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Modeling Potential Changes in Rare Species Habitat from Planned Timber Harvest in Minnesota, USA

Tyler S. Gifford [1,*], John M. Zobel [1] and Lindsey M. Shartell [2]

1 Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, USA; jzobel@umn.edu
2 Division of Fish and Wildlife, Minnesota Department of Natural Resources, Grand Rapids, MN 55744, USA; lindsey.shartell@state.mn.us
* Correspondence: giffo071@umn.edu

Abstract: In 2018, the Minnesota Department of Natural Resources conducted the Sustainable Timber Harvest Analysis that resulted in the 10-year Stand Exam List (SEL). The SEL includes stands that will be assessed for potential management action from 2021 to 2030, but the location, number, and impact of stands actually harvested remains unknown. This study sought to use modeling to assess potential habitat changes from the SEL for five threatened, endangered, or special concern wildlife species. Three simulation scenarios captured the potential range of harvest from the SEL, and the Wildlife Habitat Indicator for Native Genera and Species model assessed associated habitat changes. The most realistic simulation scenario resulted in statistically insignificant habitat changes of less than ±6%, while two scenarios providing the upper and lower extremes of harvest resulted in statistically significant changes for one species each. Scenarios that resulted in less harvest and more mature forests benefited the five species, reflecting their habitat preferences. The tempering of habitat change values in the most realistic simulation scenario provides evidence for forest management tradeoffs between different wildlife species habitat requirements, as well as other forest resource management objectives.

Keywords: threatened; endangered; special concern species; sustainable harvest; wildlife habitat modeling; simulations

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1. Introduction

Forest management in the United States has experienced paradigm shifts over the last half century, trending from economically driven, sustained-yield management to multi-resource-driven, ecosystem-wide management [1]. The shift to multiple resource, ecosystem-wide management increased the focus beyond timber production to include wildlife habitat, water quality, outdoor recreation, and many others. Nationally, in the United States, often-cited milestones in the shift to a broader environmental focus in forest management include the National Environment Policy Act (NEPA) [2] and the Endangered Species Act (ESA) [3] (e.g., [4–6]).

Within this paradigm shift, the importance of threatened, endangered, and special concern species (TESC) has persisted in the United States. This includes events from the passage of the ESA to the highly publicized conservation efforts of the northern spotted owl (*Strix occidentalus caurina* Merriam) in the Pacific Northwest in the 1990s [7] to the national delisting of the bald eagle (*Haliaeetus leucocephalus* Linnaeus) in 2007 [8]. Current efforts include the proposed national delisting of the gray wolf (*Canis lupus* Linnaeus) beginning in 2019 [9]. In terms of wildlife, federal and state entities define TESC species differently. At the federal level, endangered species indicate those nearing extinction through most of their nationwide range, while threatened species include those considered likely to meet the definition of endangered in the near future [3]. Many states operate their own definitions for TESC species. State Statute 84.0895 [10] establishes Minnesota TESC species and uses definitions for threatened and endangered species similar to those under the federal listing, but within their range across the state. Minnesota statutes further define special concern species as those not endangered or threatened, but extremely uncommon in the state, or having unique or highly specific habitat requirements that warrant careful monitoring [10].

Forest management directly affects the habitat of forest-dependent TESC species. The ESA includes an objective focused on ecosystem conservation and requires the designation of critical habitat for any listed species [3,11]. Due to this, threatened and endangered species can significantly impact forest management decisions (e.g., [12–15]). The importance of these species, coupled with the shifting forest management paradigm, leads to the question of how one can sustainably harvest timber or other forest biomass while continuing to support valuable resources for threatened and endangered wildlife. As sustainable forest management shifts to answer these questions, the sharing of information between researchers and managers is crucial, and modeling is often the most useful tool for making this connection [16]. To meet the need of multi-resource objectives in sustainable forest management, the challenge exists to develop models and predictions that incorporate multiple objectives. Mäkelä et al. [17] advise that the simultaneous modeling of multiple objectives may not be desirable due to the complexity of including many, varying priorities. Rather, they argue for combining information from the independent modeling of specific objectives, such as wildlife habitats. The state of Minnesota explored such a challenge with the 1994 Generic Environmental Impact Statement (GEIS) Study on Timber Harvesting and Forest Management in Minnesota [18], which sought to assess the environmental impacts of forest management and timber harvesting, including impacts on wildlife habitats.

Similarly, in 2018, the Minnesota Department of Natural Resources (MN DNR) completed the Sustainable Timber Harvest Analysis (STHA) to review and assess the impact of future harvest schedules across Minnesota forests, with a goal of determining the potential sustainability of harvesting approximately 3.6 million m^3/year (one million cords/year) [19]. The analysis sought to include multiple management objectives beyond timber production, including wildlife habitats. Based on the STHA modeling, MN DNR established a 10-year sustainable timber harvest level below the initial target of approximately 3.1 million m^3/year (870,000 cords/year) and an associated 10-year Stand Exam List (SEL) of forest stands to be assessed to potentially provide that timber [20]. The 10-year list contains stands scheduled for harvest assessment, but the number, location, and impact of stands ultimately selected for harvest remains unknown. On average, the MN DNR offers 60% of the stands planned for examination for sale [20]. Of particular interest is how different harvest scenarios and different numbers and combinations of stands harvested may impact wildlife habitats over the next 10 years. The Wildlife Habitat Indicator for Native Genera and Species (WHINGS) model [6,21] facilitates this type of assessment.

From common forest inventory variables, the WHINGS models estimate habitat quality and quantity for 172 native, forest-dependent wildlife species in Minnesota. The most recent update of the WHINGS models [6] builds upon work completed during the GEIS [18,21,22]. The GEIS included extensive wildlife habitat work, resulting in Habitat Suitability Index (HSI) models for Minnesota wildlife species [23]. Frelich et al. [22] revised and improved many of the foundational HSI models. Zobel and Ek [21] and Zobel et al. [6] incorporated the updated HSI equations into the WHINGS framework to better observe or forecast habitat changes due to realized or predicted trends in habitat quality, quantity, or both.

Although multiple objectives guided the creation of the 10-year SEL, the potential impact on wildlife habitat remains unknown, because not all stands in the SEL will be harvested. The objectives of this study were to use simulations of various harvest outcomes of the 10-year SEL to apply the WHINGS model to examine potential habitat changes of five forest-dependent species on the threatened, endangered, and special concern list in Minnesota.

2. Materials and Methods

2.1. Study Area

The focus areas of this study were lands owned and managed by MN DNR in the state of Minnesota, USA. Minnesota has a continental humid climate and experiences cold winters and warm summers, with an average annual temperature of 3 °C in the north and 7 °C in the south [24]. Average annual precipitation ranges from 50.8 cm in the northwest to 88.9 cm in the southeast [24]. Forest vegetation in Minnesota and on MN DNR land differs by region within the state. The northeast and southeast regions include boreal forest and temperate hardwoods, respectively, while the western portion is characterized largely by prairie. Of the approximately 20.6 million hectares of land in Minnesota, approximately 2.3 million hectares are owned and managed by MN DNR [24]. Abundant and varying native wildlife species can be found throughout the state, with management tasked to MN DNR, including species considered threatened, endangered, or of special concern, such as those in this study.

2.2. Threatened, Endangered, and Special Concern Species

The species chosen for focus in this work were derived from the Minnesota Department of Natural Resources' list of TESC species [25]. The TESC species in Minnesota are mandated by state law [10] and follow similar but separate definitions from the federal Endangered Species Act of 1973 [3]. The species on Minnesota's TESC species list were filtered to include only those that are native and largely forest dependent. Additionally, since the SEL only applies to state administered land, species were further restricted to those whose home range could conceivably exist within the spatial scale and fragmentation of MN DNR-only land. This led to the selection of five species, including four birds and one herpetofauna (Table 1).

Table 1. Five threatened, endangered, or special concern species in the state of Minnesota and their listing status according to the state of Minnesota.

Common Name	Scientific Name	State of Minnesota Status
Acadian flycatcher	*Empidonax virescens*	special concern
Cerulean warbler	*Dendroica cerulea*	special concern
Hooded warbler	*Wilsonia citrina*	special concern
Louisiana waterthrush	*Seiurus motacilla*	special concern
Timber rattlesnake	*Crotalus horridus*	threatened

While all native and forest dependent, the five TESC species in this study have other similarities and differences in their preferred and required forest habitats. The TESC bird species prefer mature hardwood forests primarily in southeastern Minnesota, including Acadian flycatcher (*Empidonax virescens* Vieillot), cerulean warbler (*Dendroica cerulea* Wilson), hooded warbler (*Wilsonia citrina* Boddaert), and Louisiana waterthrush (*Seiurus motacilla* Vieillot) [23,26]. Both the Acadian flycatcher and cerulean warbler are long-distance migrants that prefer mature deciduous forest for nesting [26]. The hooded warbler and Louisiana waterthrush are mid- to long-distance migrants whose northern range limits reach into the river valleys of Minnesota, though a slow northward expansion may be occurring [23]. Timber rattlesnakes (*Crotalus horridus* Linnaeus) prefer open spaces with a forest edge composed of primarily older forest, and its range in Minnesota is primarily restricted to the southeastern corner of the state [23,27].

2.3. Data

In cooperation with the MN DNR, we acquired the most recent iteration of their statewide forest stand inventory (FSI) data. The WHINGS framework functions with United States Forest Service, Forest Inventory and Analysis (FIA) plot-based data. Minnesota statewide FSI data are based on whole stands (rather than plots); thus, the cleaning and preparation of the data before any analysis was necessary. The cleaning and preparation of the data required frequent checks for realism and errors. Key variables utilized from FSI data for the simulations in this study and for input into the WHINGS framework included forest type, size class, stand age, stand size (hectares), site index, and administrative boundaries. Additionally, FSI and FIA codes for forest type and size classes differ, so FSI codes were mapped to their equivalent FIA codes utilizing Zobel et al. [28] to allow for input into the WHINGS framework. Additional missing or suspect data were investigated to correct errors or otherwise dropped from the analysis. Following cleaning and preparation, the final dataset comprised 194,455 stands.

The 10-year SEL for 2021–2030 contains a subset of FSI stands with additional information, including the planned stand examination year and one of three desired silvicultural prescriptions for the stand (uneven-aged management, even-aged management, or thinning). While the majority of the 35,800 stands on the SEL cleanly mapped to the same stand from FSI data, a small minority (1049 stands) did not match. Most of these SEL stands consisted of original FSI stands split into multiple sub-stands. The protocol for these non-conforming stands consisted of assigning the examination year and prescription from one SEL stand (the one mapping to the original FSI stand identifier code) to that entire FSI stand. While this protocol may result in the over- or under-treatment of an individual sub-stand, we assumed the effect negligible across all stands. Additionally, the FSI and SEL data do not document information on land use change or cover type conversion, thus leading to the modeling assumption that land use and cover type remained constant over the 10-year timeline. Consistent with the time horizon of the SEL and the typical planning horizon of the MN DNR [29], a 10-year timeframe was maintained in the modeling efforts. Figure 1 displays the extent of the FSI and SEL stands.

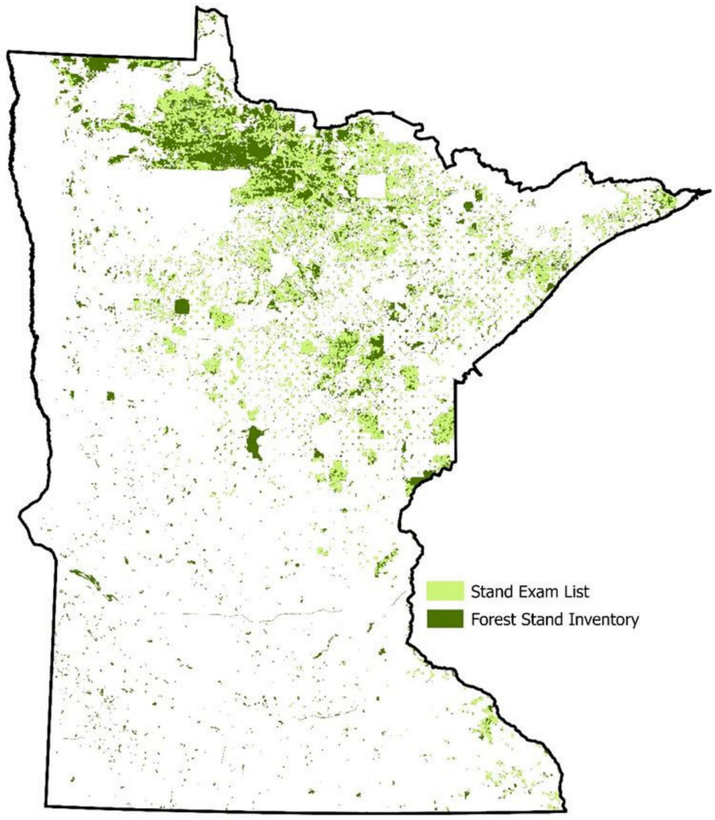

Figure 1. Forest stand inventory (FSI) stands from the Minnesota Department of Resources. Stand Exam List (SEL) stands are a subset of FSI stands scheduled for examination for potential management action.

2.4. WHINGS Framework

This study utilized the WHINGS framework to assess the habitat and habitat changes of the five TESC species. The methodology uses Habitat Suitability Index (HSI) [30] models to provide a measure of habitat quality based on forest characteristics, ranging from 0 (non-habitat) to 1 (optimal habitat). Equation (1) displays the HSI model from [6,21] for the species of interest in this study. These models depend on species habitat preferences (termed abundance codes), as defined by two main habitat characteristics: forest cover type and predominant tree size class. The latter is defined as small (diameter-breast-height (dbh) < 12.7 cm), medium (softwoods: 12.7 cm $\leq$ dbh < 22.9 cm; hardwoods: 12.7 cm $\leq$ dbh < 27.9 cm), and large (softwoods: dbh $\geq$ 22.9 cm; hardwoods: dbh $\geq$ 27.9 cm).

$$HSI = \left(\frac{\sum_{i=1}^{H} (AC_i * hectares_i)}{\sum_{i=1}^{H} hectares_i} \right) / \max(AC) \quad (1)$$

where for the four bird species, AC = abundance codes with values 0 (absent), 2 (0–1 pairs), 5 (2–10 pairs), 11 (11–51 pairs), 17 (51–100 pairs), and 35 (101–500 pairs); for timber rattlesnake, AC = 0 (absent) or 1 (present).

Habitat extent (HE) defines the quantity (in hectares) of the habitat. In WHINGS, this is the amount of forested land in the area of interest. The Habitat Unit (HU) represents the primary metric in WHINGS and adjusts the amount of habitat by its quality (HU = HIS * HE), providing a single habitat estimate that combines both quality and quantity [30,31]. The WHINGS framework also includes bootstrapping techniques to compute standard errors, facilitating statistical comparisons of HU (or HSI, HE) through time. For a full breakdown of the methodology and processes behind the WHINGS framework and the associated wildlife habitat models, see [6,21–23].

Another critical component of WHINGS is the specification of analysis units. These units represent the smallest spatial scale at which the habitat is assessed. They must encompass enough area to account for home range requirements of the species and contain enough data (i.e., stands) to achieve reliable statistical estimates [22]. Larger scale assessments aggregate analysis units into the area of interest. For this study, analysis units consisted of Individual Management Units (IMU) administered by the MN DNR. These are specific, named management areas, such as Red Lake Wildlife Management Area or Sturgeon River State Forest. A threshold of at least eight hectares (20 acres) and at least four stands was selected to provide a minimum acceptable level for home range extent and sample size. Each FSI stand received one analysis unit assignment to ensure no overlap when scaling up. If a potential analysis unit met these thresholds, then the analysis unit served as a single unit. Potential units that failed to meet the threshold were grouped together with nearby IMUs of the same management unit type (e.g., wildlife management areas (WMA) and forestry lands). Note that although the analysis units were identified by administration boundaries (IMUs), management goals often differ between management unit type and even IMUs, leading to distinct habitat availability. Additionally, the geographical proximity of grouped IMUs maintains ecological boundaries. Thus, the selection of analysis units preserves ecological differences in the habitat while providing results pertinent for management response. The number of analysis units used in this study totaled 974 units.

While the most recent form of the WHINGS framework was utilized, the problem of interest in this study (SEL and MN DNR-only lands) required minor modifications or assumptions. Any small changes from WHINGS are explicitly stated throughout this study.

2.5. Transition Protocols

Within FSI data, individual stand data remain current only to the last inventory year of each stand, and the inventory year varied from 1984 to 2020. Therefore, we needed to grow all stands to the common 2020 baseline where the SEL begins (Figure 2). In the context of WHINGS, this growth required protocols for successional or stand age transitions and increases in size class.

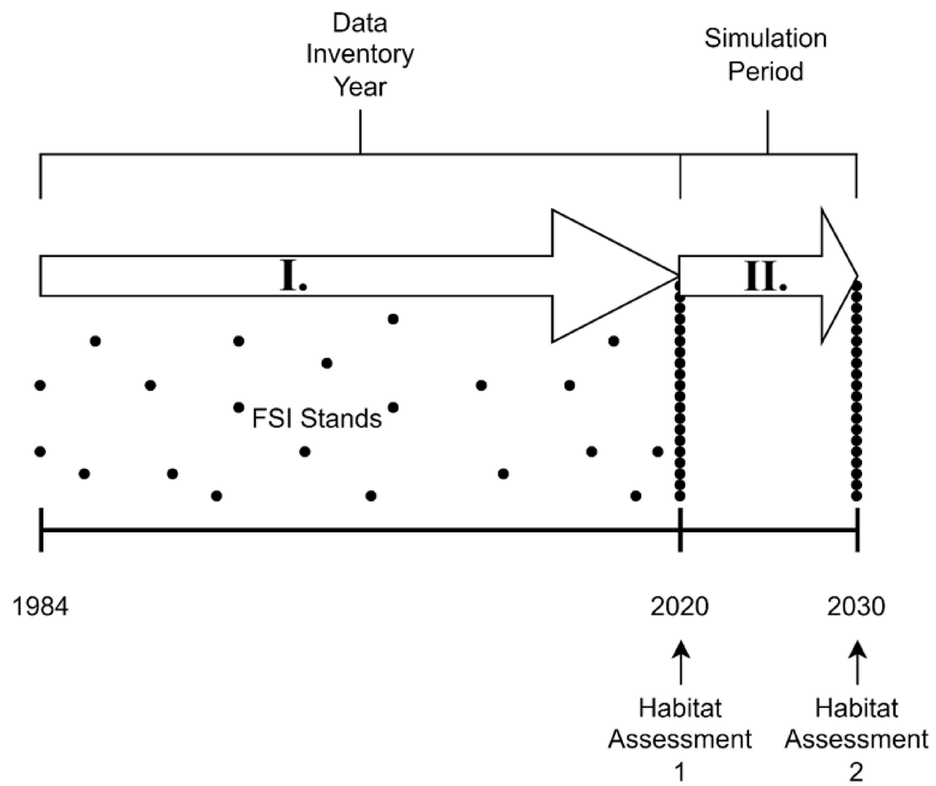

Figure 2. Schematic of two stages of stand advancement/growth and habitat assessment based on planned sustainable timber harvest in Minnesota, USA. (**I.**) Forest stand inventory (FSI) stands of various inventory years advance to a 2020 baseline with stand age and size class transition protocols. (**II.**) Stand Exam List stands enter simulated harvest scenarios while remaining FSI stands continue advancement/growth.

2.5.1. Stand Age Protocol

As stands advance, some grow beyond realistic ages for their respective forest types. Literature-based maximum ages for each forest type from [32] determined appropriate cutoffs. The modeling complexity of successional stand dynamics for multiple cover types necessitated simplified assumptions for the biological growth of stands. Stands that reached the literature-based maximum ages maintained their current cover type, but reset to age 0, then continued growing. Although not perfect, this method operates within the limits of the coarse FSI data and reflects typical MN DNR prescriptions to maintain the forest type.

2.5.2. Size Class Protocol

As stands advance, transitions between size classes are likely to occur. However, FSI data only include stand-level variables and lack detailed growth information. Therefore, a machine learning, random forest classification algorithm was used to determine the best predictors of size class from among mostly static variables. Ultimately, the predictors FSI-assigned forest type, site index, and stand age defined the classification algorithm for the predicted size class. Each stand was then advanced to 2020 by updating the stand age and applying the stand age protocol, while keeping the forest type and site index constant. The size class protocol was then applied to assign the 2020 size class.

2.6. Simulations

In order to estimate the range of possible wildlife habitat impacts on the TESC species, we simulated the growth of all FSI stands, subject to harvest prescriptions from the SEL. We assumed any harvesting stemmed solely from the MN DNR 10-year Stand Exam List, while remaining FSI stands continued to grow via the stand age and size class transition protocols. To balance realism with a simplified process, several criteria were developed to guide the simulations.

Harvest Methodology

Since not all examined stands elicit harvest, recent harvest rates informed the simulation strategy for harvest probability. As stated by the MN DNR, approximately 60% of examined stands are offered for sale, though this varies year to year [20]. To capture the upper limit of the manipulated habitat, we assumed all hectares offered are sold. To simulate harvest selection and varying harvest rates, harvest probabilities were derived from a binomial distribution with probability 0.6 ($\pm$0.05 standard deviation) (Equation (2)).

$$Binom\ (\mathrm{n, p = N\ (0.6, 0.05)}) \tag{2}$$

Lag times from stand examination to actual stand harvest also required simulation, as the habitat would not change until actual harvest. Data obtained from the MN DNR on timber sales suggested an average lag time of 2.4 years, with a standard deviation of 1.6 years [33]. Logically, the distribution of lag times cannot include negative values and will likely be skewed to the right. Therefore, a lognormal distribution was selected to simulate the lag times according to Equation (3).

$$ln\ N\ (2.4, 1.6) \tag{3}$$

Utilizing the SEL-provided stand exam year and management prescription code, stands selected for harvest received one of three simulated management prescriptions:

1. Even-aged—Stands assumed a clearcut strategy. If selected for harvest, age was reset to zero, and the stand maintained the original forest type.
2. Thinning—A thinning prescription assumed management as even-aged and "thinning from below". Since WHINGS functions track only the general size class, harvest activities do not impact stands with a thinning code. "Thinning from below" indicates the removal of smaller diameter trees. Under this assumption, the general size class will not change (e.g., a poletimber-sized stand will remain poletimber-sized even after the removal of smaller diameter trees). These stands simply continued biological growth, subject to age class and size class transition protocols.
3. Uneven-aged—With uneven-aged management, stands assumed a balance of multiple age classes. An uneven-aged harvest assumes a harvest of trees from multiple age classes, thus maintaining the general size class (e.g., a poletimber stand remains poletimber after harvest activities). Selected stands for harvest continued biological growth, unless they reached the maximum age for the cover type. If a stand reached maximum age, the harvest of older age classes was assumed, leaving the younger trees behind. Based on this assumption, stands selected for uneven-aged management that reached maximum age were reset to the midpoint of the maximum age to reflect younger age classes remaining in the stand.

2.7. Harvest Scenarios

To reflect the impacts of the 10-year SEL, stands were grown forward over a simulation period from the 2020 baseline to 2030 (see Figure 2). A series of scenarios utilized variations of the described harvest methodology to capture an envelope of possible outcomes:

1. Biological growth—Stands were grown from 2020 to 2030 subject to stand age and size class transition protocols. No harvest took place, thus no lag time, harvest probability, or management prescription was applied. Of note, this scenario is not realistic in practice, but provides a lower bound for conducting comparisons.
2. Realistic harvest/growth—All stands were grown from 2020 to 2030, subject to the harvest methodology. Stands not selected for harvest grew forward just as in the

biological growth scenario. This scenario required simulations to capture the range of possible outcomes.

3. Complete harvest—All stands were grown from 2020 to 2030, and all stands on the 10-year SEL were harvested in their examination year. Lag time and harvest probability did not apply, though the management prescription of each stand remained. Of note, this scenario is also not realistic in practice, but provides an upper bound for comparisons.

2.8. Analysis and Comparison

The WHINGS framework provided habitat assessment at the 2020 baseline and following each harvest scenario in 2030. This assessment provided estimates of habitat quality (HSI), quantity (HE), and their combination (HU) for all five species. Simulations of the realistic harvest/growth scenario used 1000 iterations and produced standard errors for significance testing at the statewide level. Since the biological growth and complete harvest scenarios did not require simulations, 1000 bootstrap samples were used to derive standard errors. In addition, simulation and bootstrap means and their variation were retained by an analysis unit to provide more fine-scale spatial changes in habitat. However, results at the individual analysis unit level did not allow for significance testing, due to a lack of degrees of freedom (n = 1, since an analysis unit represents the minimum Habitat Unit). Therefore, absolute changes $\geq$ 25% at this scale were considered significant, similar to the criteria used in the original GEIS [18], and this cutoff was used when producing all change maps. Additionally, relative standard errors (simulation or bootstrap standard errors divided by the mean) $\geq$25% were considered as indicating high variability within an analysis unit, while relative standard errors < 25% indicated low variability.

Overall, significant changes were tracked by TESC species by a harvest scenario at the statewide and analysis unit levels, with an emphasis on the realistic harvest/growth scenario. Change maps were developed for each species and each harvest scenario, where the percentage change in HU was the metric tracked. All data management, habitat projections, simulations and bootstrapping were conducted in the R statistical program [34].

3. Results

Simulations were successfully completed per the described methodology and the outputs fed into the WHINGS framework for habitat assessment. Both the Acadian flycatcher and hooded warbler habitats showed a statistically significant 3.0% decrease in HSI (habitat quality) for the realistic harvest/growth scenario and a statistically significant 10.4% decrease in HSI for the complete harvest scenario (Table 2). Cerulean warbler habitat showed statistically significant decreases in HSI of 1.8% and 6.6% for the realistic harvest/growth and complete harvest scenarios, respectively (Table 2). While not statistically significant, HU percent changes followed the same decreasing trend along the spectrum from biological growth to realistic harvest/growth to complete harvest for each of the three species. The change map in Figure 3 reflects these changes by an individual analysis unit, with more severe decreases in HU and HSI occurring in southern Minnesota and less severe decreases in central Minnesota for all three species. Note that the extent of forested land within the FSI remained constant across all simulations (i.e., we assumed no land use changes between 2020 and 2030), so results for HE were not reported.

The Louisiana waterthrush habitat displayed statewide HU and HSI percent change metrics with statistically significant increases in HU and HSI under the biological growth scenario and statistically significant decreases in HU and HSI under the complete harvest scenario (Table 2). Under the realistic harvest/growth scenario, the species showed increases in both HU and HSI, though not statistically significant. Visually, these changes occurred most drastically in the eastern half of the state (Figure 4).

Table 2. Habitat Unit (HU) and Habitat Suitability Index (HSI) percent change estimates from 2020 to 2030 on a statewide basis for five Minnesota threatened, endangered, and special concern species from the three harvest/growth simulation scenarios on Minnesota Department of Natural Resources lands. Values in bold indicant statistical significance at a 0.05 significance level. Caution should be taken in interpreting results for the biological growth and complete harvest scenarios as those scenarios are unlikely to occur in reality and rather serve as upper and lower bounds.

			HU %Change			HSI %Change	
Common Name	**Scientific Name**	**Biological**	**Realistic**	**Complete**	**Biological**	**Realistic**	**Complete**
Acadian flycatcher	*Empidonax virescens*	3.3	−2.6	−10.6	2.3	**−3.0**	**−10.4**
Cerulean warbler	*Dendroica cerulea*	3.1	−2.3	−9.8	1.7	**−1.8**	**−6.6**
Hooded warbler	*Wilsonia citrina*	3.3	−2.6	−10.6	2.3	**−3.0**	**−10.4**
Louisiana waterthrush	*Seiurus motacilla*	**13.2**	4.0	**−9.9**	**4.8**	0.2	**−6.2**
Timber rattlesnake	*Crotalus horridus*	3.8	−5.7	−19.1	1.8	−2.8	−7.6

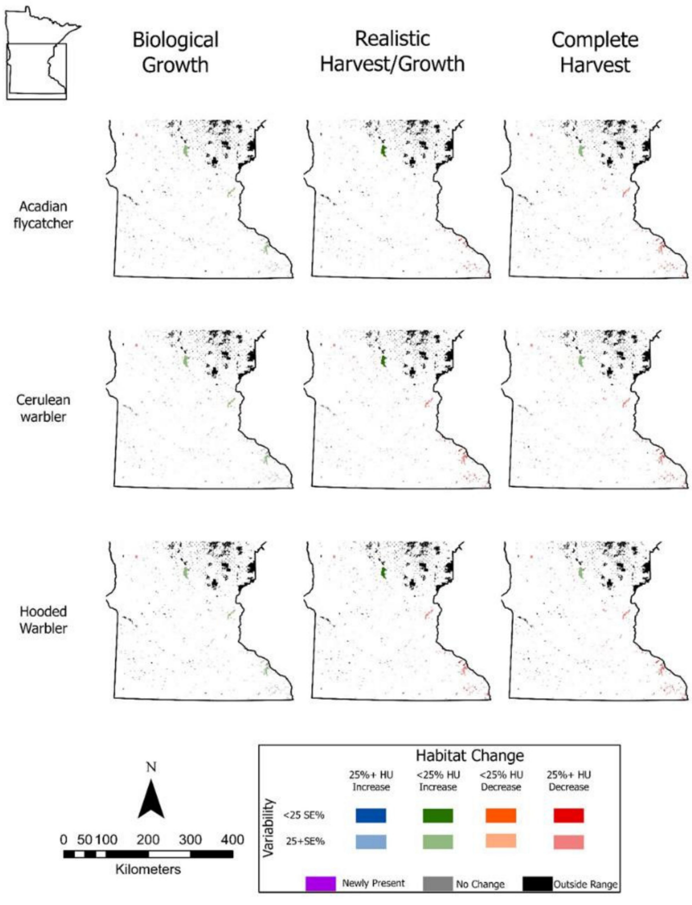

Figure 3. Habitat Unit (HU) percent change of three Minnesota threatened, endangered, and special concerns species under three simulated harvest/growth scenarios on Minnesota Department of Natural Resources lands. SE% refers to the standard error relative to the 2020 HU value.

The timber rattlesnake habitat, concentrated in southeastern Minnesota, displayed mild and nonsignificant HU and HSI changes (Table 2). These changes followed a trend of increases under the biological growth scenario to decreases in the realistic growth/harvest and complete harvest scenarios (Figure 4).

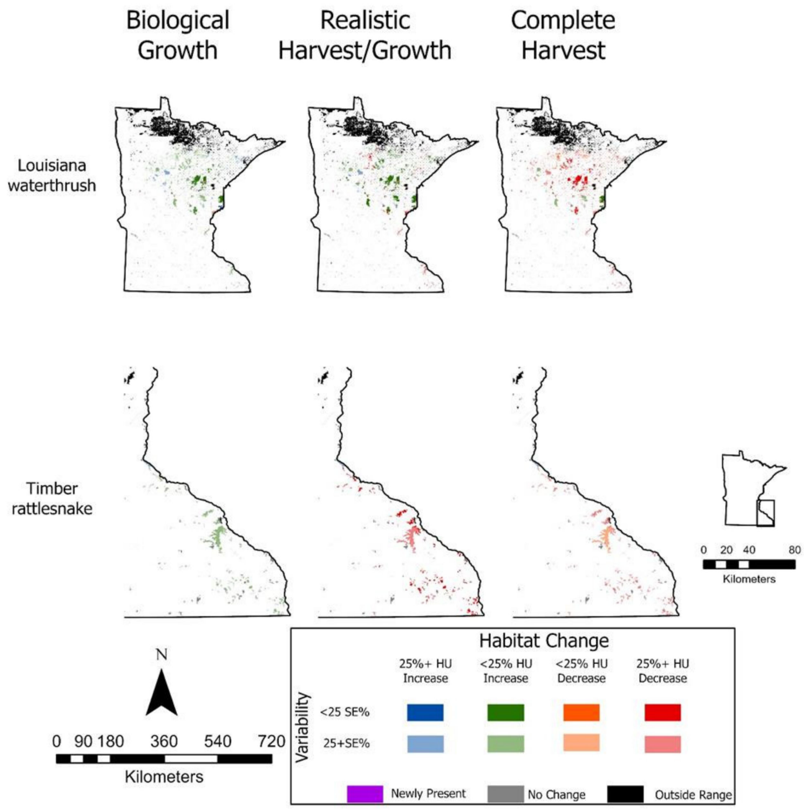

Figure 4. Habitat Unit (HU) percent change of two Minnesota threatened, endangered, and special concerns species under three simulated harvest/growth scenarios on Minnesota Department of Natural Resources lands. SE% refers to the standard error relative to the 2020 HU value.

4. Discussion

While the realistic harvest/growth scenario is the most plausible harvest scenario presented, viewing all scenarios in context with one another proved helpful. The biological growth and complete harvest scenarios provided insights into the range of possible changes. In general, the biological growth scenario showed increases in both HU and HSI, while the complete harvest scenario showed decreases in HU and HSI. Though displaying mostly decreases and one increase, the HU and HSI change values from the realistic harvest/growth scenario fell closer to the middle, with more moderate values compared to the extremes of the other two scenarios.

In this modeling effort, since forest type and extent of forest land remained consistent throughout the 10-year period, changes in size class largely drove the projected habitat changes. In the absence of harvest, stands progressed from smaller size classes to larger sizes classes. The reverse occurred for stands where harvest took place. No harvesting will favor species that prefer larger size classes, while more harvesting will favor species that prefer smaller size classes. Generally, the five TESC species analyzed in this study tended to prefer mature forests. Unsurprisingly, habitats for these species benefited from less harvest, because biological growth alone trended toward mature forests. Since the species modeled in this study are largely of mature forest preference, habitat benefits from scenarios that increase size classes are expected. This suggests that less intensive harvest will benefit the TESC species analyzed in this study. However, managing these species does not occur in a vacuum, as decisions lead to consequences for other species and forest resources.

The past literature understands and accepts the idea of tradeoffs between economic benefits and environmental protection (e.g., [35,36]). A strict focus on a single benefit, whether economic or environmental, often comes at the expense of other benefits. The majority of species in this study would benefit from reduced harvesting. However, other species in Minnesota rely on recently harvested, young forest habitats. Zobel et al. [6] confirmed these tradeoffs across all ownerships in Minnesota when analyzing wildlife species over the past 41 years, finding that the diversity of wildlife species requires a balance of forest management. Beyond the wildlife habitat, multiple forest resources show tradeoffs from harvesting, such as wood volume, carbon storage, and coarse woody debris (e.g., [37]). Meanwhile, the species in this study require targeted habitat management as they are rare or limited in their distribution. If conservation of such species is the primary management goal, targeting specific locations for habitat management efforts will be critical.

The realistic harvest/growth scenario falling between the two extremes of biological growth and complete harvest may reflect the balancing of such tradeoffs in practice, at least partially. The development of the 10-year SEL was born from the STHA, which sought to incorporate multiple forest resource objectives [19]. Relative to the others, the moderation of the realistic harvest/growth scenario may imply that it reasonably accounts for the habitat of the five TESC species amid competing objectives, if the simulated assumptions are ultimately realized. When viewed relative to the envelope, species HU changes were tempered away from declines (statistically significant for one species) of complete harvest and increases (statistically significant for one species) of solely biological growth. Percent differences for all species, whether HU or HSI, were all less than $\pm 6\%$ for the realistic harvest/growth scenario. Although opportunities to improve habitat conditions for an individual TESC species exist, the overall impact of the realistic harvest/growth scenario appears to moderate the habitat effects while considering many objectives. The translation of these results into management or policy actions will require careful consideration of priorities and tradeoffs.

Future research should address the limitations of this study, largely related to the underlying data and the broad assumptions of the harvest scenarios. Outdated FSI data may lead to inaccuracies, so improvements or an updated inventory will benefit simulations. Harvest rates and lag times likely vary by cover type and by region, so blanket assumptions of harvest rates and lag times across all cover types and all regions is an oversimplification. Future work to refine simulations with cover type and region-specific harvest methodology will improve the realism of harvest scenarios. Future research that incorporates additional species and other forest resource objectives would benefit the investigation of tradeoffs. The underlying GEIS habitat models were developed by wildlife experts, though some models are nearly 30 years old. Research trends in wildlife habitats [38] suggest that individual habitat models would benefit from assessment and updating according to emerging wildlife knowledge and research. Beyond simple updates, additions to underlying models, such as spatial interactions of multiple habitat cover types, may be beneficial. In addition, the restricted spatial and species scope of this study limits broad inference, as analysis included only MN DNR lands and only five species. Although the home ranges of the studied species allow for this narrower analysis, the inclusion of adjacent lands and all ownerships would expand the utility of the simulations. Still, these results reflect the habitat effect of modern state-agency forest management on critically important native wildlife species and provide a quantitative assessment to inform future management and policy directions.

5. Conclusions

This study utilized simulations of planned timber harvests to assess potential changes in rare species habitats in Minnesota, USA. Timber harvest scenarios were biological growth (i.e., no harvest), realistic harvest/growth, and complete harvest. The five TESC species in this study each have a preference for mature forest, and therefore, their habitat benefited the most from scenarios that included less harvest. The realistic harvest/growth scenario resulted in statistically insignificant habitat changes of less than $\pm 6\%$, while two scenarios providing the upper and lower extremes of harvest resulted in statistically significant changes for one species each. The STHA and the subsequent 10-year SEL were developed with multiple forest resource objectives in mind, and the moderating of habitat changes under the realistic scenario compared to more extreme scenarios may be a reflection of the tradeoffs from these multiple objectives. Alongside the opportunity to further advance this research, this study provides a useful assessment of the effects of agency-wide management decisions on rare species habitats.

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