 1957 and 1987. Wildlife Society Bulletin 19:46-52.

Conover M. R., W. C. Pitt, K. K. Kessler, T. J. DuBow, and W. A. Sanborn .1995. Review of human injuries, illness, and economic loses caused by wildlife in the United States. Wildlife Society Bulletin 23:407-414.

Cooperrider, A. Y. 1974. Computer simulation of the interaction of a deer population with northern forest vegetation. Ph. D. Dissertation. 229p. State University of New York.

Coulson, R. N., L. J. Folse, and D. K. Loh. 1987. Artificial intelligence and natural resource management. Science 237:262-267.

Coulson, R. N., C. N. Lovelady, R. O. Flamm, S. L. Spradling, and M. C. Saunders. 1991. Intelligent geographic information systems for natural resource management. Pages 153-172 in Ecological Studies 82:Mathematical methods in landscape ecology.

Covington, W. W., D. B. Wood, D. L. Young, D. P. Dykstra, and L. D. Garrett. 1988. TEAMS:A decision support system for multiresource management. Journal of Forestry 86(8):25-33.

Crawford, H. S. 1984. Habitat management. Pages 629-646 *in* L. K. Halls. ed. White-tailed deer:ecology and management. Stackpole Books, Harrisburg, PA

Crawford, H. S., and R. L. Marchinton. 1989. A habitat suitability index for white-tailed deer in the Piedmont. Southern Journal of Applied Forestry 13(1):12-16.

Creed, W. A., F. Haberland, B. E. Kohn, and K. R. McCaffery. 1984. Harvest management:The Wisconsin Experience. Pages 243-260 *in* L. K. Halls. ed. White-tailed deer:ecology and management. Stackpole Books, Harrisburg, PA

Crow, T. R. and E. J. Gustafson. 1997. Ecosystem management:managing natural resources in time and space. Pages 215-228 *in* K. A. Kohm, J. F. Franklin , eds. Creating a Forestry for the 21st Century, Island Press.

Davis, R., B. G. Buchanan, and E. H. Shortliffe. 1977. Production rules as a representation for a knowledge-based consultation system. Artificial Intelligence 8:15-45.

Davis, J. R., P. M. Nanninga, J. R. L. Hoare, and A. J. Press. 1989. Transferring scientific knowledge to natural resource managers using artificial intelligence concepts. Ecological Modelling 46:73-89.

DeCalesta, D. S.1994. Effect of white-tailed deer on songbirds within managed forests in Pennsylvania. Journal of Wildlife Management 58:711-718.

Decker, D. J. and K. G. Purdy. 1988. Toward a concept of wildlife acceptance capacity in wildlife management. Wildlife Society Bulletin 16:53-57.

Decker, D. J., T. L. Brown, N. A. Connelly, J. W. Enck, G. A. Pomerantz, K. G. Purdy. and W. F. Sieer. 1992. Toward a comprehensive paradigm of wildlife management:integrating the human and biological dimensions.

Pages 33-54 *in* W. R. Mangun, ed. American fish and wildlife policy:the human dimension. Southern Illinois University Press, Carbondale, Il.

Duda, R. O., P. E. Hart, K. Konolige, and R. Reboh. 1979. A computer-based consultant for mineral exploration (Technical report). SRI International.

Duda, R. O. and J. G. Gaschnig. 1981. Knowlege-based expert systems come of age. Byte, March, 238-249.

Dunning, J. B., B. J. Danielson, and H. R. Pulliam 1992. Ecological processes that affect populations in complex landscapes. Oikos 65:169-175.

Dusek, G. L., R. J. Mackie, J. D. Herriges Jr., and B. B. Compton. 1989. Population ecology of white-tailed deer along the lower Yellowstone River. Wildlife Monograph 104:1-68.

Drolet, C. A. 1976. Distribution and movement of white-tailed deer in southern New Brunswick in relation to environmental factors. Canadian Field-Naturalist 90:123-136.

Eberhardt, L. L.1960. Estimation of vital characteristics of Michigan deer herds. Ph.D. Dissertation. Michigan State University, East Lansing, MI. 192pp.

Edwards, J. S. 1991. Building knowledge-based systems:towards a methodology. Halsted Press, New York.

Ehrlich, P. R. and G. C. Daily. 1993. Science and the management of natural resources. Ecological Applications. 3(4):558-560.

Euler, D. and M. Morris, 1984. Simulated population dynamics of white-tailed deer in an any-deer hunting system. Ecological Modeling 24:281-292.

Flather, C. H. and J. R. Sauer. 1996. Using landscape ecology to test hypotheses about large-scale abundance patterns in migratory birds. Ecology 77:28-33.

Folse, L. J., J. M. Packard, and W. W. Grant, 1989. AI modeling of animal movement in a heterogeneous habitat. Ecological Modelling 46:57-72.

Franklin, J. F. 1994. Developing information essential to policy, planning, and management decision-making:the promise of GIS. Pages *in* V. A. Sample Edited Remote sensing and GIS in ecosystem management. Island Press. Washington, D.C.

Friedrich, P. D and S. M. Schmitt, 1988. Doe productivity and physical condition:1988 Spring survey results. Michigan Department of Natural Resources. Wildlife Division Report No. 3083. Lansing, Michigan.

Gavin, T. A., L. H. Suring, P. A. Vohs Jr., and E. C. Meslow, 1984. Population characteristics, spatial organization, and natural mortality in the Colombian white-tailed deer. Wildlife Monograph 91:1-41.

German, C. D. 1992. Individual based modeling of animal populations using object oriented simulation techniques: Investigating the effects of bonding, predation, and birth cover on white-tailed deer. M.S. Thesis. Texas A&M University. 149pp.

Giles, R. H. Jr. 1978. Wildlife Management. W. H. Freeman, San Francisco, CA.

______. 1998. Natural resource management tomorrow: four currents. Wildlife Society Bulletin 26(1):51-55.

Ginsberg, J. R. and E. J. Milner-Gulland. 1994. Sex-biased harvesting and population dynamics in ungulates: implications for conservation and sustainable user. Conservation Biology 8:157-166.

Goldberg, A. and D. Robson. 1983. Smalltalk-80:the language and its implementation. Addison-Wesley. Reading, MA.

Guida, G. and C. Tasso. 1994. Development of the prototype. Chapter 6:157-236 *in* Design and development of knowledge-based systems: from life cycle to methodology. John Wiley & Sons Ltd. West Sussex, England.

Gustafson, E .1998. Quantifying landscape spatial pattern: what is the state of the art? Ecosystems 1:143-156.

Halls, L. K. 1984. Research problems and needs. Pages 783-790 *in* L. K. Halls, ed. White-tailed deer: ecology and management. Wildlife Management Institute. Stackpole Books. Harrisburg, PA.

Hanley, T. A. 1996. Potential role of deer (cervidae) as ecological indicators of forest management. Forest Ecology And Management 88:(1-2) 199-204.

Harder, J. D, 1980. Reproduction of white-tailed deer in the north central United States. Pages 23-25 *in* R. L. Hine and S. Nehl. eds., White-tailed deer population management in the north central states. Proceeding of a symposium held at the 41st Midwest Fish and Wildlife Conference, Urbana, Illinois, December 10, 1979.

Hayne, D. W. 1984. Population dynamics and analysis. Page 203-210 *in* L. K. Halls ed. White-tailed Deer:Ecology and Management. Stackpole Books. Harrisburg, PA.

Hayes-Roth, F., D. A. Waterman, and D. B. Lenat. 1983. Building expert system. Addison-Wesley Publishers. Reading, MA.

High Performance Systems, Inc, 1997. STELLA. II Technical Documentation. Hanover, N H.

Hill, H. R. and D. L. Rabe, 1989. Deer checking station data -1989. Michigan Department of Natural Resources. Wildlife Division Report No. 3126. Lansing, MI.

Hill, H. R. 1996. The 1996 Deer pellet group surveys. Michigan Department of Natural Resources, Wildlife Division Report. Lansing, MI.

Jahn L.R.1959. Highway mortality as an index of deer population change. Journal of Wildlife Management 23:187-197.

Jensen, A. L, 1996. Density-dependent matrix yield equation for optimal harvest of age-structured wildlife populations. Ecological Modeling 88:125-132.

Kellert S. R. 1994. Managing for biological and sociological diversity, or 'deja vu, all over again'. Wildlife Society Bulletin, 23.2.:274-278.

Krefting L. W. and R. S. Phillips.1970. Improving deer habitat in upper Michigan by cutting mixed-conifer swamps. Journal of Forestry 68:701-704.

Langenau, E. E. Jr. 1991. Few deer, more bucks. Michigan Natural Resources, November/December, 1991, 38-39.

______.1994. 100 years of deer management in Michigan. Michigan Department of Natural Resources. Wildlife Division Report. No. 3213. Michigan Department of Natural Resources. Lansing, MI.

Leopold A .1933. Game management. Charles Scribner's Sons, New York.

Levins, R. 1966. The strategy of model building in population biology. American Scientists 54:421-431.

Larson, T. J., O. J. Rongstad, and F. W. Terbilcox. 1978. Movement and habitat use of white-tailed deer in southern central Wisconsin. Journal of Wildlife Management 42:113-117.

Li, H. B. and J. F. Reynolds. 1994. A simulation experiment to quantify spatial heterogeneity in categorical maps. Ecology 75:2446-2455

Lillesand, T. M. and R. W. Kiefer. 1994. Remote sensing and image interpretation. 3rd ed. Wiley & Sons, New York.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science 260:(5104) 17.

Maclean, GA .1994. Inventory of deer habitat in Michigan's upper peninsula utilizing Landsat Thematic Mapper data. A final report to the Michigan DNR, Wildlife Division, Michigan Department of Natural Resources. Lansing, MI.

Mallawaarachchi, T., P. A. Walker, M. D. Young, R. E. Smyth, and H. S. Lynch. 1996. GIS-based integrated modeling systems for natural resource management. Agricultural Systems 50:169-189.

Matschke G., D. S. deCalesta, and J. D. Harder.1984. Crop damage and control. Pages 647-654 *in* L. K. Halls. ed. White-tailed deer: ecology and management. Stackpole Books, Harrisburgh, PA,

McCabe, R. E. and T. R. McCabe.1984. Of slings and arrows: An historical retrospection. Pages 19-72 *in* L. K. Halls, ed. White-tailed deer: ecology and management. Stackpole Books, Harrisburg, PA.

McCaffery, K. R. 1989. Deer population dynamics and management in Wisconsin. Proceeding of Eastern Wildlife Damage Control Conference 4:155-161.

McCullough, D. R. 1979. The George Reserve deer herd: population ecology of a K-selected species. University of Michigan Press, Ann Arbor, MI.

McDermott, J. 1982. R1:A rule-based configurer of computer systems. Artificial Intelligence 19(1):39-88.

______. 1988. Preliminary steps towards a taxonomy of problem-solving methods. Pages 225-256 *in* S. Marcus, ed. Automatic knowledge acquisition for expert systems. Kluver Academic Publishers, Boston.

McGarigal K. and B. J. Marks.1994. FRAGSTATS 2.0:Spatial pattern analysis program for quantitative landscape structure. Oregon State University. Corvallis, OR.

McShea, W. J, H. B.Underwood, J. H. Rappole, eds. 1997. The science of overabundance: deer ecology and population management. Smithsonian Institution Press, Washington and London.

Mech, L. D., R. E. McRoberts, R. O. Peterson, and R. E. Page. 1987. Relationship of deer and moose populations to previous winters' snow. Journal of Animal Ecology. 56:615-627.

Meddin, D. E. and A. E. Anderson. 1979. Modeling the dynamics of a Colorado mule deer population. Wildlife Monograph 68, 1-77.

Mello, P. J.1983. A computer simulation model for the study of deer-aspen forest interactions. M. S. Thesis. Michigan State University. East Lansing, Michigan.

Michigan Department of Natural Resources. 1993. Statewide DRIP goal. Michigan Department of Natural Resources, Wildlife Diversion. Lansing, MI.

______. 1996. Michigan deer population figures (in thousands). Michigan Department of Natural Resources, Wildlife Diversion. Lansing, MI.

Miller, S. G., S. P. Brattton, and J. Hadidian. 1992. Influence of white-tailed deer on endangered and threatened vascular plants. Natural Areas Journal 12:67-74.

Milne, B. T., K. M. Johnston, and R. T. T. Forman .1989. Scale-dependent proximity of wildlife habitat in a spatially-neutral Baysian model. Landscape Ecology 2:101-110.

Minnis, D. L. 1996. Cultural carrying capacity and stakeholders' attitudes associated with the deer crop damage issue in Michigan. Ph.D. Dissertation. Michigan State University, East Lansing, MI.

Minsky, M. L. 1975. A framework for representing knowledge. Pages 211-277 *in* P. H. Winston, ed. The psychology of computer vision. McGraw-Hill, NY.

Mladenoff D. J. and F. Stearns. 1993. Eastern hemlock regeneration and deer browsing in the northern Great Lake Region: A re-examination, and model simulation. Conservation Biology 7:889-900

Mladenoff, D. J. and G. E. Host. 1994. Ecological perspective: current and potential applications of remote sensing and GIS to ecosystem analysis. Pages 218-242 *in* V. A. Sample ed. Remote sensing and GIS in ecosystem management. Washington D. C., Island Press.

Morrison, M. L., B. C. Marcot, and R. W. Mannan. 1992. Wildlife-habitat relationships: concepts and applications. The University of Wisconsin Press. Madison. 343pp.

National Research Council. 1995. Science and Endangered Species Act. Washington, DC.

Nelson M. E. and L. D. Mech.1984. Home-range formation and dispersal of deer in northern Minnesota. Journal of Mammalogy 65:567-575.

Nelson, M. E. 1994. Winter range arrival and departure of white-tailed deer in northern Minnesota. Canadian Journal of Zoology 73:1069-1076.

Nixon, C. M., L. P. Hansen, and P. A. Brewer. 1988. Characteristics of winter habitats used by white-tailed deer in Illinois. Journal of Wildlife Management 52(3):552-555.

Nixon, C. M., L. P. Hansen, P. A. Brewer, and J. E. Chelsvig. 1991. Ecology of white-tailed deer in an intensively farmed region of Illinois. Wildlife Monograph 118:1-77.

Newell, A. and Simon, H. 1973. Human Problem Solving. Englewood Cliffs, NJ:Prentice-Hall.

Newell, A. 1982. The knowledge level. Artificial Intelligence 18:87-127.
Nixon, C. M., L. P. Hansen, P. A. Brewer, and J. E. Chelsvig. 1991. Ecology of white-tailed deer in an intensively farmed region of Illinois. Wildlife Monograph 118:1-77.
Ormsby, J. P. and R. S. Lunetta. 1987. White-tailed deer food availability maps from thematic mapper data. Photogrammetric Engineering and Remote Sensing 53(8):1081-1085.

Ozaga, J. J. 1968. Variations in microclimate in a conifer swamp deeryard in northern Michigan. Journal of Wildlife Management 32:574-585.

_____, R. V. Doepker, and M. S. Sargent. 1994. Ecology and management of white-tailed deer in Michigan. Michigan Department of Natural Resources, Wildlife Division Report 3209. 73pp.

Peyton, R. B. 1987. Mechanisms affecting public acceptance of resources management policies and strategies. Canadian Journal of Fish and Aquatic Science 44:306-312.

Potvin, F. and J. Huot. 1983. Estimating the carrying capacity of a white-tailed deer wintering area in Quebec. Journal of Wildlife Management 47:463-475.

Prerau, D., M. Adler, D. K. Pathak, and A. Gunderson. 1997. Intelligent agent technology. Pages 16:1-13 *in* J. Liebowitz, ed. The Handbook of Applied Expert Systems. CRC Press LLC.

Quinlan, J. R. 1986. Induction of decision trees. Machine Learning.1:81-106.

Reynolds, K. M. 1999. EMDS users guide (version 2.0):knowledge-based decision support for ecological assessment. Gen. Tech. Rep. PNW-GTR-470. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 63 pp.

Ritchie, J. R. 1989. An expert system for a rangeland simulated model. Ecological Modeling 46:91-105.

Ross, B. A., J. R. Bray, and W. H. Marshall .1970. Effects on long-term deer exclusion on a *pinus resinosa* forest in North-Central Minnesota. Ecology 51:1089-1093

Rue, L. L. III. 1989. The deer of North America, Grolier Books Club Inc., Danbury, Connecticut.

Saarenmaa, H., Stone, N. D., Folse, L. J., Packard. J. M., Grant, W. E., Makela, M. E. and Coulson, R. N. 1988. An artificial intelligence modeling approach to simulating animal/habitat interactions. Ecological Modeling. 44:125-141.

SAS Institute Inc. 1998. SAS Language Reference. Version 7. First Edition. Cary, NC.

Schank, R. C. and R. P. Abelson. 1977. Script, plans, goals, and understanding. Lawrence Erlbaum Associates Inc. Hillsdale, NY.

Schank, R. C. 1982. Dynamic memory:a theory of learning in computers and people. Cambridge University Press.

_____. 1987. What is AI, anyway? AI Magazine 8(4):57-66.

Schmitt, S. M., S. D. Fitzgerald, T. M. Cooley, C. S. Bruning-Fann, L. Sullivan, D. Berry, T. Carlson, R. B. Minnis, J. B. Payeur, and J. Sikarskie .1997. Bovine tuberculosis in free-ranging white-tailed deer from Michigan. Journal of Wildlife Disease 33:749-758.

Schmoldt, D. and H. M. Rauscher. 1996. Building knowledge-based systems for natural resources management. Chapman & Hall. New York, NY.

Short, H. L.1986. Habitat suitability index models:white-tailed deer in the Gulf of Mexico and South Atlantic coastal plains. Biological Report 82.10.123. Washington, DC.

Shortliffe, E. H.1976. Computer-based medical consultations:MYCIN. American Elsevier. NY.

Singh, H. Data warehousing: concepts, techniques, implementations, and management. Prentice Hall PTR. Upper Saddle River, NJ.

Sparrowe, R. D. and P. F. Springer. 1970. Seasonal activity patterns of white-tailed deer in eastern South Dakota. Journal of Wildlife Management 34(2):420-444.

Stanley, T. R. 1995. Ecosystem management and the arrogance of humanism. Conservation Biology 9:255-262.

Starfield, A. M. and A. L. Bleloch. 1986. Building models for conservation and wildlife management. Macmillan Publishing Company. New York. S

Starfield, A. M. 1997. A pragmatic approach to modeling for wildlife management. Journal of Wildlife Management 61:261-270.

Stauffer, D. F. 1990. Field evaluation of an HSI model for white-tailed deer in the coastal plain. Unpublished report. Department of fisheries and wildlife sciences. Virginia Tech University

Strickland, M. D., H. J. Harju, K. R. McCaffery, H. W. Miller, L. M. Smith, and R. J. Stoll. 1994. Harvest Management. Pages 445-473 *in* T. A. Bookhout ed. Research and Management Techniques for Wildlife and Habitats. The Wildlife Society. Bethesda, MD.

Suring, L. H. and P. A. Vohs, Jr .1979. Habitat use by Columbia white-tailed deer. Journal of Wildlife Management 43(3):610-619.

Swanson, T. 1997. Global action for biodiversity. Earthscan Publications Ltd. Londson.

Sticklen, J. 1989. Problem solving architecture at knowledge level. Journal of Experimental and Theoretical Artificial Intelligence 1(1):1-52.

Tierson, W. G., G. F. Mattfeld, R. W. Sage Jr., and D. F. Behrend. 1985. Seasonal movements and home ranges of white-tailed deer in the Adirondacks. Journal of Wildlife Management 49:760-769.

Tilghman, N. G.1989. Impacts of white-tailed deer on forest regeneration in northwest Pennsylvania. Journal of Wildlife Management 53:524-532.

Turner, M. G.1989. Landscape ecology: the effect of pattern on process. Annual Review of Ecology and Systematics 20:171-197.

Turner, M. G., V. H. Dale, and R. H. Gardner.1989. Predicting across scales: Theory development and testing. Landscape Ecology 3:245-252.

Ullrey, D. E., W. G. Youatt, H. E. Johnson, L. D. Fay, and B. E. Brent. 1967. Digestibility of cedar and jack pine browse for the white-tailed deer. Journal of Wildlife Management 31:448-454.

Urbain, J. 1997. Michigan deer hunting prospects. Michigan Department of Natural Resources, Wildlife Diversion. Lansing, MI. 6pp.

Van Deelen. T. R. H. 1995. Seasonal migrations and mortality of white-tailed deer in Michigan's Upper Peninsular. Ph.D. Dissertation. Michigan State University. East Lansing. MI. 158pp.

_____, H. Campa III, J. B. Haufler, and P. D. Thompson, 1997. Mortality patterns of white-tailed deer in Michigan's Upper Peninsula. Journal of Wildlife Management 61(3):901-910

_____, T, R, H. Campa, M. Hamady, J. B. Haufler. 1998. Migration and seasonal range dynamics of deer using adjacent deeryards in northern Michigan. Journal Of Wildlife Management 62(1): 205-213.

Verme, L. J.1965. Swamp conifer deeryards in northern Michigan: their ecology and management. Journal of Forestry 63:523-530.

_____,1968. An index of winter weather severity for northern deer. Journal of Wildlife Management 32:566-574.

_____,1969. Reproductive patterns of white-tailed deer related to nutritional plane. Journal of Wildlife Management 33:881-887.

_____,1973. Movement of white-tailed deer in Upper Michigan. Journal of Wildlife Management 37:881-887.

_____, 1977. Assessment of natal mortality in Upper Michigan deer. Journal of Wildlife Management 41:700-708.

______, 1983. Sex ratio variation in Odocoileu:a critical review Journal of Wildlife Management 37:545-552

______, 1989. Decline in doe fawn fertility in southern Michigan deer. Canadian Journal of Zoology 69:25-28.

______, and J. J. Ozaga. 1971. Influence of winter weather on white-tailed deer in upper Michigan. Michigan Department of Natural Resources, Research and Development Report No. 237. Lansing, MI 14pp.

Virgós E. and J. L. Tellería. 1998. Roe deer habitat selection in Spain: constraints on the distribution of a species. Canadian Journal of Zoology 76:1294-1299.

Walker, B. 1998. The art and science of wildlife management. Wildlife Research. 25:1-9.

Wallmo, O. C., L. H. Carpenter, W. L. Regelin, R. B. Gill, and D. L. Baker. 1977. Evaluation of deer habitat on a nutritional basis. Journal of Range Management 30(2):122-127.

Walters, C. J. and J. E. Gross, 1972. Development of big game management plans through simulation modeling. Journal of Wildlife Management. 36:119-128

Walters, C.J. 1986. Adaptive Management of Renewable Resources. MacMillan, N.Y.

Wilson, M. L. and J. E. Childs. 1997. Vertebrate abundance and the epidemiology of zoonotic diseases. Pages 224-248 *in* W. J. McShea, H. B. Underwood, and J. H. Rappole. eds. The science of overabundance: deer ecology and population. Smithsonian Institution Press, Washington and London.

Woolf, A. and J. D. Harder. 1979. Population dynamics of a captive white-tailed deer herd with emphasis on reproduction and mortality. Wildlife Monograph 67:1-53.

Xie, J., H. R. Hill, S. R. Winterstein, H., III Campa, R. V. Doepker, T. R. Van Deelen, and J. Liu.1999. White-tailed deer management options model (DeerMOM): design, quantification, and application. Ecological Modelling 124 (2-3):121 -130.