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Development of landscape-scale models to describe habitat potential of white-tailed deer (*Odocoileus virginianus*) in Michigan

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DEVELOPMENT OF LANDSCAPE-SCALE MODELS TO DESCRIBE HABITAT POTENTIAL OF WHITE-TAILED DEER (*ODOCOILEUS VIRGINIANUS*) IN MICHIGAN.

By

Alexandra B. Felix

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ABSTRACT

DEVELOPMENT OF LANDSCAPE-SCALE MODELS TO DESCRIBE HABITAT POTENTIAL OF WHITE-TAILED DEER (*ODOCOILEUS VIRGINIANUS*) IN MICHIGAN

By

Alexandra B. Felix

The Michigan Department of Natural Resources has addressed a need to re-evaluate Michigan's deer population goals with a consideration of how the range of biotic and abiotic factors within landscapes influence deer habitat selection and subsequently affects populations. This study was initiated to contribute to the understanding of the relationship between white-tailed deer populations and their habitat based on the ecological potential of habitat types and how they can be managed in Michigan. Habitat types were defined in 3 areas of Michigan using digital vegetation and soil databases, empirical vegetation attribute data, and ecological classification systems. Compositional, structural, and geological information were identified for each habitat type and stored in a database. Three deer habitat requirements were identified from literature and a habitat classification key was developed, which identifies habitat suitability values associated with a range of habitat conditions within landscapes. Landscape-scale models were constructed that quantify habitat suitability for each seral stage within habitat types. The highest suitability that a habitat type could attain is indicative of habitat potential (i.e., the capability of an area being or becoming habitat based on biological and geological characteristics). The spatial distribution of habitat potential can be projected in a GIS and combined with deer demographic data to establish realistic deer management goals based on the ecological potential of landscapes and population patterns.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In Michigan, the white-tailed deer (*Odocoileus virginianus*) is an important natural and economic resource. Consequently, state agencies allocate funds to provide for research on white-tailed deer population demographic trends and habitat quality which direct deer management activities. Deer management in Michigan essentially began in 1895 with the establishment of an official hunting season, bag limit, and a required hunting license. Wildlife managers realized the importance of regulating and conserving deer numbers since unregulated commercial market hunting to meet the human demand for venison in the late 1800s drastically decreased the size of Michigan's deer herd. As a result of the early hunting regulations and an increase in early successional vegetation subsequent to logging, deer numbers began to increase in the early 1900s. In the early 1900s, the bag limit was reduced from 5 deer in 1900 to 3 in 1901, 2 in 1905 and 1 in 1915 (Langenau 1994). In 1921, the "buck law" was established, which allowed only antlered bucks to be taken by hunters (Langenau 1994).

The Game Division, of the Department of Conservation in Michigan (which later became the Department of Natural Resources) began using scientific information to form much of the basis for deer management in the late 1920s. More scientific research for game management was conducted after the Pittman-Robertson Act was established in 1937. In the 1930s, evidence of winter starvation, overbrowsing, a low buck:doe ratio, and an increase in the number of deer-vehicle accidents indicated that deer were abundant in the state. Biologists suggested that the number of deer was not in balance with the habitat and deer habitat should be managed for long-term sustainability.

In 1954, harvest of antlerless deer was permitted. Deer habitat quality, however, was reduced due primarily to forest succession (i.e. loss of early successional stage forests that provide favorable habitat), but also to heavy browsing by overabundant deer between 1940-1960. Once again, the size of the herd decreased. In the 1970s, managers realized the importance of managing vegetation communities (i.e. habitat), rather than just deer numbers in order to maintain sustainable deer populations. The Deer Range Improvement Program (DRIP), which was established in 1971, allocated a portion of the revenue from each deer license to be used for deer habitat improvement (Langenau 1994).

According to the Michigan Department of Natural Resources (MDNR), the improved habitat, a series of mild winters, and artificial feeding of deer by the public contributed to another increase in the herd size in the 1980s. In the late 1980s, MDNR stated that their goal was to maintain an annual October 1 population of 1.3 million deer, which was based on a 1971 population goal of 1 million deer in the spring herd. The MDNR restated its commitment to that goal in 1997. Many wildlife managers and stakeholder groups, however, have questioned the scientific basis of this population goal (i.e., whether this goal is based on social and biological considerations). Subsequently, there is a need to re-evaluate Michigan's deer population goals with consideration of habitat suitability and the cultural carrying capacities across the state.

Traditional deer management in Michigan largely focused on regulating the white-tailed deer population size through hunting (Langenau 1994). Based on large fluctuations in population size, spatial variations in deer numbers, and skewed buck:doe ratios throughout the history of deer management in Michigan, this approach suggests that it is difficult to obtain population management goals by primarily managing deer numbers. Perhaps an understanding of how deer habitat changes spatially and temporally would explain observed spatial and temporal differences in deer population dynamics and, therefore, aid managers in deer management and planning. Unfortunately, however, habitat information is generally not a major consideration in deer management because of the lack of definitive spatial and temporal links between habitat supply and population response. Michigan's experience with deer management has provided new insights for incorporating habitat management and planning into deer management goals.

To better incorporate habitat management into deer management goals, it is critical to understand which environmental factors (e.g., biotic and abiotic) influence the ability of the habitat to support deer and how habitat influences population characteristics and dynamics. For example, some of the most important underlying factors affecting size and productivity of white-tailed deer populations are the structure and composition of the vegetation to provide cover (Verme 1965, Mysterud and Østbye 1999) and an adequate and sustainable food source (Smith and Coggins 1984), the spatial arrangement of cover types within the habitat as determined by soils and geological characteristics (Nixon et al. 1970), and winter severity (Verme 1968). The factors that influence deer population dynamics may be difficult to analyze within forest stands since deer range widely (e.g., 333-9000+ ac in the northern Lower Peninsula, Garner 2001) to meet their habitat requirements. Subsequently, an understanding of the relationship between deer and habitat suitability at a landscape-scale is useful for state-wide deer management planning.

Temporal and spatial scales should be considered when analyzing habitat suitability. It is difficult to understand the dynamic relationships between wildlife populations and their habitats without understanding the underlying regulatory mechanisms within landscapes and the processes by which habitat within landscapes changes over time. Therefore, it may be useful to use habitat types to evaluate how habitat suitability changes throughout succession. Habitat types are areas with the same ecological characteristics that support the same successional trajectory (Daubenmire 1966). The climate, landforms, and soil characteristics such as nutrient content, moisture regime, and texture influence differences in vegetation structure and composition and successional patterns within different habitat types. By understanding how the structure and composition of vegetation changes throughout succession, it is possible to quantify the potential of the habitat to support deer throughout a successional trajectory. In addition, identifying and mapping the spatial distribution of habitat types will enable resource managers to establish long-term management objectives and specific recommendations based on the ecological potential of landscapes.

The "holistic" approach to land management emerged in the late 1970-1980s when managers started to emphasize the complexity and dynamic nature of ecological systems at several spatial and temporal scales (Grumbine 1994) instead of primarily focusing on population density as a basis for management. Clearly, there is a need in Michigan to take a more holistic or ecosystem-based approach to deer management. Such an approach should consider the spatial and temporal relationships as well as the interaction among biotic (e.g., vegetation structure and composition) and abiotic (e.g., geology and climate) factors within a landscape to understand deer habitat selection processes and provide a basis for incorporating habitat planning into deer management.

The fundamental purpose of this project was to develop landscape-scale models to quantify white-tailed deer habitat potential for 3 multi-county areas in Michigan. Habitat potential is, essentially, an assessment of the degree to which an area meets, or could potentially meet, white-tailed deer life requisites based on the availability or potential availability of ecological resources in specific areas of Michigan. The goal of this project is to contribute to the understanding of the complex relationships between white-tailed deer populations and their habitat based on the ecological potential of available habitat types and how they could be managed in Michigan.

OBJECTIVES

1. Assess the spatial patterns of white-tailed deer habitat requirements for 3 multi-county study areas in Michigan.

2. Develop spatially explicit landscape-scale models for 3 study areas in Michigan that quantify white-tailed deer habitat potential.

3. Suggest an approach for quantifying the relationships between habitat potential and deer population demographics and spatial structure.

4. Make recommendations for applying the models to managing wildlife populations and habitat within a landscape.

STUDY AREA DESCRIPTION

Three study areas were selected in Michigan in coordination with the MDNR based on the heterogeneity of habitat types and land-use patterns among the 3 areas. The first site is a 1,872 mi^2 area in the southern Lower Peninsula (SLP) consisting of Barry, Calhoun, and Eaton counties (Figure 1). The second site is a 3,132 mi^2 area in the northeast Lower Peninsula (NLP) consisting of five counties: (Alcona, Alpena, Montmorency, Oscoda, and Presque Isle). The third site is a 4,696 mi^2 area located in western Upper Peninsula (UP) and includes Baraga, Dickinson, Iron, and Marquette counties. Land-use, climate, and land cover differ among the 3 study areas in Michigan. These area differences are important because they may potentially affect the harshness of the environment and consequently, the biology and distribution of white-tailed deer within the areas. Furthermore, deer may require different structural characteristics of vegetation within each area. For example, thermal cover may be more critical in the Upper Peninsula during the cold winters than in southern Lower Michigan with mild winters. In addition, food (i.e., agricultural crops) may be more readily available in southern Michigan than in the northern region.

Climate

The SLP site generally has less variable seasonal temperatures, less snowfall, and a longer growing season than the NLP and UP sites (Table 1). Winters in the Upper Peninsula are more severe than the winter in the Lower Peninsula with generally more snowfall and colder temperatures for a longer period of time (Michigan Weather Service 1974, Albert et al. 1986).

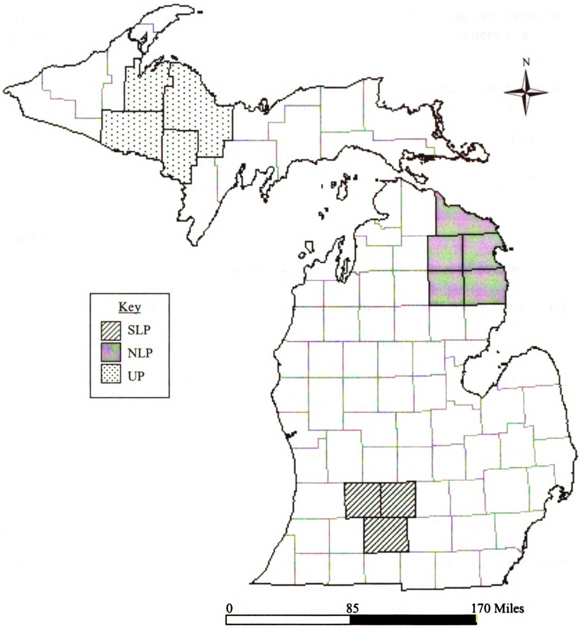


Figure 1. Location of the three study areas in Michigan used for modeling white-tailed deer habitat potential. SLP = southern Lower Peninsula; NLP = northeastern Lower Peninsula; UP = Upper Peninsula.

Table 1. Climate in Michigan by study area (Sommers 1977). Ranges are the minimum and maximum of the average values for each specified region. SLP = southern Lower Peninsula, NLP = northeastern Lower Peninsula, UP = Upper Peninsula.

Region	Average annual temp (°F)	Average precip (in)	Growing Season (days)	Average annual Snowfall (in)	No. days below 0 °F
SLP	46-48	30.8-34.1	141-154	40-60	7-10
NLP	42-44	26.5-29.8	94-156	60-80	10-29
UP	42-44	30.2-30.9	96-113	100-180	27-34

Vegetation

Cover types in the SLP consist of oak-hickory (scientific names of overstory vegetation appear in Appendix 1) and beech-maple dominated forests where forest cover occurs. These are the same cover types that occurred historically, but currently, agricultural lands also cover much of the area (Sommers 1977, Albert et al. 1986). Aspen-birch, oak-hickory, and pine-dominated forests occur in the NLP where much of the coniferous forests that occurred in pre-settlement periods were diminished from logging (Albert et al. 1986). These pre-settlement forests included jack pine, red pine, and white pine dominated forests interspersed with hemlock and aspen-birch stands (Albert et al. 1986). The UP site includes largely maple-beech-hemlock and aspen-birch dominated forests interspersed with spruce-fir dominated forests (Sommers 1977). Pre-settlement vegetation included mesic mixed forests (sugar maple, yellow birch, hemlock) and wet coniferous forests (balsam fir, spruce, tamarack, northern white cedar) interspersed with dry coniferous forests of red and white pine (Albert et al. 1986).

Land-use and topography

Alfisols, specifically Hapludalfs, in conjunction with the flat or gently rolling plains in the SLP support productive vegetation (Sommers 1977, Albert et al. 1986). Field crops such as corn, soybeans, hay, and wheat are grown over 65% of the area (United States Geological Survey 1999) in the SLP. Acidic sandy soils and spodosols occur in the NLP (Albert et al. 1986). The NLP can be characterized by lake border plains along Lake Huron and hilly lands in the inland areas (Sommers 1977). Primary land-use patterns in the NLP include recreation, such as camping and hunting, due to the large amount (i.e., approximately 35%) of state and federally owned land (MDNR-Wildlife Bureau, MDNR-Land and Mineral Services Division, Resources Mapping and Aerial Photography 2000), as well as privately owned hunt clubs, which exist in the area. Some agriculture [cropland, (e.g., alfalfa and red kidney beans), and beef and dairy cattle] occurs in the NLP as well. The UP site consists of hilly uplands (Sommers 1977). Spodosols and bedrock rich in iron occur over much of the area (Albert et al. 1986). Forest culture and recreation are primary land-uses that occur in this area.

METHODS

Empirical data used throughout this project were obtained by analyzing literature describing deer habitat requirements, vegetation physiognomy, geological characteristics, and successional patterns. There is an abundance of valuable ecological information available in the literature, which is largely underutilized. The extracted information was used for constructing deer habitat models, habitat type databases, and tables providing information on the dynamic structure and composition of vegetation throughout succession. Note: Some of the images in this thesis are presented in color.

Obtaining necessary data

I obtained and reviewed digital coverages (e.g., land cover, soils, landforms, ecoregions) from the MDNR and United States Geological Survey (USGS) to assess their utility for modeling white-tailed deer habitat potential (Appendix 2). To create different spatial layers and assess deer habitat potential, I chose data that the MDNR either uses currently or could easily obtain so that the process and models developed in this project could be incorporated into the MDNR management planning and evaluation procedures.

Land Cover

Available land cover data differed for each of the 3 study areas. For the SLP, the most current land cover data available were the 1978 Michigan Resource Information System (MIRIS) data from the MDNR (MDNR 1999) and the 1992 USGS national land cover data (USGS 1999). The MIRIS data included vegetation classification to the species level for some of the counties. Although the 1992 USGS data are more current, they are more general than the 1978 MIRIS data (Appendix 2). For example, the most specific category for vegetation classification according to the 1992 USGS data is forest type such as "evergreen forest" or "deciduous forest". This coverage was not useful for habitat suitability analysis due to the generality of the data, but it was helpful, as a double check on the distribution of certain forest types. For the NLP, available land cover data included the 1978 MIRIS data, the 1992 USGS national land cover data, and a 1993 Gap Analysis Program (GAP) Northern Lower Peninsula land cover dataset (MDNR-Wildlife Bureau and MDNR-Land and Mineral Services Division, Resource Mapping and Aerial Photography 2000). The 1993 data set was available only for the NLP and classified vegetation by vegetation type (i.e., mixed lowland hardwood, northern hardwood, or lowland broad-leaved deciduous shrub). For the UP, available land cover data included the 1978 MIRIS data and the 1991 Landsat Thematic Mapper coverage (MacLean Consultants, Ltd. 1995). The 1991 dataset was an inventory of white-tailed deer thermal cover in the Upper Peninsula (MacLean Consultants, Ltd. 1995).

Presettlement vegetation helped identify potential vegetation. This coverage was created using notes from the General Land Office Surveys, which describes vegetation conditions between 1816 and 1856 prior to intensive logging and development (Comer et al. 1995). Although there is probably bias associated with the presettlement vegetation map since it was created based on subjective descriptions of vegetation from land surveyors notes and does not include effects of disturbances and native people on vegetation composition (Comer et al. 1995), it was a useful tool when combined with soil and land type association layers to delineate ecological units.

Soils

Soils data were at the association level for all of the study areas (United States Department of Agriculture (USDA) Natural Resources Conservation Service 1998). A soil association is a natural grouping of related types of soils based on similarities in climatic or physiographic factors and soil parent materials. Soil moisture regime, soil type (i.e., sand, loam, clay), and potential dominant vegetation define the soil associations. Soil characteristics delineated edges between stands with different structural or compositional characteristics. Specific properties of series within soil associations such as texture and moisture were obtained from the Iowa State Soils Information Database (Soil Survey Division, Natural Resources Conservation Service, USDA 1996).

Land Type Associations

Land type associations (LTAs) are broad regions delineated by large scale geomorphic features defined by parent material and superficial topography (i.e., outwash plains, moraines), soil characteristics, and natural overstory vegetation at a scale of 1:60,000 (Cleland et al. 1993). Different LTAs support vegetation types that differ, either structurally or compositionally. Land type associations existed for the NLP (DeLain et al. 1999) and the UP, but were not available for southern Michigan. For the UP, the LTA boundaries were useful for delineating ecological units, but the LTA database did not indicate landform types. Possible landform types for LTA boundaries were identified from the soils database (Soil Survey Division, Natural Resources Conservation Service, USDA 1996).

Ecoregions

Ecoregions at the sub-subsection provided regional landscape ecosystem classification based on differences in climate, bedrock geology, glacial landform, and soils (Albert 1995). This coverage was available for all 3 study areas. From a deer's perspective, ecoregions are probably too broad (i.e., area of ecoregions within study area ranges from 2896-80,066 ac) to distinguish between or select features from to meet their life requisites, but the regions do represent areas with distinctive ecological conditions that affect species composition and productivity. For example, ecoregions in the northern part of the NLP distinguish areas that support mesic beech-sugar maple and wet coniferous forests while ecoregions in the southern part of the NLP distinguish xeric jack pine and oak-pine forests. The composition and arrangement of vegetation in the northern part of the NLP would provide different deer life requisites than that of the southern part of the NLP. The ecoregion coverage, therefore, was useful in landscape classification and delineation of habitat types.

Building a habitat type coverage and quantifying deer habitat potential

Habitat types

A habitat type is a geographic area with the same ecological conditions that supports the same successional trajectory (Daubenmire 1966). "Habitat typing" was used to delineate areas with very different ecological conditions that may potentially provide different habitat conditions for deer. Habitat types were used because they represent the scale at which deer select annual habitat components. For instance, early successional stages of northern hardwood habitat types may provide spring and summer food (e.g., Kohn and Mooty 1971), whereas lowland coniferous types may provide thermal cover requirements (e.g., Verme 1965). One habitat type does not contain all of the vegetation characteristics that provide annual deer life requisites. Therefore, deer may have to shift their seasonal home ranges to obtain their life requisites.

Each habitat type is characterized by a specific pattern of compositional change or successional trajectory. Since communities exhibit measurable, directional change during succession, it is possible to predict structural and compositional characteristics of the successional stages within a habitat type and evaluate those characteristics in terms of deer habitat suitability. Delineation of habitat types was useful to determine the ecological potential of the landscape to support deer and identify habitat potential (i.e., the ability of an area to provide habitat for deer based on biological and geological characteristics). Habitat types were defined by identifying characteristic combinations of climate, landform, soils, and vegetation (Kotar and Coffman 1984, Spies and Barnes 1985, Host et al. 1987).

Habitat type themes for the NLP and UP sites were delineated in ArcView 3.2 Geographic Information Systems (GIS, Environmental Systems Research Institute, Redlands, California) using several existing digital coverages obtained from MDNR: ecoregions, LTAs, soil associations, and presettlement vegetation. Ecoregions at the sub-subsection provided the basis for delineating and classifying habitat types since they define climatic-physiographic boundaries that affect species composition and plant productivity at a broad scale. At the next level, LTAs, defined primarily by landforms, were used because overstory composition and successional trends vary among landforms (Host et al. 1987). Understanding variation in landforms is useful in understanding plant species recruitment patterns, and direction of compositional change across a landscape (Host et al. 1987). Soil associations were included in the next level since potential successional patterns among habitat types vary based on differences in soil texture and moisture regime (Rowe 1969). It was essential to include underlying geologic factors in delineating habitat types because forest composition or physiognomy may be affected by characteristics of deeper soil layers (Spies and Barnes 1985). Presettlement vegetation, the final layer, described vegetation conditions prior to intensive logging, farming, and industrial development, which has significantly altered vegetation composition by favoring establishment and persistence of early successional species.

Delineation of habitat type boundaries

The boundary of a habitat type is, essentially, an intersection of ecoregions, LTAs, soil associations, and presettlement vegetation. In the process of delineating habitat types, the ecoregion sub-subsections were initially identified (Appendix 3). Within each ecoregion, 1 LTA was selected at a time for analysis. Areas within LTAs were distinguished based on 6 soil moisture classifications ranging from excessively well drained to very poorly drained. Within each moisture classification, soil type was determined (e.g., sand, loam, clay). Finally, potential vegetation was determined from the presettlement coverage (e.g., northern hardwoods, jack pine). Areas with the same ecological attributes (e.g., ecoregion and geological characteristics) could potentially support different vegetation types within a habitat type. If left undisturbed, the vegetation types would succeed to the climax vegetation. Hence, areas with the same geological characteristics, vegetation types, and climax vegetation define the same habitat type. In essence, delineation of the habitat types is hierarchical with ecoregions at the coarsest scale and habitat types at the finest scale. Information from each of the 4 layers used to create the habitat type theme was stored in a database.

Identifying successional pathways of habitat types

Using information from the literature (e.g., Livingston 1905, Harper 1918, Westveld 1933, Nichols 1935, Ku 1954, Ching 1954, Bryant 1963, Coffman et al. 1980, Eyre 1980, Kotar and Burger 2000, Burger and Kotar 1999), I identified possible successional paths for each habitat type based on soil (i.e., moisture and texture) and landform characteristics. Two or more habitat types may support similar overstory successional trajectories even if they have slightly different geological characteristics. They remain as separate habitat types, however, because although the geological conditions do not differ enough to support different overstory vegetation, the *structure* of the overstory may differ between the 2 habitat types. In addition, floristic compositional differences within the habitat type may be evident in the understory vegetation rather than the overstory (Barbour et al. 1999). For example, in the UP site, 2 possible habitat types could support aspen and sugar maple in the early-successional stages; sugar maple, red maple, yellow birch, and ironwood in the mid-successional stages; and sugar maple and hemlock in the climax state. The vegetation in both habitat types grows on well to moderately well-drained soils, but in one habitat type, the soil is more loamy, and in the other habitat type, the soil is more sandy. The more loamy habitat type supports climax understory vegetation dominated by spinulose shield fern (*Dryopteris austriaca*), hairy solomon's seal (*Polygonatum biflorum*), wild lily of the valley (*Maianthemum canadense*), lady fern (*Athrium filix-femina*), and downy violet (*Viola sproria*). The more sandy habitat type, however, lacks the nutrient-demanding species (e.g., lady fern, downy violet) that appear on the loamy soils (Coffman et al. 1980).

Validation of habitat types

Since the habitat type themes were based on several different coverages, the boundaries needed to be validated using data that were not incorporated in the process of delineating the habitat type boundaries. The habitat type theme for the NLP was overlaid onto a 1993 Landsat TM image (MDNR-Wildlife Bureau and MDNR-Land and Mineral Services Division, Resource Mapping and Aerial Photography 2000) of land cover, the habitat type theme for the UP was overlaid onto a 1991 Landsat TM image (MacLean Consultants, LTD. 1995), and the SLP habitat types were overlaid onto a 1992 satellite image (USGS 1999) to determine if the habitat type coverages agreed with actual vegetation. The datasets selected were used for validation because they are the most current digital coverages that displays vegetation types and 2 of the coverages are fairly accurate based on ground truthing and the use of aerial photos: (80.20% for the 1993 Landsat image, MDNR-Wildlife Bureau and MDNR-Land and Mineral Services Division, Resource Mapping and Aerial Photography 2000; 80-100% for the 1991 Landsat image, MacLean Consultants, Ltd. 1995). The accuracy assessment for the 1991 thematic mapper image (USGS 1999), however, was not complete. Habitat type boundaries followed the boundaries of current vegetation types closely. The edges of most vegetation types in the Landsat images were very distinctive, and it was relatively easy to determine if there were discrepancies.

The following procedure was used to validate the NLP habitat types using the1993 Landsat TM landcover data. The NLP habitat type theme was initially overlaid onto the landcover data. I selected each habitat type individually, viewed the attributes of that particular habitat type (i.e., specifically, climax vegetation, soil type and moisture regime), and determined the vegetation composition according to the 1993 dataset that occurs within the boundaries of the habitat types. I then compared the 1993 vegetation composition with the habitat type and determine if the composition could be one successional stage within the habitat type. For example, the attributes of the habitat type being evaluated may have consisted of northern hardwoods (e.g., beech-maple forest), growing on moderately well drained sandy loam. If the 1993 dataset indicated that aspen occurred within the boundaries of the habitat type, I would have concluded that the habitat type was valid. If, however, the 1993 dataset indicated that cedar occurred within the boundaries of the habitat type, I would have concluded that there was an error somewhere in the delineation process. This error most likely had occurred in the presettlement vegetation since it was based on notes from the General Land Office Survey (Comer et al. 1995), the soil associations, or the 1993 dataset. Seventeen questionable areas were identified in the NLP and then field checked. [Note: The UP habitat types were validated with a similar procedure using the 1991 image. The SLP habitat types were validated with a similar procedure using 1992 satellite image and the literature (e.g., Bryant 1963, Dodge and Harman 1985, Dodge 1987). The discrepancies in the UP and SLP were not field checked, but were addressed using literature of vegetation descriptions of the area.]

Process for quantifying habitat potential

The literature suggests that white-tailed deer habitat consists of 3 general requirements: fall and winter food and thermal cover (i.e., winter habitat), and spring and summer habitat. Fall and winter foods consist of highly preferred hard mast such as acorns and beechnuts, and such fruits as black cherries and hawthorns (Rogers et al. 1981). Deer shift their diets from grasses, leaves, and forbs to browse with the first frosts in autumn (Blouch 1984) and may supplement their diets with agriculture crops when available (Gladfelter 1984). The quality of fall and winter food affects winter survival as well as the attainment of fertility in young deer (Morton and Cheatum 1946) and productivity of older deer (Morton and Cheatum 1946, Cheatum and Severinghaus 1950).

In Michigan where deep snow restricts movements and cold temperatures and wind stress their energy reserves, deer tend to concentrate in heavy coniferous cover (i.e., thermal cover), which blocks snow and provides a more stable microclimate (Ozoga and Gysel 1972). In areas with severe winters, thermal cover is essential for deer to maintain energy reserves throughout the winter.

Early successional stages of upland hardwood and upland mixed hardwood/conifer sites provide spring and summer habitat because they support growth of herbaceous vegetation such as grasses, sedges, forbs, and ferns (Rogers et al. 1981), which are important spring and summer food items. Nutritious and easily digestible spring and summer diets are important for reproduction, body growth of fawns, and antler development (Verme and Ullrey 1984). Also, Mautz (1978) indicated that high quality summer deer foods are critical for accumulating a fat layer as their winter energy reserve.

To quantify habitat potential within each habitat type, it was necessary to identify habitat features that describe each life requisite. I constructed a habitat classification key for each of the 3 requirements that is, essentially, a summary of the information that was important for development of the habitat potential models. The habitat classification key includes: 1) variables describing vegetation structure and composition that are important for deer habitat, 2) suitability values (e.g., 0 to 1; 1 = high suitability) for each variable based on the preferred structure/composition of vegetation to provide deer habitat requirements, and 3) literature sources describing vegetation structure or white-tailed deer habitat preferences within the Great Lakes region (Appendices 4-6).

Each study area differs in geological characteristics and vegetation composition. Also, geological and ecological information that was available in one study area may not have been available in other study areas. Therefore, it was necessary to construct different models to quantify habitat potential for different study areas (Table 2).

Habitat requirement: fall and winter food

Information from the habitat type database (e.g., soil characteristics) and quantitative vegetation structural (e.g., diameter at breast height (dbh), basal area) and compositional data were included in the fall and winter food potential model. Fall and winter food potential is a function of woody browse (Equation 1), mast production (Equations 2a or 2b), and site quality (Equations 3a or 3b). Equation 4 was used to quantify the potential of a habitat type to provide fall and winter food for deer.

Table 2. Guide to equations constructed by Felix to quantify white-tailed deer habitat potential in 3 study areas of Michigan. SLP = southern Lower Peninsula, NLP = northeastern Lower Peninsula, UP = Upper Peninsula.

Area	No.	Equation	Page
ALL	(1)	Browse index = [(browse quality index) + (browse availability index)] / 2	23
SLP, NLP	(2a)	Mast index = [(spp. index) * (DBH index) * (basal area index)] + mast bonus	25
UP	(2b)	Mast index = greater of (oak HT rank * oak succ.stage rank) or (beech HT rank* beech succ. stage rank)	29
NLP	(3a)	Site quality = [(fertility index) * (moisture index) * (landform index)]/3	33
SLP, UP	(3b)	Site quality = [(fertility index) * (moisture index)/2	33
NLP, UP	(4a)	FWFP = [[2 * (browse index) + (mast index)]/3] * site quality index	36
SLP	(4b)	FWFP = [[(browse index) + (mast index)]/2] * site quality index	36
NLP, UP	(5)	Forest composition index = (forest type index) * (coniferous species index)	38
NLP, UP	(6)	$\text{Forest structure index} = \dfrac{2 * \left[\dfrac{\text{basal area index} + \text{canopy cover index} + \text{tree size index}}{3}\right] + \text{age structure index}}{3}$	40
NLP, UP	(7)	TCP = forest composition index * forest structure index * site quality index	43
ALL	(8)	SSHP = (VT preference index) * (forage avail. index) * (site quality index)	44

Browse—all study areas

Browse is defined as living twigs ≤ 0.25 inches in diameter and < 7 feet from the ground (Ryel 1953, Mackey 1996). Suitability of woody browse is a function of the average of browse quality and browse availability (Equation 1).

(1) Browse index = [(browse quality index) + (browse availability index)] / 2

Where:

Browse quality index: a 0-1 ranking of potential of browse species based on palatability and nutritional characteristics.

Browse availability index: a 0-1 ranking of the relative availability of browse within a stand.

Browse quality—Preferred browse species generally are more nutritious and palatable to deer than non-preferred species (Davenport 1941, Ullrey et al. 1964, Ullrey et al. 1967, Ullrey et al. 1968). Therefore, browse quality indices are 0 to 1 rankings of potential browse species based on nutritional characteristics (e.g., high protein, low fiber levels) and palatability. Most preferred browse species include basswood, cedar, hemlock, red maple, and sugar maple (Davenport 1941) and, therefore, received a browse quality index of 1.0. Somewhat preferred browse species include black ash, birch, black cherry, and American elm and received a browse quality index of 0.75. Less preferred browse species include aspen, beech, oak, jack pine, white pine, and balsam poplar. A browse quality index of 0.5 was assigned to those foods. "Last resort" browse species were assigned a browse quality index of 0.25 and include beech, red pine, spruce, tamarack, and balsam fir (Appendix 4a). The browse quality index for seral stages with more than one potential browse species was calculated as the average of quality indices for each dominant browse species present in the seral stage.

Browse availability—In addition to browse quality, the quantity of browse that is available to deer also influences fall and winter food suitability. Browse availability is influenced by the age of a stand. For instance, a regenerating aspen stand (0-10 years) provides an abundance of browse [i.e., many aspen stems provide twigs that are within a deer's reach (<6 ft) (Graham et al. 1963)] and received a browse availability index of 1.0. An old growth (100+ years) maple stand, however, does not provide abundant browse and received a browse availability index of 0.0.

One of 5 indices assigned to a potential browse species indicated relative browse availability (Appendix 4a). An availability index of 1.0 = high availability; 0.75 = moderately high availability; 0.5 = medium availability; 0.25 = hardly available; 0 = not available to deer based on normal browsing patterns (i.e., trace amounts of browse may be available). These indices were assigned based on the assumption that browse production is, in part, a function of stand age (Ryel 1953). Deciduous species were assumed to have high browse availability in age class 1-10 years. High browse availability of aspen continues during the 10-30 year-old age class. Browse availability tends to decrease as deciduous trees age because although edible material is produced, it is largely above the reach of deer (Graham et al.1963). Therefore, older stands have lower availability indices. Coniferous species were assumed to have high browse availability in the age class 20-50 years (Ryel 1953, Verme 1965). The amount of browse on cedar trees, for example, increases up to 3 inches DBH and then decreases due to self-pruning of lower branches (Lake States Forest Experimental Station 1940). Data describing browse production for coniferous species other than cedar (e.g., balsam fir, spruce, pine) were not found and, therefore, were assumed to follow the same relative browse production pattern as cedar.

Several potential browse species could be available in one seral stage. For example, in a 10-30 year old red oak stand (availability index = 0.5), 1-10 year old red maple (availability index = 1) could be growing in the understory. The browse availability index for the stand is the highest availability index of each potential browse species. In the above case, for instance, the browse availability index of the oak-maple stand would be 1.0.

<u>Mast—southern Lower Peninsula and northeastern Lower Peninsula</u>

In the SLP and NLP, mast is a function of the type of potential mast species, and basal area and DBH of the dominant mast producing species (Equation 2a).

(2a) Mast index = [(spp. index) * (DBH index) * (basal area index)] + mast bonus

Where:

Spp. index: a 0-1 ranking of the quality of hard mast producing species.

DBH index: a 0-1 ranking that describes the ideal DBH (in) of mast species for optimal mast production.

Basal area index: a 0-1 ranking that describes the ideal basal area (ft^2/ac) structure of mast species for optimal mast production.

Mast bonus: addition of 0.05 if mast producing species other than oak or beech are present.

Species index and mast bonus—Mast is defined as the fruit of forest trees and is categorized into hard mast (e.g., nuts such as beechnuts and acorns) and soft mast (e.g., berries such as black cherries). Mast is essential for providing fall and winter food for deer (Duvendeck 1964). In Lower Michigan, oaks are the main mast producing species (Armbruster et al. 1987, as cited in Bender and Haufler 1987). Acorns typically make up the bulk of all mast consumed by deer (Harlow et al. 1975). Therefore, sites dominated by oak are assumed to have higher fall and winter food potential than sites dominated by other mast species (e.g., beech) (Bender and Haufler 1987). Stands dominated by oak received a mast species index of 1.0 whereas stands dominated by beech received a mast species index of 0.5. Other mast species received a mast species index of 0.0 (Appendix 4b).

Although stands containing soft mast species have a mast species index equal to 0.0, they still provide some fall and winter food value to deer. Soft mast species such as black cherry may provide a supplement to fall and winter diets and therefore, presence of soft mast may increase the potential of an area to provide fall and winter food. Stands that contain soft mast species have an added suitability bonus of 0.05.

Diameter at breast height— Diameter at breast height of the dominant mast producing species describes the ideal tree size for optimal mast production. Generally, oaks (i.e., red oak, white oak, black oak) begin to bear fruit at age 25 (3-7 inches DBH), but not abundantly until around age 50 (7-12 inches DBH) (Rogers 1990, Sander 1990a, Sander 1990b). Duvendeck (1964) observed that mature oaks > 40 years and ≥ 12 inches

DBH have relatively high acorn yields. Since oaks have the potential for producing acorns when they are 3-7 inches DBH, seral stages that contain oaks 3-7 inches DBH have a DBH index of 0.5. Smaller oaks would not produce acorns and, therefore, received a DBH index of 0.0. Seral stages that could contain oak with an average DBH ≥ 12 inches received a DBH index of 1.0 Appendix 4b).

Beech trees initially start to produce mast at age 40 (approximately 4 inches DBH) but it is not until about 60 years (approximately 8 inches DBH) that they produce large quantities (Tubbs and Houston 1990). Since beech trees have the potential for producing mast when they are about 4 inches DBH, seral stages that contain beech 4 inches DBH received an index of 0.5. Anything smaller would not produce nuts and, therefore, received a DBH index of 0.0. Seral stages that could contain beech with an average DBH ≥ 12 inches DBH received a DBH index of 1.0 (Appendix 4b).

<u>Basal area</u>—The final variable for quantifying mast production is basal area (ft^2/ac) of the dominant hard mast producing species, which describes the ideal structure of a stand for optimal mast production. Data on basal area of oak and beech for different size or age classes were limited. Subsequently, the relationship between size/age, and basal area for habitat types containing oak and beech are assumed based on literature describing other aspects of oak or beech stand structure (e.g., size and stem density). The only basal area information for oak in mixed stands was from Host et al. (1987), who measured a 42-52 ft^2/ac basal area for a 71-73 year-old oak in a mixed oak ecosystem in northwest Lower Peninsula. In the SLP, oak may occur in "pure" stands [e.g., associates in the stand comprise no more than 20% of the stocking (Eyre 1980)]. Basal area of oak averaging 3-6 in DBH in pure stands can reach 40-70 ft^2/ac and stands averaging 11-20 in

DBH can reach a basal area > 90 ft^2/ac (Marty and Rudolph 1970). Basal area for different age classes of beech was estimated from data describing the average number of trees per acre in various size classes for beech in southern Michigan (Schneider 1966) (Appendix 4b).

This model assumes that acorn production is maximized when the basal area of oak exceeds 32.7 ft^2/ac (Armbruster et al. 1987, as cited in Bender and Haufler 1987) and beechnut production is maximized when basal area of beech exceeds 17 ft^2/ac. I could not find data that describe the ideal basal area of beech for optimal mast production; therefore, the following describes the process used to generate the ideal structure for beechnut production: The average maximum size of beech trees in the Lake States is approximately 20-25 inches DBH (200-250 years) (Tubbs and Houston 1990). Larger diameter trees generally have larger crowns than smaller diameter trees. Crown size seems to be an important factor in mast production in general, with larger crowns producing more mast (Christisen and Korschgen 1955, Goodrum et al. 1971, Sander 1990). Therefore, it can be assumed that the largest size trees have the largest crowns, and would produce the most mast if the entire canopy is healthy. That is, beech trees between greater than 20 inches DBH would produce the largest mast crops. Schneider (1966) estimated that a typical sugar maple-beech stand in southern Michigan supports approximately 5 trees per acre that are > 20 inches in diameter. The basal area, then, for a stand containing 5 beech trees per acre with an average DBH > 20 inches is 17 ft^2/ac.

An additional assumption regarding basal area is that a few large trees has the same potential production as many smaller trees. To have a basal area equal to 17 ft^2/ac, then, a stand where the DBH of beech averages 16.5 inches must have a stem density of 11 trees/ac. This structure is reasonable based on Schneider's (1966) data.

If a seral stage contained mast producing trees in the 10-30 year age class (mixed stands) or in the 1-10 year age class (pure stands), the stand was assumed to have a basal area that had some suitability (0.5) for mast production. It was assumed that any seral stage containing mast producing trees < 10 years-old does not have the basal area structure necessary for adequate mast production and, therefore, received a basal area index of 0.0. The basal area of oaks decreases in late successional stages in the NLP because there, oaks occur in middle successional stages and as vegetation succeeds, oaks are gradually replaced by climax vegetation such as red maple or white pine (Burger and Kotar 1999). In the SLP, oaks may be dominant in the climax stage. Therefore, basal area suitability remains optimal for mast production in later successional stages (Appendix 4b).

Mast—Upper Peninsula

In the SLP and NLP, oak and beech are dominant components of several habitat types and therefore structural data (e.g., dbh, basal area) could be associated with different successional stages within certain habitat types. In the UP, however, oak is rarely a dominant component of habitat types (Coffman et al. 1980). Subsequently, it was difficult to assign structural data for oak in different habitat types to quantify oak mast potential. A model alternative to the one for the NLP was developed for the UP site. In the UP mast model, mast is a function of potential mast species, habitat type, and successional stage (Equation 2b).

(2b) Mast index = greater of (oak HT rank * oak succ.stage rank) or (beech HT rank* beech succ. stage rank)

Where:

Oak HT rank: a 0-1 ranking of habitat types, according to the relative degree to which a habitat type can support oak.

Oak succ. stage rank: a 0-1 ranking of successional stages according to the stage at which oak would be most prevalent.

Beech HT rank: a 0-1 ranking of habitat types, according to the relative degree to which a habitat type can support beech.

Beech succ. stage rank: a 0-1 ranking of successional stages according to the stage at which beech would be most prevalent.

Oak HT rank and beech HT rank—The habitat type rank indicates in which habitat type oak or beech are more likely to occur or represent a larger basal area than oak or beech in other habitat types. This index ranks a habitat type according to the relative degree to which it can provide oak or beech mast for deer.

To rank habitat types according to the relative degree to which they can support oak, the location of oak stands in the study area was identified in ArcView from a 1991 Landsat TM image of the Upper Peninsula (MacLean Consultants, LTD. 1995). This information was converted into a shapefile, which was spatially joined with the habitat type shapefile for the UP. Once spatially joined, oak stand density within each habitat type was determined and distributed in 5 categories based on natural breaks in the data. Habitat types in each category were assigned suitability values of 0.2, 0.4, 0.6, 0.8, and

1.0 from lowest to highest category, respectively. Habitat types such as lowland sites dominated by swamp conifers that would not typically support oak received a habitat type rank index of 0.0. This approach assumed that the density of oak stands within habitat types as determined from a spatial join of information from the Landsat TM image (MacLean Consultants, LTD. 1995) and habitat type shapefiles is an accurate indicator of the relative amount of oak mast that a habitat type can potentially provide. The ranking of the habitat types based on oak stand density corresponded with descriptions from The Society of American Foresters of oak composition within different cover types (Eyre 1980).

Beech is an associate in several habitat types in the UP because many of the habitat types are characterized by well to moderately well drained sandy to loamy soils, which are conducive to supporting beech (Tubbs and Houston 1990). The 1991 Landsat TM image did not classify individual beech stands, but rather included beech in the "northern hardwood" classification (MacLean Consultants, Ltd. 1995). Habitat types were ranked according to the relative degree to which they can provide beech by first identifying the habitat types that would not typically support beech [e.g., excessively drained sandy soils or poorly drained soils (Tubbs and Houston 1990)] and assigning those habitat types a suitability index of 0.0. Habitat types characterized by drier soils (e.g., well drained or excessively well drained sand) received a suitability index of 0.8 since beech is sensitive to decreased soil moisture (Tubbs and Houston 1990). Habitat types characterized by well drained to moderately well drained sandy or loamy soils, the optimal conditions for beech production (Tubbs and Houston 1990), received a suitability index of 1.0. Because deer prefer acorns over beechnuts, and acorns make up the bulk of all mast consumed by deer (Harlow et al. 1975), the suitability values assigned to habitat types for ranking beech mast production were multiplied by 0.75. That is, the highest ranking that a habitat type could obtain for beech mast production as it relates to deer fall and winter food suitability is 0.75. This assumes that sites dominated by beech have lower mast suitability for deer than sites dominated by oak (Bender and Haufler 1987).

Oak and beech successional stage ranks—The successional stages within each habitat type were ranked according to the stage at which oak or beech would be most prevalent. Oak is generally not a climatic species and, therefore, is most prevalent in middle successional stages (i.e., 30-100 years) before it is out-competed by more shade tolerant species (Sander 1990a). Middle successional stages, then, received a 1.0 for the successional stage ranking for oak. Earlier and later stages decreased in suitability for providing oak mast. Beech, on the other hand, is highly shade tolerant and is recognized as a climax species (Tubbs and Houston 1990). Late successional stages (i.e., > 100 years) received a 1.0 for the successional stage ranking for beech because they most likely provide more beech mast than earlier stages. Suitability decreases in earlier stages.

The mast index is the larger product of (the habitat type ranking for oak * the successional stage ranking for oak) or (the habitat type ranking for beech * the successional stage ranking for beech). This model assumes that relative mast quality and production in a given area can be determined through assessment of geological conditions favorable for supporting oak and beech, and successional stages at which oak and beech are likely to be most prevalent.

Site Quality

Landform characteristics, soil chemical properties (e.g., fertility), and soil physical properties (e.g., texture and moisture content) affect the growth and productivity of forests (Merkel 1988). Therefore, an assessment of site quality based on geological attributes is essential for evaluating the productive potential of forests (Merkel 1988). Site quality is a function of soil fertility, soil moisture, and landform type in the NLP (Equation 3a) or soil fertility and soil moisture in the SLP and UP (Equation 3b). Landform information was unavailable for the SLP and UP sites.

(3a) Site quality = [(fertility index) * (moisture index) * (landform index)]/3

(3b) Site quality = [(fertility index) * (moisture index)/2

Where:

Fertility index : a 0-1 ranking of soils based on nutrient holding potential.

Moisture index: a 0-1 ranking of moisture content according to vegetation growth potential at a particular moisture content.

Landform index: a 0-1 ranking of landform type according to vegetation growth potential on soils derived from a particular landform.

Soil fertility within habitat types —Initially, habitat types with the same overstory successional trajectory were identified. If different soil types could support the same successional trajectory, the habitat types were ranked based on soil fertility (For example, beech-maple forests typically occur on loamy-sandy loam soils (Tubbs and Houston 1990). Soil fertility is naturally low in sandy soils whereas loamy and clay soils have a higher fertility (Williams 1998). Habitat types with sand received a soil fertility index of 0.6, those with sandy loam received an index of 0.8 and those with loam or clay received an index of 1.0. If, however, a trajectory occurred on *only one* soil type [e.g., jack pine communities in the NLP characteristically grow on sand (Nutter 1973, Larsen 1982)], then the fertility index for that soil type was 1.0 since there is no comparison between other soil types.

Soil moisture content within habitat types—Since soil moisture content also influences site productivity (Johnson et al. 1987), it is an important variable for determining site quality. Moisture content was ranked according to the conditions in which the habitat types typically occur. For example, cedar does not develop well on extremely wet or extremely dry sites (Johnston 1990) but does best on sites with slow drainage (Ku 1954). Therefore, poorly drained or somewhat poorly drained soils received a higher soil moisture index (e.g., 1.0) for cedar dominated communities than very poorly drained or well drained and drier sites. Black spruce, tamarack, and black ash communities grow best on the wettest sites with little or no drainage (Ku 1954) and received a moisture index of 1.0 on poorly drained or very poorly drained soils. Upland hardwoods such as sugar maple, beech, or hemlock communities develop best on moderately well drained or well drained, but not excessively well drained soils (Livingston 1905) and, therefore, received a moisture index of 1.0 on well drained soils. Excessively well drained sites received a moisture index of 1.0 for red pine and jack pine dominated vegetation types (Livingston 1905). White pine, red maple, or oak communities typically occur on well drained soils (Livingston 1905); thus well drained soils for those types of communities received a moisture index of 1.0.

Landform—Type of landform (i.e., parent materials and topography) influences soil development and plant species composition (Rowe 1969). Landform type, or variations in parent material composition and topography, may exert a significant influence on species establishment and growth (Host et al. 1987) and, therefore, is included in assessing site quality for different habitat types. Twelve landforms as indicated by the LTA coverage (DeLain et al. 1999) occurred in the NLP site: limestone/dolomite, broad moraine ridge, moraine ridge, broad flat outwash plain, narrow outwash channel, ice contact ridge, flat moraine or till plain, flat lake plain, pitted outwash plain, deltaic deposit, dune-swale complex, and drumlin field.

Habitat types with the same overstory successional trajectory were identified. If a trajectory occurred on only one LTA, the landform index for the habitat types with that specific trajectory was 1.0. If, however, different LTAs could support the same successional trajectory, the LTAs were ranked according to the degree to which they provide suitable vegetation growing conditions. For instance, cedar grows best on limestone-derived soils (Johnston 1990). Therefore, limestone-dolomite LTAs received a landform index of 1.0. Any other landform received a lower index (e.g., 0.8) because cedar does not grow best on them. Moraines and till plains typically have moderate to high fertility (Knapp 1993). Ice contact ridges have little to no nonpedogenic textural bands, which are important to forest growth whereas outwash plains have no bands and generally have low fertility (Host et al.1987). Johnson et al. (1987) observed that productivity of northern hardwoods was lower when they grow on outwash plains than other landform types. Based on the above information, for northern hardwood types, moraine ridges and till plains were ranked higher (e.g., 1.0) than ice contact ridges (e.g., 0.8), which were ranked higher than outwash plains (e.g., 0.6). Flat lake plain rankings depended on soil types since fertility of soils derived from lake plains depends largely on soil type [e.g., sands derived from lake plains are largely infertile (e.g., landform index = 0.6), whereas loams have higher fertility (e.g., landform index = 0.8 for sandy loams, and 1.0 for loams) (Knapp 1993)]. Not enough information was found to rank deltaic deposits, dune-swale complexes, or drumlin fields. These LTAs were assumed to have the same landform index as other LTAs that supported the same trajectory.

Fall and winter food potential

Fall and winter food potential in the NLP and UP is the weighted average of browse and mast production indices modified by the site quality index (Equation 4a). In the SLP, fall and winter food potential is the average of browse and mast production indices modified by the site quality index (Equation 4b).

(4a) FWFP = [[2 * (browse index) + (mast index)]/3] * site quality index

(4b) FWFP = [[(browse index) + (mast index)]/2] * site quality index

Where:

FWFP: an index of fall and winter food potential on a scale of 0-1; 1 = highest potential.

Browse index: output from Equation 1.

Mast index: output from Equation 2a or 2b.

Site quality index: output from Equation 3a or 3b.

This model assumes that in the NLP and UP, browse is twice as important in supplying fall and winter food as mast. Throughout the fall and winter in Michigan, annual fluctuations in mast production and snow cover causes mast availability to be unpredictable. Therefore, browse is the only food that is continuously available during the fall and winter (Blouch 1984). Mast is important, however, because a prolonged diet of only woody browse may cause starvation in deer (Mautz 1978). In the SLP, the model assumes that browse is not twice as important as mast since mast is more available in the SLP due to less snowfall than in the northern areas (Sommers 1977).

The model also assumes that better quality sites, as assessed by the site quality index (Equation 3) support a higher yield and quality of plants (Keorper and Richardson 1980) and, therefore, the vegetation growing on the higher quality sites would provide better habitat conditions. It is important to include site quality evaluation in a wildlife habitat assessment because the quality of soils directly affects the quality and yield of vegetation (i.e., habitat), which may affect presence, abundance, distribution, viability, or physical condition of wildlife. Research (e.g., Severinghaus and Moen 1983, Ford et al. 1997) suggests that there is a positive relationship between the physical condition of deer and habitat quality. Since soils directly affect vegetation quality and production (Denney 1944), and the physical condition of wildlife reflects variations in habitat quality (Ford et al. 1997), it is reasonable to assume that soil fundamentally affects the physical condition or distribution of wildlife (Albrecht 1944, Denney 1944, Crawford 1950). Studies to support the argument that soil conditions affect the physical condition of wildlife found that there was a positive relationship between soil fertility or quality and the physical condition of rabbits and raccoons, (as measured by size) in Missouri (Albrecht 1944, Denney 1944, Crawford 1950).

Habitat requirement: thermal cover

Information from the habitat type database and quantitative vegetation structural and compositional data from the literature were also included in the thermal cover potential model. Thermal cover potential is a function of forest composition (Equation 5), forest structure (Equation 6) and site quality (Equation 3). Equation 7 was used to quantify the potential of a habitat type to provide thermal cover for deer in the NLP and UP. Thermal cover was not considered an important deer requirement in the SLP based on unpublished data by J. Pusateri (M.S. Graduate Research Assistant at Michigan State Uiversity, Department of Fisheries and Wildlife) for southern Lower Michigan.

Forest Composition

Forest composition is a function of the type of forest (i.e., deciduous or coniferous) and the type of dominant coniferous species within a seral stage (Equation 5).

(5) Forest composition index = (forest type index) * (coniferous species index)

Where:

Forest type index: a 0-1 ranking of the relative ability of certain types of forests (e.g., coniferous, deciduous, mixed) to provide thermal cover for deer.

Coniferous species index: a 0-1 ranking of the relative ability of the dominant coniferous tree species to provide thermal cover for deer.

Forest type—Verme (1965) suggested that the type of forest overstory substantially affects the microclimate and the amount of snow that reaches the ground. Swamp conifers provide much better protection from severe temperatures and snowfall than deciduous stands. Stands comprised of a mixture of coniferous and deciduous types also provide better protection from winter weather than purely deciduous stands (Verme 1965). Seral stages in which the forest type is coniferous received a forest type index of 1.0; mixed coniferous stands received a forest type index of 0.5, and deciduous stages received a forest type index of 0.0 (Appendix 5).

Coniferous species—Northern white-cedar and hemlock are the optimal species for thermal cover protection in Michigan due to their excellent ability to protect against strong winds, block snow, and provide winter forage (Verme 1965, Euler and Thurston 1980, Blouch 1984, Doepker and Ozoga 1991). Therefore, seral stages dominated by cedar and hemlock receive a coniferous species index of 1.0. Spruce- and fir-dominated stages are less suitable as thermal cover and received a coniferous species index of 0.8. Although spruce and fir have adequate snow and wind blocking characteristics, they do not provide the excellent forage associated with cedar and hemlock (Davenport et al. 1953) and are, therefore, less suitable as wintering areas by deer. Pine stands are sometimes utilized as thermal cover only if other preferred swamp conifers are absent (Bender and Haufler 1987). Since the wind and snow interception abilities of pine are not as suitable as those of cedar, hemlock, spruce, or fir types, stages dominated by pine received a coniferous species index of 0.4 (Appendix 5).

A reduction function is used to evaluate the forest composition index. If a stand is deciduous, it has no potential for providing thermal cover. The suitability of coniferous and mixed coniferous/deciduous stands, however, depends on the type of dominant coniferous species present. Coniferous or mixed stands have the highest potential for providing thermal cover when cedar or hemlock dominates and the lowest potential when pine dominates.

Forest Structure

Important structural attributes for determining thermal cover potential include basal area, percent canopy cover, tree size (diameter), and the age structure of the forest (e.g., even-aged or uneven-aged) (Equation 6). This model assumes that deer will initially select stands based on the vertical structure of the vegetation and not the age structure of the stand. Therefore, the suitability of the vegetation structure, as indicated by the average of basal area, canopy cover, and tree size indices, is weighted twice as important in determining thermal cover potential as age structure.

$$\text{(6)} \quad \textbf{Forest structure index} = \frac{2 * \left[\dfrac{\textbf{basal area index} + \textbf{canopy cover index} + \textbf{tree size index}}{3}\right] + \textbf{age structure index}}{3}$$

Where:

Basal area index: a 0-1 ranking that describes the ideal basal area (ft^2/ac) structure for optimal thermal cover protection in lowland coniferous vegetation types.

Canopy cover index: a 0-1 ranking that describes the ideal percent canopy cover for optimal thermal cover protection.

Tree size index: a 0-1 ranking that describes the ideal average tree diameter size (in) for optimal thermal cover protection.

Age structure index: a rating of 1 if the stand is even-aged and a rating of 0 if the stand is uneven aged.

Basal area—Basal area is an important variable to quantify thermal cover suitability because it measures the ability of a stand to block wind from the side and indicates relative degree of canopy cover (Nelson 1951). Basal area categories for habitat types that could potentially provide thermal cover (e.g., lowland swamp conifers) were obtained from several sources describing the structure of cedar. [Note: Basal area data were not available for lowland conifers other than cedar. Therefore, it is assumed that basal area trends for other species will be similar to those of cedar.] Generally, increasing age of cedar is correlated with increasing basal area (Gevorkiantz and Duerr 1939), but the maximum basal area that a typical cedar stand obtains is approximately 300 ft^2/ac at maturity (100-200 years) (Johnston 1990).

This model assumes that wind blockage for white-tailed deer is maximized when the basal area is 174-261 ft^2/ac (Bender and Haufler 1987). The basal area of typical 50 year-old cedar stands (i.e., stands dominated by cedar but also contain associated species such as balsam fir, spruce species, or lowland hardwoods) is approximately 200 ft^2/ac (Johnston 1990). It was assumed that cedar stands > 30 years would have the basal area structure necessary for adequate wind blockage and, therefore, received a basal area index of 1.0 (Appendix 5). Cedar in the 10-30 year age class may have a basal area ranging from 30-100 ft^2/ac depending on site conditions (Johnston 1990). Cedar in the 10-30 year age class may provide some thermal protection although it would be less suitable than older age classes. Therefore, cedar 10-30 years of age received a basal area index of 0.5, and younger cedar stands received a 0.0.

Seral stages within certain habitat types may be dominated by species other than cedar (e.g., spruce or hemlock), but still potentially provide thermal cover for deer. Since other conifers such as spruce and hemlock commonly occur in the same seral stages as cedar, it was assumed that the basal area of stands dominated by those species would still fall within the basal area categories assigned for cedar.

Canopy cover—Information on the canopy cover structure for different age classes of stands dominated by lowland tree species was limited. It was assumed that lowland stands 1-50 years of age had 40-70% canopy cover and anything older had 70-100% canopy cover. A tight canopy (> 75% cover) appreciably reduces snowfall and wind within the stand (Verme 1965, Ozoga 1968). Therefore, seral stages with 70-100% canopy cover received a canopy cover index of 1.0 and stages with 40-70% cover received an index of 0.5 (Appendix 5).

Tree size—Highest quality deer wintering areas are generally dominated by mature or older lowland swamp conifers (Verme 1965, Ozoga 1968, Doepker and Ozoga 1991). Larger trees (i.e., pole size or larger) generally provide a more stable microclimate and better protection from wind and snowfall than smaller trees (i.e., saplings) (Verme 1965, Ozoga 1968, Ozoga and Gysel 1972). For example, a deeryard that supported a large deer herd throughout the winter near Shingleton, upper Michigan consisted mainly of cedar 6-12 inches in diameter (Verme and Johnston 1986). Cedar 4-8 inches in diameter dominated a deeryard in northern Lower Michigan (Ozoga and Gysel 1972).

The diameter of mature cedar (approximately 100 years old) can range from pole size (3-7 inches) to sawtimber size (> 9 inches) depending on site quality (Johnston 1990). Therefore, seral stages that contain lowland swamp conifers that are pole size or larger received a tree size index of 1.0. Saplings can still provide some thermal cover for deer. Thus, sapling-size trees (0.5-3.0 inches dbh) received a tree size index of 0.5 and anything smaller received a 0.0 (Appendix 5).

Age structure—Verme (1965) indicated that deer did not use uneven-aged stands dominated by large cedar for thermal cover. In uneven-aged stands, much of the snowfall is not intercepted and accumulated on the ground (Verme 1965). In addition, the understory is relatively drafty and prone to wide temperature fluctuations, thus providing little thermal protection for deer (Verme 1965).

Even-aged stands provide the best conditions for thermal protection (Verme 1965). Lowland coniferous stands are typically even-aged until about 150-200 years when windfall of old trees creates an uneven structure. Therfore, seral stages > 150 years-old received an age structure index of 0.0 and stages < 150 years-old received an index of 1.0 (Appendix 5).

Thermal cover potential

Thermal cover potential is calculated by the following reduction function (Equation 7):

(7) TCP = forest composition index * forest structure index * site quality index

Where:

TCP: an index of thermal cover potential on a scale of 0-1; 1 = highest potential.

Forest composition index: output from Equation 5.

Forest structure index: output from Equation 6.

Site quality index: output from Equation 3a or 3b.

This model assumes that forest composition, forest structure, and site quality are equally important in determining the potential of an area to provide thermal cover. Deer select stands for thermal cover based on the forest composition and forest structure variables, which are unique to particular stands. Site quality, however, affects the size and productivity of vegetation and is unique to individual habitat types. Recall that the structure of stands varies widely. Diameter of mature cedar, for example, can range from pole size to sawtimber size (Johnston 1990). Ryel (1953) observed that where site quality differed, the ages of trees of the same diameter also differed. That is, for a given diameter, the average age of trees from high quality sites (as assessed by ring evaluation and soil conditions) was lower than the average age of trees from lower quality sites (Ryel 1953). Therefore, the site quality index indicates that the structure (e.g., diameter, basal area) of vegetation growing on higher quality habitat types would be on the upper end of the range and, therefore, would provide better habitat conditions than vegetation growing on lower quality habitat types.

Habitat requirement: spring and summer habitat

In the NLP and UP, spring and summer habitat potential, a critical requirement for reproduction, growth of fawns, and antler development (Verme and Ullrey 1984), is primarily a function of habitat type and successional stage (Equation 8).

(8) SSHP = (VT preference index) * (forage avail. index) * (site quality index)

Where:

SSHP: an index of spring and summer habitat potential on a scale of 0-1; 1= highest potential.

VT preference index: a 0-1 ranking of the relative ability of vegetation types to provide spring and summer habitat requirements (e.g., food, cover) based on deer preference for specific vegetation types (Kohn and Mooty 1971, McCaffery et al. 1974, Mackey 1996).

Forage availability index: a 0-1 ranking that reflects the intensity of summer deer use based on the relative amounts of forage available in different successional stages.

<u>VT preference index</u>—During the spring and summer, white-tailed deer appear to utilize some habitat types more than others. The most important factor governing deer use of habitat types appears to be availability of preferred forage species (Kohn and Mooty 1971, McCaffery et al. 1974). Track counts and observations of deer locations in Minnesota indicated a preference for upland deciduous and upland mixed (i.e., deciduous and coniferous) vegetation types over upland coniferous types, lowland types, and fields or grassy open areas (Kohn and Mooty 1971). For example, on a tracking survey, Kohn and Mooty (1971) observed that 70% of deer tracks occurred in upland deciduous and mixed types, which comprised 52% of the total tracking route. Fifty-four percent of radio collared deer were located in these types, which accounted for 53% of deer home ranges.

This suggests that deer use of upland deciduous and upland mixed types is greater than availability, and therefore, deer are selecting for those types over other vegetation types (Kohn and Mooty 1971). Kohn and Mooty (1971) observed that deer used the upland deciduous and mixed types intensively for morning and evening foraging. Specifically, deer utilized aspen for summer foraging (Kohn and Mooty 1971). McCaffery et al. (1974), Stormer and Bauer (1980), and Mackey (1990) reported that white-tailed deer also intensively used aspen for summer foraging in Wisconsin and Michigan. Since the upland deciduous and mixed vegetation types provide spring and summer food for deer, the habitat type preference index for these types is 1.0 (Appendix 6).

Deer use of upland coniferous vegetation types in Minnesota was not as extensive as deer use of the upland deciduous and mixed types (Kohn and Mooty 1971). For example, deer tracks were observed in 7.5% of upland coniferous vegetation types, which accounted for 10% of the tracking route (Kohn and Mooty 1971). Upland coniferous types comprised an average of 24% of deer home ranges, and radio-collared deer were located in those areas approximately 24% of the time (Kohn and Mooty 1971). These data suggest that since use of upland coniferous types is proportional to availability, deer are not actively selecting for coniferous types. Although coniferous types do not provide the excellent forage that upland deciduous and mixed types provide during the spring and summer, Kohn and Mooty (1971) observed that upland coniferous types may be important for bedding during midday. Therefore, upland coniferous vegetation types received a 0.4 for the habitat type preference index.

Kohn and Mooty (1971) observed that deer tended to avoid lowland areas during the spring and summer. Approximately 5% of tracks and 0.6% of deer locations occurred in lowland coniferous, lowland deciduous, and lowland shrub vegetation types, which comprised 19.1% or the track route and 2.9% of deer home ranges (Kohn and Mooty 1971). Mackey (1990) observed that deer in the Stonington Peninsula of Michigan's Upper Peninsula used lowland coniferous vegetation (e.g., cedar) more than expected in the summer. Deer in other parts of the Upper Peninsula, however, did not use lowland coniferous types. Since deer use lowland types for spring and summer habitat less than other vegetation types, these types received a vegetation type preference index of 0.2. Although lowland areas are generally not utilized extensively in the spring and summer, the vegetation type preference index is not 0 because lowland areas and wetlands may be important providers of aquatic emergent plants, which may be an important source of nutrients for deer (Davenport 1941) (Appendix 6).

Successional stage index—Nutritious and palatable forage is critical in the spring when deer are nutritionally stressed following the winter, and metabolic rates begin to increase as deer prepare for fawning and antler growth (Verme 1969). Studies conducted in Minnesota (Kohn and Mooty 1971), Wisconsin (McCaffery et al. 1974), and Michigan (Stormer and Bauer 1980) indicated that in the spring and summer, white-tailed deer tend to utilize early successional stages (i.e., 1-30 years) of upland habitat types, which provide more spring and summer forage than mature (i.e., 30-100 years) or late successional (i.e., > 100 years) forests.

In Minnesota, deer use of upland forested habitat types was inversely proportional to the age of the stand since the availability and quality of spring and summer forage tends to decrease as stands mature (Kohn and Mooty 1971, Stormer and Bauer 1980). For example, leaves of aspen, and current year's growth of plants (e.g., aspen, maple, honeysuckle) < 3 m tall comprised approximately 70% of the total food consumed during the summer in Minnesota (Kohn and Mooty 1971). The most intensive use of stands within upland deciduous and upland mixed forest types occurred when the trees were < 30 feet tall and < 10 feet apart (Kohn and Mooty 1971), which is characteristic of early successional stages. In Wisconsin, summer deer distribution among forest types reflected the distribution of aspen (McCaffery et al. 1974). Similarly, in Michigan, leaves of regenerating aspen rated high in preference as summer deer food (Stormer and Bauer 1980).

Deer use of a particular habitat type largely depends on the successional stage of the forest. For example, Kohn and Mooty (1971) observed that the most intensively used areas within a deer's home range were in early successional stages and were less intensively used after the trees reached maturity. Studies have suggested that over time, natural plant succession can result in deficiencies in the quantity and quality of spring and summer deer food (Verme 1969). Since spring and summer deer food is more abundant and more preferred in early successional vegetation types of upland deciduous and mixed forests and spring and summer use declines in later successional forests, early successional stages received a 1.0 for the forage availability index. Middle successional stages of habitat types dominated by upland deciduous and upland mixed vegetation received a 0.6 and late successional types received a 0.2 (Appendix 6).

Upland coniferous vegetation may be important as bedding areas and were most intensively used in Minnesota when trees were 11-29 feet apart and slightly over 50 feet tall (Kohn and Mooty 1971). Early successional stages of upland coniferous types may also provide some food and therefore, the successional stage index is 1.0 for early stages and middle stages of habitat types dominated by upland conifers throughout succession. Suitability declines to 0.5 for mature stages of upland coniferous types (Appendix 6). Lowland types are assumed to follow the same suitability pattern throughout succession as upland deciduous and mixed types. Therefore, early successional stages received a 1.0, middle stages received a 0.6, and late stages received a 0.2.

Spring and summer habitat potential

This model assumes that the type of vegetation (e.g., upland deciduous, mixed deciduous and coniferous, lowland coniferous), successional stage as an index to the relative amount of forage available, and site quality are equally important in determining the potential of an area to provide spring and summer habitat for deer. Deer select stands based on the vegetation composition indicative of the habitat type, and also, the degree of maturity of the vegetation. Site quality (Equation 3) affects the size and productivity of vegetation (Merkel 1988) and is unique to different habitat types. It is assumed that higher quality sites support a higher yield and nutritional quality of plants (Keorper and Richardson 1980) and therefore, would provide better spring and summer habitat conditions for deer.

RESULTS

Southern Lower Peninsula

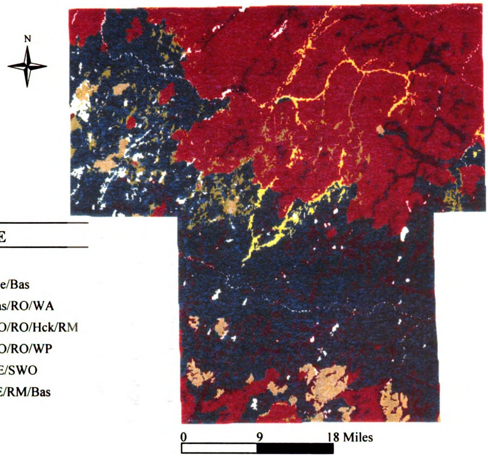
Successional pathways

There were 995 polygons delineated in the SLP site with 6 possible successional pathways (Table 3, Figure 2). The SLP site is divided into 2 broad forest types:

Table 3. Possible successional pathways and proportion of the southern Lower Peninsula study area within each successional trajectory (Traj.). Dominant overstory vegetation is identified for early-, mid-, and late-successional stages. A = aspen, AE = American elm, BA = black ash, Bas = basswood, BC = black cherry, Bee = beech, Bir = white birch, CO = black oak, Cw = cottonwood, For = forbs, G = grass species, Hck = hickory species, LBr = lowland brush, RM = red maple, RO = red oak, Sdg = seedges, Shr = shrub, SM = sugar maple, SiM = silver maple, SWO = swamp white oak, WA = white ash, Wil = willow species, WO = white oak, WP = white pine. Open Water includes all lakes and rivers.

Traj.	Prop.	EARLY	MID	LATE
0	0.021	Open Water		
1	0.399	A	SM/Bee/Bas/RM/WA	SM/Bee/Bas
2	0.028	A/RO/Hck/BC	RM/SM/RO/WO/BC	RM/Bas/RO/WA
3	0.398	G/Sdg/For	G/Shr/BO/WO/BC	WO/BO/RO/Hck/RM
4	0.028	G/Sdg/For	G/Shr/BO/WO/RO/Hck	WO/BO/RO/WP
5	0.109	LBr	T/BA/Bir/RM/AE	RM/AE/SWO
6	0.017	Wil/Cw	SiM/AE/GA/Cw	SM/AE/RM/Bas

sugar maple-beech in the northern part and oak-hickory in the southern part (Dodge 1987). Nearly 40% of the study area (north) consists of mesic northern hardwood-dominated habitat types with aspen dominating early successional stages; sugar maple, beech, basswood, red maple, and white ash dominating middle stages; and sugar maple, beech and basswood dominating late successional stages (Table 3, Trajectory 1).



KEY

	EARLY	MID	LATE
0	Lake/River		
1	A	SM/Bee/Bas/RM/WA	SM/Bee/Bas
2	A/RO/Hck/BC	RM/SM/RO/WO/BC	RM/Bas/RO/WA
3	G/Sdg/For	G/Shr/BO/WO/BC	WO/BO/RO/Hck/RM
4	G/Sdg/For	G/Shr/BO/WO/RO/Hck	WO/BO/RO/WP
5	LBr	T/BA/Bir/RM/AE	RM/AE/SWO
6	Wil/Cw	SiM/AE/GA/Cw	SM/AE/RM/Bas

Figure 2. Location of areas with the same successional pathway in southern Michigan (Barry, Calhoun, and Eaton Counties). Vegetation codes for early, middle, and late successional stages are as follows: A = aspen, AE = American elm, BA = black ash, Bas = basswood, BC = black cherry, Bee = beech, Bir = white birch, CO = black oak, Cw = cottonwood, For = forbs, G = grass species, Hck = hickory species, LBr = lowland brush, RM = red maple, RO = red oak, Sdg = seedges, Shr = shrub, SM = sugar maple, SiM = silver maple, SWO = swamp white oak, WA = white ash, Wil = willow species, WO = white oak, WP = white pine.

Approximately 40% of the study area (south) consists of dry central hardwood-dominated habitat types with grasses, sedges, and forbes dominating early successional stages; grasses, shrubs, black oak, white oak, and black cherry dominating middle stages; and white oak, black oak, red oak, hickories, and red maple dominating late stages (Table 3, Trajectory 3). Eleven percent of the study area is in lowland deciduous types (Table 3, Trajectories 5-6). Other habitat types each comprised < 3% of the SLP site (Table 3).

Habitat suitability curves for each successional trajectory

Appendix 7 illustrates how fall and winter food, and spring and summer habitat suitability for deer changes throughout succession in the SLP. Fall and winter food suitability is generally highest during middle stages (ages 30-100) when the quality and abundance of mast and browse is high. Late successional stages generally do not provide high fall and winter food suitability for deer in the SLP. Fall and winter food suitability increases, however, in late successional stages habitat types where beech is dominant in climax stages (e.g., Appendix 7, Trajectory 1) and beech mast is available. Thermal cover does not seem to be a primary winter habitat requirement for deer in the midwest oak-hickory region, which includes southern Lower Michigan (Torgerson and Porath 1984). Spring and summer habitat suitability for deer in the SLP is highest in early successional stages (< 30 years).

Habitat potential

The habitat potential index within a habitat type for each deer habitat requirement was determined as the highest suitability for the requirement that a habitat type could attain based on vegetation and geological characteristics. Distinct regional differences in habitat potential are evident in the SLP study site (Figure 3, Figure 4). The distinct differences mirror the distribution of the mesic northern hardwoods and central hardwoods habitat types. The northern hardwoods do not provide as high quality fall and winter food or spring and summer habitat as those habitat types dominated by grasses, sedges, forbes in early stages and oak in later stages.

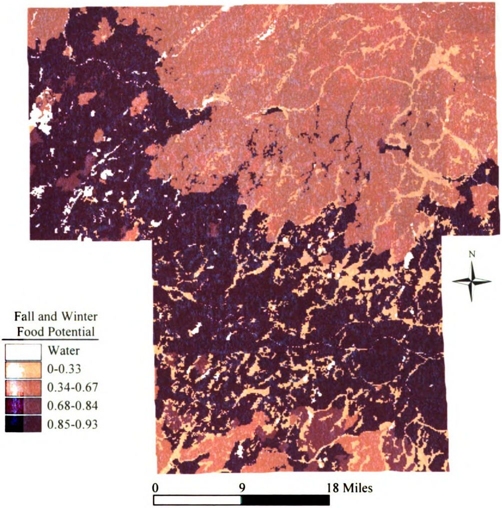


Figure 3. Distribution of white-tailed deer fall and winter food potential throughout a 1,872 mi^2 area in southern Lower Peninsula, Michigan (Barry, Calhoun, and Eaton Counties). Fall and winter food potential categories are classified based on natural breaks.

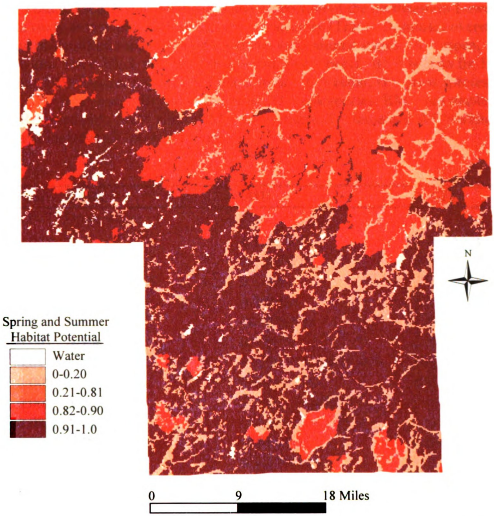


Figure 4. Distribution of white-tailed deer spring and summer habitat potential throughout a 1,872 mi^2 area in southern Lower Peninsula, Michigan (Barry, Calhoun, and Eaton Counties). Spring and summer habitat potential categories are classified based on natural breaks.

Northeastern Lower Peninsula

Successional pathways

Six hundred and thirty-two polygons were delineated in the NLP study site with 24 possible successional pathways (Table 4, Figure 5).

Table 4. Possible successional pathways and proportion of the northeastern Lower Peninsula study area within each successional trajectory (Traj.). Dominant overstory vegetation is identified for early-, mid-, and late successional stages. A = aspen, AE = American elm, BA = black ash, Bas = basswood, Bee = beech, BF = balsam fir, Bir = white birch, BP = balsam poplar, BS = black spruce, C = cedar, G = grass species, H = hemlock, JP = jack pine, LBr = lowland brush, O = oak species, RM = red maple, RO = red oak, RP = red pine, Shr = shrub, SM = sugar maple, T = tamarack WP = white pine. Open Water includes all lakes and rivers.

Traj.	Prop.	EARLY	MID	LATE
0	0.017	Open Water		
1	0.018	A	A/RM/WP	WP/RM/Bee/SM
2	0.266	A	O/RM/WP	WP/RM
3	0.009	A/BP	BA/AE	RM/SM/BA
4	0.001	A/BP/Bir	A/BP/BA	BA/C
5	0.037	A/Bir	BF/WS/RM	C/BF/RM
6	0.001	A/Bir	BS/BF/C	C/BS/BF
7	0.012	A/Bir	RM/Bee/WA/Bas/WP	SM/Bee/H
8	0.008	A/Bir	RM/Bee/WP	WP/RM/Bee/SM/WA
9	0.006	A/Bir	SM/Bee/Bas/RM/WA	SM/Bee
10	0.082	A/Bir	SM/Bee/Bas/RM/WA	SM/Bee/Bas
11	0.007	A/Bir	SM/O/Bee	SM/Bee/H
12	0.003	A/Bir	WP/RM/Bee	WP/RM/Bee/SM
13	0.016	A/Bir	BS/BF/C	C/BS/BF
14	0.013	A/JP	JP/RP	RO/RM/WP
15	0.011	A/O	O/RM/WP/BC	WP/RM/Bee/SM
16	0.018	LBr	BS/T/BF/C/BA	BS
17	0.016	JP/WP/RP/O	JP/WP/RP/RM/BC	WP/RM
18	0.001	LBr/T/BA/Bir	T/BA/RM	C/BS/BF
19	0.009	LBr	BS/T/BF/C/WP	BS/T
20	0.098	LBr/A/Bir/BP/BA	C/BS/BF	C/H
21	0.056	LBr/Bir/T/BA	C/BS/BF	C/BS/BF
22	0.025	LBr/Bir/T/BA	T/BA/RM	C/BS/BF
23	0.233	Shr/G	JP/RP/WP/O	WP/RP/O/JP
24	0.037	T/BA/Bir/RM	T/BA/Bir/RM/C	C/BS/BF

KEY

	EARLY	MID	LATE
0	Lake/River		
1	A	A/RM/WP	WP/RM/Bee/SM
2	A	O/RM/WP	WP/RM
3	A/BP	BA/AE	RM/SM/BA
4	A/BP/Bir	A/BP/BA	BA/C
5	A/Bir	BF/WS/RM	C/BF/RM
6	A/Bir	BS/BF/C	C/BS/BF
7	A/Bir	RM/Bee/WA/Bas/WP	SM/Bee/H
8	A/Bir	RM/Bee/WP	WP/RM/Bee/SM/WA
9	A/Bir	SM/Bee/Bas/RM/WA	SM/Bee
10	A/Bir	SM/Bee/Bas/RM/WA	SM/Bee/Bas
11	A/Bir	SM/O/Bee	SM/Bee/H
12	A/Bir	WP/RM/Bee	WP/RM/Bee/SM
13	A/Bir	BS/BF/C	C/BS/BF
14	A/JP	JP/RP	RP/RM/WP
15	A/O	O/RM/WP/BC	WP/RM/Bee/SM
16	LBr	BS/T/BF/C/BA	BS
17	JP/WP/RP/O	JP/WP/RP/RM/BC	WP/RM
18	LBr/T/BA/Bir	T/BA/RM	C/BS/BF
19	LBr	BS/T/BF/C/WP	BS/T
20	LBr/A/Bir/BP/BA	C/BS/BF	C/H
21	LBr/Bir/T/BA	C/BS/BF	C/BS/BF
22	LBr/Bir/TBA	T/BA/RM	C/BS/BF
23	Shr/G	JP/RP/WP/O	WP/RP/O/JP
24	T/BA/Bir/RM	T/BA/Bir/RM/C	C/BS/BF

Figure 5. Location of areas with the same successional pathway in northeastern Michigan (Presque Isle, Alpena, Montmorency, Alcona, and Oscoda Counties). Vegetation codes for early, middle, and late successional stages are as follows: A = aspen, AE = American elm, BA = black ash, Bas = basswood, Bee = beech, BF = balsam fir, Bir = white birch, BP = balsam poplar, BS = black spruce, C = cedar, G = grass species, H = hemlock, JP = jack pine, LBr = lowland brush, O = oak species, RM = red maple, RO = red oak, RP = red pine, Shr = shrub, SM = sugar maple, T = tamarack WP = white pine.

Approximately 27% of the study area consists of an uplands dry-mesic hardwoods habitat type with aspen dominating early successional stages; red oak, red maple, and white pine dominating middle successional stages; and white pine and red maple dominating late successional stages (Table 4, Trajectory 2). Approximately 23% of the study area consists of excessively dry mixed hardwood-conifer habitat type with shrubs and grass species dominating early stages; jack pine, red pine, white pine, and oak species dominating middle stages; and white pine, red pine, oak species, and jack pine dominating late successional stages (Table 4, Trajectory 23). Only 10% of the study area is dominated by lowland brush, aspen, balsam poplar, and black ash in early stages; cedar, spruce, and fir in the middle stages, and cedar with hemlock and other conifer species as minor components in late successional stages (Table 4, Trajectory 20). Other habitat types each comprise < 10% of the NLP study area (Table 4).

Habitat suitability curves for each successional trajectory

Appendix 8 illustrates how the suitability of vegetation to provide fall and winter food, thermal cover, and spring and summer habitat for deer changes throughout succession in the NLP. Fall and winter food suitability generally is highest during early and middle successional stages (< 30-100 years) when browse and mast is most abundant. Late successional stages generally do not provide high fall and winter food suitability for deer. Habitat types in the NLP that have thermal cover potential (e.g., poorly drained sites that support lowland conifers at some time during succession) generally provide best thermal protection for deer in the middle to late successional stages (> 100 years). Suitability tends to decrease in late stages (> 150 years) when lowland conifers become uneven-aged. Spring and summer habitat suitability for deer is highest in early successional stages (< 30 years).

Habitat potential

Distinct regional differences in habitat potential are evident throughout the NLP study area (Figures 6-8). The distinct differences tend to follow habitat types which distinguish vegetation in the northern portion (i.e., predominantly poorly drained, coniferous types), from vegetation in the southern portion (i.e., predominantly dry-mesic deciduous or mixed coniferous-deciduous types). It is evident that, according to the model, habitat types in the southern portion of the study area have higher fall and winter food potential than those in the northern portion (Figure 6).

The reverse pattern is evident for the distribution of thermal cover (Figure 7). High thermal cover potential mirrors the distribution of habitat types characterized by poorly drained soils and dominated by conifers, which occur in the northern portion of the study area. Habitat types dominated by hardwood forests, mixed coniferous-deciduous forests, and upland coniferous sites in the southern portion of the study area will never provide high thermal cover protection for deer.

Habitat types that support upland mixed coniferous-deciduous and upland deciduous vegetation throughout succession largely occur in the northern portion of the study area and have high potential for providing spring and summer habitat (Figure 8).

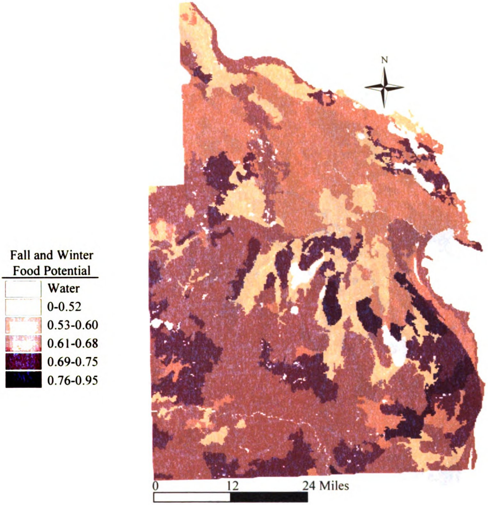


Figure 6. Distribution of white-tailed deer fall and winter food potential throughout a 3,132 mi^2 area in northeastern Lower Peninsula, Michigan (Presque Isle, Alpena, Montmorency, Alcona, and Oscoda Counties). Fall and winter food potential categories are classified based on natural breaks.

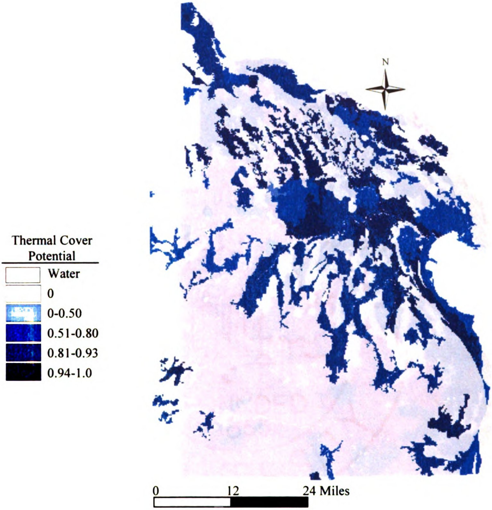


Figure 7. Distribution of white-tailed deer thermal cover potential throughout a 3,132 mi^2 area in northeastern Lower Peninsula, Michigan (Presque Isle, Alpena, Montmorency, Alcona, and Oscoda Counties). Thermal cover potential categories are classified based on natural breaks.

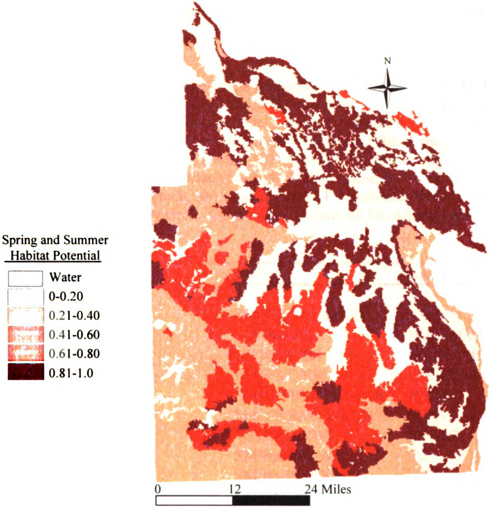


Figure 8. Distribution of white-tailed deer spring and summer habitat potential throughout a 3,132 mi^2 area in northeastern Lower Peninsula, Michigan (Presque Isle, Alpena, Montmorency, Alcona, and Oscoda Counties). Spring and summer habitat potential categories are classified based on equal intervals.

Upper Peninsula

Successional pathways

There were 1,848 polygons delineated in the UP study site with 16 possible successional pathways (Table 5, Figure 9). Approximately 53% of the study area

Table 5. Possible successional pathways and proportion of the Upper Peninsula study area within each successional trajectory (Traj.). Dominant overstory vegetation is identified for early-, mid-, and late-successional stages. A = aspen, AE = American elm, BA = black ash, Bas = basswood, Bee = beech, BF = balsam fir, Bir = white birch, BP = balsam poplar, BS = black spruce, C = cedar, G = grass species, H = hemlock, Iw = ironwood, JP = jack pine, LBr = lowland brush, RM = red maple, RO = red oak, RP = red pine, Shr = shrub, Spg = sphagnum, SM = sugar maple, T = tamarack, WA = white ash, WP = white pine, YB = yellow birch. Open Water includes all lakes and rivers.

Traj.	Prop.	EARLY	MID	LATE
0	0.024			
1	0.001	A	SM/RM/Iw/Bas/YB	SM/H
2	0.006	A/BP	WA/BA/AE	WA/RM/SM/BA
3	0.011	A/BP/Bir	BF/WS/C/BS	H/RM/SM
4	0.035	LBr/A/BP/Bir	BF/WS/C/RM	H/RM/SM
5	0.030	A/Bir	SM/WP/RM/YB/RO/BF	H/RM
6	0.283	A/Bir	SM/YB/RM/Iw/BF/WS	SM/H
7	0.022	A/Bir	WP/RP/BF/WS	RM/RO
8	0.058	A/SM	SM/Bas/RM/Bee	SM
9	0.016	A/SM	SM/Bas/RM/YB/Iw	H/SM
10	0.222	A/SM	SM/RM/YB/Iw	SM/H
11	0.030	A/SM/WA	SM/Bas/Iw/Bee/WA/AE	SM
12	0.031	LBr	LBr/Bir/RM/BP	BS/C/H
13	0.094	LBr	T/BA/Bir/RM	C/BS/BF
14	0.066	LBr/Bir/BP	C/BS/BF	C/H
15	0.049	Shr/G	JP	JP/RP
16	0.023	Spg/LBr	BS/T/BF/C	BS/T

KEY

	EARLY	MID	LATE
0	Lake/River		
1	A	SM/RM/Iw/Bas/YB	SM/H
2	A/BP	WA/BA/AE	WA/RM/SM/BA
3	A/BP/Bir	BF/WS/C/BS	H/RM/SM
4	LBr/A/BP/Bir	BF/WS/C/RM	H/RM/SM
5	A/Bir	SM/WP/RM/YB/RO/BF	H/RM
6	A/Bir	SM/YB/RM/Iw/BF/WS	SM/H
7	A/Bir	WP/RP/BF/WS	RM/RO
8	A/SM	SM/Bas/RM/Bee	SM
9	A/SM	SM/Bas/RM/YB/Iw	H/SM
10	A/SM	SM/RM/YB/Iw	SM/H
11	A/SM/WA	SM/Bas/Iw/Bee/WA/AE	SM
12	LBr	LBr/Bir/RM/BP	BS/C/H
13	LBr	T/BA/Bir/RM	C/BS/BF
14	LBr/Bir/BP	C/BS/BF	C/H
15	Shr/G	JP	JP/RP
16	Spg/LBr	BS/T/BF/C	BS/T
17	Exposed Bedrock		

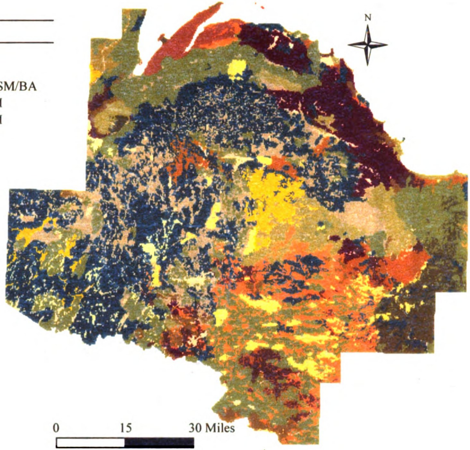


Figure 9. Location of areas with the same successional pathway in Upper Michigan (Baraga, Marquette, Dickinson, and Iron Counties). Vegetation codes for early, middle, and late successional stages are as follows: A = aspen, AE = American elm, BA = black ash, Bas = basswood, Bee = beech, BF = balsam fir, Bir = white birch, BP = balsam poplar, BS = black spruce, C = cedar, G = grass species, H = hemlock, Iw = ironwood, JP = jack pine, LBr = lowland brush, RM = red maple, RO = red oak, RP = red pine, Shr = shrub, Spg = sphagnum, SM = sugar maple, T = tamarack, WA = white ash, WP = white pine, YB = yellow birch.

consists of mesic northern hardwood-dominated habitat types with aspen dominating early successional stages; sugar maple, red maple, ironwood, and basswood dominating middle stages (with various species representing minor components); and sugar maple and hemlock dominating late successional stages (i.e., Table 5, Trajectories 6, 9, 10). Approximately 16% of the study area is dominated by poorly drained cedar-spruce-fir forests (Table 5, Trajectories 13, 14). Other habitat types each comprise < 6% of the UP study site (Table 5).

Habitat suitability curves for each successional trajectory

Appendix 9 illustrates how fall and winter food, thermal cover, and spring and summer habitat suitability for deer changes throughout succession in the UP. Fall and winter suitability is generally highest during middle stages (Ages 50-100) when the quality and abundance of browse and mast is high. Late successional stages generally do not provide high fall and winter food suitability for deer in the UP. Habitat types in the UP that have thermal cover potential generally provide the best thermal protection for deer in the middle to late stages (> 100 years). Suitability tends to decrease in stages > 15 years when lowland coniferous stands become uneven-aged due to windfall or other disturbances. Spring and summer habitat suitability for dee in the UP is highest in early successional stages (< 30 years).

Habitat potential

No distinct regional differences in habitat potential are evident in the UP study site (Figures 10-12 as were evident in the NLP (Figures 6-8). Habitat types in the UP are more "patchy" or interspersed than in the NLP due to geological fragmentation caused by glacial activity. For example, areas characterized by mesic loamy soils that support northern hardwoods are frequently interspersed within areas characterized by shallow underlying bedrock that cause high water tables and support swamp conifers. Generally, fall and winter food potential is highest in Iron, southern Baraga, and central Marquette counties in habitat types that provide conditions conducive for supporting oak and beech (e.g., mesic northern hardwoods) (Figure 10). Drier, more sandy areas in Marquette and poorly drained areas throughout the study area do not provide high fall and winter food potential.

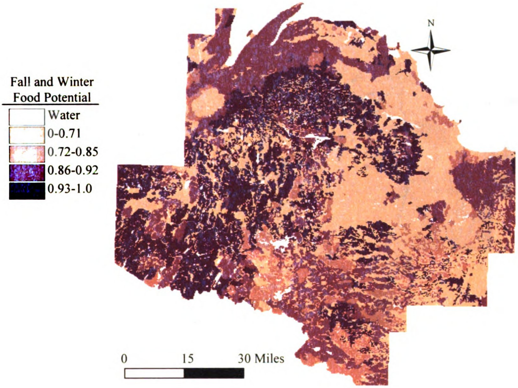


Figure 10. Distribution of white-tailed deer fall and winter food potential throughout a 4,696 mi^2 area in the Upper Peninsula, Michigan (Baraga, Dickinson, Iron, and Marquette Counties). Fall and winter food potential categories are classified based on natural breaks.

Habitat types that provide high thermal cover potential are interspersed throughout the study area and support lowland swamp conifers (Figure 11). Several habitat types in the UP study site have high spring and summer habitat potential for deer because they support aspen in early successional stages, which deer highly prefer during the spring and summer (Kohn and Mooty 1971, Mackey 1996) (Figure 12).

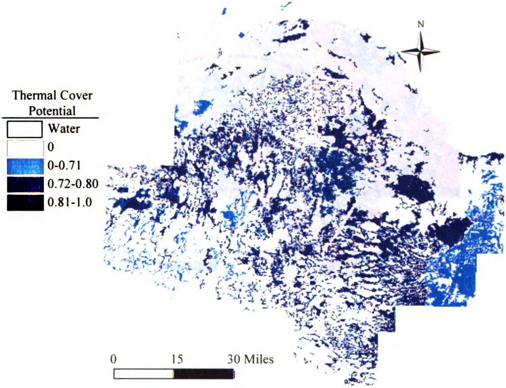


Figure 11. Distribution of white-tailed deer thermal cover potential throughout a 4,696 mi^2 area in the Upper Peninsula, Michigan (Baraga, Dickinson, Iron, and Marquette Counties). Thermal cover potential categories are classified based on natural breaks.

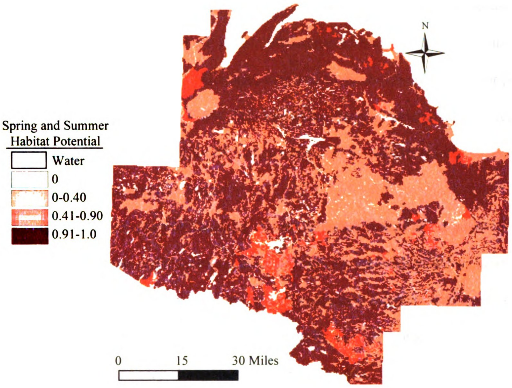


Figure 12. Distribution of white-tailed deer spring and summer habitat potential throughout a 4,696 mi^2 area in the Upper Peninsula, Michigan (Baraga, Dickinson, Iron, and Marquette Counties. Spring and summer habitat potential categories are classified based on natural breaks.

DISCUSSION

Consideration of agriculture in habitat potential models

In some areas of Michigan, white-tailed deer have evolved some dependence on agriculture (Gladfelter 1984, Braun 1996). For example, in the Midwest agriculture region, which includes southern Michigan, corn and soybeans comprise a major portion of a deer's fall diet (Gladfelter 1984). It is important, then, to understand how agriculture affects white-tailed deer habitat if one's objectives were to quantify white-tailed deer habitat suitability at a specified time.

Agriculture, as a habitat variable, was not included in the habitat potential models for the following reasons: First, the suitability of agriculture fields as a deer food source depends on the size of the field, the crop species cultivated, the type of tillage practice (e.g., fall plowed, no-till), and the distance to protective cover (Bender and Haufler 1984). These variables may change annually or seasonally.

Second, deer utilization of agriculture crops for food will differ in different areas of Michigan. For example, in the SLP, 65% of the area is in agriculture (as calculated with data from U.S. Geological Survey 1999); in the NLP, 10% of the area is in agriculture (as calculated with data from MDNR-Land and Mineral Services Division, Resource Mapping and Aerial Photography 2000); and in the UP, only 5% of the study area is in agriculture (as calculated with data from MacLean Consultants, Ltd. 1995). Deer utilization of agriculture crops has been studied in the NLP (e.g., Braun 1996), but has not been quantified in other areas. The presence of agriculture would most likely enhance food suitability if the fields are planted in preferred food types or if adequate cover is still available.

Third, factors such as agriculture and other land use are always going to modify the current habitat conditions for deer. White-tailed deer habitat potential, however, is an inherent characteristic, or a property, of the land. The habitat potential models constructed for this thesis are intended to serve as a foundation for analyzing white-tailed deer habitat within landscapes, and the relationship between landscape characteristics and deer demographics or distribution.

Value of habitat typing

Traditionally, natural resource classification or planning has been based on existing vegetation conditions or biotic attributes and developed for specific uses. Land cover classification, for example, is used widely by wildlife managers for habitat planning. Land cover databases indicate the type of material that covers the earth's surface at a specific location at a specific time. They do not consider, however, how abiotic factors might influence the distribution of wildlife and other natural resources. Consequently, when using land cover classification to evaluate wildlife species responses to management or to ecosystem change, managers must make assumptions about potential vegetation and successional dynamics, which could lead to unrealistic predictions.

Ecological classifications, an alternative to land cover classification, is based on ecological potential and is necessary to effectively manage natural systems. Habitat typing, a type of ecological classification, uses natural vegetation trajectories (i.e., biotic attributes) and geological features (i.e., abiotic attributes) to separate large heterogeneous areas into smaller, ecologically homogeneous units that are useful for management (Stocker et al. 1977, Kotar and Burger 2000). Each habitat type possesses unique biological and geological characteristics and is different from the rest. The habitat type database developed in this project incorporated information from other habitat typing guides (e.g., Coffman et al. 1980, Burger and Kotar 1999, Kotar and Burger 2000), soils associations, land type associations, ecoregions, and presettlement and current vegetation to recognize areas with the same ecological conditions that support the same successional trajectory (Figures 2, 5, 9). This habitat typing procedure provides a basis for better understanding the relationship between ecosystem structure, processes, composition, and the distribution of natural resources than solely examining land cover. For example, this project demonstrates the value of using habitat typing to describe the spatial and temporal distribution of deer habitat and how managers can use that information for deer management and planning throughout the state.

Habitat typing provides a logical separation of ecological units that are essential for effective natural resource management. An important key for wildlife management, for instance, is an understanding of the ecological and geological characteristics that drive the distribution of habitat. Several researchers have used land cover to map the distribution of deer habitat, which could determine the location for potential habitat improvement programs. But perhaps those areas identified for habitat improvement could never provide optimal conditions to provide certain deer habitat requirements based on inherent characteristics. For example, in the NLP, habitat types that support aspen, balsam poplar, and birch in early stages; aspen, balsam poplar, black ash in middle stages; and black ash, cedar in late stages have medium fall and winter food potential (0.65), medium thermal cover potential (0.50), and low spring and summer habitat potential (0.20). Programs to "improve" habitat for deer in these areas would still not result in providing excellent habitat conditions for deer (Appendix 8, Figure A8-4). Distinguishing habitat types that could potentially provide deer habitat from those that may not provide certain requirements would help identify target areas for habitat management. This project has clearly demonstrated the applicability of using an ecological classification system (i.e., habitat typing) coupled with landscape-scale models to identify areas for possible habitat management by recognizing those habitat types that have potential for providing specific white-tailed deer habitat components.

Since managers are facing increasing pressure to manage for the habitat needs of a growing list of species, many agencies are shifting their management approach from focusing on single species to maintenance of the structure, composition, and processes within entire systems over a broad planning landscape (i.e., an ecosystem-based management approach). Ecological classification systems will also aid managers in developing ecosystem-based management approaches. Ecosystem-based management implies incorporation of ecological processes (e.g., succession), and properties of landscapes at a broad spatial scale. The foundation for incorporating those ecosystem-based management concepts is habitat typing. By identifying boundaries of habitat types, managers can better understand the ecological processes such as succession, which occur within the habitat type. By analyzing several habitat types together, managers can understand community processes (e.g., dynamics of poorly drained coniferous forests). And by analyzing many habitat types at a broad spatial scale, managers can begin to understand spatial distribution of communities and species, spatial interrelations, and processes that occur throughout a landscape. With the emergence of new perspectives for management including ecosystem-based strategies, the habitat typing process will become increasingly important to managers interested in conserving ecosystem processes and ecological integrity.

Applications of habitat potential models

The MDNR has indicated that there is an urgent need to revisit Michigan's deer population goals and develop a deer management strategy that is scientifically based and considers the ecological relationship between population characteristics, dynamics, and distribution, and habitat dynamics and distribution (W. Moritz, MDNR, Wildlife Division, personal communication). The use of habitat potential models is the fundamental key for meeting the MDNR's need.

In natural resource management, habitat analyses based on existing land cover databases are often used to explain the distribution and structure of populations. If it is true that the distribution and structure of wildlife populations is determined only by the existing structure and composition of vegetation, it would be pointless to investigate anything other than that. However, no previous studies have investigated the relationship between habitat potential and the variations in population demographics. Perhaps inherent characteristics of habitat types can explain the distribution of deer or the occurrence of certain demographics. Perhaps the *existing* structure and composition of vegetation alone does not drive the distribution of deer but vegetation physiognomy, in combination with soil and geological conditions, does. Or perhaps *habitat potential*, a measure of the ability of an area to provide suitable deer habitat, explains trends in the distribution of deer or spatial trends in the distribution of deer demographics (Felix et al. In Press). For example, Verme (1973) observed that the dispersal tendencies of deer in the Upper Peninsula, Michigan were not different than those that occurred 30 years earlier, despite appreciable changes in habitat. It is evident that existing vegetation conditions were not the only factors influencing deer dispersal patterns because the habitat changed. Perhaps underlying characteristics or the area, or habitat potential, does play a role in determining dispersal patterns.

The boundaries and dynamics of habitat types do not change, unless they undergo natural or anthropogenic disturbances beyond conditions defined by their historical range of variability. Land cover, however, does change. If indeed there is a quantifiable relationship between habitat potential within habitat types and deer distribution or demographic patterns, managers can start to make more realistic predictions and recommendations for deer management. First, managers will be able to determine which areas are likely to support specific deer demographics such as larger antler beams, higher antler points and high fawn:doe ratios. Second, managers will be able to predict the distribution or movements of deer based on the location of habitat types that provide deer habitat requirements and the existing vegetation type of the respective habitat type. Third, managers will be able to define biologically meaningful deer management unit boundaries.

Understanding the relationship between habitat potential and deer demographics

Felix et al. (In Press) began initial investigations regarding the relationship between habitat potential and deer population demographics. Based on analysis of variance and Tukey-Kramer multiple comparison tests, we concluded that there was a significant ($P < 0.001$) negative relationship between fall and winter food potential and the distribution of yearling average antler beam diameters collected within each township from 1999 hunter harvest data in the NLP study area. Although the relationship was not positive, it was evident that distinct regional patterns existed both in the distribution of habitat components and deer demographics. We are further investigating the relationship between fall and winter food potential, thermal cover potential, and spring and summer habitat potential with other demographic parameters as well (Felix et al., unpublished data).

To provide meaningful results, the scale at which population demographic data are collected must be compatible with that of habitat types. In the Felix et al. (In Press) study, we used 1999 data collected at the township scale. As such, fall and winter food potential had to be re-scaled to that of the township. We re-scaled fall and winter food potential by calculating a weighted average of fall and winter food potential based on the proportion of each habitat type within each township. Re-scaling had to be done to conduct statistical analyses. The problem with re-scaling habitat potential to fit within township boundaries is that resolution is lost at the ecological scale that is important for deer. It would be ideal if hunter harvest data could be collected within habitat types, but if that is not feasible, at least it should be collected by townships (or section, if possible). Data collected by county is useless for this type of analysis because county boundaries are too large to describe deer demographic or movement patterns. There is a pressing need for a dataset that is collected consistently for several years at a scale that can be compatible with habitat types in order to effectively quantify the relationship between habitat potential and trends in deer distribution and demographics.

Understanding the relationship between habitat potential and deer spatial structure

Research (e.g., Felix et al., unpublished data) has also begun assessing the utility of white-tailed deer habitat potential models to understand deer spatial structure and subsequently define biologically meaningful deer management units (DMUs). Researchers (e.g., Verme 1973, VanDeelen et al. 1998) have argued that information on dispersal patterns would facilitate delineation of realistic management units for various herds. I would argue that information on dispersal patterns in conjunction with how they relate to habitat potential would facilitate establishment of deer management units based on similar ecological properties and similar potentials to provide deer life requisites.

We overlaid winter and summer home ranges of migratory deer (i.e., seasonal home ranges > 1 km apart) and non-migratory deer (i.e., overlapping seasonal home ranges) in the northeastern Lower Peninsula (Garner 2001) on the maps depicting habitat potential, which produced a product that indicated what proportion of each home range was in high or low habitat potential (Felix et al. 2002). It was evident that the juxtaposition of habitat types is useful in determining if or where deer move. For example, lowland swamp conifers are important for providing winter habitat requirements and early successional stages of northern hardwoods are important for providing summer habitat. It is apparent that habitat types cannot provide both winter and summer habitat requirements for deer. Therefore, it may be necessary for deer to shift their seasonal home ranges to obtain their annual life requisites (e.g., migratory deer), unless habitat types that provide seasonal life requisites occur adjacent to each other, thus allowing deer to obtain habitat requirements without moving (e.g., non-migratory deer).

The results of the analysis implied that habitat potential models can be used to explain spatial movement patterns of deer based on knowledge of the distribution of habitat types that can provide deer life requisites. An understanding of how deer movement patterns relate to habitat potential, in conjunction with identification of areas with similar population management goals, may aid in establishing effective and biologically meaningful deer management units.

Recommendations for applying habitat potential models to managing wildlife populations and habitat

The future of natural resources lies in maintaining the composition of native ecosystems through management that considers spatial and temporal patterns of ecological processes, the role of abiotic factors within systems, and how they influence ecosystem structure, function, and composition. Managers have begun to adopt this framework, but in doing so, have identified information needs at different levels of biological organization. First, knowledge of the spatial arrangement of ecosystems within landscapes allows managers to understand landscape structure, which, in turn, provides predictive ability on how properties of landscapes influence processes at the ecosystem and species levels (Haber 1990). Second, there is a pressing need to identify the composition and structure of species within ecological communities so managers can determine if inherent ecosystems exist and if ecosystems are functioning within their historical range of variability (Haufler et al. 2002). Haufler et al. (2002) indicated that such information is critical because an understanding of ecosystems is fundamental to making planning decisions for biodiversity. Third, there is a need for definitive spatial and temporal links between habitat supply and wildlife species response (e.g., viability). The use of habitat typing and the concept of habitat potential as a framework for managing systems has several applications at each of these levels of biological organization.

Landscape-level

Haufler et al. (2002) suggest that landscape-level planning should consider the amount of area needed to provide all successional stages of all native ecosystems to maintain species and processes associated with each ecosystem. The habitat type databases and spatial projections developed in this project are tools to aid in landscape-level planning since they identify boundaries of ecosystems (e.g., habitat types) and describe the successional pathway within habitat types. Using the habitat type database as a tool, managers can, first of all, identify the boundaries and properties (e.g., soils, land type associations, and potential vegetation) of ecosystems within the landscape. Secondly, through the spatial projections, managers can assess the structure of landscapes by quantifying the heterogeneity, size, arrangement, and connectivity of ecosystems (Noss 1990). These landscape characteristics affect the relationship between communities within different ecosystems and the distribution and dynamics of species (Noss 1990). Third, managers can compare the arrangement of habitat types and their ecological potentials with current conditions to assess if all stages of all habitat types are represented within the landscape. Haufler et al. (2002) indicated that representation of all potential ecological conditions within a planning landscape would allow for the maintenance of ecosystem integrity and biological diversity. Information identified at the landscape-level can then be linked to management at the ecosystem and species levels.

Ecosystem-level

Ecosystems are dynamic and require ecological processes to fluctuate within the historical range of variability for long-term functioning and sustainability. Natural variability within ecosystems allows them to withstand a range of disturbances without changing the processes that control its behavior (Haufler et al. 2002). Human use of resources tends to reduce the variability of ecosystems so that a steady flow of goods and services can be produced to satisfy human demands (Gunderson et al. 1995). Where once the threat of species extinction was perceived as the only problem resulting from the reduction of variability and diversity within systems, the loss of entire ecosystems is now a very real threat (Grumbine 1994, Noss et al. 1997). Management at the ecosystem-level, however, is beginning to be conducted to maintain ecological sustainability and consider natural processes that contribute to the variability in composition, structure, and function within systems (Vogt et al. 1997). Tools such as habitat type databases and spatial projections of habitat types could help managers maintain ecological integrity by identifying the ecological boundaries that delineate different systems, and describing structure, composition, and natural processes that are characteristic of each system (e.g., within habitat types).

Noss et al. (1997) indicated that managers lack information on the composition of potential vegetation, which is essential for understanding temporal changes within ecosystems. Habitat type maps and databases, such as those developed for this study, can be used to identify ecosystems that can potentially provide unique or rare characteristics and subsequently be managed to maintain those conditions. For example, Michigan has lost nearly all of its mature-old growth successional stages of oak, white pine-red pine, and beech-maple communities (Noss et al. 1997). Some areas that once provided these conditions cannot be realistically restored because they have been converted to cities or other developments. However, habitat type maps can identify other areas that could potentially be restored to those old growth communities. Figure 13, for instance, illustrates the location of habitat types that have the potential to provide old growth beech-sugar maple communities. The majority of these sites currently support early successional stages of northern hardwoods (44%) or agriculture (20%).

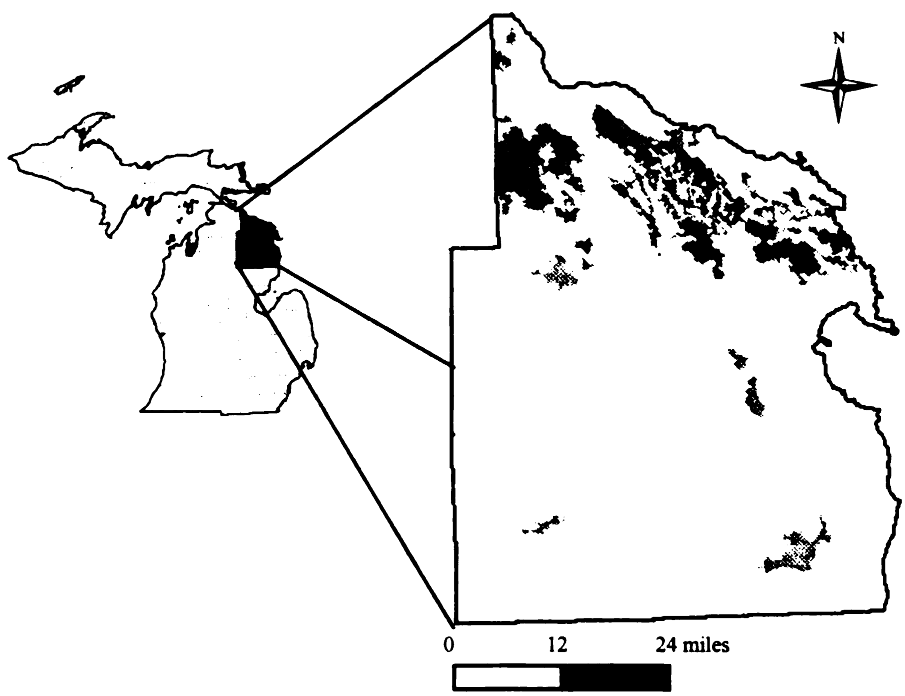


Figure 13. Location of areas in northeastern Lower Peninsula, Michigan that have the potential to support old growth beech-sugar maple forests based on the spatial output from the habitat type database for the northeastern Lower Peninsula developed by.

The habitat type databases can also be used for planning at the ecosystem-level. For example, the Civilian Conservation Corps established red pine plantations throughout Michigan beginning in the 1930s. Managers within the MDNR have indicated they would like to manage state forests for broad ecological objectives and would like to restore certain areas to natural vegetation by cutting red pine plantations on sites that would not naturally support red pine. They are, however, unsure what vegetation would regenerate subsequent to cutting red pine (B. Mastenbrook, MDNR, personal communication). Managers can use the habitat type database to identify the geological characteristics and successional paths inherent to those sites selected for cutting. Subsequently, managers can understand how the vegetation composition will change on those sites following the cutting of red pine.

Currently, the habitat type databases developed for this project contain information on successional trajectories, geological characteristics, and vegetation structural characteristics for each habitat type delineated. The databases only provide vegetation structural information for variables important for quantifying white-tailed deer habitat potential. They could, however, be the foundation for including additional vegetation structural characteristics or other information unique to different habitat types (e.g., the historical range of variability of conditions found within habitat types or frequency of processes driving those conditions). With knowledge of the historical range of conditions within habitat types and comparison of those to current conditions, managers can devise plans to either maintain the system if it is functioning within the historical range or restore systems that are not operating within the historical range of variability. An understanding of the historical range of variability within ecosystems can also provide insights to the needs of species that depend on certain vegetation types within ecosystems, and subsequently management can be linked between the ecosystem- and species-levels (Haufler et al. 2002).

Managers can use the habitat type database in conjunction with the habitat potential model process at the ecosystem-level to develop habitat potential models for communities that utilize the same resources. For example, research has indicated that management of forest birds has traditionally occurred within stands but perhaps would be more meaningful and effective if managers understood how habitat relationships, distributions, composition, and dynamics of bird species changes as vegetation changes temporally within ecosystems (Franzreb et al. 2000). Habitat potential models can be developed for bird communities that utilize the same ecosystem (e.g., northern hardwoods). Potential habitat for assemblages of birds can then be projected throughout space and time, giving managers an indication of which areas can provide vegetation conditions that are important for providing habitat requirements for groups of birds and when those vegetation conditions would be provided (Figure 14). Comparison of this potential with current distributions of species or assemblages of species would help managers identify areas that are not providing habitat for certain bird assemblages and should be targeted for forest bird management.

Species-level

Certain species may be targeted for management because of special interest (e.g., game species), conservation concern (e.g., restored or endangered species), or because they indicate trends or conditions in ecosystems (Haufler et al. 2002). Typical management questions for species are how, where, or when should managers manipulate

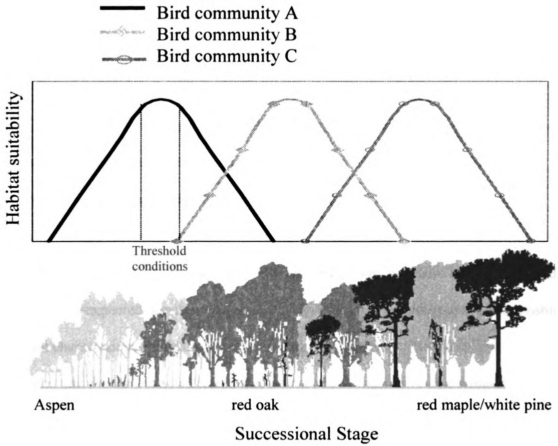


Figure 14. Hypothetical example of how managers might use habitat types and habitat potential modeling to understand temporal changes in forest bird community distribution. Output from habitat potential models developed for each bird community could produce suitability curves that would indicate which seral stages provide habitat for different forest bird communities. Viability of each bird community decreases below the threshold habitat conditions.

populations or habitat to obtain management objectives? Answers to these questions requires an understanding of how the distribution of ecological and geological characteristics drives the distribution of habitat. The ecological and geological information contained in the habitat type database and the modeling process used in this study can be used to develop habitat potential models for other species, thereby addressing the need for better defined relationships between wildlife species and the biotic and abiotic factors that define their habitat.

For example, moose (*Alces alces*) have generated the attention of Michigan biologists because they have not attained expected growth rates and population size since their re-establishment into the western Upper Peninsula in the mid 1980s. Michigan DNR biologists are concerned that uncertainties about moose population numbers and factors affecting population dynamics will hinder moose management efforts (Dodge 2002). Recent research has revealed that low moose reproductive rates have contributed to slower-than-expected population growth, but no studies have analyzed the relationship of habitat characteristics and components to moose productivity (Dodge 2002). Thompson and Stuart (1998) indicated that attempting to manage moose without knowledge of the relationships between the capability of an area to support moose and moose productivity is costly and ineffective, wastes time and resources, and may jeopardize moose populations. Clearly, there is a need to understand what underlying mechanisms influence elements of moose population dynamics (e.g., mortality, reproduction, movement) and demographic parameters (e.g., density, sex ratio, antler size).

Current research indicates that habitat potential can explain patterns in the distribution of white-tailed deer with specific demographic characteristic (Felix et al. In press) and spatial movement patterns (Felix et al. unpublished data). Therefore, it is reasonable to suggest that managers could use the same process to address similar population management questions for moose; specifically, what is causing low productivity? An evaluation of moose habitat potential throughout the western Upper Peninsula would entail identifying minimum winter and summer habitat requirements (e.g., food quantity and nutritional qualities, thermal cover) for moose, determining the types of soils and landforms on which vegetation providing moose habitat is most productive and assessing changes in suitability over space and time. Information on the spatial and temporal distribution of moose habitat, in conjunction with information on population dynamics (e.g., Dodge 2002) will allow managers to determine factors influencing observed low productivity rates. Subsequently, managers can target management activities on those specific factors influencing low production to sustain moose populations in Michigan that are in balance with the potential of the land.

Different species utilize habitat types at different scales. Deer and moose, for example, utilize many habitat types to obtain their life requisites. Smaller species, however, could obtain their life requisites within 1 stand or within regions of 1 stand. For example, red-backed salamanders (*Plethodon cinereus*) inhabit stands of northern hardwood habitat types that have appropriate soil properties and vegetation structure (Hanaburgh 2001). Sometimes, species such as salamanders are selected as indicators of specific ecological conditions such as soil type or specific stand characteristics such as amount of down woody debris (Hanaburgh 2001). Use of habitat type databases and maps and habitat potential models for indicators to assess the distribution and potential availability of specific ecological conditions is an important technique for biodiversity management. For example, a manager could use habitat type maps and databases to identify areas that could provide stand and soil conditions necessary for the salamanders. Microsite conditions within habitat types specific to salamanders or other small species could be incorporated into the database. The process used to quantify habitat potential for deer in this study could be adapted to quantify habitat potential at smaller scales for salamanders to produce a product that identifies which areas have the potential to provide specific ecological conditions necessary to sustain salamanders and other species associated with those conditions.

Often, habitat is not considered as much as it could be in species management, but rather, managers emphasize population management. Or, if habitat is considered in species management, conditions are usually assessed from existing land cover conditions and does not consider how abiotic factors might influence habitat composition and the distribution of wildlife. Subsequently, when predicting species response to management activities or ecosystem change, managers must make assumptions about species-habitat relationships, potential vegetation, and spatial and temporal changes in habitat. Making assumptions, in turn, could lead to unrealistic predictions.

Databases that contain information on spatial and temporal changes in vegetation structure and composition within habitat types and models that quantify habitat potential for various species are important tools for wildlife mangers to make realistic predictions based on: 1) an understanding of the spatial and temporal distribution of habitat requirements for a species; 2) quantified relationships between habitat potential and population demographics; and 3) identified factors that drive distributions of populations and productivity. Regardless of the reason for management of selected wildlife species (i.e., special interest, management concern, or as indicators), an understanding of habitat potential-population relationships is essential for effective, efficient, sustainable, and scientific species management.

Validation

The purpose of modeling is to represent a simplified version of a real-life system and provide an opportunity to explore ideas regarding ecological systems (Jackson et al. 2000). One of the challenges in modeling is evaluating the behavior of the model as it relates to real systems and with respect to how it is intended to be used (i.e., validation). The habitat type themes and the white-tailed deer habitat potential models developed in this thesis have yet to be validated.

The first step in validation is to assess whether or not the structure and functional relationships of the models and habitat type themes describe the composition and dynamics of deer habitat and how deer respond to it. The second step is to evaluate the correspondence between model behavior, expected patterns, and data from real systems. The following are some suggestions to validate the habitat type theme and habitat potential models.

Habitat type themes

The habitat type themes can be used to identify the location, composition, and successional dynamics within habitat types. The distribution of habitat types according to the habitat type themes developed in this thesis does seem reasonable and was verified, in part, through comparisons with satellite images of vegetation cover and land use (see methods section "Validation of habitat types" p. 18). Only some of the habitat types in the northern Lower Peninsula have been ground-truthed. The location of habitat types should be ground-truthed to validate the spatial arrangement of habitat types. Habitat types would need to be identified in the field through identification of soil properties and plants indicative of specific habitat types (e.g., Coffman et al. 1980, Burger and Kotar 1999).

Validation of successional pathways and structural characteristics of vegetation with in habitat types could be accomplished with a field study that used exclosures established in different vegetation types within habitat types. Exclosures would allow the investigator to observe how the composition and structure of vegetation changes in the absence of browsing.

White-tailed deer habitat potential models

The habitat potential models were constructed to describe inherent land characteristics and classify habitat types in a way that is ecologically meaningful to deer (Figures 3, 4, 6, 7, 8, 10, 11, 12). This type of information, when assessed with population demographic characteristics and movement data will help managers determine where it is necessary to establish different deer management goals or re-define biologically meaningful deer management units based on deer biology and the capability of areas to provide habitat components.

The model variables selected and the structure of the models to quantify white-tailed deer habitat potential seem logical and justified based on analysis of literature describing white-tailed deer habitat (see "Process for quantifying habitat potential" p. 14). Some variables or the model structure may need additional adjustment as more data become available. For example, white-tailed deer habitat components have not been quantified in southern Lower Michigan. Some of the information used to construct the models was based on preliminary data from initial studies with radio collared deer (e.g., J. Pusateri, graduate research assistant, Michigan State University, Department of

Fisheries and Wildlife). The models should be validated in the series of steps described below.

First, a relationship between habitat suitability to population viability metrics (e.g., fawn:doe ratios, yearling antler beam diameters, femur fat, winter survival) would have to be determined for each habitat requirement. For example, winter survival may be a suitable metric to evaluate thermal cover suitability, whereas, yearling antler beam diameters may be a suitable index to evaluate the relationship between population conditions and spring and summer habitat. Some assumptions, however, may be critical when investigating the relationship between habitat suitability and population viability. That is, density dependent factors may affect the observed relationship. For instance, within a population, antler beam diameter, weight, and reproductive rates of white-tailed deer vary with the nutritional level within a population (Severinghaus and Moen 1983). The nutritional level within a population is a function of population density as well as habitat quality and soil properties. To accurately quantify a relationship between habitat conditions and population viability, however, the population would need to be below the threshold that would adversely affect deer conditions and productivity. The second step in validating the habitat potential models is to assess current habitat conditions in successional stages of different habitat types. Then it can be determined where current conditions fall along the habitat suitability curves for each habitat type. Finally, research could examine the correspondence between the suitability of different habitat components and population metrics. It would not be necessary to evaluate parts of the models separately since the variables in the model are assumed to together represent the ability of vegetation types to provide deer habitat components.

Future directions

The MDNR has assumed a leadership role implementing ecosystem management to conserve, protect, and manage Michigan's natural resources for current and future generations (MDNR 2002). As such, the MDNR has begun to appoint management teams for different ecoregions of Michigan to develop strategies to sustain and enhance representative ecosystems within Michigan's ecoregions. The tools developed in this thesis (e.g., habitat type databases and themes, habitat potential modeling process) will help aid managers in accomplishing ecosystem management goals that sustain functional ecological systems while maintaining economic success and social acceptance. For example, the habitat type themes and databases indicate the location and properties of habitat types within different ecoregions of Michigan. They can help identify specific habitat types that should be maintained in a certain ecological state (e.g., for endangered species) or that should be managed to sustain specific public benefits (e.g., hunting or other recreation) and opportunities (e.g., education) into the future. In addition, the habitat potential models can serve as a framework for managing species or communities or for developing models that simulate possible future outcomes of potential habitat management situations.

When a house is being built, the carpet is not installed first. The foundation is poured and the framework is constructed before the finishing touches are added. The use of habitat typing and the habitat potential models developed in this project are pieces of the foundation and framework for ecosystem management. The foundation and framework must be solid (i.e., validation is critical) and then the finishing touches be added and fine-tuned to meet different ecological objectives. I encourage managers to validate, develop, modify, incorporate additional pieces of information, and apply the concepts presented in this thesis to help guide ecosystem management goals, protect Michigan's natural resources, and sustain Michigan's leadership role in ecosystem management.

APPENDICES

Appendix 1. Scientific names of overstory vegetation that was mentioned in the text of this thesis.

Common name	**Scientific name**
American elm	*Ulmus americana*
Aspen	*Populus tremuloides/grandidentata*
Balsam fir	*Abies balsamea*
Balsam poplar	*Populus spp.*
Basswood	*Tilia americana*
Beech	*Fagus grandifolia*
Black ash	*Fraxinus nigra*
Black cherry	*Prunus serotina*
Black oak	*Quercus velutina*
Black spruce	*Picea mariana*
Cedar	*Thuja occidentalis*
Cottonwood	*Populus deltoides*
Green ash	*Fraxinus pennsylvanica*
Hemlock	*Tsuga canadensis*
Hickory	*Carya spp.*
Ironwood	*Ostrya virginianus*
Jack pine	*Pinus banksiana*
Red maple	*Acer rubrum*
Red oak	*Quercus rubra*
Red pine	*Pinus resinosa*
Silver maple	*Acer saccharinum*
Sugar maple	*Acer saccharum*
Swamp white oak	*Quercus bicolor*
Tamarack	*Larix laricina*
White ash	*Fraxinus americana*
White birch	*Betula papyrifera*
White oak	*Quercus alba*
White pine	*Pinus strobus*
White spruce	*Picea glauca*
Willow	*Salix spp.*
Yellow birch	*Betula alleghaniensis*

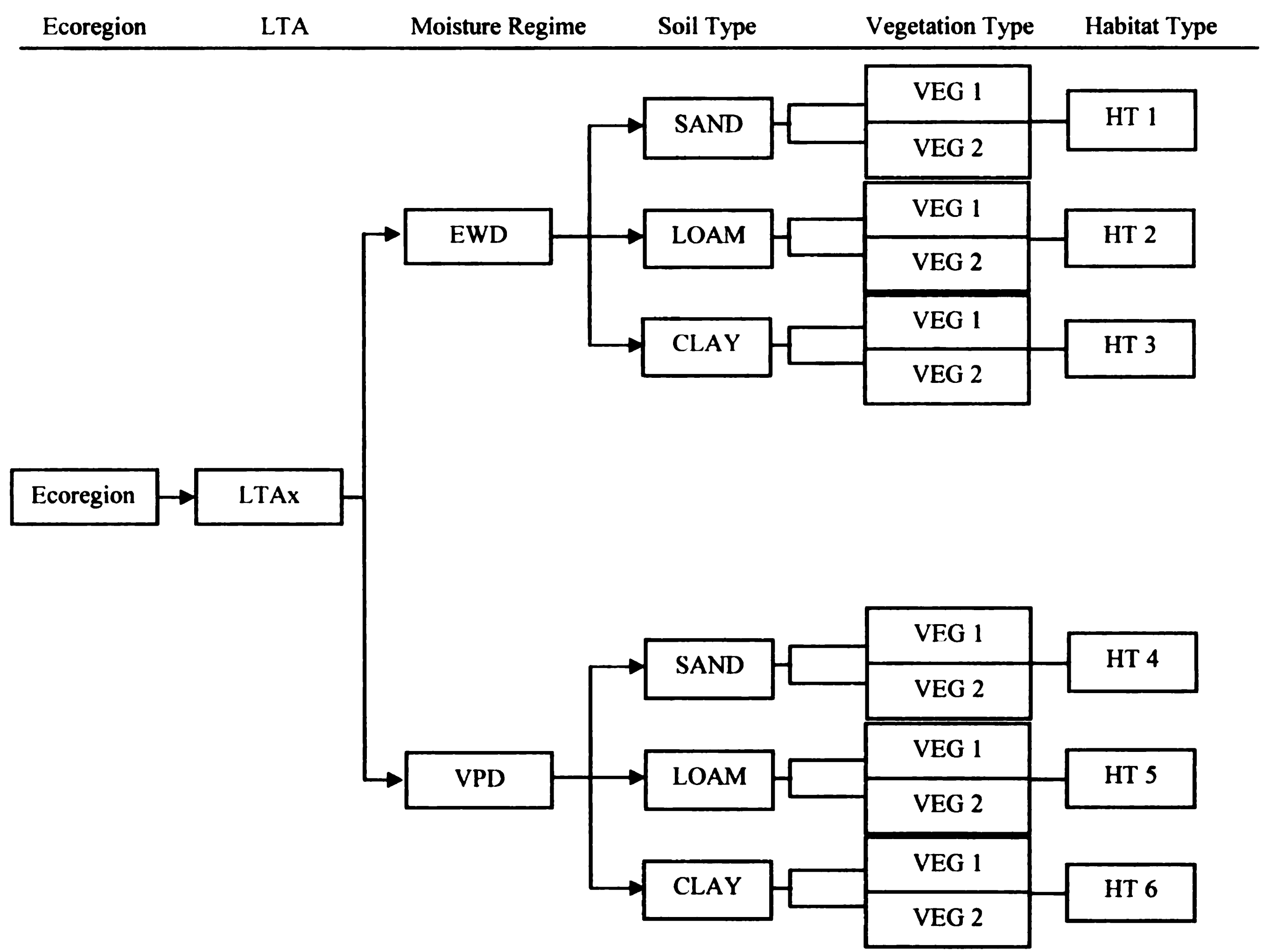
Appendix 2. List of available databases and descriptions investigated for the development of habitat types.

Coverage	Description	Usefulness
Albert's Ecoregions	Provides regional landscape ecosystem classification based on differences in climate, bedrock, geology, glacial landforms, and soils.	Although these areas are too large for deer to distinguish between, these areas do represent land units that differ in structure and processes as well as in abiotic components. This is the broadest level in the hierarchy of habitat classification.
Land Type Associations	Nested within climatic/physiographic zone (Ecoregions). These are based primarily on glacial landforms and potential natural vegetation.	Useful for delineating ecological boundaries based on landforms, soils, and vegetation.
Soil Associatons	Delineates areas with different soil associations. Soil associations describe different soil texture and moisture, and nutrient regimes.	Although different associations may support similar climax vegetation types, the structure of vegetation may very on different soils. Useful for delineating boundaries between habitat types.
Vegetation		
Presettlement	Describes composition of vegetation in Michigan based on surveys conducted between 1816-1856 by the General Land Office.	Indicates potential climax vegetation types and allows analysis of spatial changes of vegetation types.
1978 MIRIS	Describes composition and structure of vegetation in Michigan in the late 1970s.	Indicates what vegetation looked like in late 1970s.
1992 USGS Ntl Land Cover	Regional land cover classification based on 30-m landsat thematic mapper data. Broad forest class resolution (e.g., deciduous/coniferous forest classes).	Not very useful for habitat modeling; very general classification. May be used as a double check on the distribution of forest types.

Appendix 2. Cont'd.

Coverage	Description	Usefulness
1991 Landsat TM	Inventory of white-tailed deer thermal cover in the Upper Peninsula based on Landsat TM data.	Includes vegetation types important in winter habitat.
1993 Landsat TM	Description of vegetation in northeast LP based on Landsat TM data. Gives detailed species or species group breakdown in forest classes.	Describes current vegetation and does not indicate potential vegetation. Useful for validation of habitat types and assessing current vegetation.

Appendix 3. Conceptual diagram for the process of defining and delineating habitat types. LTA_x = land type association x. One LTA was selected at a time for analysis. Six moisture classes were used: excessively well drained (EWD), well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained (VPD). VEG = vegetation type. HT = habitat type.



Appendix 4a. Habitat classification key describing fall and winter food habitat requirements (browse component), suitability indices (SI) on a scale of 0-1 (1 = high and 0 = poor), and sources.

Component: Browse

Variable	Options	SI	Literature
Browse quality	cedar	1.00	Davenport 1941
	hemlock	1.00	Ullrey et al. 1964
	red maple	1.00	Ullrey et al. 1967
	sugar maple	1.00	Ullrey et al. 1968
	silver maple	1.00	Rogers et al. 1981
	basswood	0.75	
	black ash	0.75	
	birch (white and yellow)	0.75	
	black cherry	0.75	
	American elm	0.75	
	willow	0.75	
	aspen	0.50	
	balsam poplar	0.50	
	ironwood	0.50	
	jack pine	0.50	
	oak	0.50	
	white pine	0.50	
	beech	0.25	
	balsam fir	0.25	
	cottonwood	0.25	
	red pine	0.25	
	spruce	0.25	
	tamarack	0.25	
Browse availability	aspen		Graham et al. 1963
	Age		(for all age classes)
	1-10	1.00	
	10-30	1.00	
	30-50	0.50	
	50-100	0.00	
	100+	0.00	

Appendix 4a. Cont'd

Variable	Options	SI	Literature
Browse avail. (cont.)	other deciduous		
	Age		
	1-10	1.00	
	10-30	0.50	
	30-50	0.00	
	50-100	0.00	
	100+	0.00	
	coniferous		Ryel 1953
	Age		Verme 1965
	1-10	0.75	
	10-30	1.00	
	30-50	0.75	
	50-100	0.50	
	100+	0.00	
	lowland brush	1.00	

Appendix 4b. Habitat classification key describing fall and winter food habitat requirements (mast component), suitability values (SI) on a scale of 0-1 (1 = high and 0 = poor), and sources.

Component: Mast

Variable	Options		SI	Literature
Mast species type	hard mast			Harlow et al. 1975
	oak (black, red, white)		1.00	
	beech		0.75	
	other		0.00	
Mast bonus	soft mast		+ 0.05	Rogers et al. 1981
Basal area	oak in mixed stands			Bender and Haufler 1987
	Stand age	ft²/ac		Host et al. 1987
	1-10	no data	0	
	10-30	no data	0.5	
	30-50	42-52	1.00	
	50-100	no data	1.00	
	100+	no data	0.25	

Appendix 4b. Cont'd

Variable	Options		SI	Literature
Basal Area (cont.)	oak in pure stands			Marty and Rudolph 1970
	Stand age	ft^2/ac		
	1-10	20-40	1.00	
	10-30	40-70	1.00	
	30-50	60-90	1.00	
	50-100	90+	1.00	
	100+	90+	1.00	
	beech			Tubbs and Houston 1990
	Stand age	ft^2/ac		
	1-10	0	0.00	
	10-30	1-10	0.50	
	30-50	14-35	1.00	
	50-100	40-70	1.00	
	100+	70-75	1.00	
DBH	oak			Sander 1990a, b
	Stand age	inches		Duvendeck 1964
	1-10	0-2	0.00	
	10-30	3-6	0.50	
	30-50	7-12	1.00	
	50-100	11-20	1.00	
	100+	20+	1.00	
	beech			Tubbs and Houston 1990
	Stand age	inches		
	1-10	0	0.00	
	10-30	0-1	0.00	
	30-50	2-7	0.50	
	50-100	8-13	1.00	
	100+	14-24	1.00	

Appendix 5a. Habitat classification key describing thermal cover habitat requirements (forest composition component), suitability indices (SI) on a scale of 0-1 (1 = high and 0 = poor), and sources.

Component: Forest Composition

Variable	Options	SI	Literature
Forest Type	Coniferous	1.00	Verme 1965
	Mixed	0.50	
	Deciduous	0.00	
Coniferous Species	Cedar	1.00	Davenport et al. 1953
	Hemlock	1.00	Verme 1965
	Spruce	0.80	Euler and Thurston 1980
	Fir	0.80	Bender and Haufler 1987
	Pine	0.40	Blouch 1984

Appendix 5b. Habitat classification key describing thermal cover habitat requirements (forest structure component), suitability suitability indices (SI) on a scale of 0-1 (1 = high and 0 = poor), and sources.

Component: Forest Structure

Variable	Options		SI	Literature
Basal Area for lowland conifers	*Stand age*	ft^2/ac		Bender and Haufler 1987
	1-10	0-30	0.00	Johnston 1990
	10-30	30-100	0.50	
	30-50	174-261	1.00	
	50-100	174-261	1.00	
	100+	300 max	1.00	
Canopy Cover	*Stand age*	%		Verme 1965
	1-50	40-70	0.50	Ozoga 1968
	50+	70-100	1.00	
Tree Size (DBH)	*Stand age*	inches		Verme 1965
	1-10	0	0.00	Ozoga 1968
	10-30	0-0.5	0.00	Ozoga and Gysel 1972
	30-50	0.5-3	0.50	Johnston 1990
	50-100	3-9	1.00	
	100+	9+	1.00	

Appendix 5b. (Cont'd)

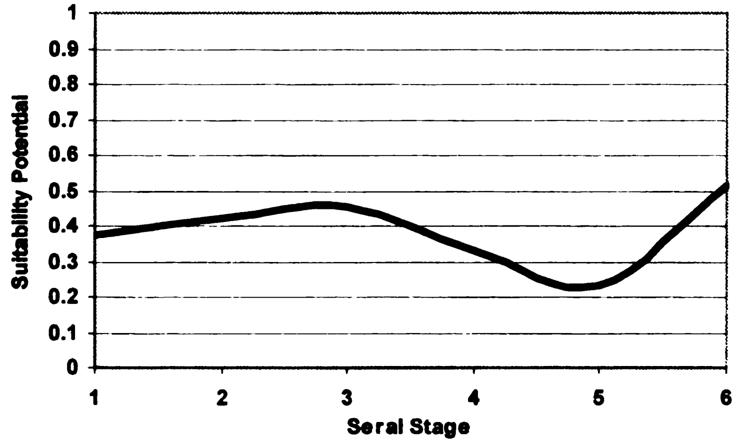
Variable	Options		SI	Literature
Age Structure	*Stand age*	structure		
	< 150	even-aged	1.00	Verme 1965
	> 150	uneven-aged	0.00	

Appendix 6. Habitat classification key describing spring and summer habitat requirements, suitability indices (SI) on a scale of 0-1 (1 = high and 0 = poor), and sources.

Variable	Options	SI	Literature
Vegetation Type Preference	Openings	1.00	Kohn and Mooty 1971
	Upland deciduous	1.00	McCaffery et al. 1974
	Upland mixed	1.00	Stormer and Bauer 1980
	Upland coniferous	0.40	Mackey 1996
	Lowland shrub/brush	0.30	
	Lowland deciduous	0.20	
	Lowland mixed	0.20	
	Lowland coniferous	0.20	
Forage Availability			
-for upland deciduous, upland mixed, and lowland types	Early successional	1.00	Verme 1969
	Early-mid successional	0.80	Kohn and Mooty 1971
	Mid successional	0.60	McCaffery et al. 1974
	Mid-late successional	0.40	Stormer and Bauer 1980
	Late successional	0.20	Mackey 1996
-for upland coniferous	Early successional	1.00	
	Early-mid successional	1.00	
	Mid successional	1.00	
	Mid-late successional	0.50	
	Late successional	0.50	

Appendix 7. White-tailed deer habitat suitability curves for each successional trajectory in southern Lower Michigan. The curves display habitat dynamics for fall and winter food, and spring and summer habitat components based on habitat potential models developed in this document.

A.



B.

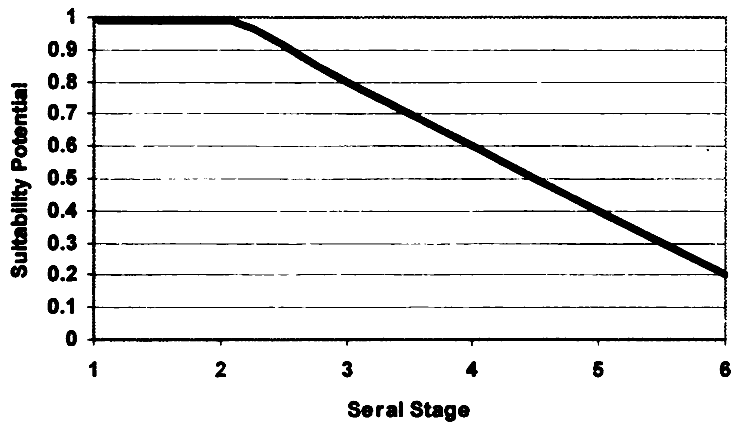
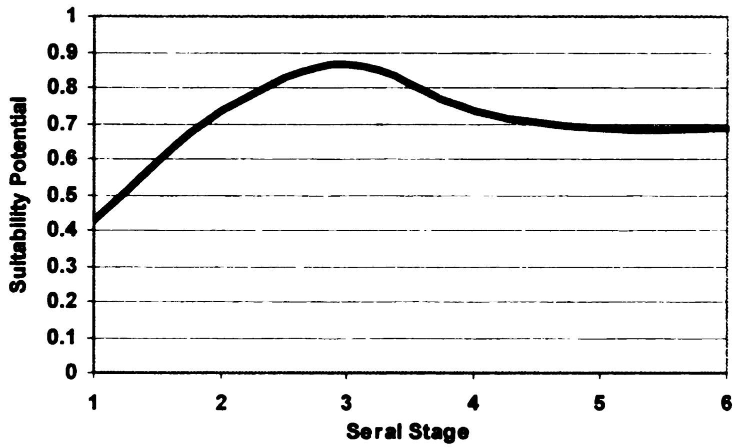


Figure A7-1. Suitability curves for fall and winter food (A), and spring and summer habitat (B), for areas that support aspen in early successional stages (1-2; ages < 30 years), sugar maple-beech-basswood-red maple-white ash in middle stages (3-4; ages 30-100 years), and sugar maple-beech-basswood in late stages (5-6; ages > 100 years).

A.



B.

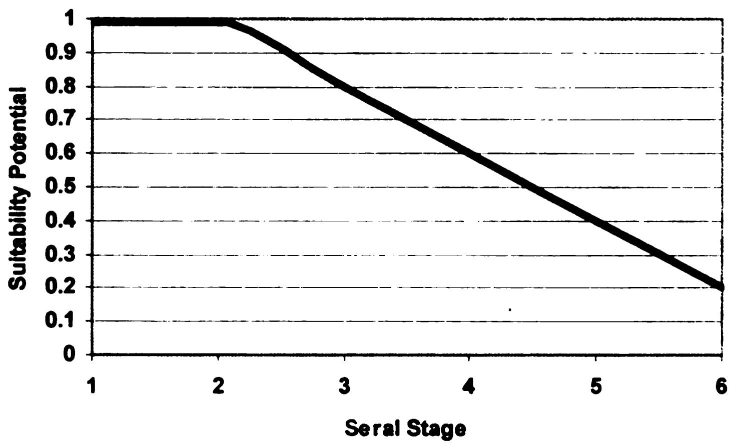
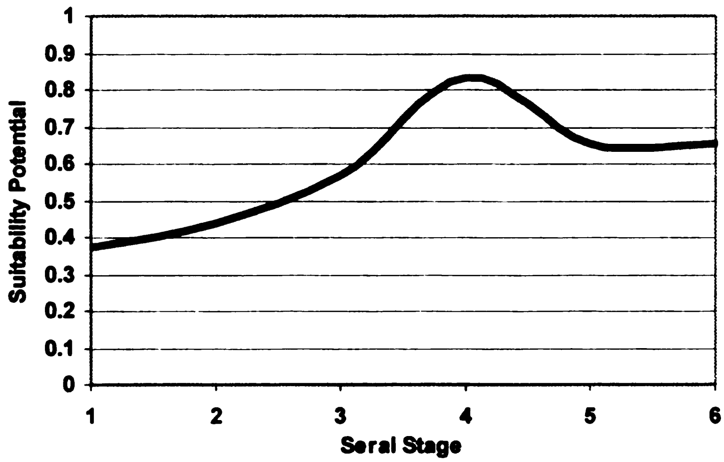


Figure A7-2. Suitability curves for fall and winter food (A), and spring and summer habitat (B) for areas that support aspen-red oak-hickory-black cherry in early successional stages (1-2; ages < 30 years), red maple-sugar maple-red oak-white oak-black cherry in middle stages (3-4; ages 30-100 years), and red maple-basswood-red oak-white ash in later stages (5-6; ages > 100 years).

A.



B.

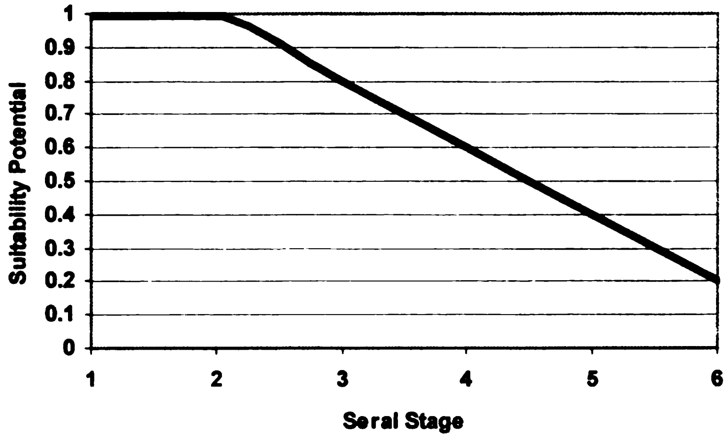
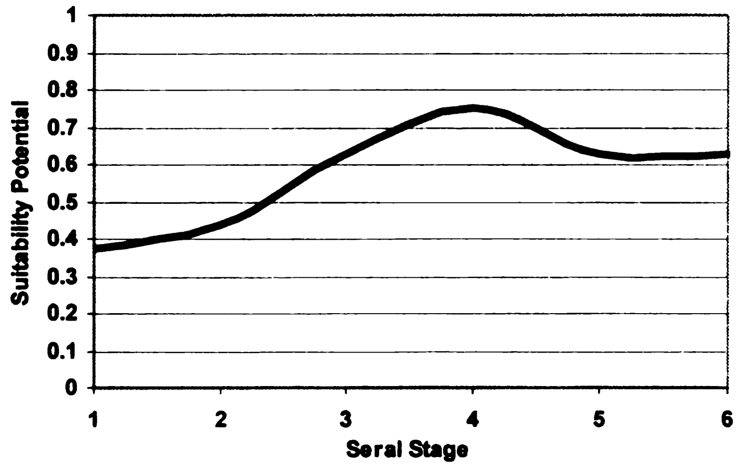


Figure A7-3. Suitability curves for fall and winter food (A), and spring and summer habitat (B) for areas that support grass-sedges-forbs in early successional stages (1-2; ages < 30 years), grass-shrubs-black oak-white oak-black cherry in middle stages (3-4; ages 30-100 years), and white oak-black oak-red oak-hickory-red maple in later stages (5-6; ages > 100 years).

A.



B.

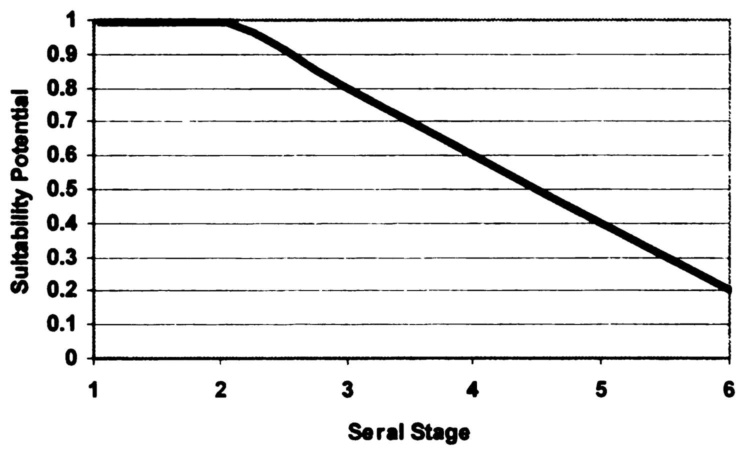


Figure A7-4. Suitability curves for fall and winter food (A), and spring and summer habitat (B) for areas that support grass-sedges-forbs in early successional stages (1-2; ages < 30 years), grass-shrubs-black oak-white oak-red oak-hickory in middle stages (3-4; ages 30-100 years), and white oak-black oak-red oak-white pine in later stages (5-6; ages > 100 years).

A.

B.

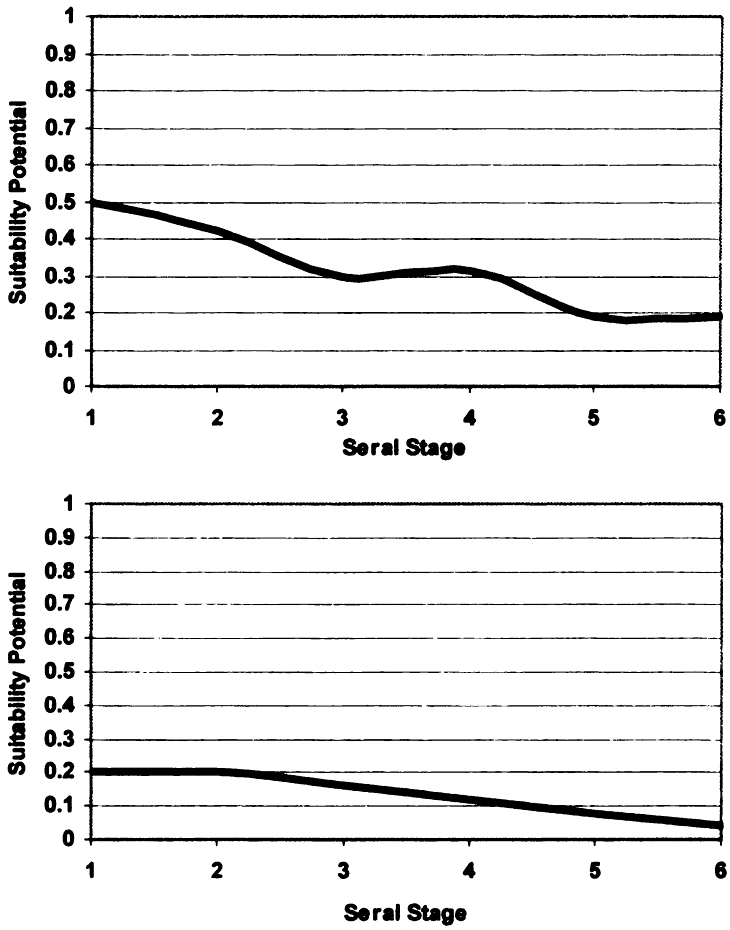


Figure A7-5. Suitability curves for fall and winter food (A), and spring and summer habitat (B) for areas that support lowland brush in early successional stages (1-2; ages < 30 years), tamarack-black ash-birch-red maple-American elm in middle stages (3-4; ages 30-100 years), and red maple-American elm-swamp white oak in later stages (5-6; ages > 100 years).

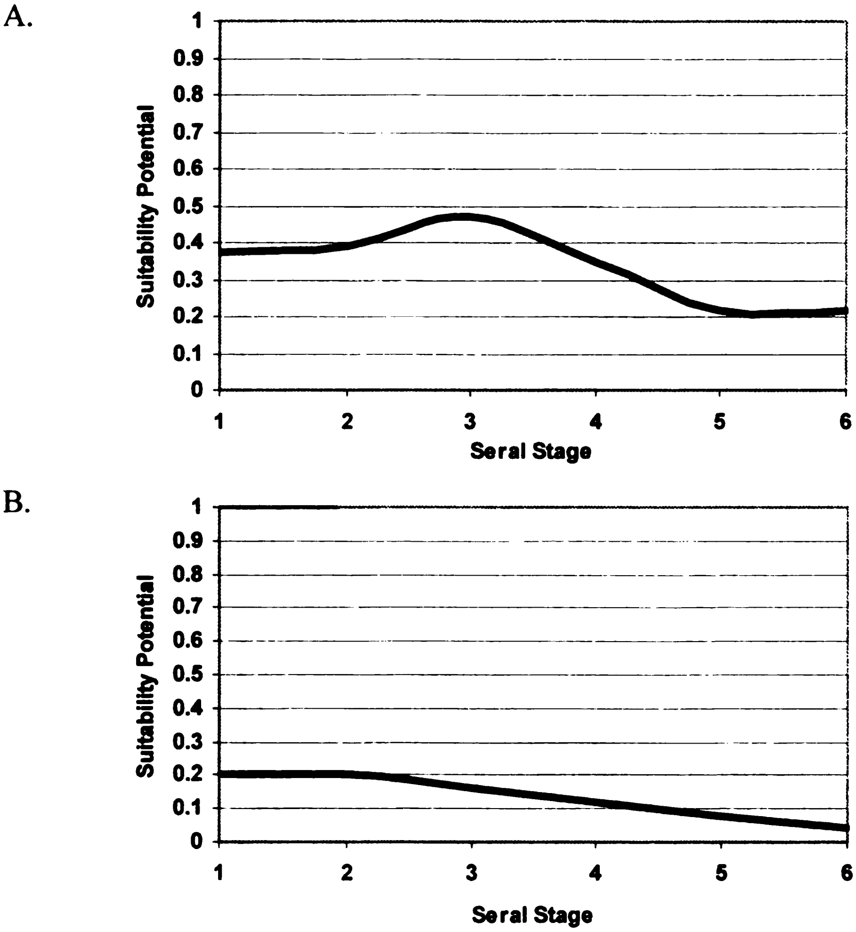


Figure A7-6. Suitability curves for fall and winter food (A), and spring and summer habitat (B) for areas that support willow-cottonwood in early successional stages (1-2; ages < 30 years), silver maple-American elm-green ash-cottonwood in middle stages (3-4; ages 30-100 years), and sugar maple-American elm-red maple-basswood in later stages (5-6; ages > 100 years).

Appendix 8. White-tailed deer habitat suitability curves for each successional trajectory in northeastern Lower, Michigan. The curves display habitat dynamics for fall and winter food, thermal cover, and spring and summer habitat components based on habitat potential models developed in this document.

A.

B.

C.

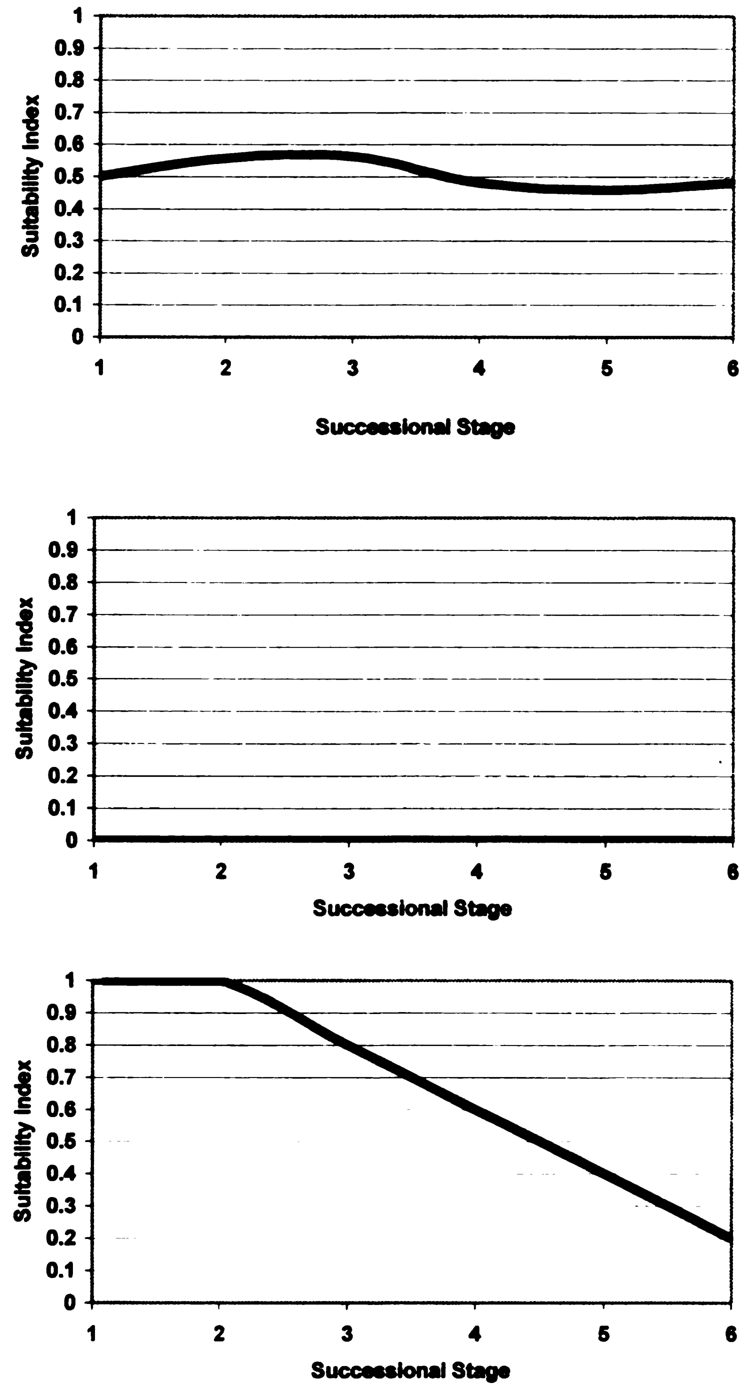
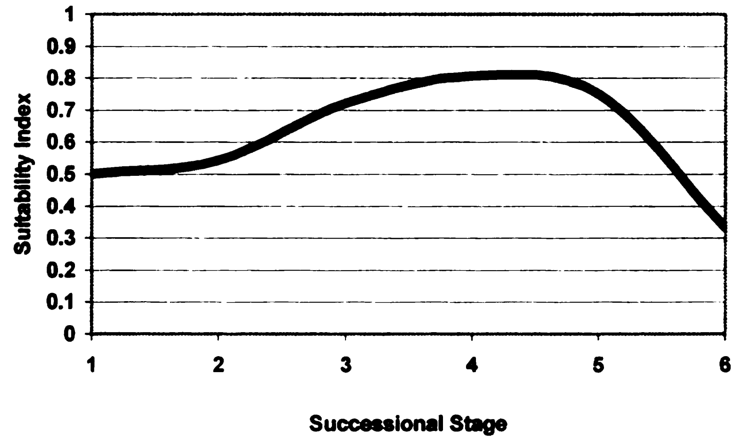
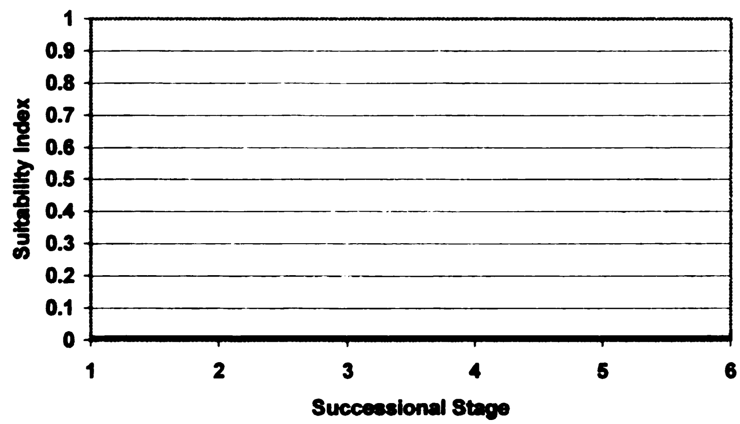


Figure A8-1. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen in early successional stages (1-2; ages < 30 years), aspen-red maple-white pine in middle stages (3-4; ages 30-100 years), and white pine-red maple-beech-sugar maple in late stages (5-6; ages > 100 years).

A.



B.



C.

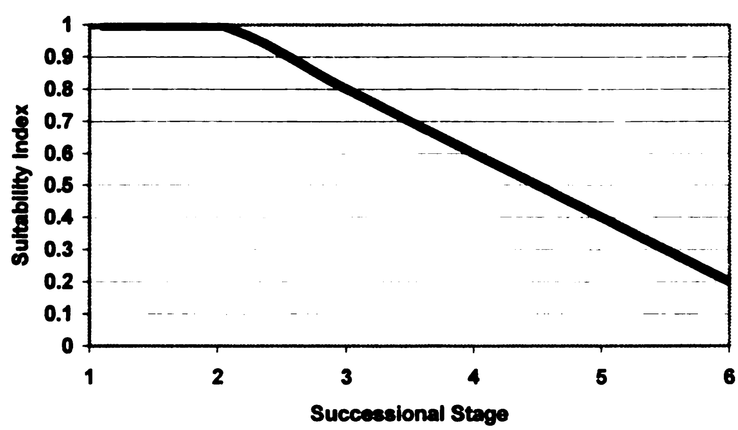
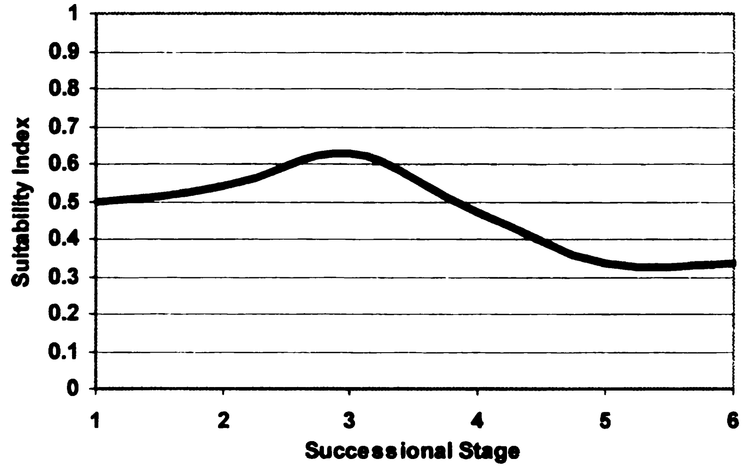
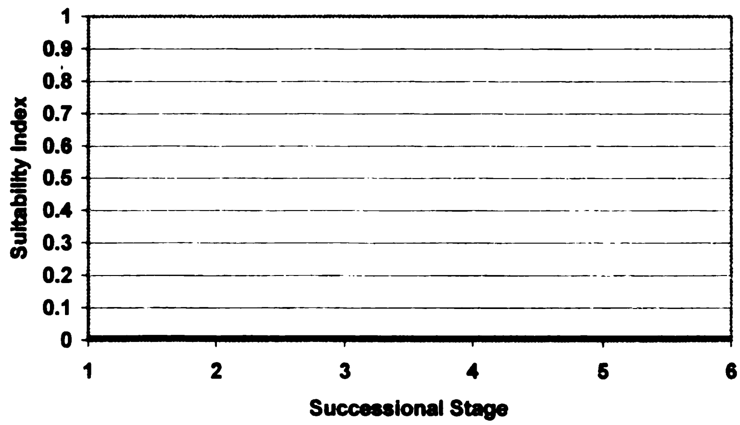


Figure A8-2. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen in early successional stages (1-2; ages < 30 years), oak-red maple-white pine in middle stages (3-4; ages 30-100 years), and white pine-red maple in later stages (5-6; ages > 100 years).

A.



B.



C.

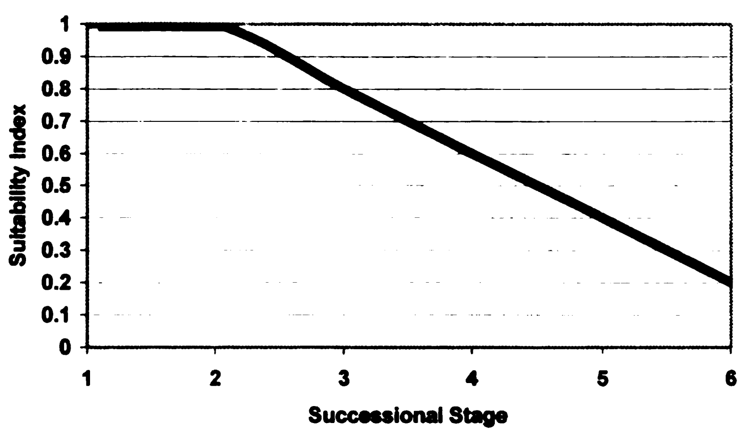


Figure A8-3. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-balsam poplar in early successional stages (1-2; ages < 30 years), black ash-American elm in middle stages (3-4; ages 30-100 years), and red maple-sugar maple-black ash in later stages (5-6; ages > 100 years).

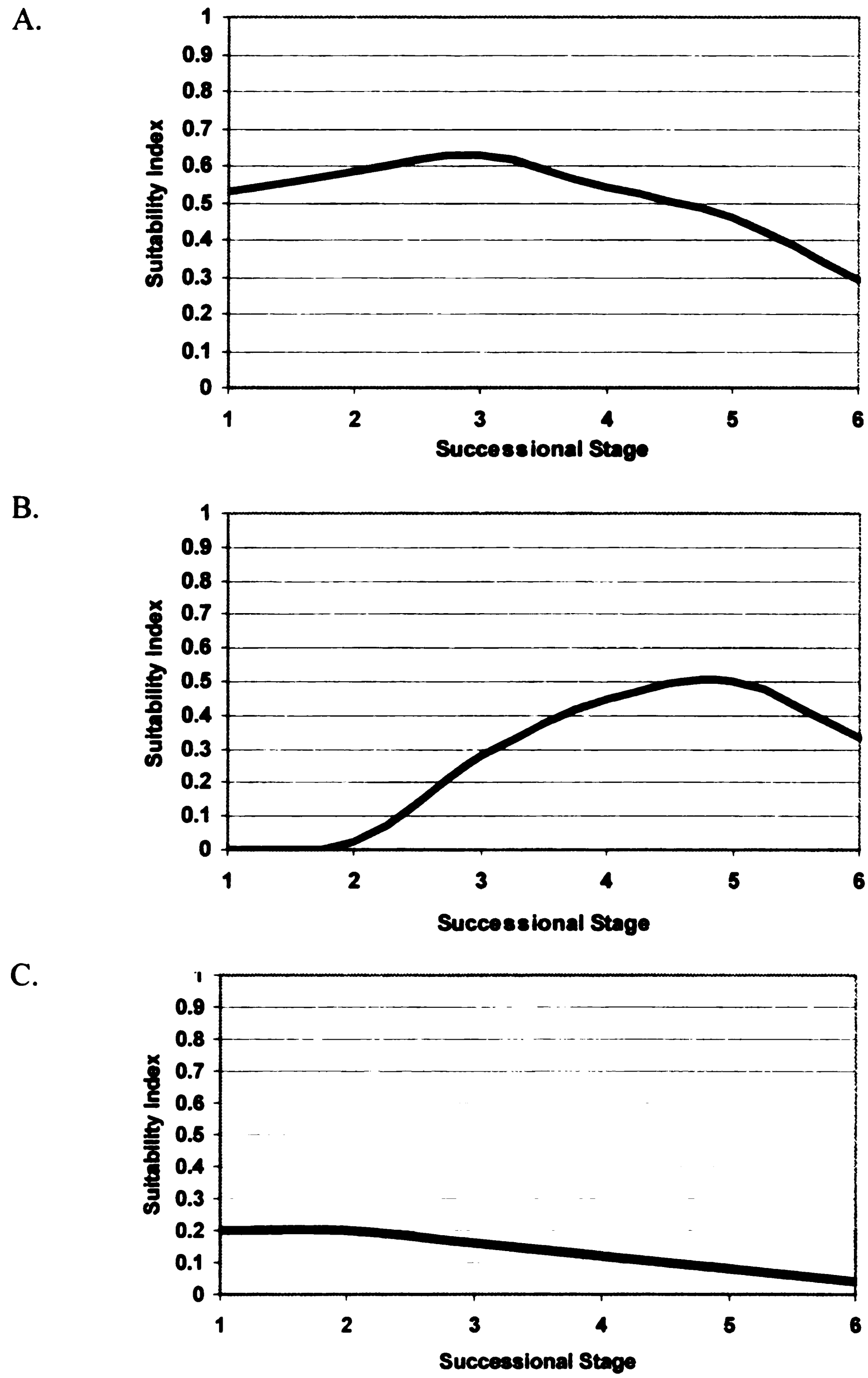
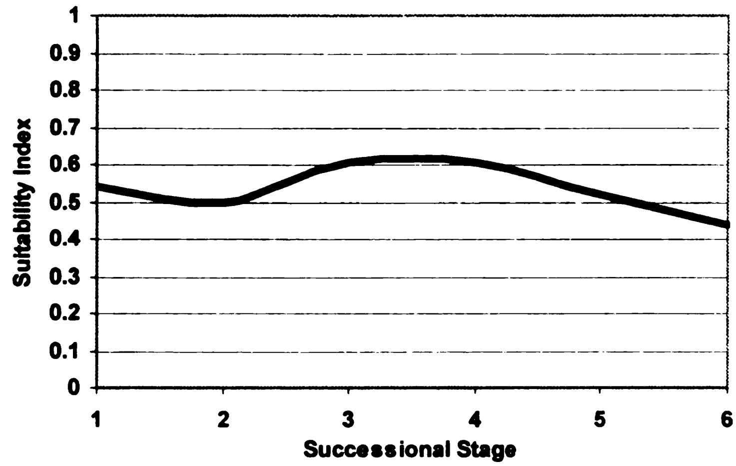
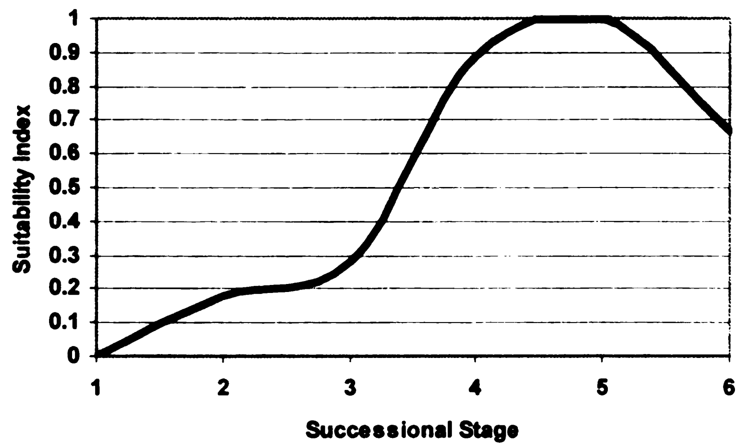


Figure A8-4. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-balsam poplar-birch in early successional stages (1-2; ages < 30 years), aspen-balsam poplar-black ash in middle stages (3-4; ages 30-100 years), and black ash-cedar in later stages (5-6; ages > 100 years).

A.



B.



C.

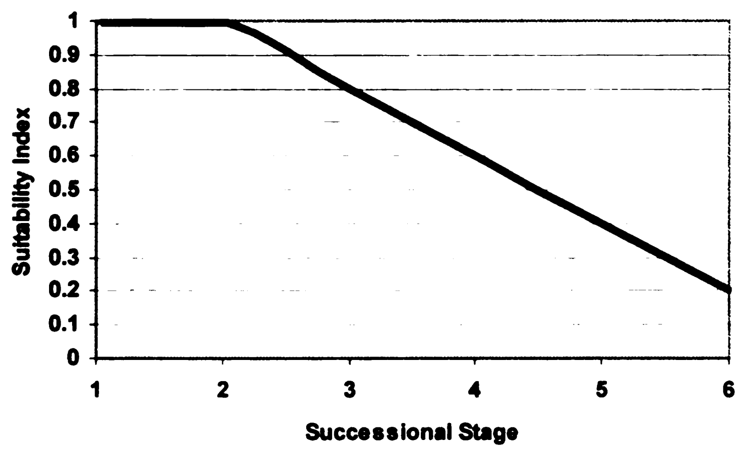
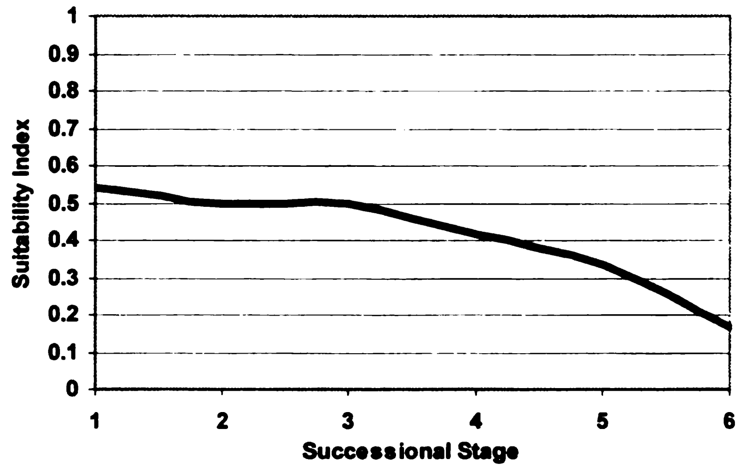


Figure A8-5. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), balsam fir-white spruce-red maple in middle stages (3-4; ages 30-100 years), and hemlock-cedar-balsam fir-red maple in later stages (5-6; ages > 100 years).

A.



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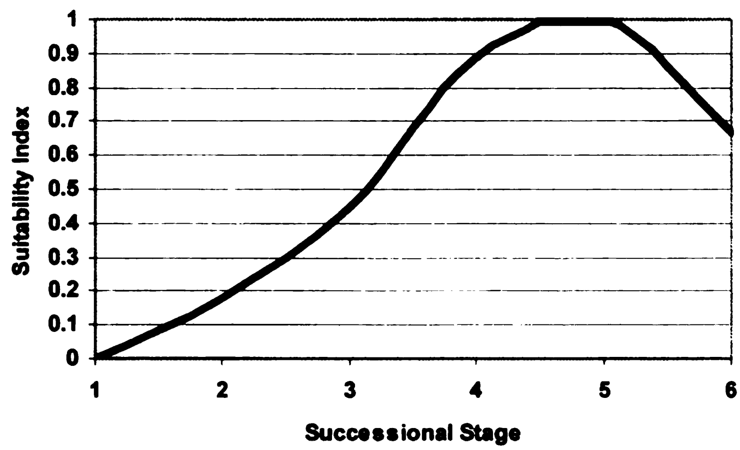


C.

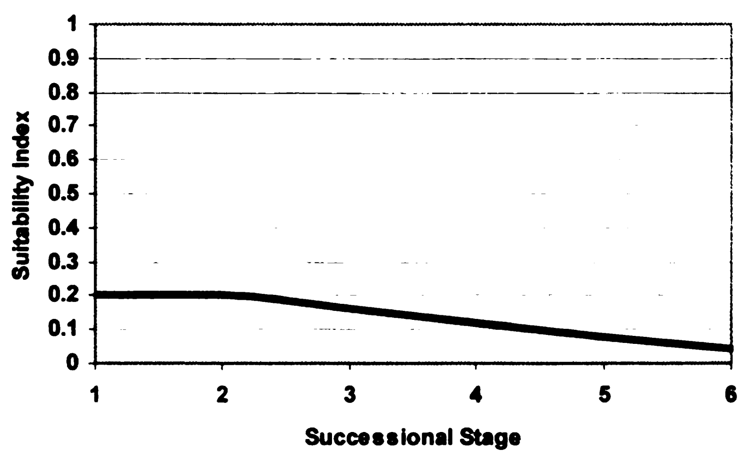
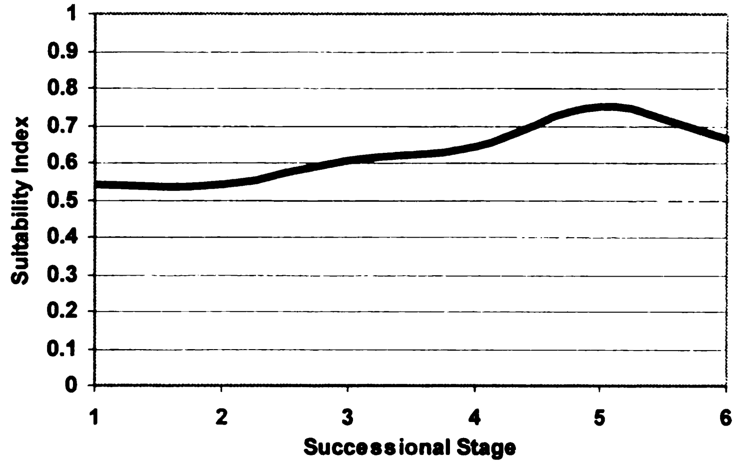
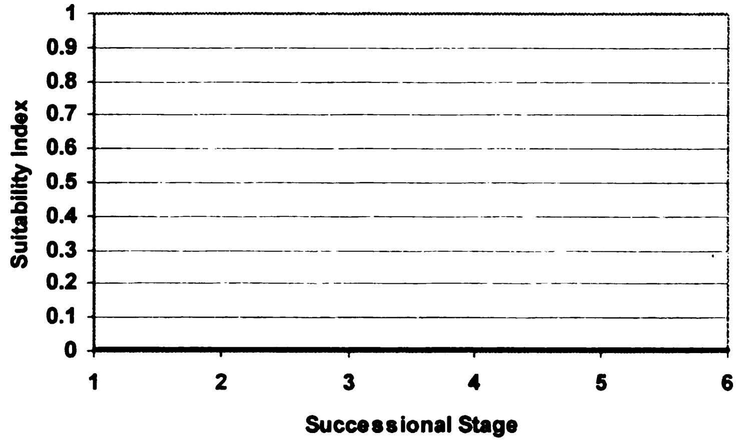


Figure A8-6. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), black spruce-balsam fir-cedar in middle stages (3-4; ages 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; ages > 100 years).

A.



B.



C.

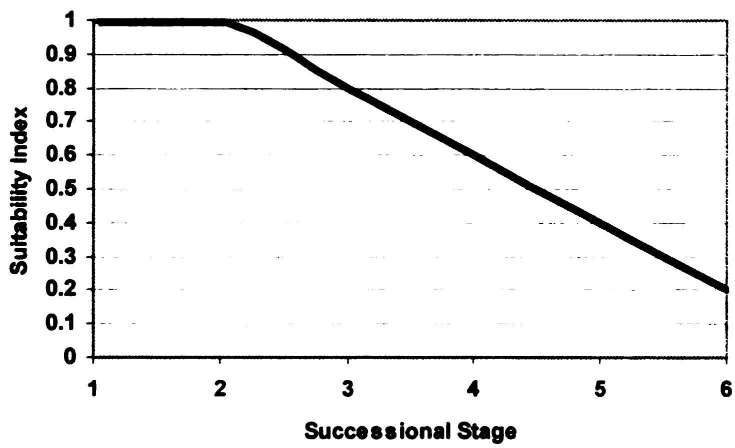


Figure A8-7. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), red maple-beech-white ash-basswood-white pine in middle stages (3-4; ages 30-100 years), and sugar maple-beech-hemlock in later stages (5-6; ages > 100 years).

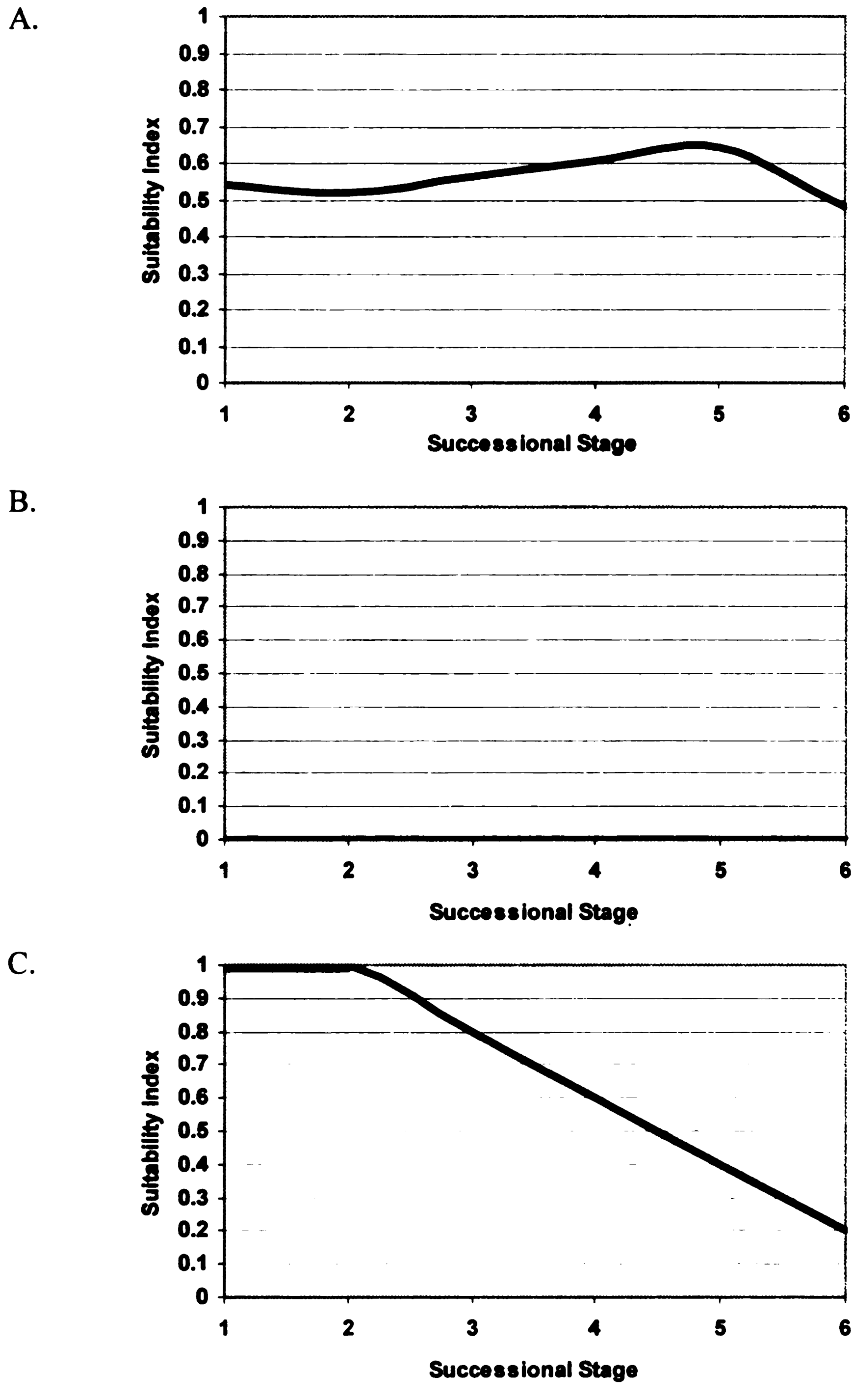


Figure A8-8. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), red maple-beech-white pine in middle stages (3-4; ages 30-100 years), and white pine-red maple-beech-sugar maple-white ash in later stages (5-6; ages > 100 years).

A.

B.

C.

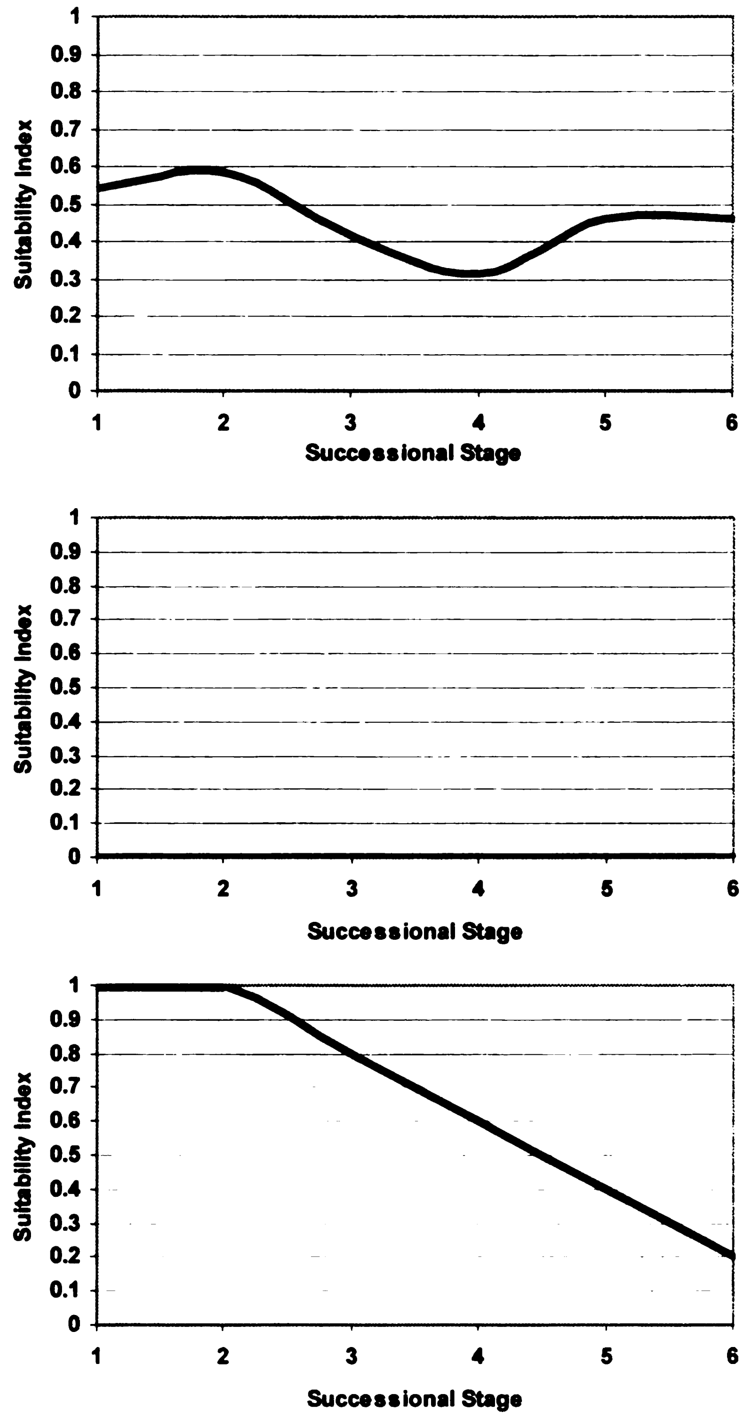


Figure A8-9. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), sugar maple-beech-basswood-red maple-white ash in middle stages (3-4; ages 30-100 years), and sugar maple-beech in later stages (5-6; ages > 100 years).

A.

B.

C.

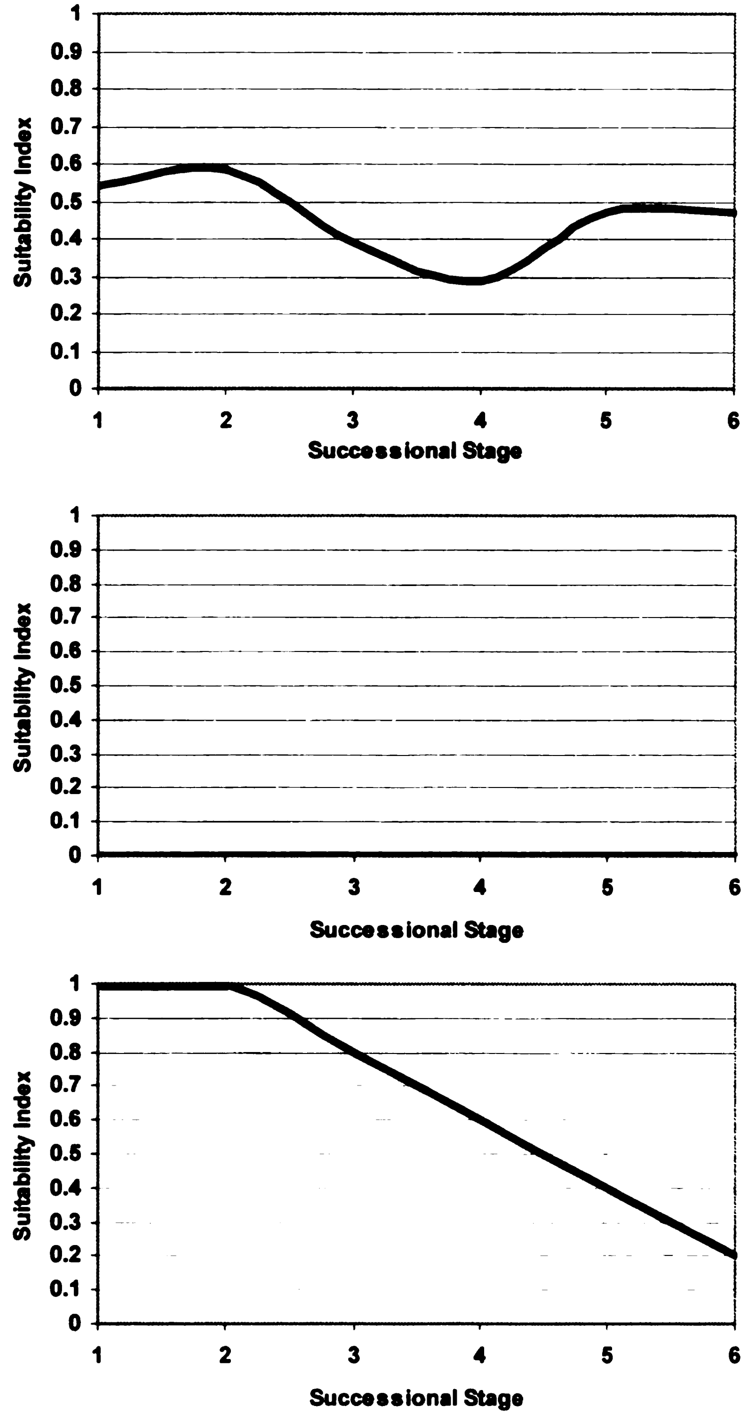
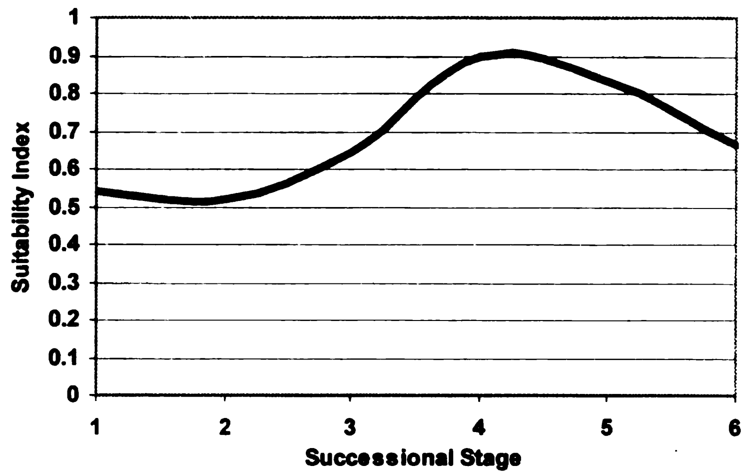
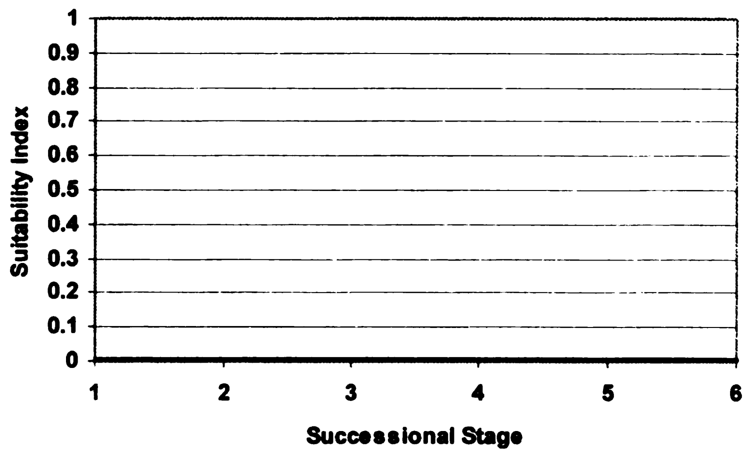


Figure A8-10. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), sugar maple-beech-basswood-red maple-white ash in middle stages (3-4; ages 30-100 years), and sugar maple-beech-basswood in later stages (5-6; ages > 100 years).

A.



B.



C.

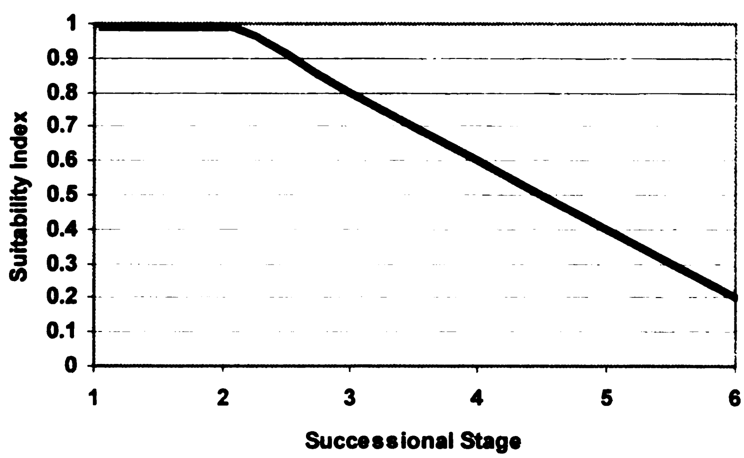


Figure A8-11. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), sugar maple-oak-beech in middle stages (3-4; ages 30-100 years), and sugar maple-beech-hemlock in later stages (5-6; ages > 100 years).

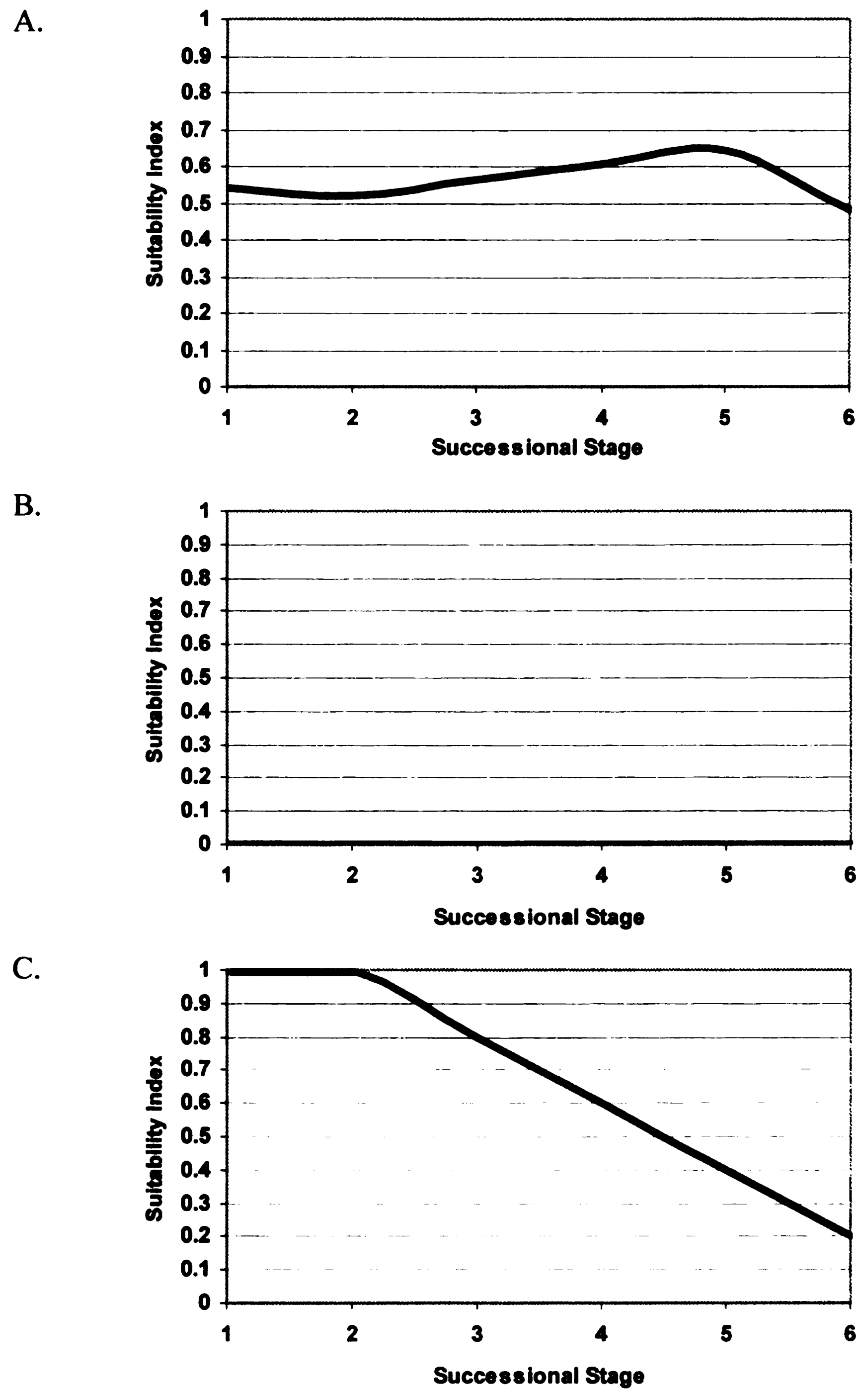


Figure A8-12. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), white pine-red maple-beech in middle stages (3-4; ages 30-100 years), and white pine-red maple-beech-sugar maple in later stages (5-6; ages > 100 years).

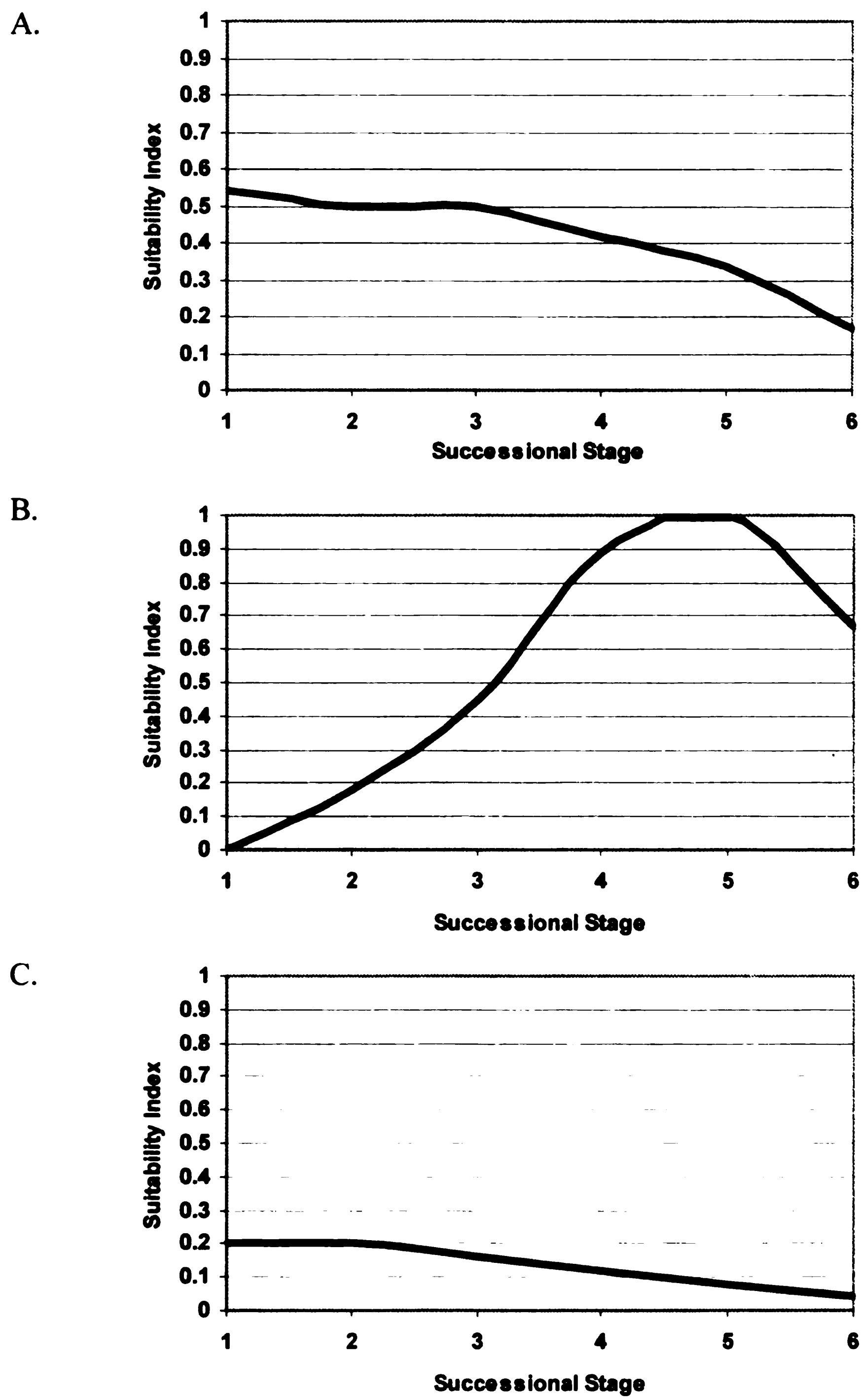


Figure A8-13. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), black spruce-balsam fir-cedar in middle stages (3-4; ages 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; ages > 100 years).

A.

B.

C.

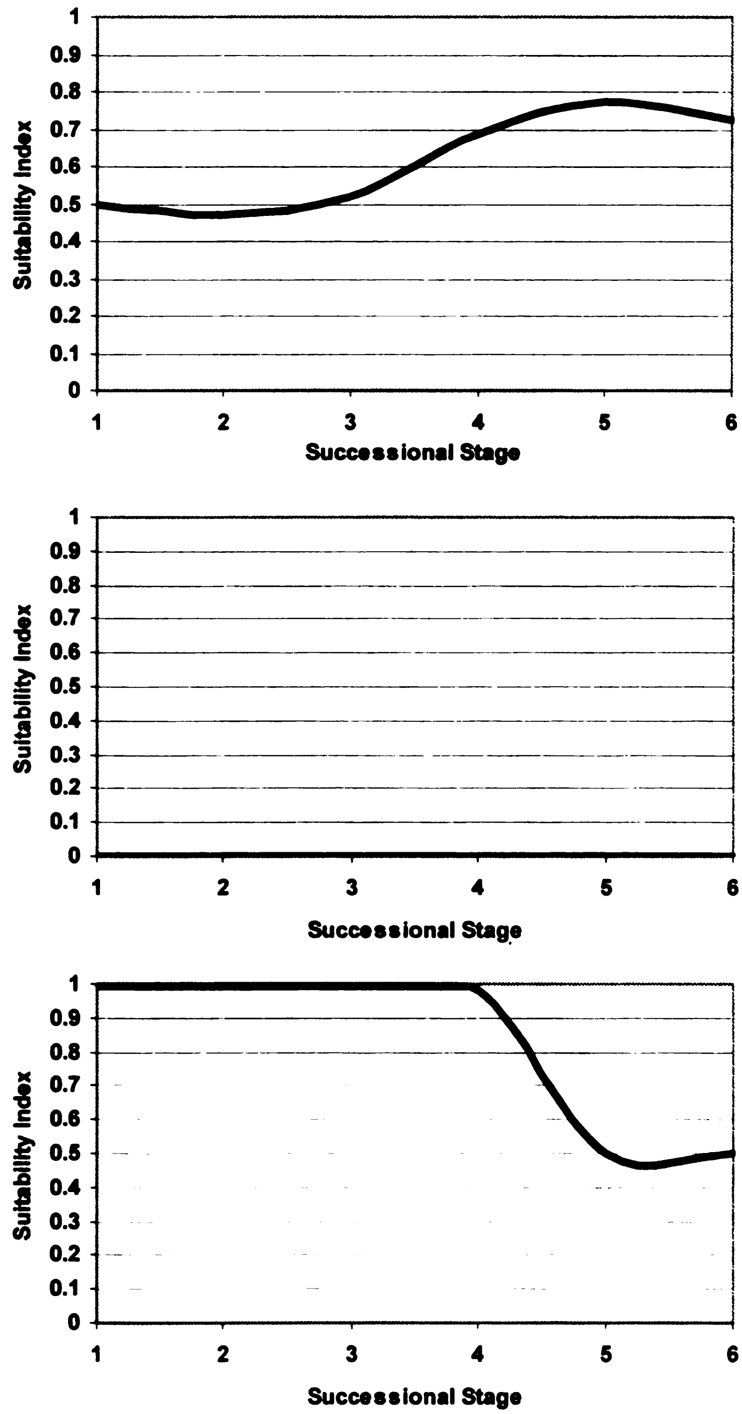


Figure A8-14. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-jack pine in early successional stages (1-2; ages < 30 years), jack pine-red pine in middle stages (3-4; ages 30-100 years), and red oak-red maple-white pine in later stages (5-6; ages > 100 years).

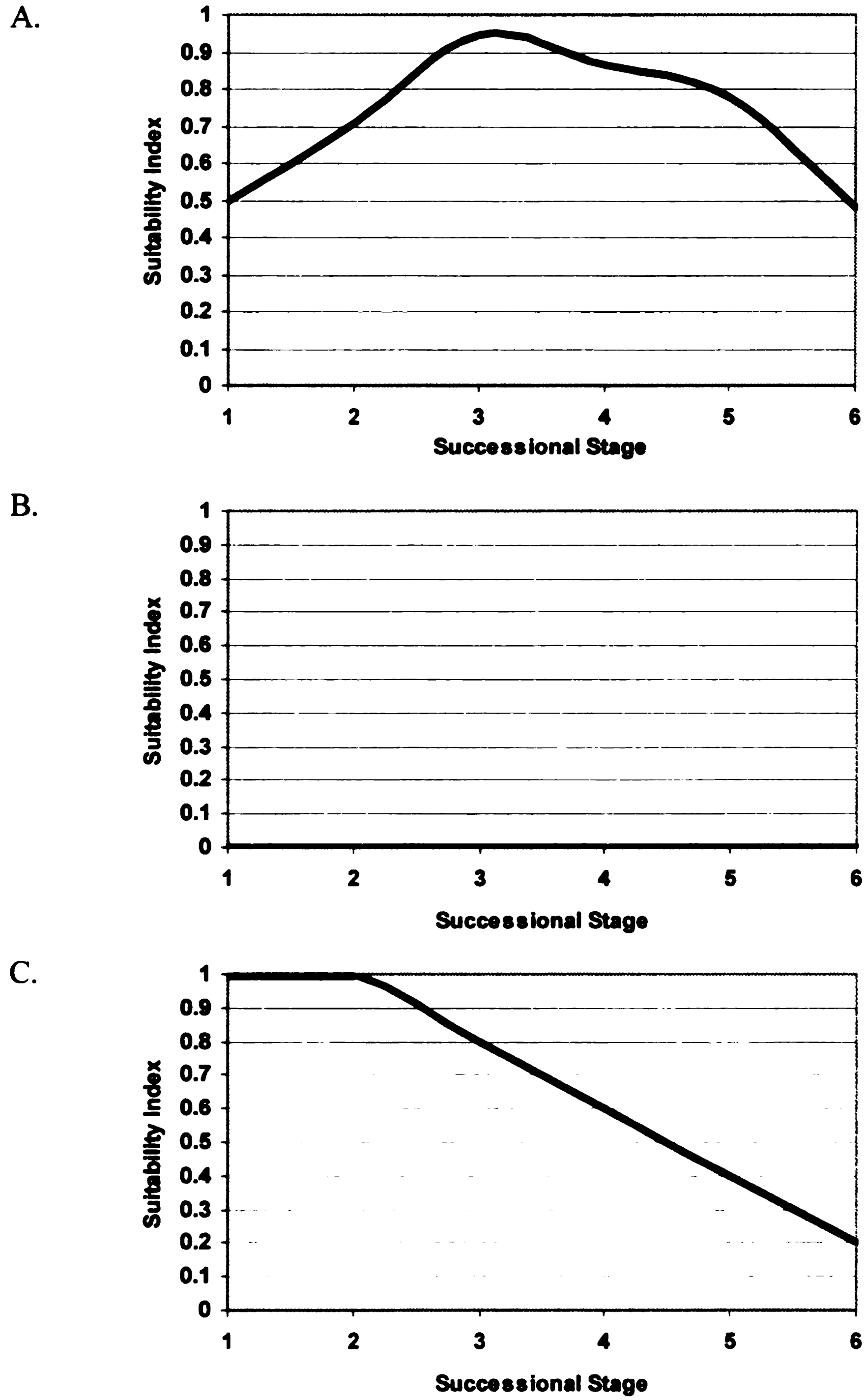


Figure A8-15. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-oak in early successional stages (1-2; ages < 30 years), oak-red maple-white pine-black cherry in middle stages (3-4; ages 30-100 years), and white pine-red maple-beech-sugar maple in later stages (5-6; ages > 100 years).

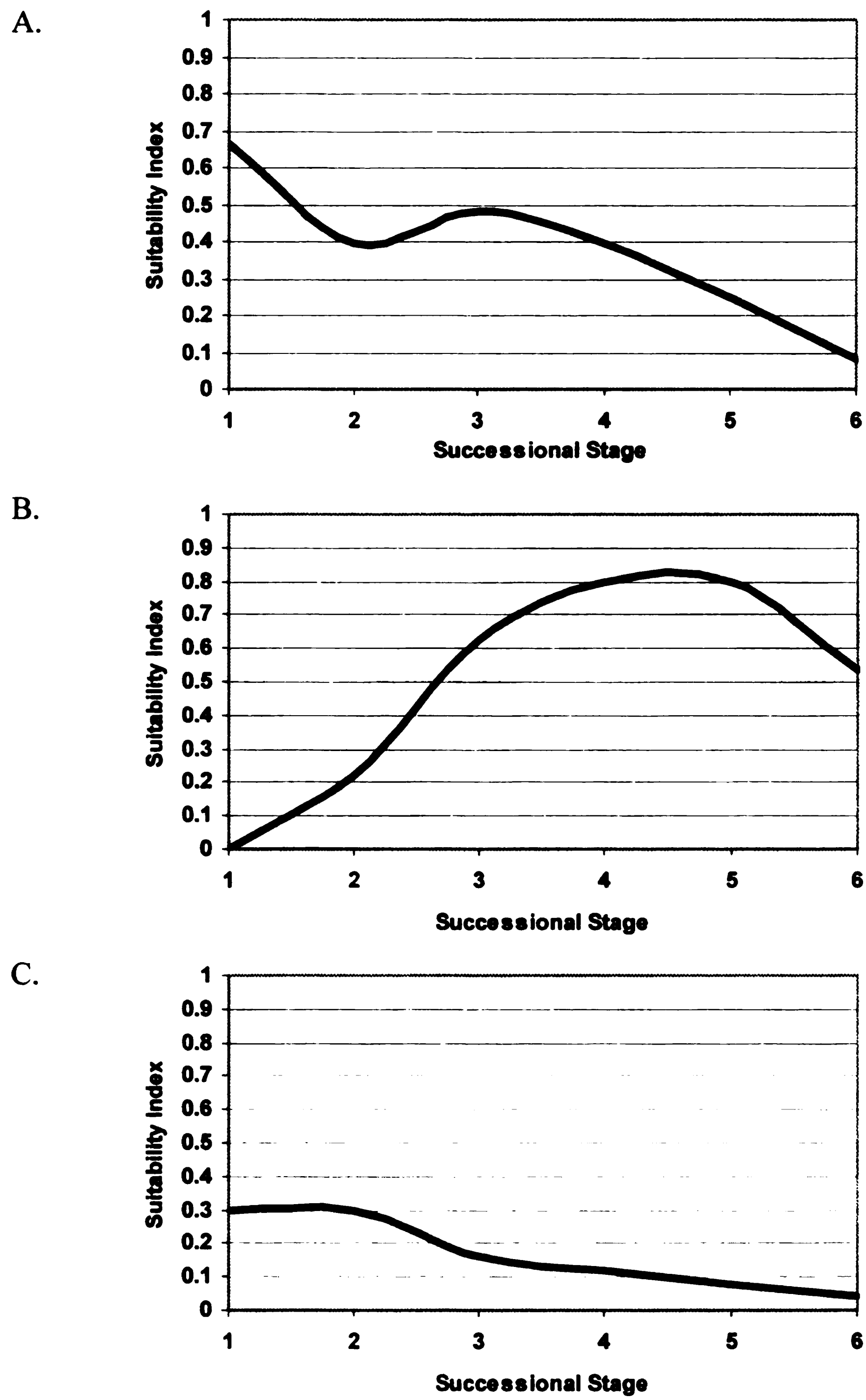


Figure A8-16. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush in early successional stages (1-2; ages < 30 years), black spruce-tamarack-balsam fir-cedar-black ash in middle stages (3-4; ages 30-100 years), and black spruce in later stages (5-6; ages > 100 years).

A.

B.

C.

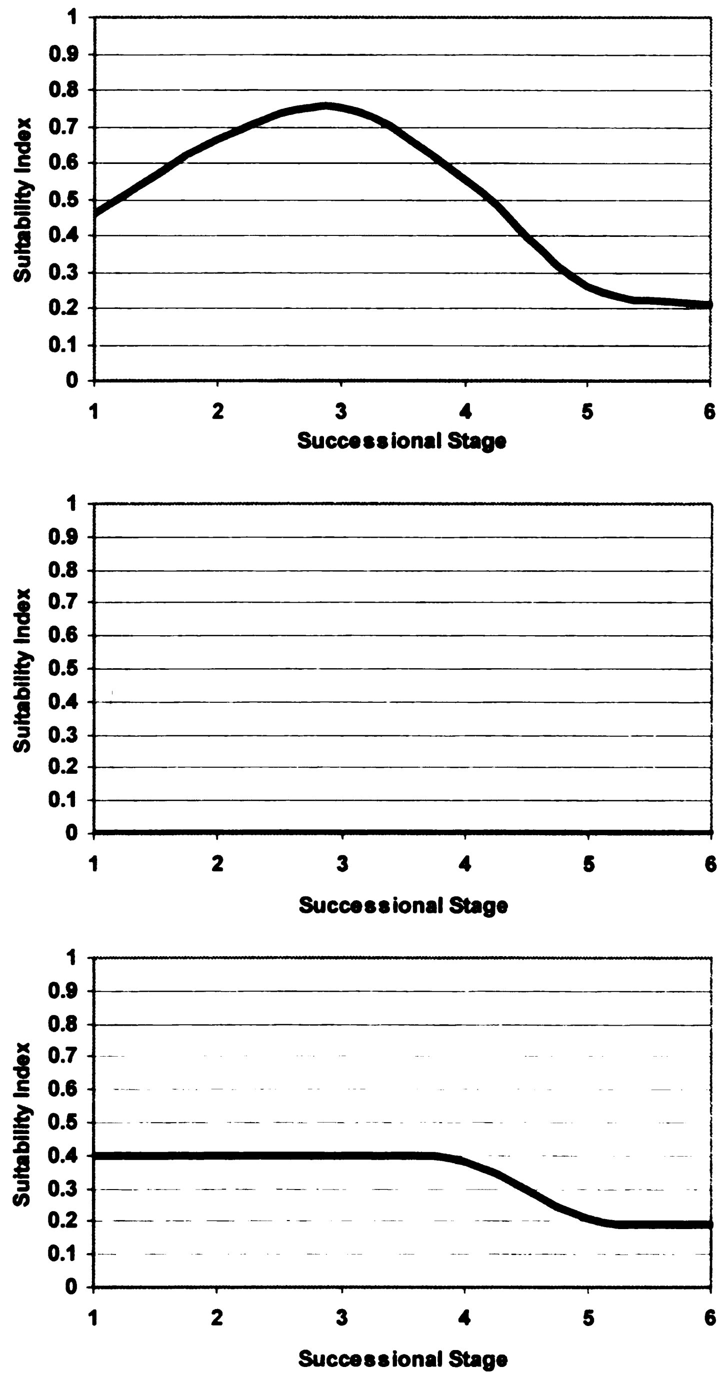
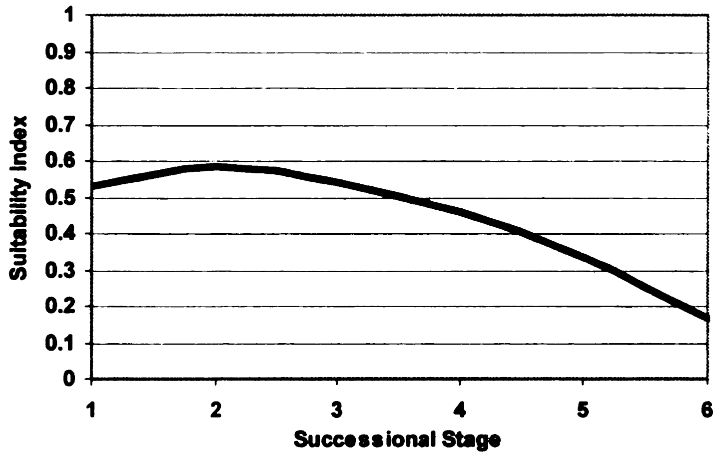
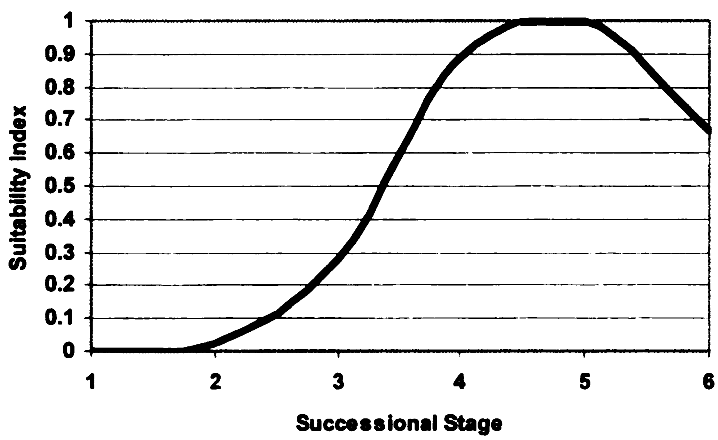


Figure A8-17. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support jack pine-white pine-red pine-oak in early successional stages (1-2; ages < 30 years), jack pine-white pine-red pine-red maple-black cherry in middle stages (3-4; ages 30-100 years), and white pine-red maple in later stages (5-6; ages > 100 years).

A.



B.



C.

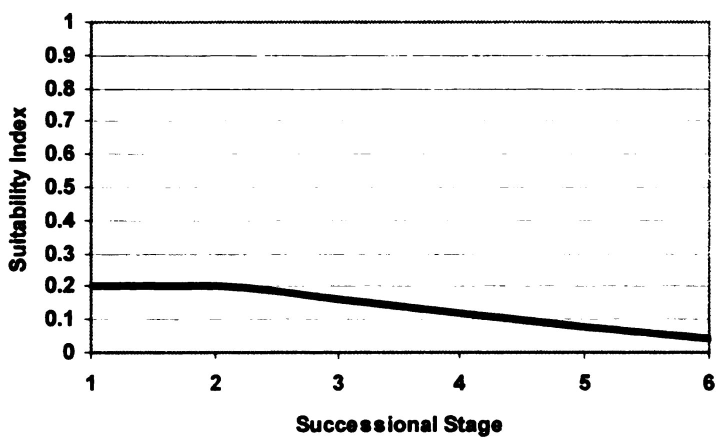


Figure A8-18. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support tamarack-black ash-birch in early successional stages (1-2; ages < 30 years), tamarack-black ash-red maple in middle stages (3-4; ages 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; ages > 100 years).

A.

B.

C.

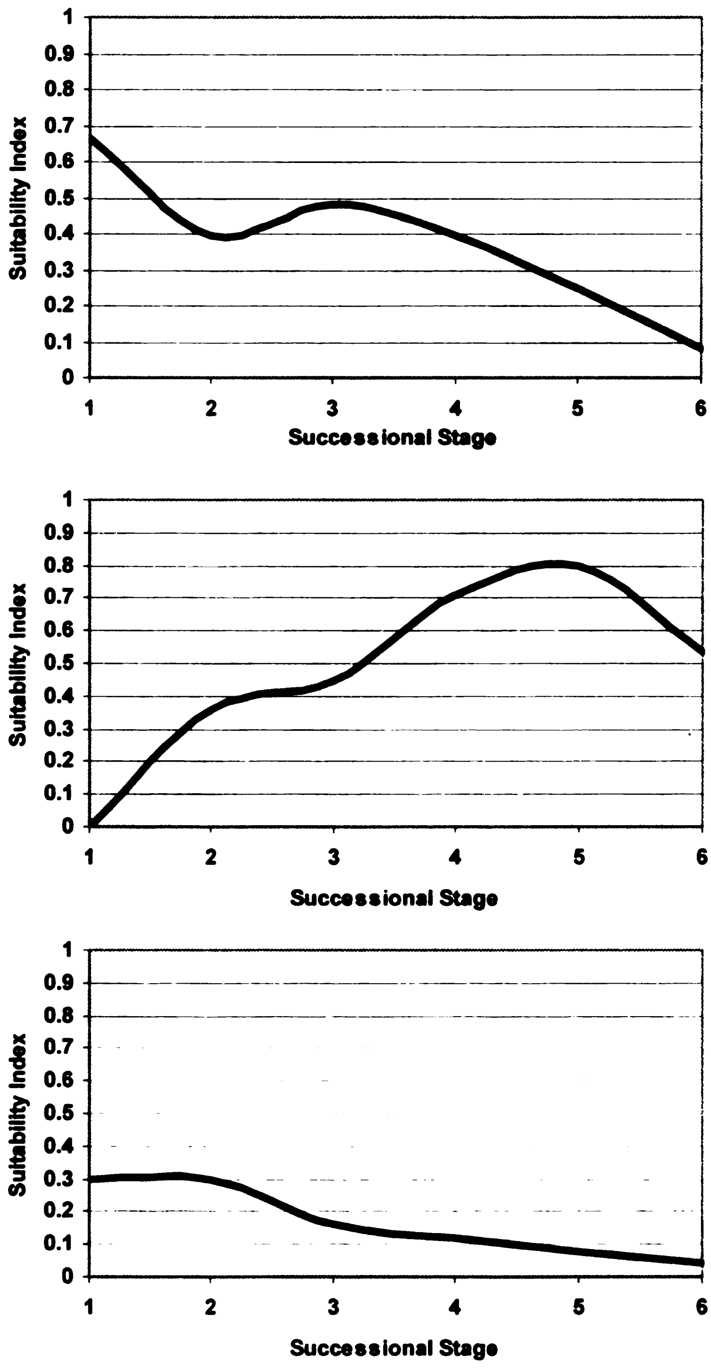
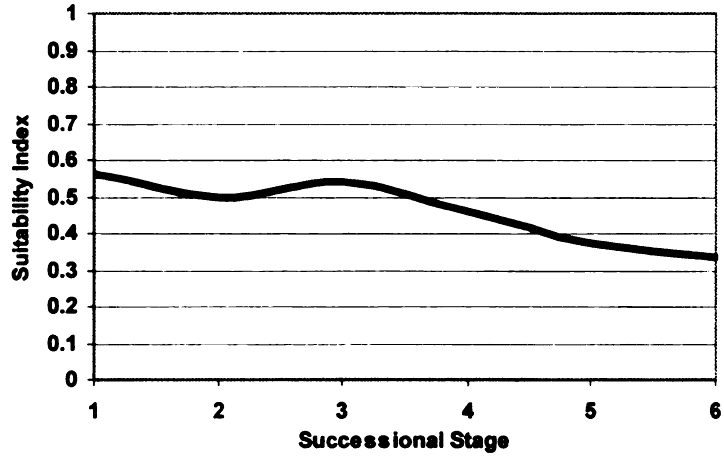
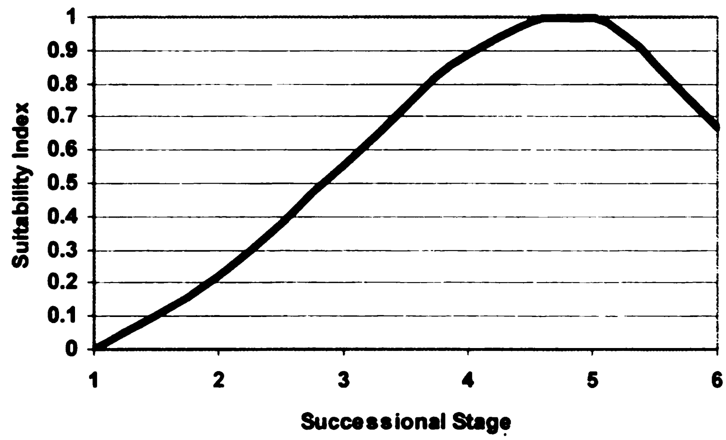


Figure A8-19. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush in early successional stages (1-2; ages < 30 years), black spruce-tamarack-balsam fir-cedar-white pine in middle stages (3-4; ages 30-100 years), and black spruce-tamarack in later stages (5-6; ages > 100 years).

A.



B.



C.

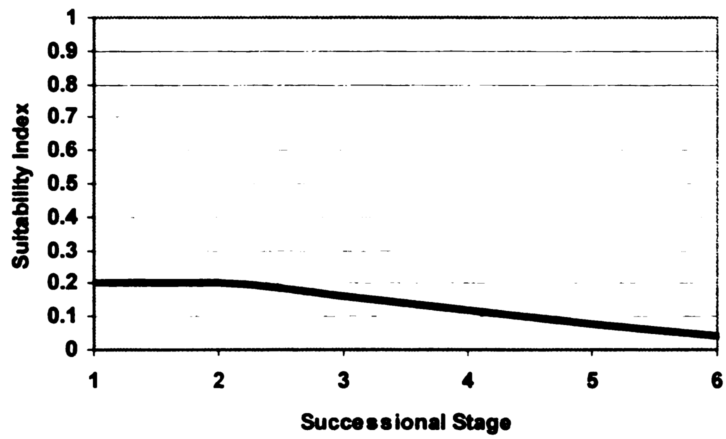


Figure A8-20. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush-aspen-birch-balsam poplar-black ash in early successional stages (1-2; ages < 30 years), cedar-black spruce-balsam fir in middle stages (3-4; ages 30-100 years), and cedar-hemlock in later stages (5-6; ages > 100 years).

A.

B.

C.

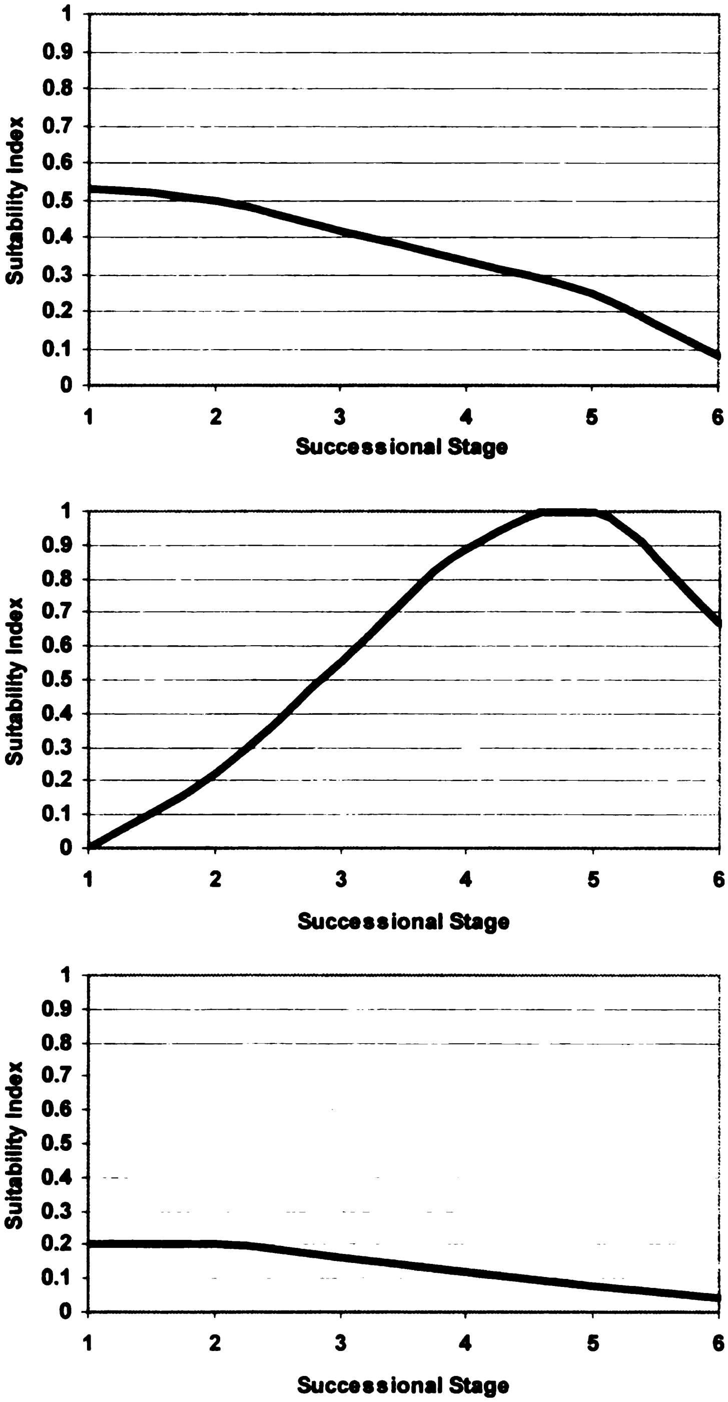


Figure A8-21. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush-birch-tamarack-black ash in early successional stages (1-2; ages < 30 years), cedar-black spruce-balsam fir in middle stages (3-4; ages 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; ages > 100 years).

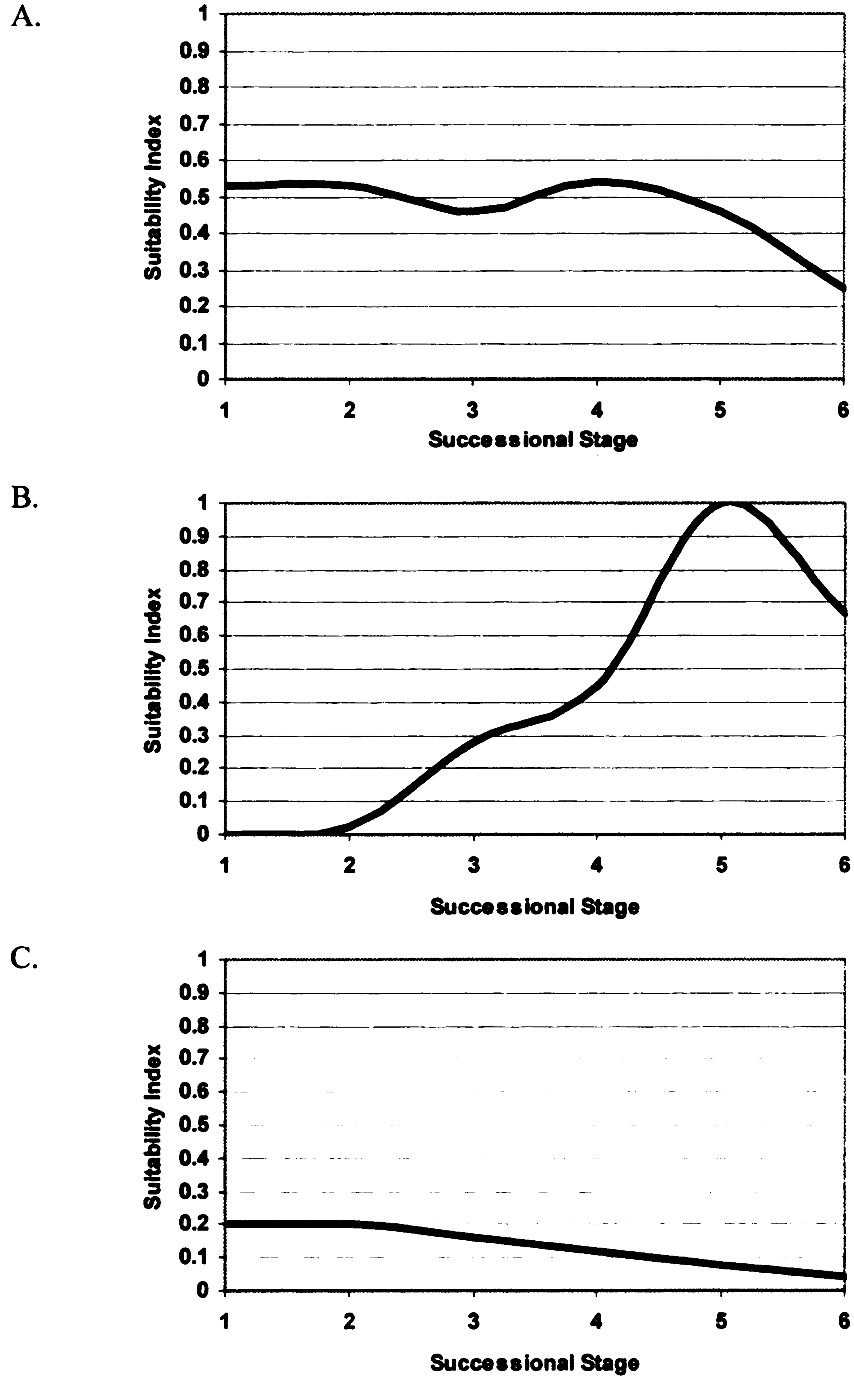


Figure A8-22. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush-birch-tamarack-black ash in early successional stages (1-2; ages < 30 years), tamarack-black ash-red maple in middle stages (3-4; ages 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; ages > 100 years).

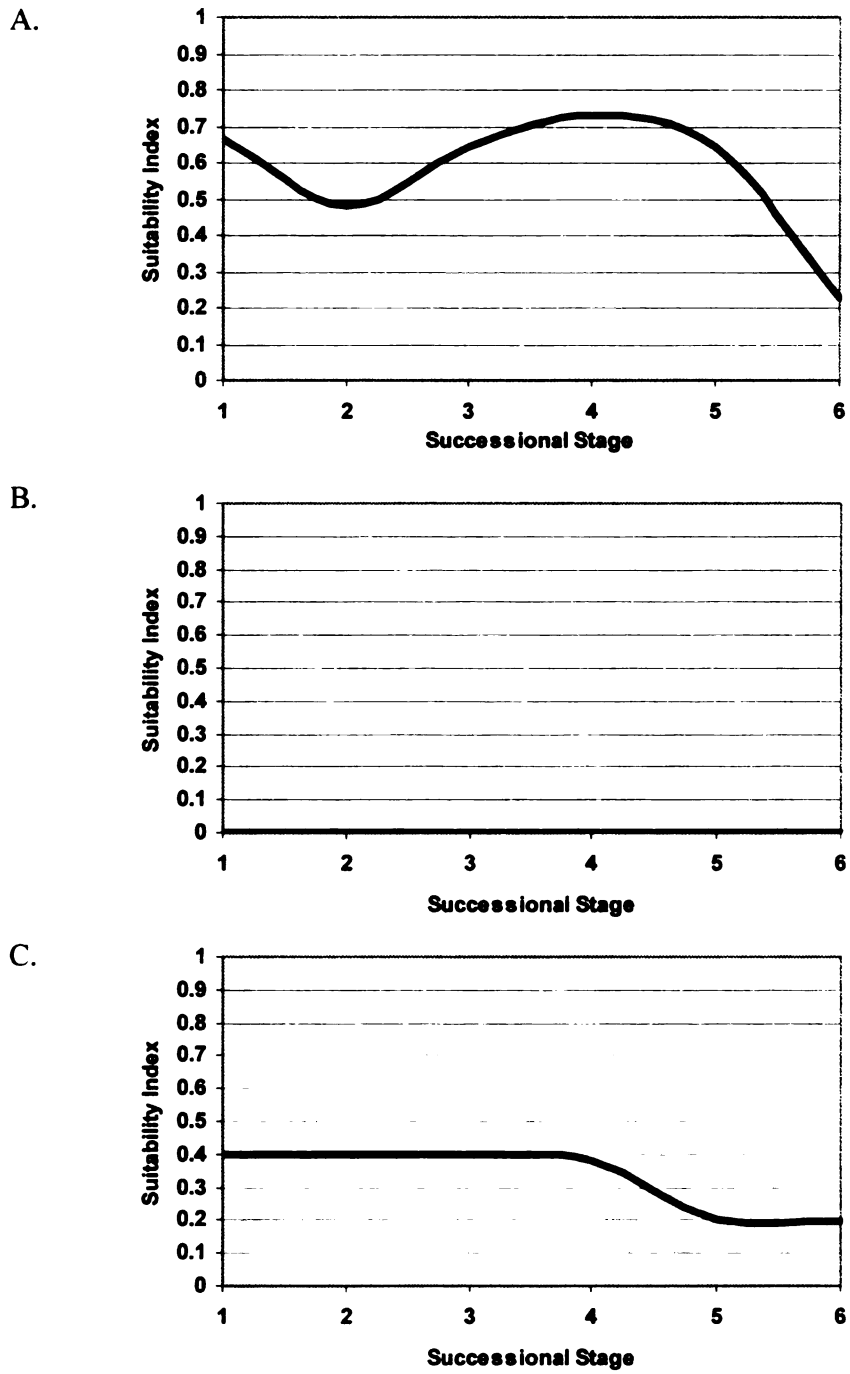


Figure A8-23. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support shrubs-grass in early successional stages (1-2; < 30 years), jack pine-red pine-white pine-oak in middle stages (3-4; 30-100 years), and white pine-red pine-oak-jack pine in later stages (5-6; > 100 years).

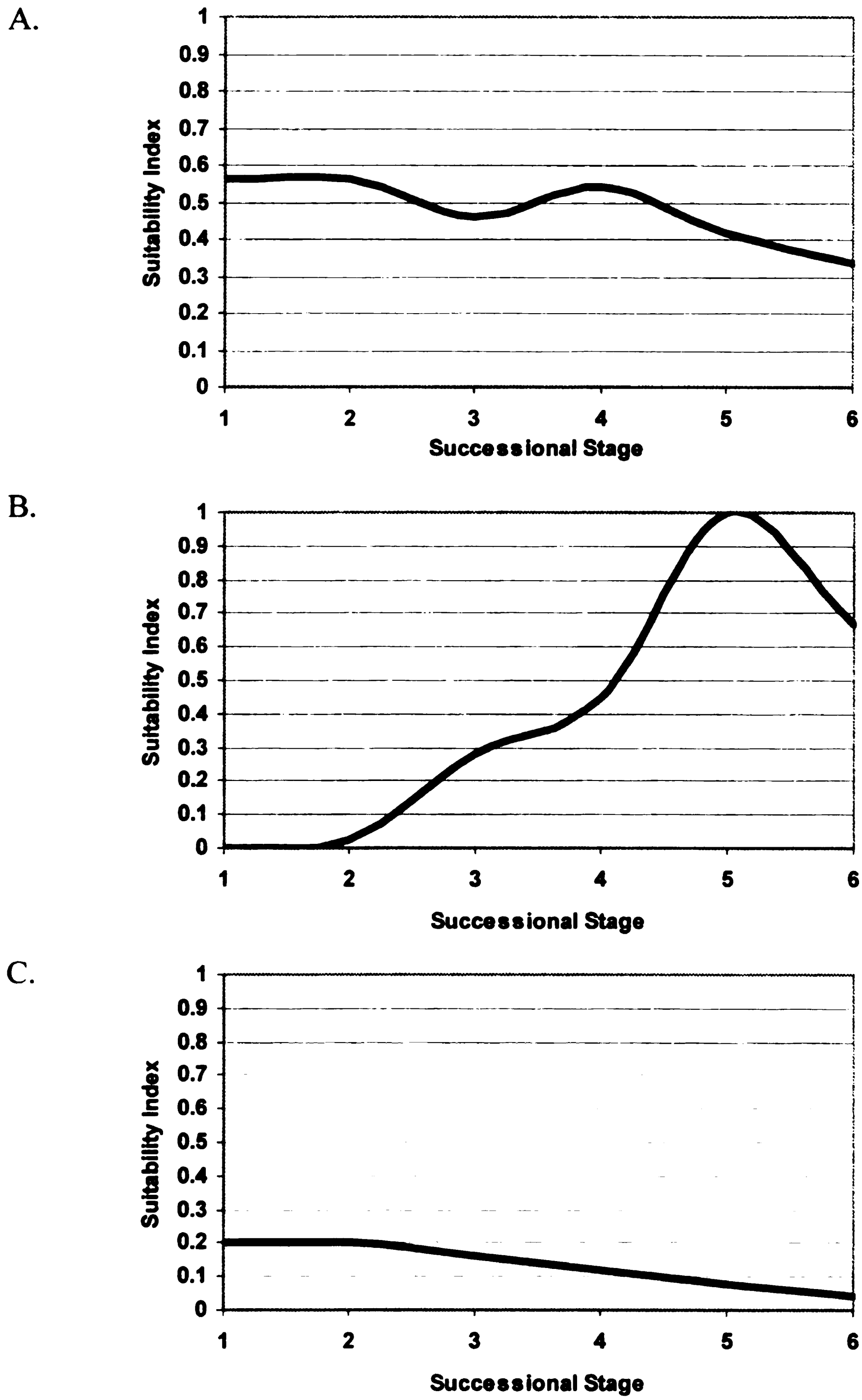


Figure A8-24. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support tamarack-black ash-birch-red maple in early successional stages (1-2; < 30 years), tamarack-black ash-birch-red maple-cedar in middle stages (3-4; 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; > 100 years).

Appendix 9. White-tailed deer habitat suitability curves for each successional trajectory in the Upper Peninsula, Michigan. The curves display habitat dynamics for fall and winter food, thermal cover, and spring and summer habitat components based on habitat potential models developed in this document.

A.

B.

C.

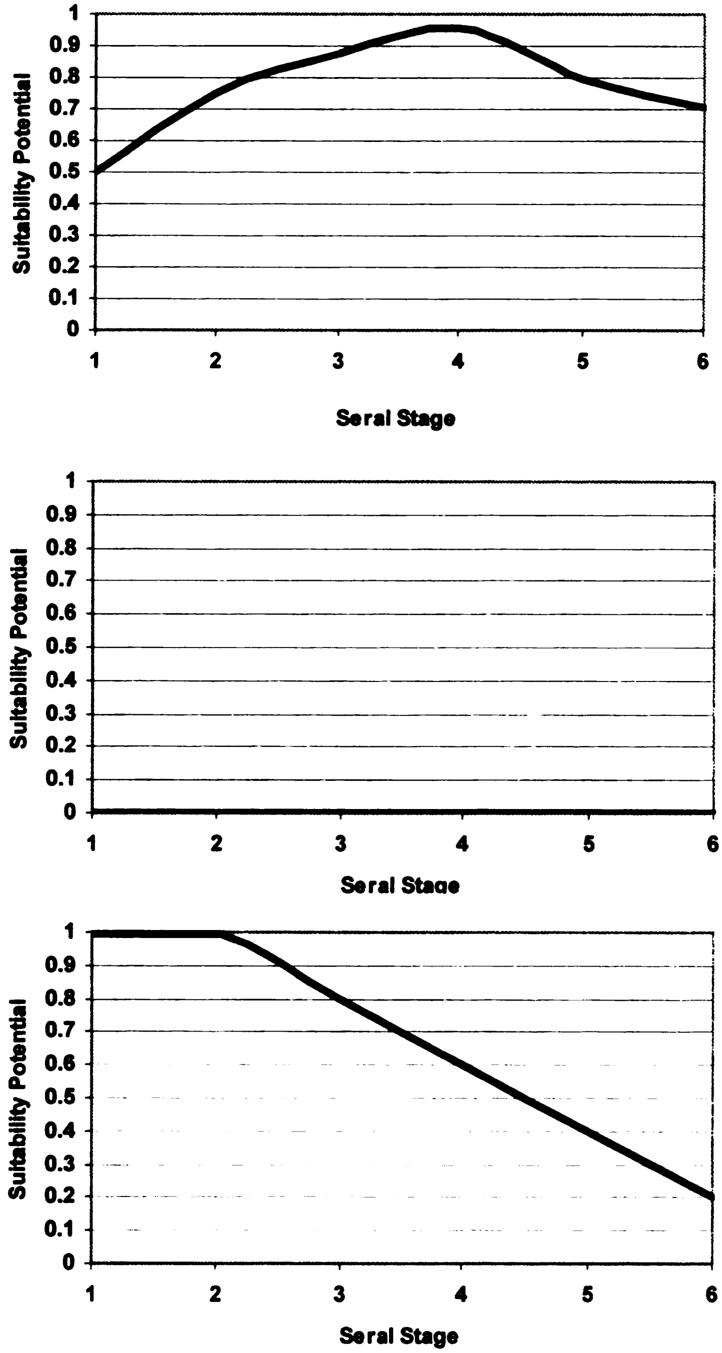
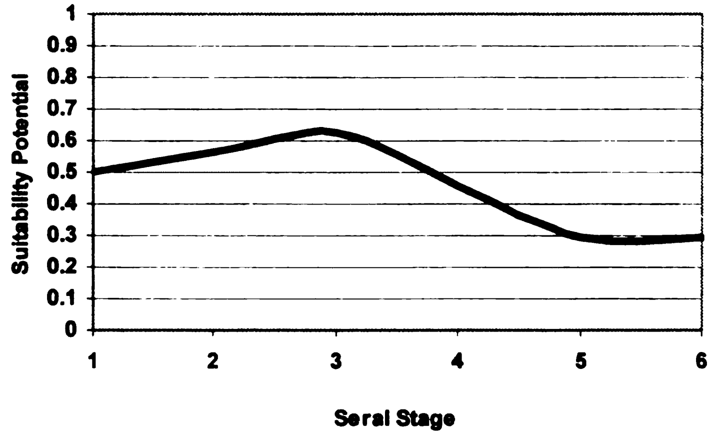
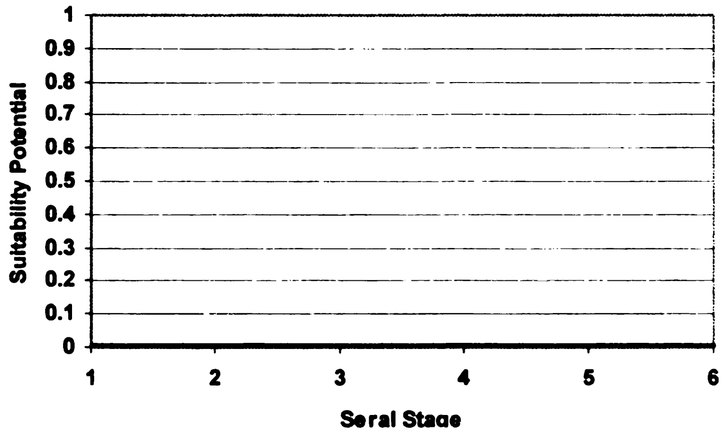


Figure A9-1. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen in early successional stages (1-2; ages < 30 years), sugar maple-red maple-ironwood-basswood-yellow birch in middle stages (3-4; ages 30-100 years), and sugar maple-hemlock in late stages (5-6; ages > 100 years).

A.



B.



C.

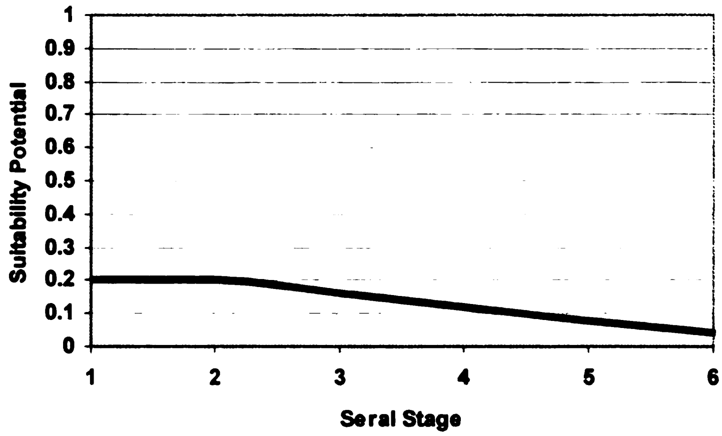


Figure A9-2. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-balsam poplar in early successional stages (1-2; ages < 30 years), white ash-black ash-American elm in middle stages (3-4; ages 30-100 years), and white ash-red maple-sugar maple-black ash in later stages (5-6; ages > 100 years).

A.

B.

C.

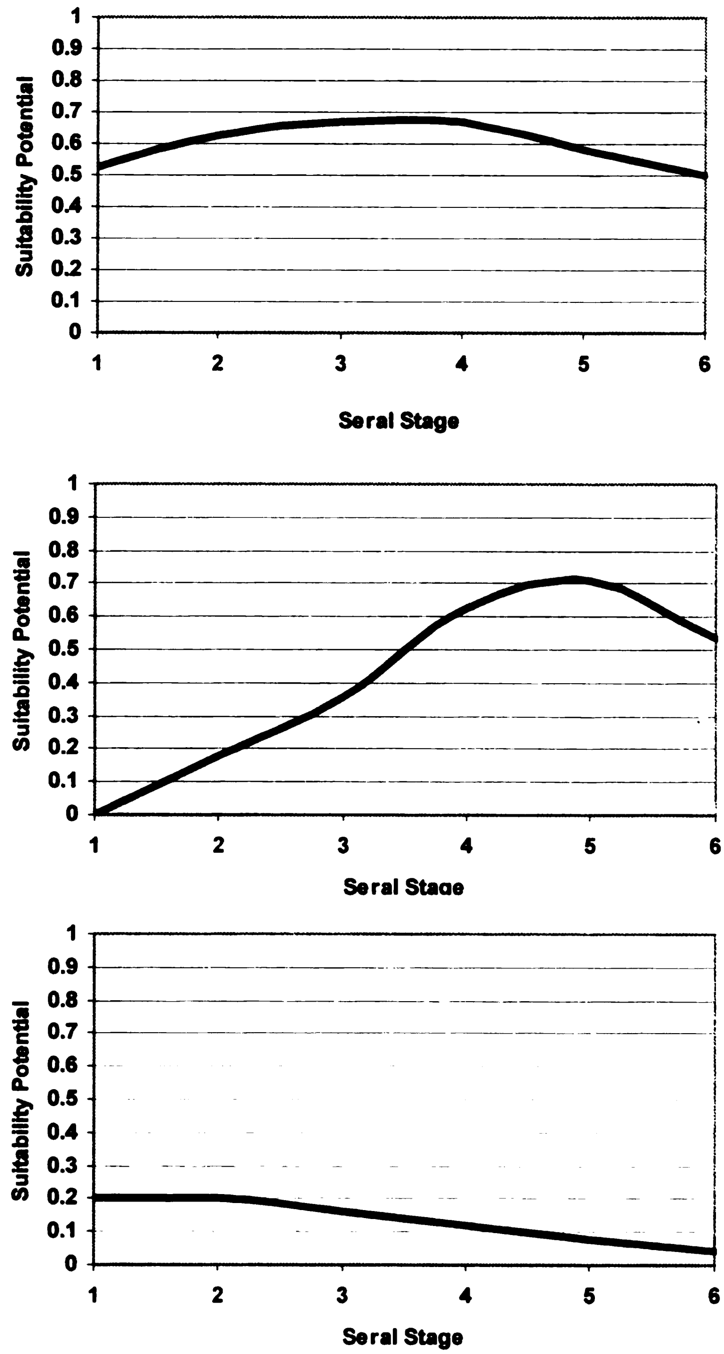
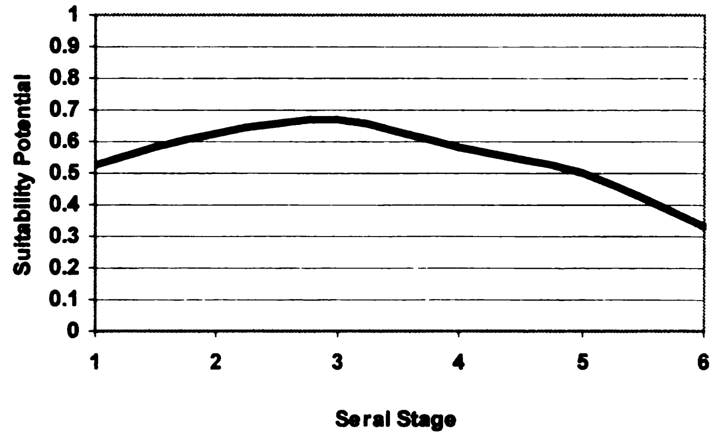
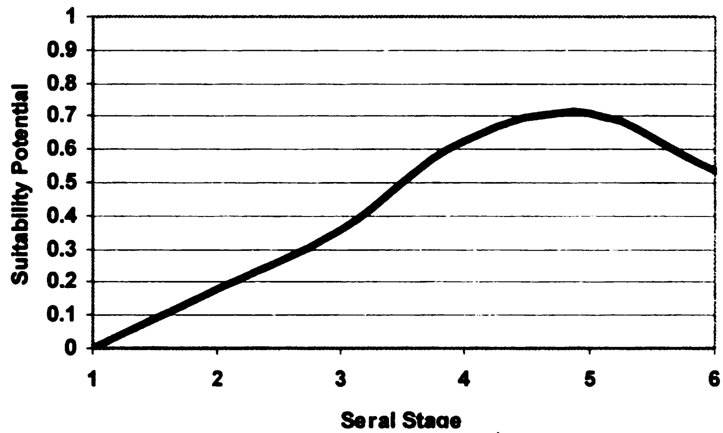


Figure A9-3. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-balsam poplar-birch in early successional stages (1-2; ages < 30 years), balsam fir-white spruce-cedar-black spruce in middle stages (3-4; ages 30-100 years), and hemlock-red maple-sugar maple in later stages (5-6; ages > 100 years).

A.



B.



C.

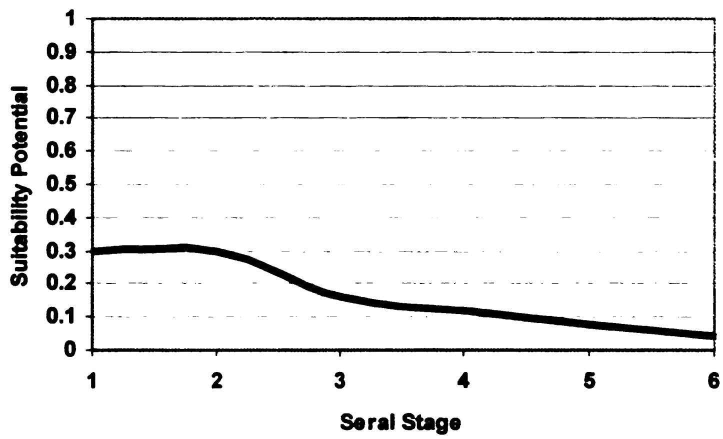
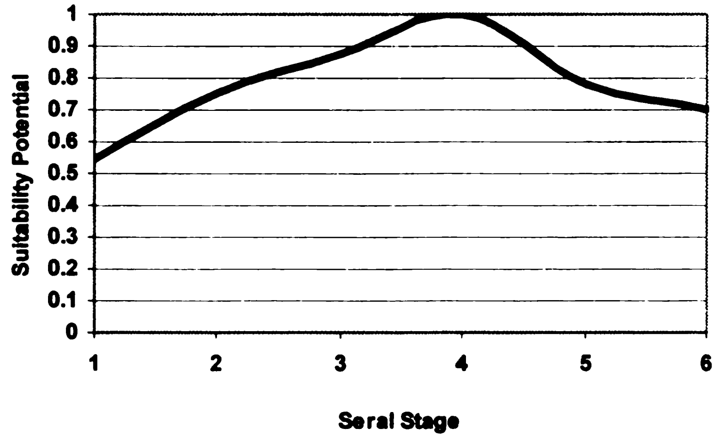
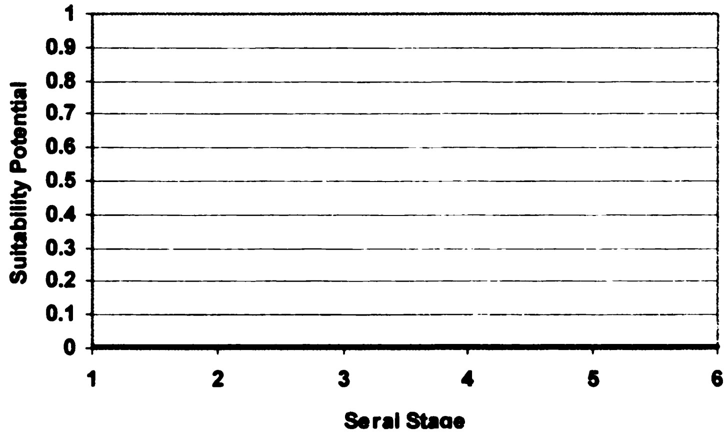


Figure A9-4. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush-aspen-balsam poplar-birch in early successional stages (1-2; ages < 30 years), balsam fir-white spruce-cedar-red maple in middle stages (3-4; ages 30-100 years), and hemlock-red maple-sugar maple in later stages (5-6; ages > 100 years).

A.



B.



C.

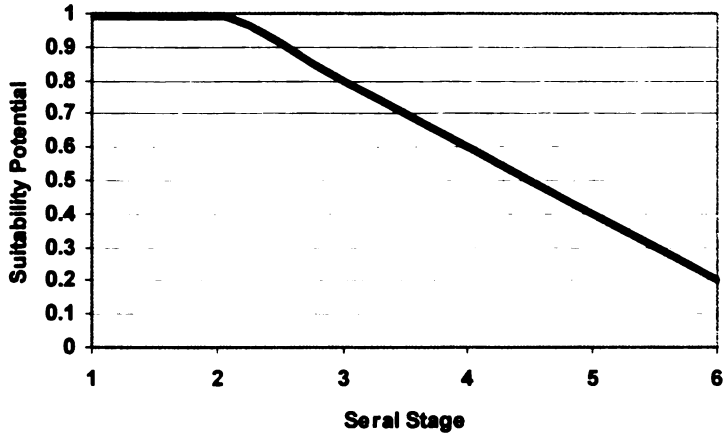


Figure A9-5. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), sugar maple-white pine-red maple-yellow birch-red oak-balsam fir in middle stages (3-4; ages 30-100 years), and hemlock-red maple in later stages (5-6; ages > 100 years).

A.

B.

C.

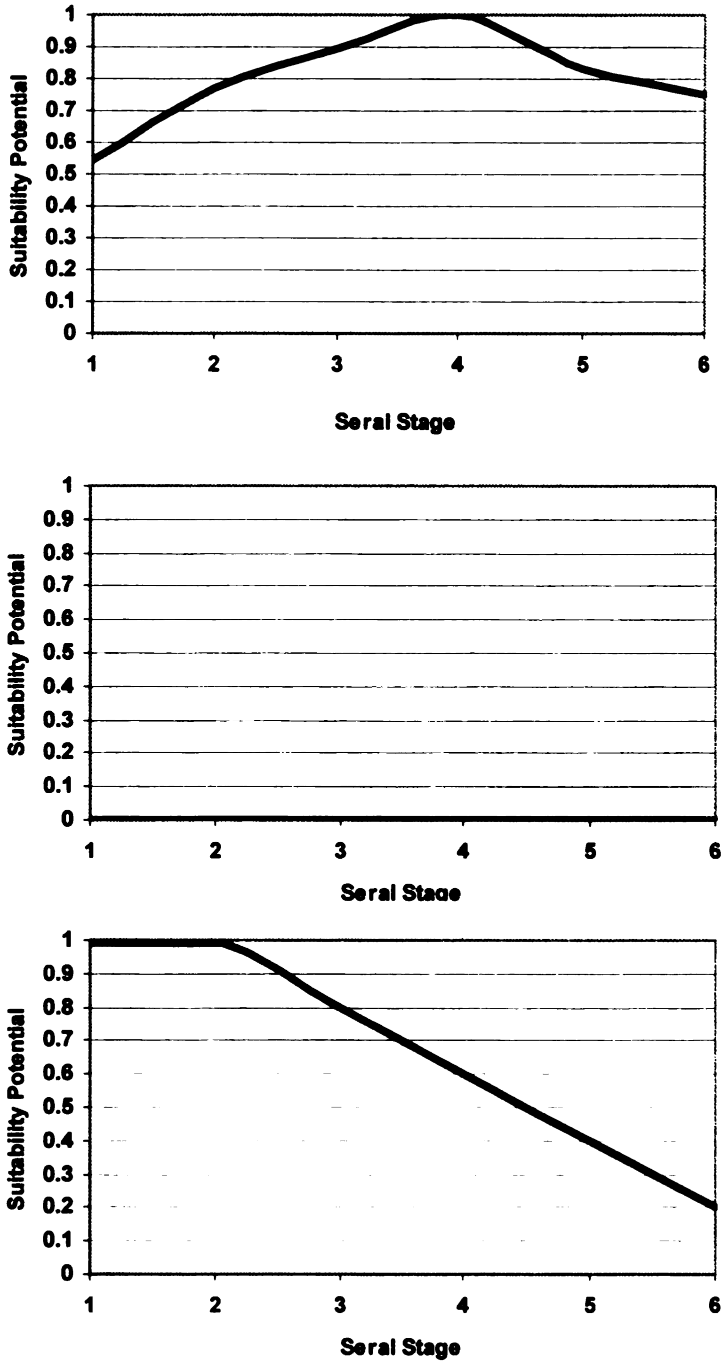


Figure A9-6. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), sugar maple-yellow birch-red maple-ironwood-balsam fir-white spruce in middle stages (3-4; ages 30-100 years), and sugar maple-hemlock in later stages (5-6; ages > 100 years).

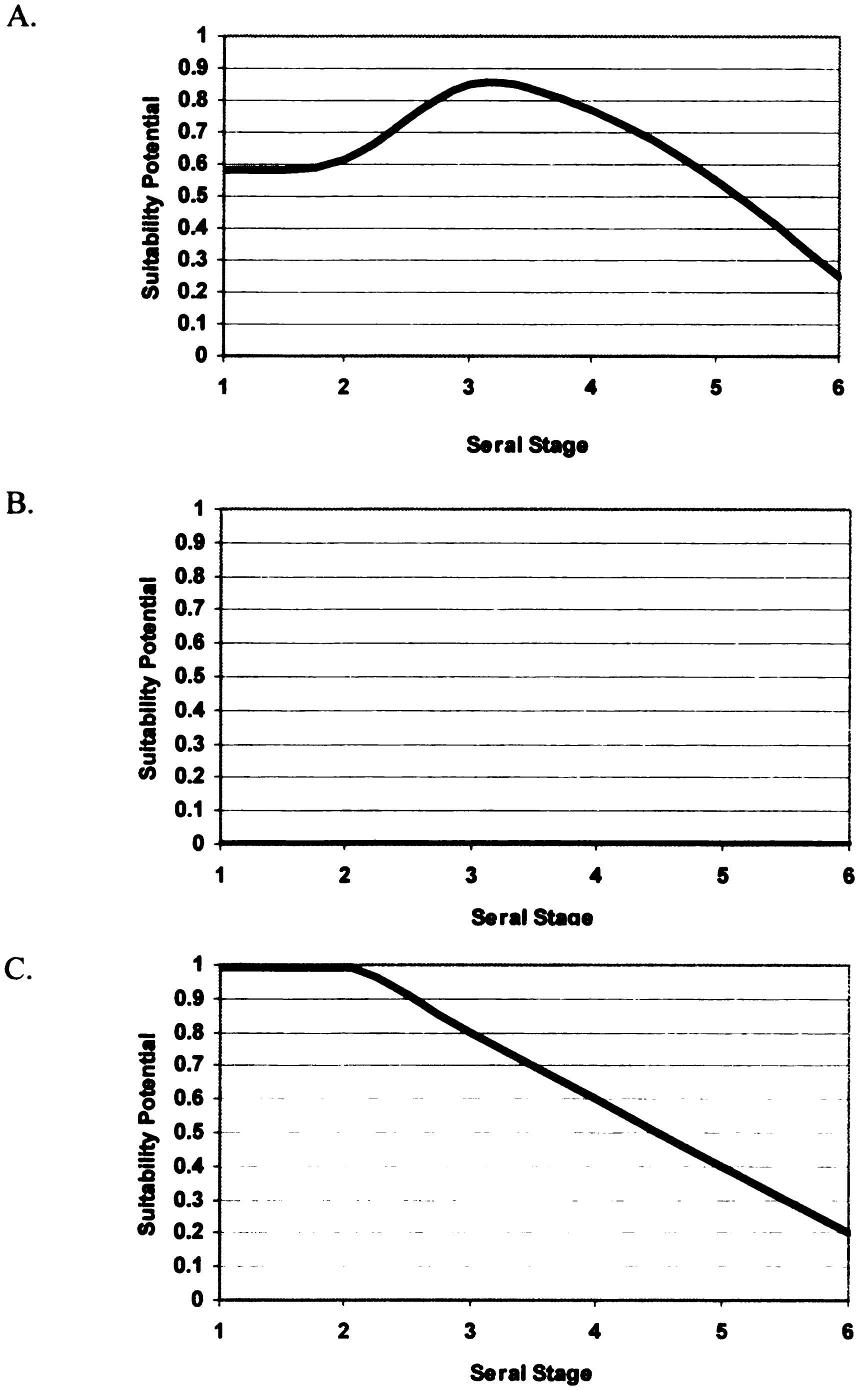


Figure A9-7. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-birch in early successional stages (1-2; ages < 30 years), white pine-red pine-balsam fir-white spruce in middle stages (3-4; ages 30-100 years), and red maple-red oak in later stages (5-6; ages > 100 years).

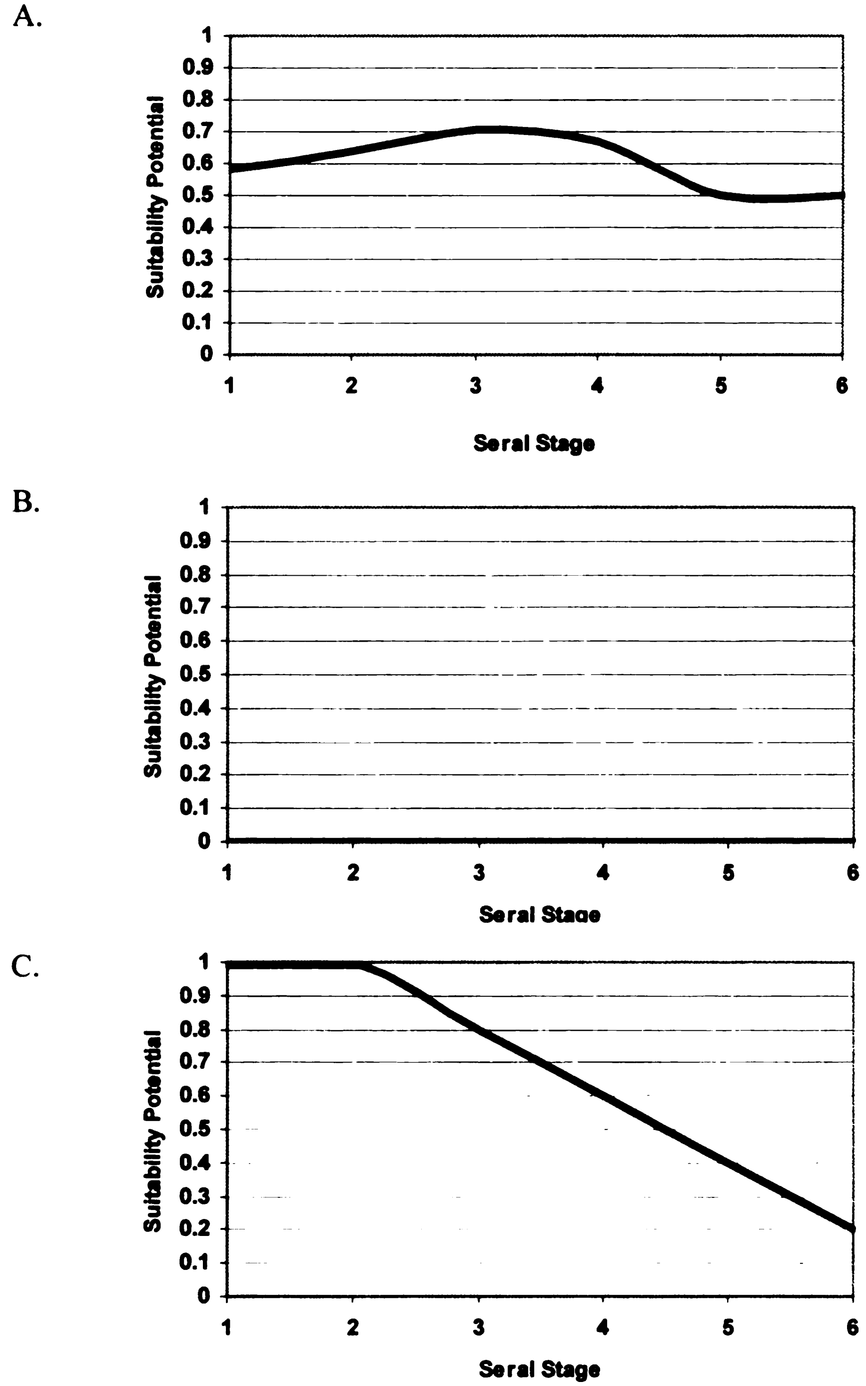


Figure A9-8. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-sugar maple in early successional stages (1-2; ages < 30 years), sugar maple-basswood-red maple-beech in middle stages (3-4; ages 30-100 years), and sugar maple in later stages (5-6; ages > 100 years).

A.

B.

C.

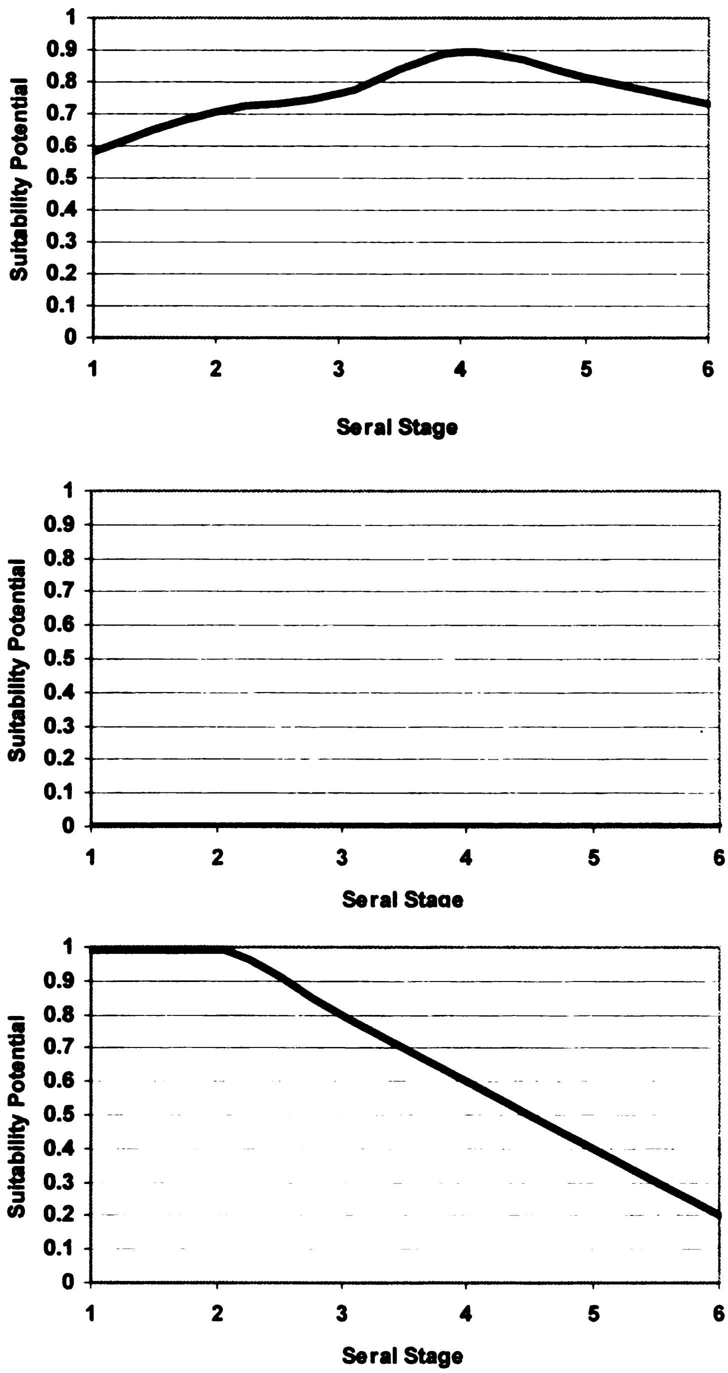
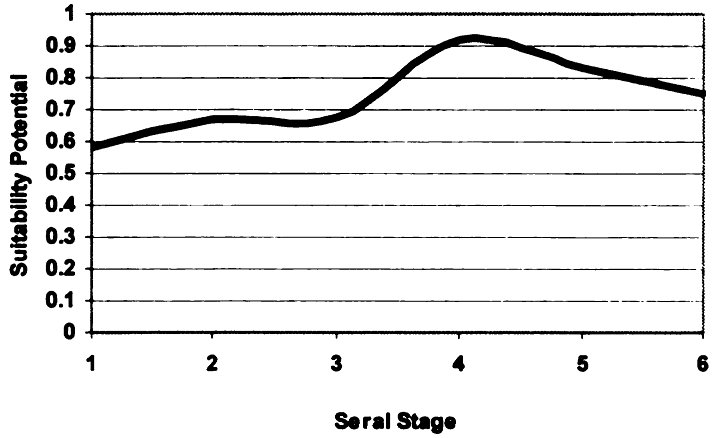
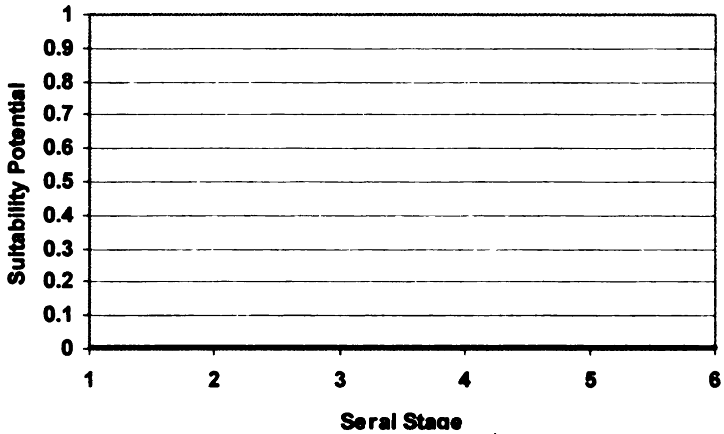


Figure A9-9. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-sugar maple in early successional stages (1-2; ages < 30 years), sugar maple-basswood-red maple-yellow birch-ironwood in middle stages (3-4; ages 30-100 years), and hemlock-sugar maple in later stages (5-6; ages > 100 years).

A.



B.



C.

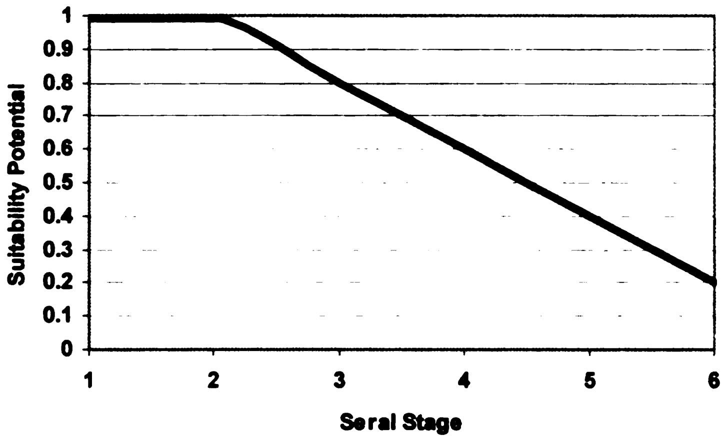


Figure A9-10. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-sugar maple in early successional stages (1-2; ages < 30 years), sugar maple-red maple-yellow birch-ironwood in middle stages (3-4; ages 30-100 years), and sugar maple-hemlock in later stages (5-6; ages > 100 years).

A.

B.

C.

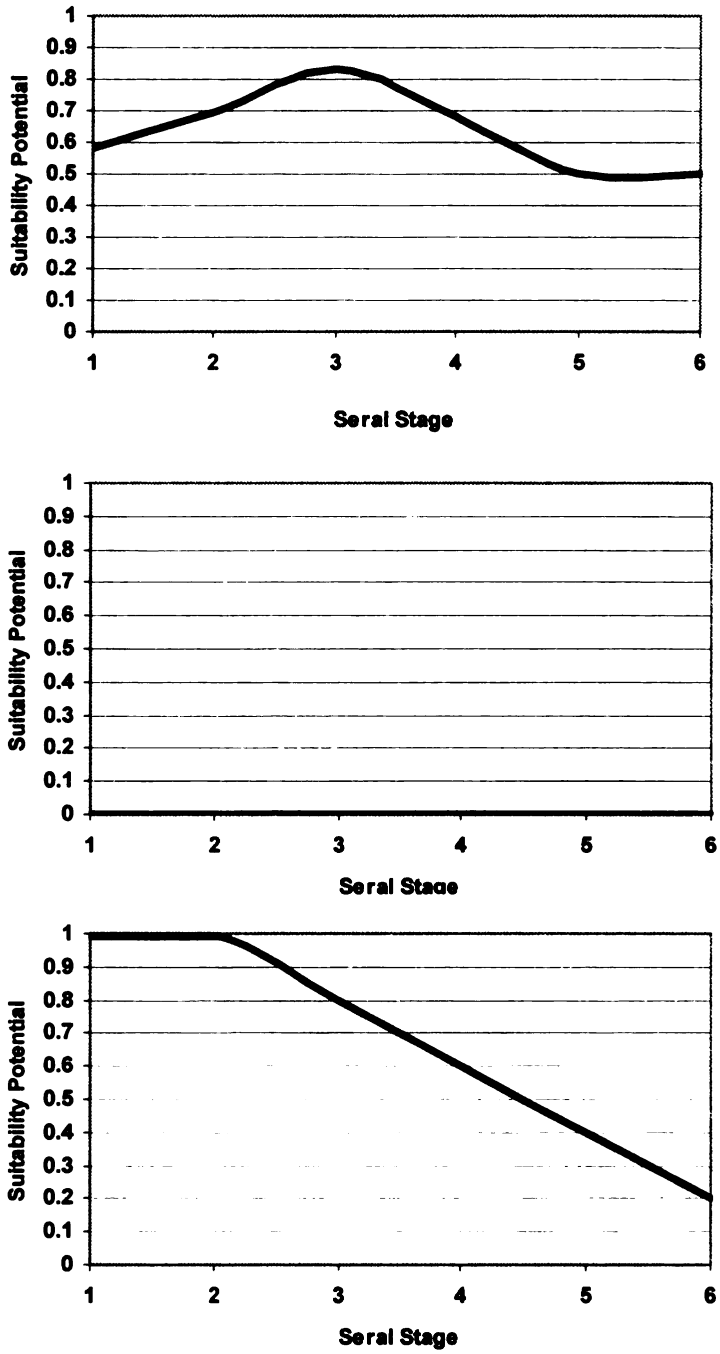
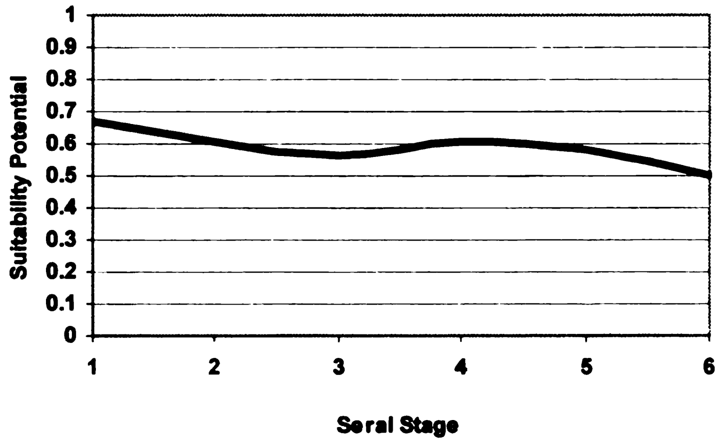
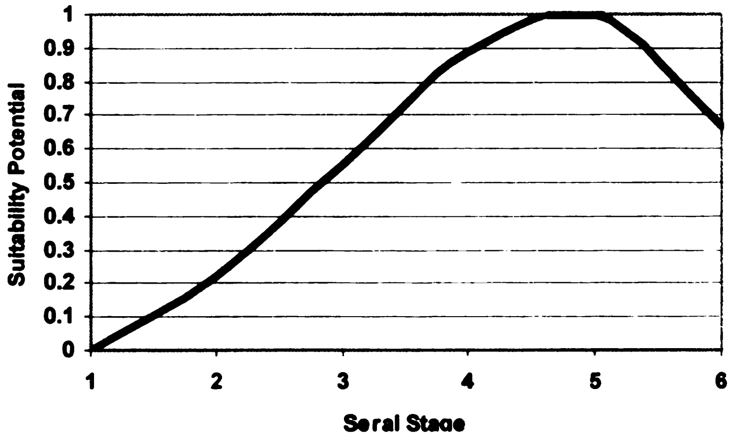


Figure A9-11. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support aspen-sugar maple-white ash in early successional stages (1-2; ages < 30 years), sugar maple-basswood-ironwood-beech-white ahs-American elm in middle stages (3-4; ages 30-100 years), and sugar maple in later stages (5-6; ages > 100 years).

A.



B.



C.

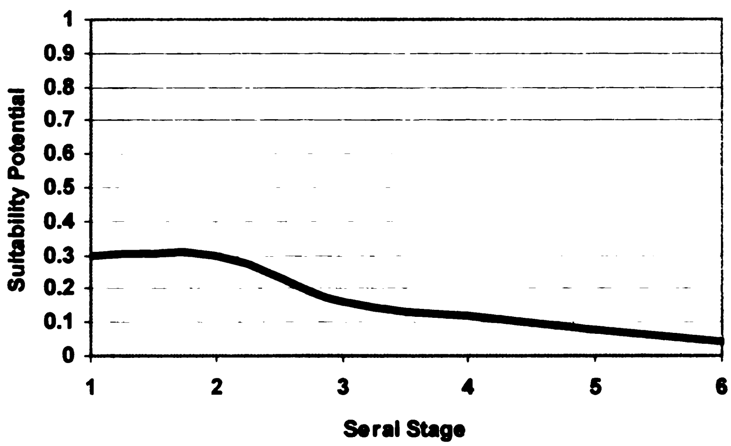


Figure A9-12. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush in early successional stages (1-2; ages < 30 years), lowland brush-birch-red maple-balsam poplar in middle stages (3-4; ages 30-100 years), and black spruce-cedar-hemlock in later stages (5-6; ages > 100 years).

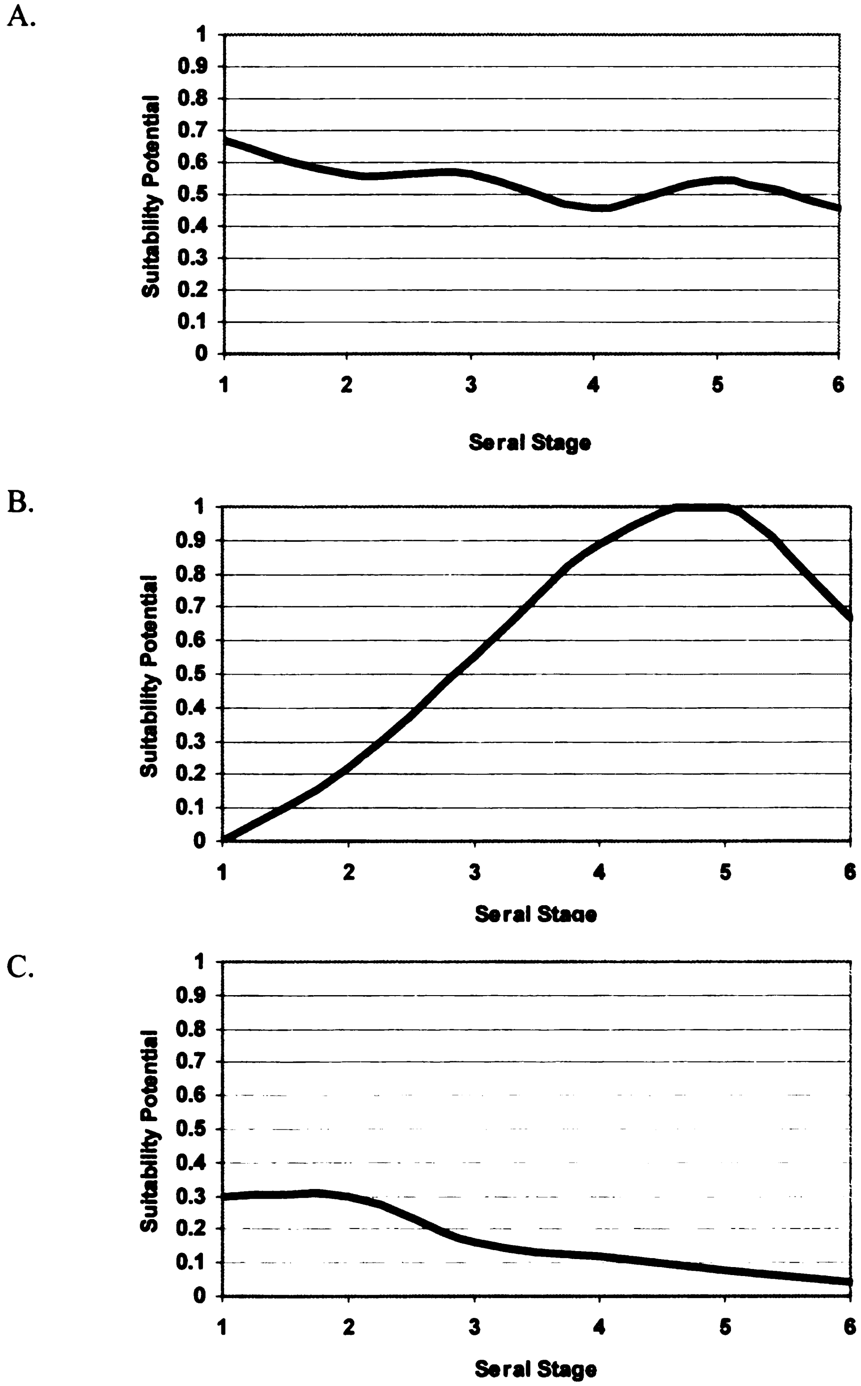
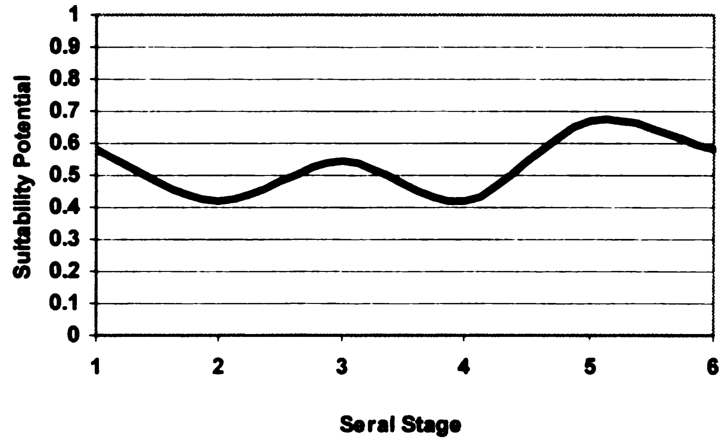
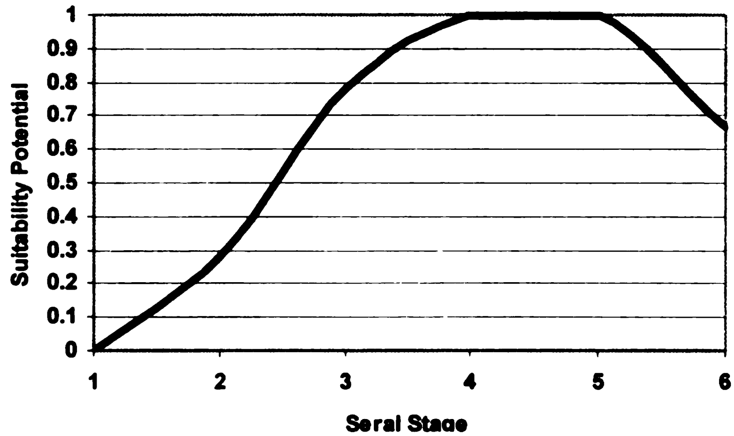


Figure A9-13. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush in early successional stages (1-2; ages < 30 years), tamarack-black ash-birch-red maple in middle stages (3-4; ages 30-100 years), and cedar-black spruce-balsam fir in later stages (5-6; ages > 100 years).

A.



B.



C.

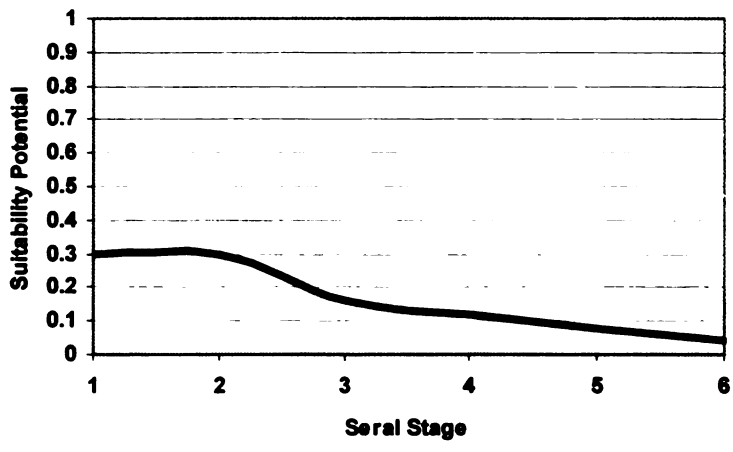


Figure A9-14. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support lowland brush-birch-balsam poplar in early successional stages (1-2; ages < 30 years), cedar-black spruce-balsam fir in middle stages (3-4; ages 30-100 years), and cedar-hemlock in later stages (5-6; ages > 100 years).

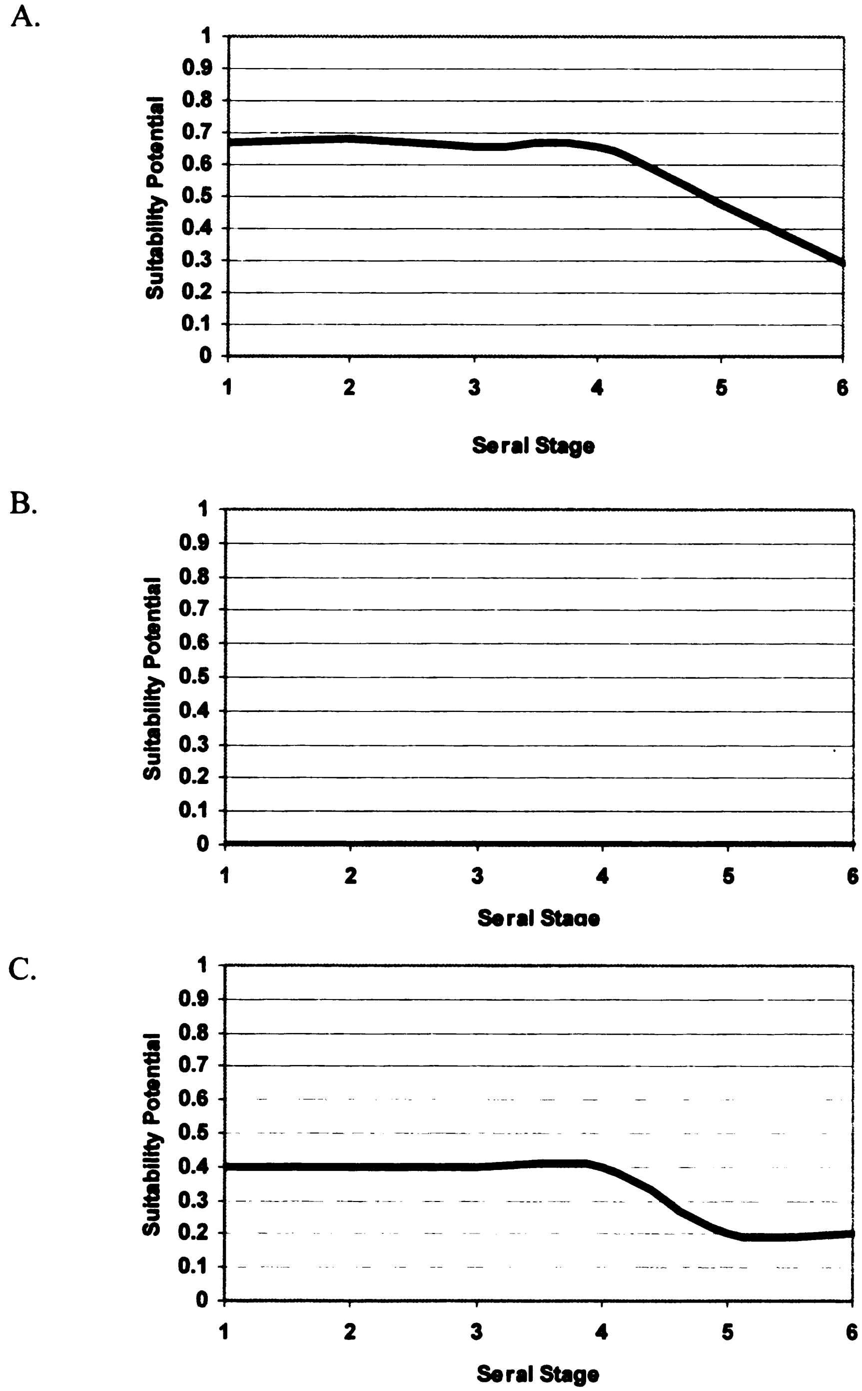


Figure A9-15. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support shrubs-grass in early successional stages (1-2; ages < 30 years), jack pine in middle stages (3-4; ages 30-100 years), and jack pine-red pine in later stages (5-6; ages > 100 years).

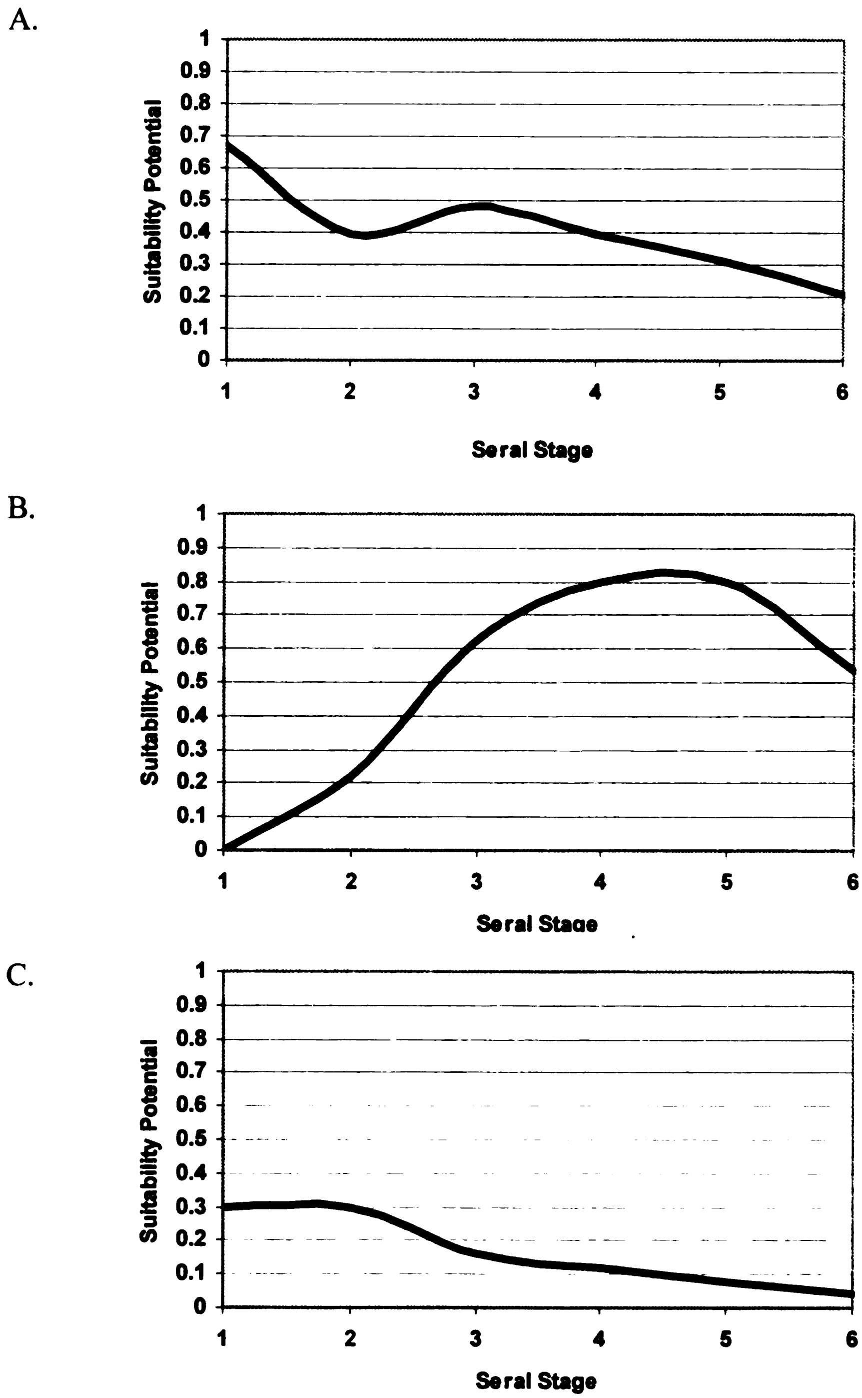


Figure A9-16. Suitability curves for fall and winter food (A), thermal cover (B), and spring and summer habitat (C) for areas that support sphagnum-lowland brush in early successional stages (1-2; ages < 30 years), black spruce-tamarack-balsam fir-cedar in middle stages (3-4; ages 30-100 years), and black spruce-tamarack in later stages (5-6; ages > 100 years).

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