HABITAT ASSOCIATIONS OF RED-SHOULDERED HAWKS IN CENTRAL MINNESOTA LANDSCAPES

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ABSTRACT

The red-shouldered hawk (*Buteo lineatus*) is a species of special conservation concern in much of the Great Lakes region, although little information exists about its habitat associations at the landscape scale. I conducted repeated call-broadcast surveys and nest searches in central Minnesota in 2004 and 2005 to assess habitat characteristics associated with red-shouldered hawk nest sites and occupancy. For call broadcast surveys, I estimated the probability of detection and occupancy, and assessed habitat associations at 2 spatial scales (100 and 314-ha circular plots), which were based on reported minimum and maximum red-shouldered hawk home-range size. To evaluate red-shouldered hawk habitat associations at nests, I used standard logistic regression methods to compare nests sites to random sites at 3 spatial scales (25-ha, 100-ha, and 314-ha circular plots). I estimated habitat amount, average patch size, patch density, edge density, and habitat diversity at all 3 spatial scales. I chose 4 study areas that represent a gradient of habitat conditions, from large, contiguous tracts of mature forest to small, isolated stands that have been fragmented and reduced in size, mostly due to timber harvest. In 2004, I conducted call broadcast surveys at 128 locations in 2 study areas, and in 2005, I surveyed 247 locations in 4 study areas. Estimates of probability of detection ranged from 0.1747 to 0.7500 and occupancy ranged from 0.5948 to 1.00 across years and study areas. I found a total of 68 red-shouldered hawk nests at 3 study areas in 2004 and 2005. For both nest sites and call-broadcast survey locations, I developed models relating habitat characteristics at multiple spatial scales to red-shouldered hawk nest site use and occupancy, and assessed support for these models using an Information-Theoretic framework. Overall, the amount of non-forest (grass, clear-cut area, forest <5 years old) and the amount of mature deciduous forest (>40 years old) had the strongest association with red-shouldered hawk occupancy and nest sites, but their importance varied across years, study areas, and survey techniques. The amount of non-forest was negatively correlated and amount of mature deciduous forest was positively correlated with red-shouldered hawk occupancy and nest-sites. Red-shouldered hawk nests in central Minnesota were associated with the amount of mature deciduous forest in combination with low levels of non-forest. With call broadcast surveys, red-shouldered hawk occupancy was either associated with amount of mature deciduous forest or limited amount of non-forest, rather than the combination of both, as observed for nest sites. Other metrics describing patterns of mature deciduous forest, such as the number of patches, mean patch size, and landscape diversity were retained in some best-supported models and may be important in red-shouldered hawk-habitat associations. Based on circular plots surrounding nests, the lower limit of mature forest (including mature deciduous and mature coniferous) at red-shouldered hawk nests was approximately 30% and did not vary across spatial scale. Most nests and call broadcast sites with red-shouldered hawk responses were associated with ≥40% and averaged approximately 50% mature deciduous forest. My findings suggest that red-shouldered hawks are associated with a high proportion of mature forest and a small proportion of open, non-forested areas across a range of spatial scales.

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INTRODUCTION

The red-shouldered hawk (*Buteo lineatus*) is currently listed as a state endangered or threatened species in Iowa, Illinois, Michigan, and Wisconsin, and as a species of special concern in Minnesota, Ohio, and Indiana (Crocoll 1994). Numerous studies suggest that red-shouldered hawks prefer to nest in mature, contiguous forest (Titus and Mosher 1981, Bednarz and Dinsmore 1982, Bryant 1986, Dijak et al. 1990, Bosakowski et al. 1992), and apparent population declines are thought to be primarily due to habitat loss and alteration (Coffin and Pfannmuller 1988, Bloom et al. 1993, Crocoll 1994). Yet, the specific reasons for apparent population declines remain unclear (Crocoll 1994). Some populations of red-shouldered hawks tolerate moderate forest fragmentation and high levels of human activity (Bloom et al. 1993; Dykstra et al. 2000, 2001a, 2001b; Balcerzak and Wood 2003). Many studies indicate that the presence of nearby wetlands and small bodies of water, in combination with at least some mature forest, are significant predictors of nesting habitat for red-shouldered hawks (Bednarz and Dinsmore 1981, Bosakowski et al. 1992, Dykstra 2001b, Balcerzak and Wood 2003). Additionally, Bednarz and Dinsmore (1982) suggested that as habitat alteration occurs, red-shouldered hawks could be displaced by red-tailed hawks (*Buteo jamaicensis*), which prefer a patchwork of woodland and large open areas (Preston and Beane 1993). However, the response of red-shouldered hawks to habitat change is not well understood and may vary among regions. This, in combination with a general lack of information on red-shouldered hawk-habitat relations throughout much of its range, confounds land management decisions intended to minimize impacts and provide for habitat protection for this species.

In Minnesota, the Generic Environmental Impact Statement on Timber Harvesting and Management in Minnesota (Jaakko Pöyry Consulting, Inc. 1992) predicted that the population size of red-shouldered hawks in Minnesota would decline statewide under all possible projected timber harvests. However, since that assessment was prepared, red-shouldered hawks have been documented breeding at relatively high densities in large, continuous tracts of forest in central Minnesota [at Camp Ripley Army National Guard Training Site (Belleman 1998, McLeod et al. 2000) and on the west side of Lake Mille Lacs (Stucker et al. 2004)], and at lower densities in other portions of the state (McLeod 1996, McLeod et al. 2000, Stucker et al. 2004). In 1994 and 1995, Belleman (1998) examined breeding ecology and habitat use of red-shouldered hawks on and adjacent to Camp Ripley Army National Guard Training Site and documented a high density of breeding red-shouldered hawks. McLeod (1996) found that red-shouldered hawks occurred at lower breeding densities in north-central Minnesota in areas with less contiguous forest and higher timber harvest. Further, she found that habitat use in north-central Minnesota differed from habitat use of red-shouldered hawks at Camp Ripley, suggesting a need for additional information regarding habitat requirements of red-shouldered hawks across Minnesota landscapes.

My objective was to evaluate and compare habitat characteristics associated with red-shouldered hawk occupancy and nest sites in central Minnesota in 2004 and 2005. Specifically, I sought to address the relationship between the size and spatial distribution of mature forest patches with occupancy rates and nest sites of red-shouldered hawks over multiple spatial scales and across a gradient of habitat conditions.

STUDY AREA

I conducted my study primarily on the Camp Ripley Army National Guard Training Site (hereafter Camp Ripley), the Pillsbury State Forest (hereafter Pillsbury), and The Nature Conservancy Lake Alexander Preserve (hereafter TNC), all located in central Minnesota, in northwestern Morrison and southern Cass Counties (Figure 1). In 2005, I expanded call broadcast surveys for red-shouldered hawks to the Foothills State Forest (hereafter Foothills) (Figure 1). Camp Ripley is bounded by the Crow Wing and Mississippi Rivers to the north and to the east and covers approximately 21,465 ha (53,000 acres). Pillsbury begins approximately 15 km north of the northern boundary of Camp Ripley and covers approximately 6,000 ha (14,756 acres). Foothills begins approximately 30 km north of Pillsbury and covers approximately 17,877 ha (43,960 acres). TNC lies directly west of Camp Ripley and includes approximately 1,400 ha of the eastern half of the Lake Alexander Preserve (Figure 1).

These areas lie within the transition zone of deciduous and northern coniferous forests of the Laurention Mixed Forest and the Eastern Broadleaf Forest provinces (Almendinger et al. 2000). Most of the study area is located on the St. Croix Moraine land-type association and is characterized primarily by irregular, steep-sided knob-and-kettle topography. Soils are predominantly well-drained sand and loam (Almendinger et al. 2000). Historically the study area was predominantly mixed pine and hardwood forests. Beginning in the mid-1800s, various land practices, including timber harvest and agriculture, greatly altered the area (Camp Ripley Environmental Office 2002). Currently, the study areas represent a gradient of habitat conditions from large, contiguous tracts of mature forest to small, isolated stands that have been fragmented and reduced in size, mostly due to timber harvest (Table 1). Camp Ripley consists of both fragmented and large blocks of relatively contiguous upland forest, including approximately 5,000 ha of potential red-shouldered hawk habitat (Belleman 1998). Major portions of this habitat are frequently included in military firing-range safety buffer zones and as a result, development has been limited to secondary roads or trails and small-scale logging. Both Pillsbury and Foothills are managed for multiple-use, including recreation and timber harvest, and are characterized by numerous, scattered clear-cuts and regenerating aspen (*Populus* spp.) stands of varying sizes and ages mixed with upland hardwood-pine forest (Table 1). Most of the TNC preserve is protected by restricted access and consists of contiguous upland forest (Table 1).

Current canopy vegetation is predominantly aspen (*Populus* spp.)/birch (*Betula* spp.) or oak (*Quercus* spp.)/northern hardwood types, which are characterized by red oak (*Quercus rubra*), quaking and big-tooth aspen (*Populus tremuloides* and *P. grandidentata*), red and sugar maple (*Acer rubrum* and *A. saccharum*), and paper birch (*Betula papyrifera*) (Camp Ripley Environmental Office 2002). Additional species found at lower densities include white and burr oak (*Quercus alba* and *Q. macrocarpa*), American basswood (*Tilia americana*), green ash (*Fraxinus pennsylvanica*), and some widely scattered American elm (*Ulmus americana*) and red, white, and jack pine (*Pinus resinosa*, *P. strobes*, and *P. banksiana*).

METHODS

Field Techniques

Call-broadcast Surveys

Broadcasting conspecific vocalizations has been shown to be an effective method for locating and measuring relative abundance of secretive, woodland raptors (Rosenfield et al. 1988, Mosher et al. 1990, Kennedy and Stahlecker 1993) and may provide a useful tool for monitoring red-shouldered hawk populations in central Minnesota (McLeod 1996, McLeod and Andersen 1998). Call-broadcast surveys are particularly useful in locating red-shouldered hawks early in the breeding season, prior to egg hatch, when they are more likely to respond to broadcast vocalizations (McLeod 1996, McLeod and Andersen 1998). I established survey stations to measure red-shouldered occupancy rates (i.e., the proportion of sites occupied) at all study areas. I established 90 survey stations at Camp Ripley and 41 survey stations at Pillsbury from which I conducted call-broadcast surveys from late March to early May in 2004. In 2005, I established 130, 39, 10, and 69 survey stations at Camp Ripley, Pillsbury, TNC, and Foothills, respectively, from which I conducted call-broadcast surveys from early April to mid-May. I expanded surveys at Camp Ripley in 2005 to include more stations in the southern portion of the area where I suspected there were fewer red-shouldered hawks. I selected survey stations within study areas randomly using a random point generator in ESRI® ArcView (Environmental Systems Research Institute, Redlands, Calif.) (use of trade names does not imply endorsement by the U.S. Geological Survey or the University of Minnesota) with the Minnesota Department of Natural Resources (MDNR) Random Point extension. I rejected sampling random points that occurred >500 m from an accessible road or trail, that occurred in military ordinance impact zones or on private property, or did not include any mature forest within a 1-km^2 radius. As suggested by McLeod (1996), I spaced survey stations ≥0.8 km apart.

I surveyed stations in the morning, beginning one-half hour after sunrise and ending no later than 1130 hours. McLeod (1996) showed that red-shouldered hawks were less likely to respond during the period from 1030–1500 hours. I did not conduct surveys in inclement weather, such as continuous rain, fog, or other conditions that limited visibility within 1 km or wind speeds > Beaufort 3 (12–19 km/hr). I recorded temperature, wind speed, percent cloud cover, and precipitation at the beginning of each survey and noted any changes in precipitation, wind speed, or cloud cover as they occurred during surveys.

I followed call–broadcast techniques described by Iverson and Fuller (1991), McLeod (1996), and McLeod and Andersen (1998). I broadcast a red-shouldered hawk call for 20 sec, followed by a 40-sec listening period, and repeated this pattern 6 times, followed by a final 4-minute listening period for a total time at each station of 10 minutes. I broadcast the red-shouldered hawk call from the Stokes Field Guide to Bird Songs of Eastern and Central North America (Elliot et al. 1997) using a hand-held megaphone attached to a portable compact disc player. During call broadcasts, I held the megaphone at a height of approximately 1.5 m and rotated the megaphone 120° between each 20 sec broadcast. I adjusted output of the megaphone to between 100 and 110 dB at 1 m from the source using a sound-level meter set on slow response and C weighting (McLeod 1996).

For each raptor detection at a survey station, I recorded the raptor species and type of response. I classified types of hawk response to broadcasting as follows: (1) flew over or circled silently, (2) approached station silently, perched silently, (3) called, (4) flew over or circled and called, (5) approached the station and called, and (6) perched and called (Dykstra et al. 2001a). In addition, after each hawk response I recorded the following data; time elapsed since start of broadcast, estimated distance and direction to responding bird, and species, age, and sex of bird. I estimated distances to the location of responding birds using a laser rangefinder, based on either visual observation of birds or estimates of their location based on aural detections. Observers with high auditory acuity and the ability to recognize red-shouldered hawks by sight and sound conducted call playback surveys.

Nest Surveys

I initiated ground searches for nests at all study areas except Foothills in 2004 and 2005. I used opportunistic searches in these areas during leafless periods to maximize the number of nests located. Most call playback surveys were completed by 1100 and I searched for nests in afternoons by concentrating in areas with prior detections of red-shouldered hawks from broadcast call surveys. To reduce bias in where I found nests, I also conducted random searches in areas with no red-shouldered hawk responses, but that contained at least some older trees capable of supporting nesting red-shouldered hawks. In addition, I organized 5 systematic searches in 2004 and 7 systematic searches in 2005 where 2–6 people walked in a line space approximately 50-m apart and scanned all trees for nests. I used systematic searches in areas where a pair of red-shouldered hawks exhibited strong nest-defense behavior, but where no nest had been found.

I considered a nest to be occupied if there was evidence of eggs, an incubating adult, fresh eggshell fragments, or young in the nest (Steenhof 1987, Steenhof and Newton *In press*). I checked all occupied nests to determine status and number of young every 5–10 days, or as weather or military training activity permitted. I continued to check all nests until failure or fledging occurred.

I estimated reproductive success and productivity based on nest observations. I defined success as a breeding pair that produced ≥1 young at the minimum of 80% of the average age at first flight (Steenhof 1987, Steenhof and Newton *In press*), which is approximately 38 days for red-shouldered hawks (Bent 1937). I classified a nest as failed when a previously occupied nest was destroyed, abandoned, or produced no young that survived to fledge. I checked all nests where no activity was observed at least 1 additional time to confirm failure and calculated dates of nest failure using Mayfield's (1961, 1975) method, using the date halfway between the date of the last observed nesting activity and the date when no further activity was observed as the time of failure.

I calculated traditional nesting success as the proportion of occupied nests that were successful out of the total occupied nests. In addition, I used Mayfield's method (1961, 1975) to calculate nesting success based on exposure days and the method outlined by Steenhof (1987) to estimate productivity based on the number of young produced per breeding pair. Due to high variability in nesting success between years and the relatively short duration of the study, I was unable to evaluate habitat characteristics associated with nest success (Dinsmore et al. 2002).

Landscape Characterization

At each survey station, nest, and random point I analyzed habitat using Geographic Information Systems (GIS) to estimate habitat characteristics from 1-m resolution Digital Orthophoto Quadrangle (DOQ) images taken in 2003, digitized color infrared aerial photos taken in 1999 (Morrison County) and 2003 (Cass County), and digitized vector-based forest inventory data available from the MNDNR and Camp Ripley Environmental Office that reflected current conditions. Of the digitized vector-based forest inventory data available, 84.9% was previously ground checked by MNDNR or Camp Ripley employees. I consolidated the forest inventory data into 5 land-cover classifications based on main cover type, main cover age, density, and diameter at breast height (DBH), if applicable: (1) WET - all wetlands and open water, (2) NON - non-forest areas including grass, brush, roads, clear-cut areas, and forest < 5 years old, (3) YNG - forest between 5 and 40 years old, (4) DEC – deciduous forest > 40 years old, and (5) CON - coniferous forest > 40 years old. I then checked my classification against the digitized photos for any visible differences. If there was a discrepancy between the forest inventory data and the photos or no land classification information was available, I hand-digitized land-cover class polygons using ESRI® ArcView (version 9.0, Environmental Systems Research Institute, Redlands, Calif.) and assigned a habitat type based on careful examination of the photos. The minimum mapping unit (resolution) was approximately 200 m^2.

To estimate accuracy of forest inventory information and my land classification, I ground checked 130 survey stations across the study areas to confirm that the data reflected field conditions. Without prior knowledge of the site's map classification, I visually estimated the stand's main cover type, main cover age, density, and diameter at breast height (DBH). I then classified each location into a single cover class and estimated classification accuracy from agreement (%) with the cover class map. I ground-checked 60 points at Camp Ripley, 30 points at Pillsbury State Forest, and 40 points at Foothills State Forest. Overall map classification accuracy averaged 90.8%. At Camp Ripley, 55 (92%) of the 60 stations stand characterizations were classified correctly. At Pillsbury State Forest 28 (93%) of the 30 points and at Foothills 35 (87.5%) of the 40 points were classified correctly.

I described landscape characteristics within a 100-ha and a 314-ha circular area around nest sites and survey locations, and at nest sites I included an additional 25-ha analysis area. The 100-ha (1 km^2, 564-m radius) zone corresponded to the minimum reported home-range size for eastern red-shouldered hawks (Crocoll, 1994, Moorman and Chapman 1996, Balcerzak 2001). The 314-ha (3.14 km^2, 1,000-m radius) zone corresponded to the maximum home-range size for eastern red-shouldered hawks (Bednarz and Dinsmore 1981, Crocoll 1994). I included the finer 25-ha (0.25 km^2, 282-m radius) area surrounding nest sites. I used the ESRI® ArcView extensions Patch Analyst (Elkie et al. 1999) and Spatial Analyst to analyze areas and calculate landscape variables in each analysis area. I used the program FRAGSTATS (McGarigal and Marks 1995) to estimate edge density because Patch Analyst overestimates amount of edge.

Habitat Metrics

I measured 11 habitat characteristics to describe habitat amounts, pattern of mature deciduous forest stands, and landscape pattern (Table 2). I chose landscape characteristics based on previous studies of red-shouldered hawk nesting habitat and on their ability to describe habitat amounts, patterns, and configuration. I avoided choosing measurements such as fractal dimension and contagion because they often do not measure obvious differences in landscape pattern and can be highly correlated to one another (Li and Reynolds 1994). Although I still expected some correlation between variables (see Model Development section), I incorporated them all in model development in order to include all hypothesized models prior to analysis.

Model Development

With 9 of the 11 habitat metrics (excluded amount young and amount coniferous forest), I developed 20 *a priori* models that hypothesized potential relationships between occupancy/nest sites and landscape-level habitat patterns (Table 3). I chose these models after extensive review of the literature and prior to analysis. I grouped my models into 4 main categories: (1) habitat amount models, (2) patch size and density models, (3) edge-effect models and (4) landscape-pattern models.

I developed habitat amount models based on the hypothesis that red-shouldered hawks select areas because of the amount of a particular habitat type or types present. Red-shouldered hawks nest in mature forest habitats and numerous studies suggest that amount of mature forest is associated with red-shouldered hawk presence and nest-site selection (Bednarz and Dinsmore 1981, 1982, Bryant 1986, Bloom et al. 1993, Moorman and Chapman 1996, Dykstra et al. 2000, McLeod et al. 2000, Balcerzak and Wood 2003). Additionally, declines in red-shouldered hawk populations are attributed to loss of mature forest habitat (Crocoll 1994). Although in a different forest type, Bednarz and Dinsmore

(1981) found that the total forest cover available was an important descriptor of habitat used by red-shouldered hawks in Iowa floodplain forests and suggested a critical forest size of 250 ha. In Ontario, Naylor et al. (2004) found that nesting activity was positively associated with the area of uncut mature deciduous forest. My models reflected these prior findings by predicting a positive association between occupancy/nest sites and amount mature deciduous forest (models 2a, 2c, 2g; Table 3).

Only one study in West Virginia examined the association of amount of core mature forest with red-shouldered hawk presence (Balcerzak and Wood 2003) and it had found no relationship. However, because others have suggested that these birds need large amounts of intact mature forest (Bednarz and Dinsmore 1981, Crocoll 1994) I hypothesized that the amount of core mature forest would be positively associated with red-shouldered hawk occupancy (models 2b and 3; Table 3).

Many studies have reported that the amount, number, and proximity of wetlands were important predictors of red-shouldered hawk habitat (Bednarz and Dinsmore 1981, Titus and Mosher 1981, Bosakowski et al. 1992, Howell and Chapman 1997, Dykstra et al. 2000, Dykstra et al. 2001, Balcerzak and Wood 2003). Both Dykstra et al. (2001) and Balcerzak and Wood (2003) found the amount of wetland to be the only significant predictor of red-shouldered hawk presence at the landscape-level. I included amount of wetlands in my *a priori* models and predicted a positive relationship between red-shouldered hawk occupancy/nest sites and amount of wetland (model 2d; Table 3).

My *a priori* models containing the amount of non-forest reflected my hypothesis that red-shouldered hawk occupancy and nest sites were negatively associated with the amount of non-forest (models 2f and 2g; Table 3). Preston and Beane (1993) and Crocoll

(1994) suggested that as forest is fragmented and large open areas created, habitat may become more suitable for red-tailed hawks and lead to competition for nesting habitat between red-shouldered and red-tailed hawks. Dykstra et al. (2001) found red-shouldered hawk response rates to call broadcast surveys were inversely related to red-tailed hawk response rates. Moorman and Chapman (1997) found red-shoulder hawks farther from open habitats than red-tailed hawks. Additionally, both Bloom et al. (1993) and Howell and Chapman (1997) found that red-shouldered hawks used non-forested habitat less than expected relative to availability in their home ranges.

Few studies have examined the influence of patch size and patch density on red-shouldered hawk-habitat associations. Two studies conducted in the eastern and southeastern United Sates found no association between mature forest patch size and patch density on red-shouldered hawk occupancy (Moorman and Chapman 1997, Balcerzak and Wood 2003). Thus, I created patch size and density models (models 3; Table 3) that reflected the hypothesis that red-shouldered hawks need large amounts of intact mature forest (Crocoll 1994). Therefore, I hypothesized that the average patch size of mature deciduous forest was positively associated and the number of mature deciduous patches negatively associated with red-shouldered hawk occupancy and nest sites.

My edge-effect models reflected the hypothesis that the amount of edge was positively associated with red-shouldered hawk occupancy and nest sites (models 4; Table 3). Although Crocoll (1994) suggested that the creation of edge may increase competition between red-shouldered and red-tailed hawks, other studies have reported that red-shouldered hawk nesting and presence were positively influenced by the amount of edge (Bednarz and Dinsmore 1982, Moorman and Chapman 1997). Increased edge is likely due to the small openings created by wetlands that are often associated with red-shouldered hawk habitat and may serve as important hunting areas (Bednarz and Dinsmore 1982).

Only one study has examined the effects of landscape pattern (diversity and evenness) on red-shouldered hawk occupancy and it reported no effect (Balcerzak and Wood 2003). However, I developed my landscape pattern models with the idea that red-shouldered hawks need large areas of intact mature forest for nesting (models 5; Table 3). Therefore, my landscape pattern models reflected my hypothesis that red-shouldered hawks are associated with landscapes with low diversity (mostly mature deciduous forest) and low evenness (large amount of mature deciduous forest).

Because of high correlation ($r > 0.60$) between 2 mature deciduous habitat metrics (Table 2 and 3) I evaluated a reduced set of 16 *a priori* models. I eliminated 4 models from the initial set of models because of redundancy in the inclusion of 2 correlated metrics (i.e., amount mature deciduous forest and amount core deciduous forest). I continued to include the model with a correlated metric if it was the only covariate (i.e., amount of core deciduous forest alone) or if was in a model with an uncorrelated metric (i.e., amount core deciduous forest and edge density) to examine if it performed differently than the amount of mature deciduous forest.

Data Analyses

Call-broadcast Surveys --At call-broadcast stations I used methods developed by MacKenzie et al. (2002) to estimate occupancy and examine habitat characteristics associated with occupancy. MacKenzie et al. (2002) proposed a model and likelihood-based method for estimating site-occupancy rates when detection probabilities are <1. Their estimator allows for the inclusion of covariate information, such as site characteristics describing habitat type and patch size, time, and weather, which could influence both the probability of detection and occupancy. MacKenzie et al. (2002) used probabilistic arguments similar to those used in closed-population mark-recapture models to construct a likelihood method for estimating probability of detection (p) and the proportion of sites occupied (ψ). Thus, I recorded data from each survey site, including those where no red-shouldered hawk was detected, to establish a detection history for each occasion I sampled a site, which consisted of a vector of 1s and 0s representing detection and non-detection, respectively (MacKenzie et al. 2002). I estimated probability of detection and the proportion of area occupied by creating a model for each detection history. Each time I sampled a site (a sampling occasion), red-shouldered hawks were either detected, reflecting occupancy, $\psi \times p$, or not detected, which could occur when red-shouldered hawks were present but not detected, $\psi \times (1 - p)$, or were not present, $(1 - \psi)$. I extended these general arguments for all sampling occasions and sites, and maximized the model likelihood for the observed set of data to obtain parameter estimates for p and ψ (MacKenzie et al. 2002). Habitat covariate information was incorporated using a logistic model:

$$\psi = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k) / [1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k)]$$

where β_1 to β_k are constants estimated from the available data, x_1 to x_k are the independent habitat variables, and the probability of occupancy (ψ) is the parameter of interest. I performed this analysis using the software program PRESENCE (URL: http://www.mbr-pwrc.usgs.gov/software.html).

I included additional covariates in all models developed for the data from call-broadcast surveys. One assumption of the occupancy models developed by MacKenzie et al. (2002) is that probability of detection and occupancy are constant across sites and sampling occasions or that any heterogeneity can be attributed to known covariates. The probability of detecting red-shouldered hawks can vary throughout the breeding season and is known to vary depending on breeding stage (e.g., courtship, incubation, nestling period, and fledgling period; McLeod and Andersen 1998, Henneman unpublished data). Therefore, I included time-specific detection probability estimates for each sampling occasion within 2004 and 2005. This meant that I determined a different estimate of detection probability for each time the sites were sampled for each year. This added an additional 6 parameter estimates for 2004 and 5 parameter estimates for 2005. Time-specific estimates were more applicable than breeding stage because the surveys were limited to 1 or 2 breeding stages. Additionally, I included study area as a covariate in models to allow occupancy to vary based on the study area.

To analyze red-shouldered hawk-habitat associations based on call-broadcast surveys, I evaluated the 16 *a priori* models (Table 3) at both the 100 and 314-ha scales. Because I added additional survey points and study areas in 2005, I evaluated these 16 *a priori* models for different combinations of study areas and years. In total I evaluated models in 3 different combinations: (1) Camp Ripley and Pillsbury in 2004 (or all points sampled in 2004), (2) all points in 2005 (includes points from Camp Ripley, Pillsbury, Foothills, and TNC), and (3) a multi-season model for points sampled at Camp Ripley and Pillsbury in both 2004 and 2005 (MacKenzie et al. 2003). Due to problems with model convergence and unreasonable estimates of occupancy, which likely was due to low probability of detection at Foothills, I was unable to specifically analyze characteristics associated with occupancy at that study area.

Nests -- To examine habitat associations of red-shouldered hawks at nest sites, I used standard logistic regression to distinguish between nests and random point locations at 3 spatial scales. I chose the random sites using a random point generator in ESRI® ArcView 3.3 (Environmental Systems Research Institute, Redlands, Calif.) with the MNDNR Random Point extension. I excluded random points that did not fall in a mature deciduous stand >40 years old. I did this because I was most interested in the specific characteristics of mature deciduous stands that promote red-shouldered hawk nest-site selection and occupancy. I performed this analysis in PROC LOGISTIC in the program SAS 9.1 (SAS Institute Inc. 2002) and the logistic model had the following form:

$$\pi = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k) / [1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k)]$$

where β_1 to β_k are constants to be estimated from the available data, x_1 to x_k are the independent habitat variables, and the dependent data are categorized as 1 for nest sites and 0 for random sites.

To examine habitat associations at nest sites, I evaluated the 16 *a priori* models (Table 3) for all nests combined (includes TNC nests), nests from Camp Ripley, and nests from Pillsbury only, to evaluate potential differences across study areas.

Model Selection

I developed multiple *a priori* hypothesized models to represent relationships between habitat and nest-site selection and occupancy of red-shouldered hawks based on information from the literature and prior research. I used model selection based on information theory (e.g., Akaike's Information Criterion, AIC; Burnham and Anderson 2002) to identify the model or set of models best supported by my data (Burnham and Anderson 2002) and to describe the relationship between landscape variables and red-shouldered hawk occupancy at nests and survey stations. I used AIC adjusted for small sample size (AIC_c) to rank the models:

$$AIC_c = -2 \log(L(\theta)) + 2K + (2K(K + 1)/(n - K - 1))$$

where θ is the response variable (probability of occupancy or nest site), log(L(θ)) is the value of the log-likelihood function at its maximum, K is the total number of estimable parameters in the particular model, and *n* is sample size. The model with the lowest AIC_c value is highest ranked and subsequent models are ranked according to increasing AIC_c values. I then calculated Akaike weights, w_i, for each model, which is the weight of evidence for the model given the data (Burnham and Anderson 2002). I considered models within 2 AIC_c units of the top model as competing models. I further evaluated competing models using 95% confidence intervals of slope parameter estimates to assess their importance in the model.

Model Validation

Information-theoretic model selection approaches such as AIC select the best model(s) from the candidate set of models available (Burnham and Anderson 2002). Model ranking does not provide an absolute measure of model fit, but will simply select the "best" model regardless of the quality of the candidate set. Therefore, Burnham and Anderson (2002) recommended that a global model should be evaluated for goodness-of-fit, with the idea that if the global model fits the data adequately, then the more parsimonious model of the set will also fit the data adequately.

Call Broadcast Surveys --To assess the fit of the site-occupancy models from call broadcast surveys I used the method presented in MacKenzie and Bailey (2004) where a simple Pearson's chi-square statistic is calculated and a parametric bootstrap procedure (1,000 bootstraps) is used to determine whether the observed statistic is unusually large. At each scale, I fit a global model including the 9 habitat metrics (Table 2) to demonstrate that the model adequately fit the data. Unlike mark-recapture methodology, this method allows for the inclusion of covariate information that varies across sites and an overdispersion parameter, $\hat{c}$, can be estimated. If the model is an adequate description of the data, then $\hat{c}$ should be approximately 1 and no variance inflation factor (QAIC) is needed (MacKenzie and Bailey 2004).

Nest Surveys – There is no consensus on the use of one overall goodness-of-fit test for logistic regression (Allison 1999, Agresti 2002). Therefore, I applied several techniques to assess goodness-of-fit of my global model from nest surveys. In order to evaluate overall goodness-of-fit, I fit a global model containing all 9 habitat variables (Table 2) at each spatial scale for all nests from both 2004 and 2005. First, I used a Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000) where observations were classified into distinct groups based on fitted probabilities, which allowed chi-square testing. I compared the Hosmer-Lemeshow test statistic to a chi-square distribution, where large values and corresponding low *P*-values indicated a lack of fit. Second, I evaluated global models using max-scaled R^2 (Nagelkerke 1991), which is similar to R^2 in linear regression (Alison 1999). Finally, I used receiver operating characteristic (ROC) curve and jackknife cross-validation to examine the agreement between model predictions and actual observations. ROC analysis evaluates the proportion of correctly and incorrectly classified predictions over a continuous range of threshold probability cut-off levels (Hosmer and Lemeshow 2000) and provides an area-under-the-curve estimate, which is the measure of the model's discrimination ability. In jackknife cross-validation, a single observation was removed from the data set and the remaining data were used to estimate the model parameters. For jackknife cross-validation, I used a probability threshold of 0.5 to distinguish between predictions of nest versus random sites.

RESULTS

Call Broadcast Surveys

In 2004 at Camp Ripley and the Pillsbury, I surveyed 131 call-broadcast survey stations from 26 March – 1 May, 121 (92%) of which I surveyed ≥4 times. In 2005, I surveyed 243 broadcast call survey stations from 2 April – 11 May, with 174 (71.6%) sampled ≥4 times. I used response data (detection/nondetection) from the call-broadcast surveys to estimate probability of detection and occupancy rates for each study location (Table 4). Probability of detection at Camp Ripley was lower in 2004 than 2005. Occupancy rate for red-shouldered hawks at Camp Ripley was higher in 2004 than 2005, but in 2005 I surveyed more in the southern portion of Camp Ripley where I suspected there were fewer red-shouldered hawks. At Pillsbury, the probability of detection and occupancy estimates were slightly lower in 2005 than in 2004 (Table 4). Probability of detection was much lower at Foothills than at the other study sites (Table 4). At

Foothills, of the 20 points that had ≥1 red-shouldered hawk detection, 16 points had only 1 response across all sampling occasions.

When I examined habitat characteristics at all survey points across study areas based on whether there was a red-shouldered hawk response without taking probability of detection into account, I found differences in points between those with ≥1 red-shouldered hawk response and those with no response (Table 5). Stations that had ≥1 red-shouldered hawk response generally had lower amount of non-forest, especially at the 314-ha spatial scale (Table 5). Points with responses also had greater proportion of mature deciduous forest, greater proportion of core forest, and larger mean patch size (Table 5). In addition, stations with a red-shouldered hawk response had less landscape diversity and landscape evenness (Table 5).

When modeling occupancy, I did not find evidence of lack of fit of my global model, either when using data from 2004 (100-ha scale: $P = 0.2238$, $\hat{c} = 1.074$; 314-ha scale: $P = 0.2557$, $\hat{c} = 1.070$) or from 2005 (100-ha scale: $P = 0.3996$, $\hat{c} = 1.021$; 314-ha scale: $P = 0.2607$, $\hat{c} = 1.086$).

I evaluated models in 3 different combinations: (1) Camp Ripley and Pillsbury in 2004 (or all points sampled in 2004), (2) all points in 2005 (includes points from Camp Ripley, Pillsbury, Foothills, and TNC), and (3) a multi-season model for points sampled at Camp Ripley and Pillsbury in both 2004 and 2005 as follows:

Camp Ripley and Pillsbury 2004 – Red-shouldered hawk occupancy was most closely associated with the amount of non-forest (NON) for all sites surveyed in 2004. There were 2 best-supported, competing models (NON, DEC+NON) at both spatial scales (100-ha and 314-ha) for call-broadcast surveys conducted at Camp Ripley and

Pillsbury in 2004 (Table 6). The amount of non-forest (NON) had the strongest association with probability of occupancy at both spatial scales, and confidence intervals around estimates of the slope parameters did not overlap zero. The negative effect of amount of non-forest was stronger at the broader 314-ha scale than at the 100-ha scale (Table 6). The amount of mature deciduous forest along with amount of non-forest (DEC+NON) was in the second, and only, competing model (within 2 AIC_c units) for both scales. The 95% confidence of the slope parameter for the amount of deciduous forest overlapped zero, suggesting this variable was uninformative. The cumulative weights for amount non-forest from the 2 models were 0.52 and 0.69 for the 100-ha and 314-ha scale, respectively (Table 6).

All Points 2005 -- At the 100-ha spatial scale, for all points surveyed from all study areas (Camp Ripley, Pillsbury, Foothills, and TNC) in 2005, the amount of mature deciduous forest (DEC) had the strongest relationship with red-shouldered hawk occupancy (Table 6). At this scale there were 6 competing models that all included amount mature deciduous forest (DEC, DEC +EDGE, DEC+EVEN, DEC+NON, DEC+DIV, DEC+WET). Only the best-supported model, mature deciduous forest alone (DEC), had a slope parameter estimate with a 95% confidence interval that did not overlap zero. This suggests that the remaining top-ranked models included variables that were uninformative about their association with red-shouldered hawk occupancy. The cumulative Akaike weight of all the models with amount mature deciduous forest was 0.91. At the 314-ha scale, a model that included the amount of mature deciduous forest, landscape diversity, and landscape evenness (DEC+DIV+EVEN) had the strongest association with red-shouldered hawk occupancy (w = 0.43, Table 6). The best-supported model exhibited a positive relationship between red-shouldered hawk occupancy and the amount mature deciduous forest, a negative relationship with increased landscape diversity, and a negative relationship with landscape evenness.

Camp Ripley & Pillsbury Multi-season 2004 & 2005 – At both spatial scales the amount of non-forest (NON) was most strongly associated with red-shoulder hawk occupancy and was the only model whose 95% confidence interval of the slope parameter estimate did not overlap zero (Table 6). The amount of mature deciduous forest and landscape evenness (DEC+EVEN) were included in the best-supported model at the 314 ha scale, but their 95% confidence intervals of the parameter estimates overlapped zero. The negative relationship with amount of non-forest was greater at the 314-ha scale than at the 100-ha scale.

Nests

In 2004, I found 37 nests at Camp Ripley (*n* = 22), Pillsbury (*n* = 11), and TNC (*n* = 4) (Table 7). Seventeen nesting attempts were successful and produced a minimum of 34 ($\bar{x}$ = 2.0 young/successful nest) young (Table 7). In 2005, I found a total of 41 nests at Camp Ripley (*n* = 24), Pillsbury (*n* = 12), and TNC (*n* = 6) (Table 7). Ten nesting attempts were successful and produced a minimum of 19 ($\bar{x}$ = 1.9 young/successful nest) young. Reproductive success and number of young fledged were considerably lower in 2005 than in 2004, and in 2005, lower at Pillsbury than Camp Ripley (Table 7).

In 2004, all nests I found were in aspen/birch or oak/northern hardwood stands >40 years old. In 2005, I found most nests in aspen/birch or oak/northern hardwood forest stands >40 years old. At Camp Ripley I found 1 nest in a mixed conifer stand >40 years old that had scattered mature oaks, and 1 nest in an oak/northern hardwood stand <40 years old with scattered older trees. One nest I found at Pillsbury was in an aspen clear-cut <5 years old that contained few standing trees. The amount of non-forest habitat type was low at nest sites for all scales (Table 8, Figure 2). The mean amount of mature deciduous forest was high at nests sites and decreased with increasing scale (Table 8, Figure 2). Similarly, the mean amount of core mature deciduous forest decreased with increasing scale (Table 8). However, at all scales I found substantial variability in the amount of mature deciduous forest and non-forest habitat type (Figure 2).

To evaluate overall goodness-of-fit, I fit a global model containing all 9 habitat variables at the 3 spatial scales for all nests from both 2004 and 2005. At the smallest 25-ha scale I did not find evidence of lack of fit for the global model (H-L *P*-value =0.6232). However the max-scaled R^2 was relatively low at 0.2533, but the percent correct classification was 75.8% and 66.2% based on ROC and jackknife cross-validation techniques, respectively. Again, at the 100-ha scale I did not find evidence for lack of fit of the global model (H-L *P*-value = 0.2458). The max-rescaled R^2 improved somewhat to 0.3349 and the model correctly classified 78.5% and 63.2% of predicted values based on ROC and cross-validation methods, respectively. I did not detect evidence of lack of fit for the global model at the 314-ha scale (H-L Goodness-of-fit P = 0.8949). The max-rescaled R^2 was greatest at 0.3818 at this scale. The percent correct classification for the ROC analysis was 79.8% and 64.0% based on jackknife cross-validation.

All Nests -- For all nests combined (n = 68), only 1 model (DEC + NON) was retained at all 3 spatial scales. The amount of mature deciduous forest (DEC) and the amount of non-forest (NON) had the strongest association with nest sites (Table 9). The model incorporating mature deciduous forest plus non-forest had Akaike weights of 0.54, 0.74, 0.80 at the 25-ha, 100-ha, and 314-ha scales, respectively. The amount of mature deciduous forest had a positive association and the amount of non-forest a negative association with nest sites at all scales and none of the slope parameter estimate intervals overlapped zero (Table 9). Although the parameter estimates for the amount of mature deciduous forest (DEC) were similar across all 3 spatial scales, the negative effect of non-forest increased with increasing spatial scale.

Camp Ripley Nests Only -- As with all the nests combined, the model that included amount of mature deciduous forest (DEC) and the amount of non-forest (NON) was retained as the best-supported model (DEC + NON) at all 3 spatial scales with Akaike weights of 0.64, 0.36, and 0.39 at the 25-ha, 100-ha, and 314-ha scale, respectively (Table 9). The amount of mature deciduous forest was positively and the amount of non-forest negatively associated with red-shouldered hawk nest sites. At the 100-ha scale, I retained a second competing model including mature deciduous forest only (DEC) with an Akaike weight of 0.18. At this scale the slope parameter's 95% confidence interval for the best-supported model (DEC + NON) overlapped zero while the confidence intervals for parameter estimates in the second-best-supported model (DEC) did not (Table 9), suggesting that the amount of non-forest was either too imprecise to adequately measure its effect or it had little effect. The slope parameter intervals did not differ appreciably across scales (Table 9).

Pillsbury Nests Only -- When I analyzed Pillsbury nests alone, there was no clear association between nest sites and habitat characteristics. At the 25-ha scale the amount of mature deciduous forest (DEC), landscape diversity (DIV), and landscape evenness (EVEN) were included in the best-supported models (DEC+DIV+EVEN, DEC+DIV), but the 95% confidence intervals of parameter estimates overlapped zero (Table 9). At the 100-ha scale, there were 5 top-ranked models, which suggested the importance of limited non-forest (NON, DEC+NON), greater amount of deciduous forest (DEC+EDGE, DEC+NON, DEC), and greater amount of core forest (CORE+EDGE). The amount of edge (EDGE) was included in 2 of these top models (DEC+EDGE, CORE+EDGE), yet its relationship with nests sites was not clear (Table 9). As with the 25-ha scale, all of the best-supported models had slope parameters with 95% confidence intervals that overlapped zero. At the 314-ha scale, there was only 1 best-supported model, which contained the number of mature deciduous patches (NUMP). As the number of mature deciduous patches decreased the association with red-shouldered hawk nests increased. This model had an Akaike weight of 0.81 and its 95% confidence interval of the parameter estimate did not overlap zero.

DISCUSSION

My analysis of habitat associations of red-shouldered hawks indicated that higher amounts of mature deciduous forest and smaller amounts of non-forest had the strongest association with red-shouldered hawk occupancy and nest-sites. Consistently, habitat amounts of mature deciduous forest and non-forest were retained in the best-supported models and had the strongest effects. Red-shouldered hawk nests in central Minnesota were positively associated with the amount of mature deciduous forest in combination with low levels of non-forest. With call broadcast surveys, red-shouldered hawk occupancy was either associated with amount of mature deciduous or a limited amount of non-forest, rather than the combination of both, as observed for nest sites. This is consistent with studies in other portions of red-shouldered hawk range that suggest that they are associated with mature forest stands (Titus and Mosher 1981, Bednarz and Dinsmore 1982, Bryant 1986, Dijak et al. 1990, Bosakowski et al. 1992, Naylor et al. 2004) and may be affected by the creation of large non-forested areas (Preston and Beane 1993, Crocoll 1994, Dykstra et al. 2001, Moorman and Chapman 1997).

Although I found habitat amounts to be most strongly associated with red-shouldered hawk occupancy, other habitat metrics were contained in some competing models and may be important. Most noticeable was the relationship between the number of mature deciduous patches and nest sites at Pillsbury State Forest at the 314-ha scale ($w = 0.81$). This relationship suggests that there may be negative effects of fragmentation of mature forest patches and at some point it may not simply be the amount of mature deciduous forest that influences red-shouldered hawk habitat associations. Landscape-pattern metrics (diversity and evenness) were also associated with red-shouldered hawk nest sites and occupancy, but the relationship was unclear due to imprecise and varying (both positive and negative) effects.

I designed this study to include study areas with varying landscape structure and composition to provide insight into red-shouldered hawk habitat associations. Yet, at Pillsbury, habitat associations of red-shouldered hawks at nest sites were not clear. At Pillsbury, only the number of mature deciduous forest patches at the broadest spatial scale (314-ha buffer zone) had clear association with red-shouldered hawk nests. The uncertainty of what habitat characteristics are important at Pillsbury may reflect several factors. A smaller number of nests at Pillsbury likely made it more difficult to precisely estimate the association habitat characteristics had with nest sites. It may also indicate that habitat associations at Pillsbury are more complex than I captured in this study. Pillsbury's landscape is characterized by numerous, scattered clear-cuts and regenerating aspen stands of varying sizes and ages mixed with upland hardwood-pine forest. This complex landscape may have characteristics that I did not capture with the habitat metrics I measured and may be of importance to breeding habitat of red-shouldered hawks. Such characteristics could be related to finer delineations of forest types or more detailed description of landscape structure.

At Foothills, occupancy estimates were lower than those for my other study areas. High estimates of occupancy at Camp Ripley, Pillsbury, and TNC were correlated with substantial numbers of nesting red-shouldered hawks. I did not conduct nest searches at Foothills and therefore, it is unclear how occupancy compared to the number of nests. The lower estimates of occupancy at Foothills may reflect that the area constitutes lower quality habitat for red-shouldered hawks. When I included call broadcast data from Foothills into my analysis of habitat associations, the amount of mature deciduous forest was most strongly associated with red-shouldered hawk occupancy. Yet, across the landscape, Foothills contained a similar amount of mature deciduous forest as my other study areas. However, mature deciduous forest may be distributed differently across this landscape, as the amount of core forest was small compared with other sites.

Analysis at call-broadcast stations and nest sites measure different aspects of red-shouldered hawk-habitat associations. Nest sites represent a specific location where sufficient resources are present to support nest establishment. A response detected during a call-broadcast survey reveals a hawk was in the area, but provides little insight into how the hawk was using the habitat or the potential quality of that habitat. Therefore, habitat associations determined from nest surveys and call broadcast surveys could provide different information. I found the resulting associations were similar for both survey types. As well, I found few differences in red-shouldered hawk habitat associations at different spatial scales. Scale is an important consideration when investigating habitat relationships and should be evaluated at multiple and relevant spatial scales (Harbin and Wu 2004, Johnson et al. 2004). Examining my data *post hoc* indicated that the broadest scale (314-ha scale) consistently had the greatest support (lowest AIC values) given the data, suggesting the important influence broad landscape scale could have on habitat associations of red-shouldered hawks. It could also suggest that potentially an even broader scale than I considered in this study could be important to understanding habitat associations of red-shouldered hawks.

I found distinct differences in habitat associations of red-shouldered hawks across years. Red-shouldered hawks were most strongly associated with limited amount of non-forest in 2004. In 2005, I found occupancy was positively associated with amount of mature deciduous forest. In 2005, I expanded my call-broadcast surveys across more sites (southern portion of Camp Ripley, TNC, Foothills). In general, the additional sites sampled only in 2005 contained a lower proportion of mature deciduous forest than the sites surveyed in both years. It appears that in 2004, when there were large amounts of mature deciduous forest across survey sites, the amount of non-forest was most strongly related to red-shouldered occupancy. In 2005, when I expanded into study areas with less mature deciduous forest, the amount of mature deciduous forest was most strongly associated with red-shouldered hawk occupancy. This may suggest that when sufficient levels of mature deciduous forest were available, then the amount of non-forest had the strongest association with red-shouldered hawk occupancy. But as the amount of mature deciduous forest decreased, there may be a threshold where the amount of mature deciduous forest reached a lower limit and became the most influential habitat characteristic.

My study areas generally had large amounts of mature forest. Even random sites and sites without red-shouldered hawk responses still averaged 40–45% mature deciduous forest. For the 3 spatial scales surrounding nests that I investigated, I found red-shouldered hawk nests with as little as 13% mature deciduous forest, but in these cases, total forest cover was >60%, with increased amounts of mature coniferous and/or young forest. Overall, from the areas of analysis surrounding nests, it appeared that the lower limit of mature forest (including mature deciduous and mature coniferous) at red-shouldered hawk nests was approximately 30% and did not vary across spatial scale. Most nests and call broadcast sites with red-shouldered hawk responses were associated with ≥40% and averaged closer to 50% mature deciduous forest. Based on home-range analysis, Dykstra et al. (2001) concluded that red-shouldered hawks used moderately-developed landscapes in Ohio, provided that ≥40% of the approximately 90-ha home-range was comprised of mature forest. Similarly, Bloom et al. (1993) suggested that 39% mature woodland was adequate to support a breeding pair at the home-range scale of approximately 100 ha. Both of these studies were in suburban areas where red-shouldered hawks may exhibit different habitat associations than red-shouldered hawks in my study. In landscapes similar to those in my study areas, Naylor et al. (2004) found red-shouldered hawks in Ontario required ≥20 ha (25%) mature uncut or lightly selection-cut hardwood forest within 500 m of primary nests. In other studies, red-shouldered hawks typically had 20–50 ha (25–65%) of preferred forest habitat associated with nest sites (Bosakowski et al. 300-m radius 1992, Moorman and Chapman 1996 564-m radius, Howell and Chapman 1997 100 ha home-range), although Bednarz and Dinsmore (1982) suggested they need as much as 250 ha of mature forest habitat.

Increased amounts of non-forest could affect red-shoulder hawks in several ways. Large open areas may make nests more susceptible to predation by great horned owls (*Bubo virginianus*) or raccoons (*Procyon lotor*), the most common predators of red-shouldered hawk nests (Craighead and Craighead 1956, Portnoy and Dodge 1979, Crocoll and Parker 1989). Increased non-forest habitat could also alter available food resources or affect hunting behavior or efficiency because red-shouldered hawks hunt mostly from perches (Bloom et al. 1993, Crocoll 1994). Additionally, several authors (Titus and Mosher 1981, Bednarz and Dinsmore 1982, Bryant 1986) have suggested that as forested landscapes are altered by logging, converted to agriculture, or further developed by human encroachment, red-shouldered hawks may be displaced by competition with red-tailed hawks. Specifically, red-shouldered hawks may compete with red-tailed hawks for nesting habitat at forest edges and where mature forest has been reduced in size (Crocoll 1994). Red-tailed hawks prefer open areas for hunting and their numbers have increased due to clearing of forest by logging and for agriculture (Preston and Beane 1993). Overall, red-tailed hawks were rare on my study areas (Henneman, unpublished data), but they occupied the larger open areas at Camp Ripley and Foothills.

Some studies have shown that red-shouldered hawks can tolerate habitat loss, alteration, and fragmentation in the form of human development and encroachment (Bloom et al. 1993, Dykstra et al. 2000, 2001). In my study, a pair of red-shouldered hawks nested both years only 15 m from a home with numerous buildings and continuous activity (i.e., ATVs, chainsaws, and lawnmowers) and I found other nests near busy roads, homes, and in areas with moderate military training activity. Most of the non-forested areas of my study consisted of clear-cut areas, grassland, and military training or impact areas at Camp Ripley. Non-forested areas are generally larger and more open when created through timber harvest or conversion to agriculture compared to those created through development, which might influence red-shouldered hawks differently in different landscapes. At Pillsbury, red-shouldered hawks nested and occupied a landscape that contained smaller stands of mature deciduous forest with more, but generally small, open non-forested areas. Although the small non-forested patches were mostly clear-cut areas, this landscape may be in fact more similar to light-to-moderate human-developed suburban landscapes than to typical heavily-managed forests and agricultural areas.

My findings suggest that retaining large amounts of mature deciduous forest and limiting the amount of non-forest are both important in promoting nesting and occupancy by red-shouldered hawks in central Minnesota. Land managers hoping to promote occupancy by red-shouldered hawks should likely avoid creating large clear-cut areas and instead use management practices that preserve the characteristics of forested landscapes (e.g., thinning and light-selection cuts). Within forested landscapes, there may be potential for small areas of intense timber harvest, as long as sufficient amounts of mature forest (>50% of the landscape) remain.

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Table 1. Landscape characteristics of 4 study areas (CR = Camp Ripley, PSF = Pillsbury State Forest, FH = Foothills State Forest, TNC = The Nature Conservancy Lake Alexander Preserve) surveyed for red-shouldered hawks in central Minnesota in 2004 and 2005.

Study area	Proportion						Mean mature deciduous patch size (ha)	Median mature deciduous patch size (ha)	Mean non-forest patch size (ha)	Median non-forest patch size (ha)
	non-forest [a]	mature deciduous [b]	wetland /water [c]	young forest [d]	mature coniferous [e]	core forest [f]				
CR	0.22	0.45	0.10	0.18	0.06	0.13	24.43	4.63	38.37	1.42
PSF	0.13	0.51	0.13	0.18	0.05	0.11	61.73	1.89	6.35	2.43
FH	0.13	0.42	0.16	0.22	0.06	0.06	26.05	2.36	5.82	3.41
TNC	0.10	0.65	0.20	0.03	0.02	0.25	58.75	1.14	4.86	0.80

[a] Non-forested areas including grass, brush, roads, clear-cut areas, and forest < 5 years old
[b] Deciduous forest >40 years old.
[c] All wetlands and open water
[d] All forest between 5 and 40 years old
[e] Coniferous forest > 40 years old
[f] Core forest is mature deciduous forest ≥100 m from a polygon edge.

Table 2. Abbreviations and descriptions of variables used to evaluate habitat associations of red-shouldered hawks in central Minnesota.

Variable	Description
Habitat Type Amounts:	
DEC [a]	Amount (proportion) of mature deciduous forest (>40 years old) within the circular plot.
NON	Amount (proportion) of non-forest within the circular plot.
WET	Amount (proportion) of wetlands and open water within the circular plot.
CON	Amount (proportion) of mature coniferous forest (>40 years old) within the circular plot.
YNG	Amount (proportion) of young forest (5<YNG<40 years old) within the circular plot.
Mature Deciduous Forest Pattern:	
CORE [a]	Total amount of core habitat occupied by mature deciduous forest. Core habitat is defined as habitat ≥100 m from a polygon edge.
SIZE [a]	Mean size of habitat patches of a mature deciduous forest within a circular plot.
NUMP [a]	Number of patches of mature deciduous forest within a circular plot.
EDGE	Edge density (the amount of edge between mature deciduous patches and all other habitat types within a circular plot divided by the area of mature deciduous patches).
Landscape Pattern:	
DIV	Relative habitat diversity within a circular plot measured as Shannon's diversity index that equals 0 when there is only one patch and increases as the number of patch types or the proportional distribution of patch types increases (McGargil and Marks 1993).
EVEN	Distribution and abundance of habitat patches within the circular plot measured as Shannon's evenness index which equals 0 when the landscape contains only one patch.

[a] Highly correlated variables ($r > 0.60$)

Table 3. Set of models hypothesized *a priori* and used to evaluate habitat associations of red-shouldered hawks in central Minnesota. Nest site and probability of occupancy are response variables and the model structure is the logit function of the logistic regression model.

1. **Null hypothesis:** (No effect due to landscape variables) $\boldsymbol{\beta_0}$ [a]

2. **Habitat amount models:** (Red-shouldered hawks select areas based on the amount of a particular habitat type or types)

a) Positive effect of amount of mature deciduous forest:	$\boldsymbol{\beta_0 + \beta_1 DEC}$
b) Positive effect of amount of core mature deciduous forest:	$\boldsymbol{\beta_0 + \beta_1 CORE}$
c) Positive effect of amount of mature deciduous forest and positive effect of amount of core forest:	$\beta_0 + \beta_1 DEC + \beta_2 CORE$
d) Positive effect of amount of wetland and open water:	$\boldsymbol{\beta_0 + \beta_1 WET}$
e) Positive effect of amount of mature deciduous forest and positive effect of amount of wetland:	$\boldsymbol{\beta_0 + \beta_1 DEC + \beta_2 WET}$
f) Negative effect of amount of non-forest:	$\boldsymbol{\beta_0 + \beta_1 NON}$
g) Positive effect of amount of mature deciduous forest and negative effect of amount of non-forest:	$\boldsymbol{\beta_0 + \beta_1 DEC + \beta_2 NON}$

3. **Patch size and patch density models** (Red-shouldered hawks select areas based on the size and number of mature deciduous forest patches)

a) Positive effect of amount of mature deciduous forest and positive effect of patch size:	$\boldsymbol{\beta_0 + \beta_1 SIZE}$ $\beta_0 + \beta_1 DEC + \beta_2 SIZE$
b) Positive effect of amount of mature deciduous forest and positive effect of patch density:	$\boldsymbol{\beta_0 + \beta_1 NUMP}$ $\beta_0 + \beta_1 DEC + \beta_2 NUMP$

Table 3. Continued.

4. Edge effect models: (Red-shouldered hawks select areas with large amounts of core forest and large amounts of edge between mature deciduous forest and non-forest)

a) Positive effect of amount of core forest and positive effect of edge:	$\boldsymbol{\beta_0 + \beta_1}$**CORE** $\boldsymbol{+ \beta_2}$**EDGE**
b) Positive effect of amount of mature deciduous forest and positive effect of edge:	$\boldsymbol{\beta_0 + \beta_1}$**DEC** $\boldsymbol{+ \beta_2}$**EDGE**
c) Positive effect of amount of core forest, positive effect patch size, and positive effect of edge:	$\beta_0 + \beta_1$CORE $+ \beta_2$SIZE $+\beta_3$ EDGE

5. Landscape diversity models: (Red-shouldered hawks select areas of low habitat heterogeneity)

a) Negative effect of habitat diversity:	$\boldsymbol{\beta_0 + \beta_1}$**DIV**
b) Positive effect of amount of mature deciduous forest and negative effect of habitat diversity:	$\boldsymbol{\beta_0 + \beta_1}$**DEC** $\boldsymbol{+ \beta_2}$**DIV**
c) Negative effect of patch abundance and distribution:	$\boldsymbol{\beta_0 + \beta_1}$**EVEN**
d) Positive effect of amount of mature deciduous forest and negative effect of patch abundance and distribution:	$\boldsymbol{\beta_0 + \beta_1}$**DEC** $\boldsymbol{+ \beta_2}$**EVEN**
e) Positive effect of amount of mature deciduous forest, negative effect of habitat diversity, and negative effect of patch abundance and distribution:	$\boldsymbol{\beta_0 + \beta_1}$**DEC** $\boldsymbol{+ \beta_2}$**DIV** $\boldsymbol{+ \beta_3}$**EVEN**

[a] **bold type =** models included in reduced set of *a priori* models used in analysis. Other models were eliminated due to inclusion of more than one highly correlated variable.

Table 4. Red-shouldered hawk probability of detection and occupancy rates determined from call-broadcast surveys conducted in central Minnesota in 2004 and 2005.

Study Site	Year	No. of call broadcast stations	Probability of detection	Occupancy rate (*SE*)
Camp Ripley	2004	90	0.5067	0.7722 (0.0490)
	2005	130	0.5202	0.7277 (0.0458)
Pillsbury State Forest	2004	41	0.6708	0.9782 (0.0242).
	2005	39	0.5879	0.8880 (0.0550)
TNC Lake Alexander	2005	10	0.7500	1.00
Foothills State Forest	2005	69	0.1747	0.5948 (0.1548)

TABLE 5. Mean values (SE) of 9 habitat variables measured at 247 call-broadcast stations in central Minnesota in 2005.

Scale (ha)	RSHA Response?	*n*	NON (SE)	DEC (SE)	WET (SE)	CORE (SE)	NUMP (SE)	MPS (SE)	EDGE (SE)	DIV (SE)	EVEN (SE)
100	Response	150	0.131 (0.010)	0.537 (0.017)	0.102 (0.008)	0.133 (0.011)	4.11 (0.19)	21.2 (1.7)	82.8 (1.7)	1.24 (0.01)	0.858 (0.006)
	No Response	97	0.159 (0.014)	0.415 (0.017)	0.133 (0.012)	0.076 (0.011)	4.39 (0.23)	14.0 (1.5)	77.1 (2.4)	1.31 (0.02)	0.878 (0.007)
314	Response	150	0.137 (0.009)	0.531 (0.014)	0.112 (0.007)	0.138 (0.008)	7.42 (0.34)	38.0 (3.2)	70.8 (1.3)	1.33 (0.01)	0.861 (0.005)
	No Response	97	0.182 (0.013)	0.394 (0.013)	0.138 (0.010)	0.071 (0.008)	9.46 (0.42)	17.7 (1.5)	68.5 (1.8)	1.41 (0.01)	0.886 (0.006)

Table 6. AIC, ΔAIC, AIC weight, parameter estimates, and 95 % confidence intervals for top competing models (< 2 AIC from best-supported model) evaluating habitat associations of red-shouldered hawks using call broadcast surveys in central Minnesota in 2004 (Camp Ripley and Pillsbury), 2005 (all study areas) and for both years combined (points sampled both years at Camp Ripley and Pillsbury).

	100-ha						314-ha					
Year	MODEL	K	AIC_c	Δ AIC_c	AIC_c weight	Parameter estimates (95% C.I.)	MODEL	K	AIC_c	Δ AIC_c	AIC_c weight	Parameter estimates (95 % C.I.)
2004	**NON**	9	806.79	0	0.369	β_0 = 1.94 (1.08, 2.80)	**NON**	9	800.79	0	0.4131	β_0 = 2.599 (1.505, 3.692)
						β_1 = -5.02 (-9.05, -1.0)						β_1 = -8.909 (-14.151, -3.666)
	DEC + NON	10	808.56	1.77	0.152	β_0 = 1.43(-0.75, 3.63)	DEC + NON	10	801.57	0.78	0.2797	β_0 = 1.240 (-1.341, 3.822)
						β_1 =0.81 (-2.45, 4.09)						β_1 = 2.256 (-1.785, 6.297)
						β_2 = -4.47 (-9.05, 0.11)						β_2 = -7.350 (-13.198, -1.502)
2005	**DEC**	9	1033.99	0	0.309	β_0 = -0.67 (-1.62, 0.27)	**DEC + DIV**	11	1016.64	0	0.4345	β_0 = -5.375 (-11.560, 0.809)
						β_1 =3.86 (1.86, 5.85)	**+EVEN**					β_1 = 6.469 (3.269, 9.669)
	DEC + EDGE	10	1034.78	1.69	0.133	β_0 = -0.90 (-1.98, 0.17)						β_2 = -6.738 (-11.640, -1.837)
						β_1 =3.37 (1.09, 5.66)						β_3 = 14.859 (6.951, 22.766)
						β_2 =0.006 (-0.008, 0.020)	DEC + EVEN	10	1018.55	1.91	0.1672	β_0 = -7.082 (-13.212, -0.951)
	DEC + EVEN	10	1034.96	1.87	0.121	β_0 = -1.70 (-7.24, 3.85)						β_1 = 7.563 (4.481, 10.645)
						β_1 =4.04 (1.80, 6.29)						β_2 = 5.667 (-0.535, 11.869)
						β_2 =1.07 (-4.65, 6.80)						
	DEC + NON	10	1034.97	1.88	0.121	β_0 = -0.50 (-1.86, 0.85)						
						β_1 =3.68 (1.45, 5.90)						
						β_2 =-0.52 (-3.46, 2.43)						
	DEC + DIV	10	1035.04	1.95	0.116	β_0 = -1.13 (-5.18, 2.92)						
						β_1 =4.02 (1.55, 6.50)						
						β_2 =0.30 (-2.31, 2.91)						
	DEC + WET	10	1035.08	1.99	0.114	β_0 = -0.69 (-1.70, 0.33)						
						β_1 =3.86 (1.86, 5.85)						
						β_2 =0.13 (-3.27, 3.52)						
Multi-	**NON**	11	1442.33	0	0.354	β_0 = 1.94 (1.09, 2.80)	**NON**	11	1436.09	0	0.3806	β_0 = 2.628 (1.526, 3.731)
Season						β_1 =-5.05 (-9.06, -1.05)						β_1 = -9.049 (-14.331, -3.768)
2004 &	DEC + NON	12	1444.03	1.7	0.151	β_0 = 1.37 (-0.83, 3.56)	DEC + NON	12	1436.73	0.64	0.2764	β_0 = 1.170 (-1.453, 3.794)
2005						β_1 =0.94 (-2.40, 4.27)						β_1 = 2.449 (-1.735, 6.633)
						β_2 =-4.43 (-8.97, 0.11)						β_2 = -7.409 (-13.307, -1.512)
							DEC +	12	1438.08	1.99	0.1407	β_0 = -11.716 (-20.700, -2.73)
							EVEN					β_1 = 7.035 (2.684, 11.385)
												β_2 = 10.915 (1.859, 19.972)

[a] **Bold type** = model with 95% confidence interval of slope parameter estimates that do not overlap zero
[b] K is the number of parameters included in the model
[c] ΔAIC is the difference in AIC values between each model and the lowest AIC model
[d] AIC weight is the model weight

Table 7. Red-shouldered hawk nests and reproductive success at Camp Ripley, the Pillsbury State Forest, and The Nature Conservancy Lake Alexander Preserve in central Minnesota in 2004 and 2005.

Study site	Year	No. of occupied nest sites	No. of nesting attempts	No. of successful nests	No. of young fledged	Apparent nest success	Mayfield nest success
Camp Ripley	2004	22	20	11	22	0.50	0.49
	2005	24	24	7	13	0.29	0.25
Pillsbury State Forest	2004	11	10	5	10	0.45	0.44
	2005	12	12	1	2	0.08	0.13
The Nature Conservancy	2004	4	3	1	2	0.25	0.05
	2005	6	6	2	4	0.33	0.24

Table 8. Mean values (SE) of 9 habitat variables measured at red-shouldered hawk nest sites and random sites in central Minnesota at 3 spatial scales.

Scale (ha)	Sites	*n*	NON (SE)	DEC (SE)	WET (SE)	CORE (SE)	NUMP(SE)	MPS (SE)	EDGE (SE)	DIV (SE)	EVEN (SE)
25	All nests	68	0.056 (0.011)	0.747 (0.024)	0.090 (0.010)	0.263 (0.028)	1.77 (0.11)	13.53 (0.88)	108.48 (3.19)	0.93 (0.03)	0.82 (0.02)
	CR nests	41	0.042 (0.010)	0.749 (0.034)	0.078 (0.012)	0.289 (0.035)	1.85 (0.15)	13.02 (1.16)	104.59 (4.15)	0.89 (0.04)	0.83 (0.03)
	PSF nests	20	0.086 (0.029)	0.723 (0.037)	0.102 (0.018)	0.219 (0.055)	1.60 (0.13)	13.36 (1.49)	110.99 (6.03)	1.02 (0.07)	0.80 (0.05)
	TNC nests	7	0.053 (0.020)	0.806 (0.049)	0.127 (0.029)	0.241 (0.076)	1.71 (0.57)	17.02 (2.90)	124.08 (6.36)	0.90 (0.06)	0.83 (0.02)
	Random sites	68	0.158 (0.022)	0.581 (0.026)	0.102 (0.017)	0.142 (0.022)	2.15 (0.15)	9.34 (0.77)	103.20 (3.77)	1.04 (0.03)	0.88 (0.01)
100	All nests	68	0.073 (0.008)	0.666(0.020)	0.109 (0.011)	0.230 (0.020)	2.50 (0.23)	43.60 (3.47)	82.41 (2.31)	1.17 (0.02)	0.85 (0.01)
	CR nests	41	0.068 (0.011)	0.679 (0.028)	0.088 (0.013)	0.249 (0.027)	2.51(0.34)	47.79 (4.65)	79.87 (2.86)	1.16 (0.03)	0.84 (0.01)
	PSF nests	20	0.092 (0.016)	0.593 (0.026)	0.140 (0.022)	0.175 (0.032)	2.75 (0.31)	30.47 (4.97)	86.09 (5.16)	1.27 (0.03)	0.85 (0.01)
	TNC nests	7	0.053 (0.006)	0.796 (0.046)	0.147 (0.038)	0.274 (0.055)	1.71(0.29)	56.61 (10.4)	86.77 (1.94)	0.96 (0.04)	0.85 (0.02)
	Random sites	68	0.184 (0.021)	0.492 (0.023)	0.129 (0.017)	0.116 (0.016)	2.85 (0.25)	29.88 (2.80)	75.10 (2.51)	1.25 (0.02)	0.86 (0.01)
314	All nests	68	0.088 (0.007)	0.618 (0.018)	0.118 (0.011)	0.187 (0.014)	6.41 (0.41)	45.51 (5.02)	72.38 (1.49)	1.30 (0.02)	0.85 (0.01)
	CR nests	41	0.085 (0.010)	0.624 (0.024)	0.096 (0.013)	0.213 (0.020)	7.56 (0.54)	36.08 (4.08)	69.30 (1.85)	1.31 (0.02)	0.85 (0.01)
	PSF nests	20	0.102 (0.009)	0.561 (0.026)	0.138 (0.020)	0.127 (0.020)	4.85 (0.50)	49.05 (9.11)	75.91 (2.79)	1.37 (0.02)	0.86 (0.01)
	TNC nests	7	0.065 (0.008)	0.742 (0.042)	0.191 (0.043)	0.208 (0.035)	4.14 (0.94)	90.66(29.92)	80.34 (3.04)	0.99 (0.03)	0.79 (0.02)
	Random sites	68	0.196 (0.019)	0.460 (0.022)	0.140 (0.015)	0.119 (0.014)	8.47 (0.50)	24.21 (2.48)	63.65 (1.90)	1.36 (0.01)	0.86 (0.01)

Table 9. AIC, ΔAIC, AIC weight, parameter estimates, and 95% confidence intervals for top competing models (<2 AIC from top model) evaluating habitat associations at red-shouldered hawk nest sites versus random sites in central Minnesota in 2004 and 2005.

Study Area	Scale (ha)	MODEL	K[b]	AIC_c	Δ AIC_c[c]	AIC_c weight[1]	Parameter estimate (95% C.I)
ALL NESTS	25	**DEC + NON** [a]	3	168.51	0.00	0.5442	β_0 = -1.70 (-3.37, -0.02) β_1 = 3.05 (0.87, 5.22) β_2 = -3.79 (-7.52, -0.07)
	100	**DEC + NON**	3	159.24	0.00	0.7367	β_0 = -1.71 (-3.46, 0.04) β_1 = 3.90 (1.39, 6.42) β_2 = -5.02 (-9.31, -0.73)
	314	**DEC + NON**	3	158.28	0.00	0.7990	β_0 = -1.00 (-2.90, 0.89) β_1 = 3.46 (0.73, 6.19) β_2 = -6.94 (-12.18, -1.71)
CR NESTS	25	**DEC + NON**	3	120.69	0.00	0.6464	β_0 = -1.60 (-3.50, 0.31) β_1 = 2.55 (0.09 5.02) β_2 = -6.35 (-11.72, -0.97)
	100	DEC + NON	3	119.32	0.00	0.3500	β_0 = -2.23 (-4.39, -0.07) β_1 = 3.90 (0.91, 6.89) β_2 = -4.67 (-10.10, 0.76)
		DEC	2	120.67	1.35	0.1785	β_0 = -3.60 (-5.30, -1.90) β_1 = 5.36 (2.70, 8.02)
	314	**DEC + NON**	3	121.20	0.00	0.3887	β_0 = -1.53 (-3.84, 0.78) β_1 = 3.34 (0.09, 6.59) β_2 = -5.84 (-12.09, -0.40)
PSF NESTS	25	DEC + DIV +EVEN	4	83.39	0.00	0.4664	β_0 = -5.00 (-10.99, 1.0) β_1 = 6.12 (1.74, 10.51) β_2 = 4.66 (0.88, 8.43) β_2 = -5.94 (-12.17, 0.31)
		DEC + DIV	3	85.21	1.83	0.1872	β_0 = -7.60 (-12.72, -2.48) β_1 = 6.15 (2.02, 10.28) β_2 = 2.38 (-0.30, 5.06)
	100	NON	2	89.19	0.00	0.2004	β_0 = -0.46 (-1.21, 0.30) β_1 = -5.22 (-10.45, 0.02)
		DEC + EDGE	3	90.43	1.23	0.1084	β_0 = -4.16 (-6.84, -1.49) β_1 = 2.81 (-0.48, 6.11) β_2 = 0.019 (-0.006, 0.043)
		DEC + NON	3	90.15	1.32	0.1039	β_0 = -1.56 (-4.08, 0.96) β_1 = 1.70 (-2.01, 5.41) β_2 = -3.94 (-9.72, 1.85)
		DEC	2	90.50	1.30	0.1047	β_0 = -2.85 (-4.73, -0.96) β_1 = 3.15 (-0.02, 6.33)
		CORE + EDGE	3		1.89	0.0781	β_0 = -3.47 (-5.75, -1.18) β_1 = 2.87 (-0.81, 6.55) β_2 = -0.024 (-0.001, 0.049)
	314	**NUMP**	2	79.81	0.00	0.8072	β_0 = 1.20 (-0.20, 2.60) β_1 = -0.38 (-0.61, -0.14)

[a] **Bold type** = model with 95% confidence interval of slope parameter estimates that do not overlap zero
[b] K is the number of parameters included in the model
c ΔAIC is the difference in AIC values between each model and the lowest AIC model
[d] AIC weight is the model weight

Figure 1. Location of study areas in central Minnesota where red-shouldered hawk habitat associations were evaluated in 2004 and 2005.

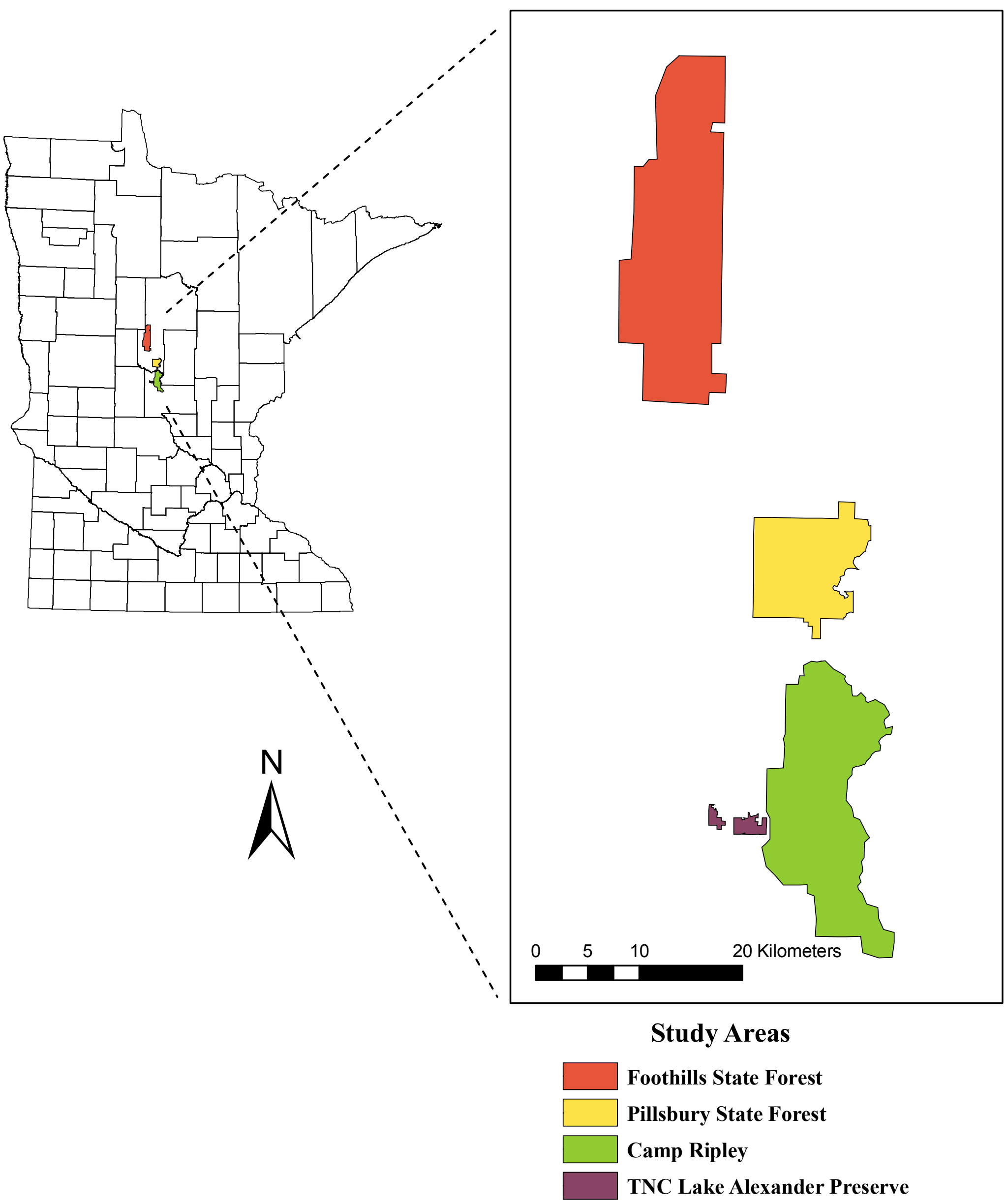
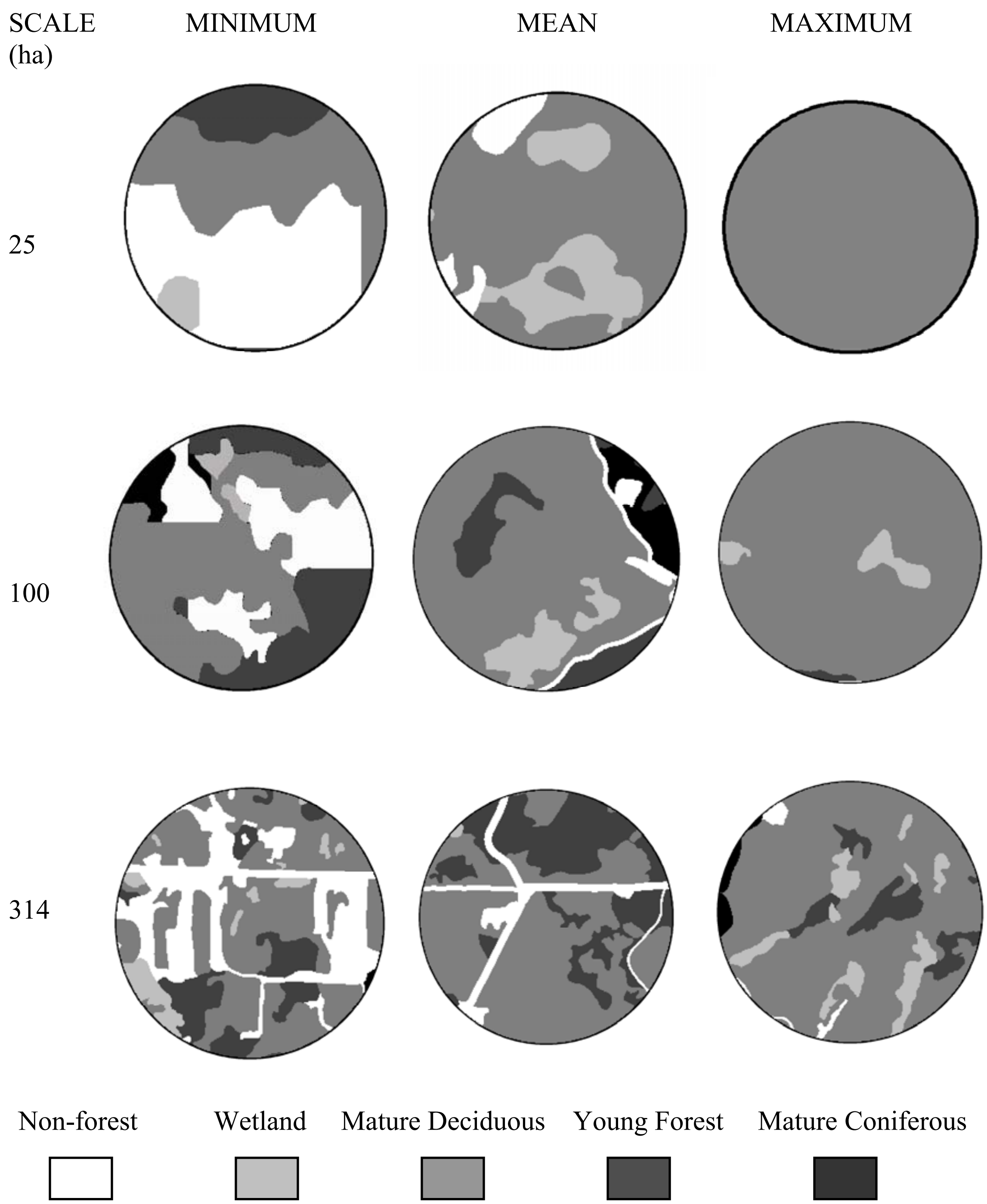


Figure 2. Classified images that most closely approximate the minimum, the mean, and the maximum amount of mature deciduous forest at red-shouldered hawk nest sites (n = 68) measured at 3 spatial scales in central Minnesota.



Appendix 1. AIC, ΔAIC, AIC weight, and number of parameters for models of habitat associated with red-shouldered hawk nests from all study areas in central Minnesota in 2004 and 2005.

SCALE (ha)	MODEL	K[a]	AIC_c	Δ AIC_c[b]	AIC_c weight[c]
25	DEC + NON	3	168.51	0.00	0.5442
	DEC	2	170.95	2.45	0.1606
	DEC + EVEN	3	172.71	4.20	0.0668
	DEC + WET	3	172.93	4.42	0.0600
	DEC + DIV	3	173.03	4.53	0.0569
	DEC + EDGE	3	173.04	4.54	0.0565
	DEC + DIV +EVEN	4	174.69	6.18	0.0248
	NON	2	174.86	6.35	0.0228
	CORE + EDGE	3	178.30	9.79	0.0041
	SIZE	2	180.37	11.86	0.0015
	CORE	2	180.61	12.10	0.0013
	DIV	2	183.04	14.53	0.0004
	EVEN	2	186.67	18.17	0.0001
	NUMP	2	188.47	19.96	0.0000
	INTERCEPT	1	188.57	20.06	0.0000
	EDGE	2	191.47	22.97	0.0000
	WET	2	192.22	23.71	0.0000
100	DEC + NON	3	159.24	0.00	0.7367
	DEC	2	163.58	4.34	0.0845
	DEC + EDGE	3	164.85	5.62	0.0446
	DEC + EVEN	3	165.17	5.93	0.0382
	DEC + DIV	3	165.55	6.31	0.0315
	DEC + WET	3	165.63	6.39	0.0304
	DEC + DIV +EVEN	4	167.28	8.04	0.0133
	NON	2	167.56	8.32	0.0116
	CORE + EDGE	3	168.22	8.98	0.0083
	CORE	2	172.92	13.68	0.0008
	SIZE	2	183.44	24.20	0.0000
	DIV	2	186.74	27.50	0.0000
	EDGE	2	188.05	28.81	0.0000
	EVEN	2	190.52	31.28	0.0000
	INTERCEPT	1	190.57	31.33	0.0000
	NUMP	2	191.51	32.27	0.0000
	WET	2	191.64	32.40	0.0000
314	DEC + NON	3	158.28	0.00	0.7990
	NON	2	162.69	4.41	0.0885
	DEC	2	164.96	6.68	0.0285
	DEC + EDGE	3	165.25	6.98	0.0246
	DEC +EVEN	3	165.47	7.19	0.0221
	DEC + DIV +EVEN	4	166.60	8.32	0.0126
	DEC + WET	3	166.90	8.62	0.0108
	DEC + DIV	3	167.04	8.77	0.0101
	CORE + EDGE	3	169.05	10.77	0.0037
	SIZE	2	174.91	16.63	0.0002
	EDGE	2	179.99	21.72	0.0000
	CORE	2	180.82	22.55	0.0000
	NUMP	2	182.70	24.42	0.0000
	DIV	2	186.32	28.04	0.0000
	EVEN	2	190.31	32.03	0.0000
	INTERCEPT	1	190.57	32.29	0.0000
	WET	2	191.21	32.93	0.0000

[a] K is the number of parameters included in the model
[b] ΔAIC is the difference in AIC values between each model and the lowest AIC model
[c] AIC weight is the model weight

Appendix 2. AIC, ΔAIC, AIC weight, and number of parameters for models of habitat associated with red-shouldered hawk nests from Camp Ripley in central Minnesota in 2004 and 2005.

SCALE (ha)	MODEL	K	AIC_c	ΔAIC_c	AIC_c weight
25	DEC + NON	3	120.69	0.00	0.6464
	NON	2	123.14	2.46	0.1897
	DEC	2	125.69	5.00	0.0532
	DEC + DIV	3	127.08	6.40	0.0265
	DEC + EDGE	3	127.09	6.40	0.0265
	DEC + WET	3	127.77	7.08	0.0188
	DEC+EVEN	3	127.81	7.12	0.0185
	DEC + DIV +EVEN	4	129.12	8.43	0.0096
	CORE	2	130.11	9.42	0.0059
	CORE + EDGE	3	131.33	10.64	0.0032
	DIV	2	133.99	13.30	0.0008
	SIZE	2	134.83	14.14	0.0006
	EVEN	2	138.77	18.08	0.0001
	INTERCEPT	1	139.49	18.80	0.0001
	NUMP	2	139.75	19.06	0.0000
	WET	2	140.82	20.13	0.0000
	EDGE	2	141.55	20.86	0.0000
100	DEC + NON	3	119.32	0.00	0.3500
	DEC	2	120.67	1.35	0.1785
	DEC + WET	3	121.77	2.44	0.1033
	DEC + EVEN	3	122.35	3.03	0.0772
	DEC + SDI	3	122.52	3.20	0.0709
	NUMP	2	122.59	3.26	0.0687
	DEC + EDGE	3	122.76	3.44	0.0629
	DEC + DIV +EVEN	4	123.79	4.47	0.0376
	NON	2	124.68	5.35	0.0242
	CORE	2	125.75	6.43	0.0141
	CORE + EDGE	3	126.07	6.74	0.0121
	SIZE	2	133.11	13.78	0.0004
	DIV	2	134.25	14.92	0.0002
	WET	2	138.65	19.33	0.0000
	INTERCEPT	1	139.49	20.17	0.0000
	EVEN	2	139.95	20.63	0.0000
	EDGE	2	140.20	20.88	0.0000
314	DEC + NON	3	121.20	0.00	0.3887
	DEC	2	123.30	2.10	0.1363
	NON	2	123.38	2.18	0.1309
	DEC + EVEN	3	124.37	3.17	0.0800
	DEC + WET	3	124.58	3.38	0.0719
	DEC + DIV +EVEN	4	124.95	3.75	0.0599
	DEC + DIV	3	125.36	4.16	0.0488
	DEC + EDGE	3	125.40	4.20	0.0479
	CORE + EDGE	3	126.53	5.33	0.0272
	CORE	2	129.06	7.86	0.0077
	SIZE	2	136.37	15.17	0.0002
	DIV	2	136.79	15.59	0.0002
	WET	2	137.39	16.19	0.0001
	EDGE	2	137.86	16.66	0.0001
	INTERCEPT	1	139.49	18.29	0.0000
	EVEN	2	139.67	18.47	0.0000
	NUMP	2	141.00	19.80	0.0000

[a] K is the number of parameters included in the model

[b] ΔAIC is the difference in AIC values between each model and the lowest AIC model

[c] AIC weight is the model weight

Appendix 3. AIC, ΔAIC, AIC weight, and number of parameters for models of habitat associated with red-shouldered hawk nests from Pillsbury State Forest in central Minnesota in 2004 and 2005.

SCALE (ha)	MODEL	K	AIC_c	$\Delta\ AIC_c$	AIC_c weight
25	DEC + DIV +EVEN	4	83.39	0.00	0.4664
	DEC + DIV	3	85.21	1.83	0.1872
	DEC	2	86.44	3.06	0.1013
	DEC + WET	3	87.78	4.40	0.0519
	DEC + EDGE	3	88.00	4.62	0.0465
	DEC + EVEN	3	88.37	4.99	0.0387
	DEC + NON	3	88.58	5.20	0.0348
	SIZE	2	89.40	6.01	0.0232
	NUMP	2	90.64	7.25	0.0125
	EVEN	2	91.09	7.71	0.0100
	NON	2	91.52	8.13	0.0081
	CORE + EDGE	3	92.57	9.19	0.0048
	INTERCEPT	1	92.59	9.21	0.0047
	CORE	2	92.86	9.47	0.0041
	EDGE	2	93.84	10.46	0.0025
	DIV	2	94.64	11.25	0.0017
	WET	2	94.67	11.28	0.0017
100	NON	2	89.19	0.00	0.2004
	DEC + EDGE	3	90.43	1.23	0.1084
	DEC + NON	3	90.51	1.32	0.1039
	DEC	2	90.50	1.30	0.1047
	CORE + EDGE	3	91.08	1.89	0.0781
	DEC + DIV	3	91.44	2.24	0.0654
	EDGE	2	91.31	2.12	0.0697
	DEC + WET	3	91.80	2.61	0.0545
	DEC + EVEN	3	91.97	2.78	0.0501
	CORE	2	92.66	3.46	0.0356
	INTERCEPT	1	92.59	3.40	0.0368
	DEC + DIV +EVEN	4	93.40	4.20	0.0246
	WET	2	94.50	5.31	0.0142
	EVEN	2	94.58	5.39	0.0136
	SIZE	2	94.61	5.42	0.0134
	DIV	2	94.63	5.43	0.0133
	NUMP	2	94.63	5.44	0.0133
314	NUMP	2	79.81	0.00	0.8072
	SIZE	2	84.43	4.62	0.0804
	EDGE	2	86.04	6.23	0.0361
	DEC + EDGE	3	87.24	7.43	0.0198
	NON	2	87.29	7.48	0.0192
	CORE + EDGE	3	88.07	8.26	0.0131
	DEC + NON	3	89.23	9.42	0.0073
	DEC	2	90.31	10.50	0.0043
	DEC + DIV	3	90.48	10.67	0.0039
	DEC + EVEN	3	91.60	11.79	0.0022
	DEC + WET	3	92.04	12.23	0.0018
	DEC + DIV +EVEN	4	92.58	12.77	0.0014
	INTERCEPT	1	92.59	12.78	0.0014
	DIV	2	94.56	14.75	0.0005
	EVEN	2	94.56	14.75	0.0005
	CORE	2	94.68	14.87	0.0005
	WET	2	94.69	14.88	0.0005

[a] K is the number of parameters included in the model
[b] ΔAIC is the difference in AIC values between each model and the lowest AIC model
[c] AIC weight is the model weight

Appendix 4. Habitat models and associated AIC values for red-shouldered hawk call-broadcast survey locations in central Minnesota, 2004-2005.

	100-ha					314-ha				
	MODEL	**K**	**AICc**	**Δ AICc**	**AICc weight**	**MODEL**	**K**	**AICc**	**Δ AICc**	**AICc weight**
CR & PSF	NON	9	806.79	0	0.369	NON	9	800.79	0	0.4131
2004	DEC + NON	10	808.56	1.77	0.152	DEC + NON	10	801.57	0.78	0.2797
	EVEN	9	809.47	2.68	0.097	DEC + EVEN	10	802.95	2.16	0.1403
	DEC	9	810.22	3.43	0.066	DEC + DIV + EVEN	11	804	3.21	0.083
	CORE	9	810.45	3.66	0.059	DEC	9	805.89	5.1	0.0323
	DIV	9	810.52	3.73	0.057	DEC + DIV	10	806.53	5.74	0.0234
	SITE + SURVEY	8	810.55	3.76	0.056	DEC + WET	10	807.76	6.97	0.0127
	DEC + EVEN	10	810.83	4.04	0.049	CORE	9	808.71	7.92	0.0079
	DEC + DIV	10	811.78	4.99	0.030	SITE + SURVEY	8	810.55	9.76	0.0031
	DEC + WET	10	812.19	5.4	0.025	WET	9	811.82	11.03	0.0017
	WET	9	812.49	5.7	0.021	EVEN	9	811.92	11.13	0.0016
	DEC + DIV + EVEN	11	812.76	5.97	0.019	DIV	9	812.41	11.62	0.0012
	INTERCEPT	2	851.81	45.02	0	INTERCEPT	2	851.81	51.02	0
	NUMP	9	874.65	67.86	0	NUMP	9	876.33	75.54	0
	EDGE	9	876.33	69.54	0	SIZE	9	876.33	75.54	0
	SIZE	9	876.33	69.54	0	EDGE	9	876.33	75.54	0
	CORE + EDGE	10	878.33	71.54	0	DEC + EDGE	10	878.33	77.54	0
	DEC + EDGE	10	878.33	71.54	0	CORE + EDGE	10	878.33	77.54	0
ALL - 2005	DEC	9	1033.09	0	0.309	DEC + DIV + EVEN	11	1016.64	0	0.4345
	DEC + EDGE	10	1034.78	1.69	0.133	DEC + EVEN	10	1018.55	1.91	0.1672
	DEC + EVEN	10	1034.96	1.87	0.121	DEC	9	1019.36	2.72	0.1115
	DEC + NON	10	1034.97	1.88	0.121	SIZE	9	1019.51	2.87	0.1035
	DEC + DIV	10	1035.04	1.95	0.117	DEC + EDGE	10	1020.87	4.23	0.0524
	DE + WET	10	1035.08	1.99	0.114	DEC + NON	10	1021.15	4.51	0.0456
	DEC + DIV + EVEN	11	1036.94	3.85	0.045	DEC + WET	10	1021.31	4.67	0.0421
	CORE + EDGE	10	1038.04	4.95	0.026	DEC + DIV	10	1021.36	4.72	0.041
	EDGE	9	1041.18	8.09	0.005	CORE + EDGE	10	1028	11.36	0.0015
	SIZE	9	1041.86	8.77	0.004	CORE	9	1029.61	12.97	0.0007
	CORE	9	1042.61	9.52	0.003	DIV	9	1034.77	18.13	0.0001
	DIV	9	1043.97	10.88	0.001	NUMP	9	1035.59	18.95	0
	NON	9	1044.86	11.77	0.001	NON	9	1038.51	21.87	0
	EVEN	9	1047.4	14.31	0	EDGE	9	1040.93	24.29	0
	SITE + SURVEY	8	1048.23	15.14	0	EVEN	9	1047.3	30.66	0
	NUMP	9	1048.88	15.79	0	SITE + SURVEY	8	1048.23	31.59	0
	WET	9	1050.21	17.12	0	WET	9	1049.99	33.35	0
	INTERCEPT	2	1120.45	87.36	0	INTERCEPT	2	1120.45	103.81	0

Appendix 4. Continued.

	100-ha					314-ha				
	MODEL	**K**	**AICc**	**Δ AICc**	**AICc weight**	**MODEL**	**K**	**AICc**	**Δ AICc**	**AICc weight**
CR & PSF MULTI-SEASON 2004 & 2005	NON	11	1442.33	0	0.3535	NON	11	1436.09	0	0.3806
	DEC + NON	12	1444.03	1.7	0.1511	DEC + NON	12	1436.73	0.64	0.2764
	DIV	11	1444.99	2.66	0.0935	DEC + EVEN	12	1438.08	1.99	0.1407
	EVEN	11	1444.99	2.66	0.0935	DEC + DIV + EVEN	13	1438.31	2.22	0.1254
	DEC	11	1445.72	3.39	0.0649	DEC	11	1441.1	5.01	0.0311
	CORE	11	1446.08	3.75	0.0542	DEC + DIV	12	1441.95	5.86	0.0203
	DEC + EVEN	12	1446.27	3.94	0.0493	DEC + WET	12	1442.98	6.89	0.0121
	SITE + SURVEY	10	1446.36	4.03	0.0471	CORE	11	1443.89	7.8	0.0077
	DEC + DIV	12	1447.16	4.83	0.0316	SITE + SURVEY	10	1446.36	10.27	0.0022
	DEC + WET	12	1447.7	5.37	0.0241	WET	11	1447.54	11.45	0.0012
	DEC + DIV + EVEN	13	1448.16	5.83	0.0192	EVEN	11	1447.79	11.7	0.0011
	WET	11	1448.29	5.96	0.018	DIV	11	1448.1	12.01	0.0009
	NUMP	11	1474.41	32.08	0	INTERCEPT	4	1499.02	62.93	0
	INTERCEPT	4	1499.02	56.69	0	EDGE	11	1521.59	85.5	0
	EDGE	11	1521.59	79.26	0	NUMP	11	1521.59	85.5	0
	SIZE	11	1521.59	79.26	0	SIZE	11	1521.59	85.5	0
	CORE + EDGE	12	1523.59	81.26	0	DEC + EDGE	12	1523.59	87.5	0
	DEC + EGDE	12	1523.59	81.26	0	CORE + EDGE	12	1523.59	87.5	0